Fluorination by Sulfur Tetrafluoride

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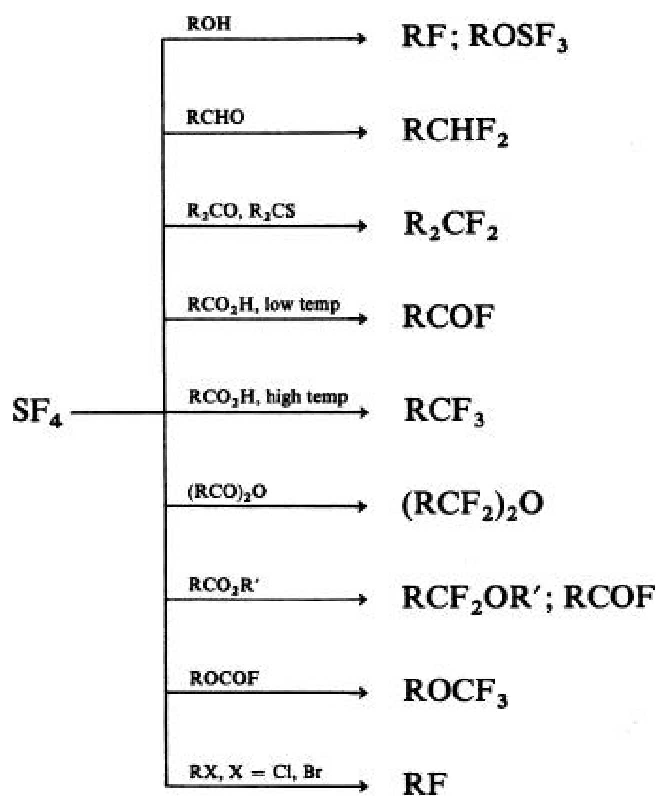
1. Introduction

This chapter is an update of Chapter 1 of Volume 21 of *Organic Reactions*, (1) based on the nearly 110 publications that have appeared from 1972 through 1982. Since the nature of the reaction and its mechanistic considerations have been clearly described in the previous chapter, they are not repeated. However, mechanisms involving the reaction of sulfur tetrafluoride with certain specific compounds are discussed under "Scope and Limitations".

Sulfur tetrafluoride continues to be one of the more common fluorinating agents, especially for relatively inert substrates. Its synthetic applications are summarized in Scheme 1.

Scheme 1.



2. Scope and Limitations

2.1. Alcohols

2.1.1.1. Haloalcohols

It has been suggested that an alkoxysulfur trifluoride is an intermediate in the replacement of a hydroxyl group by fluorine with sulfur tetrafluoride. (2) In a test of this proposal, α , α , ω -trihydroperfluoroalkoxysulfur trifluorides have been isolated from the reaction of α , α , ω-trihydroperfluoroalkanols with sulfur tetrafluoride in the presence of alkali metal fluorides at –60° to 20°. (3) Alkoxysulfur trifluorides **1** are colorless liquids that are readily

$$H(CF_2)_nCH_2OH \xrightarrow[\text{KF or NaF, } -60 \text{ to } 20^\circ]{SF_4} \underset{\mathbf{1}}{H(CF_2)_nOSF_3}$$

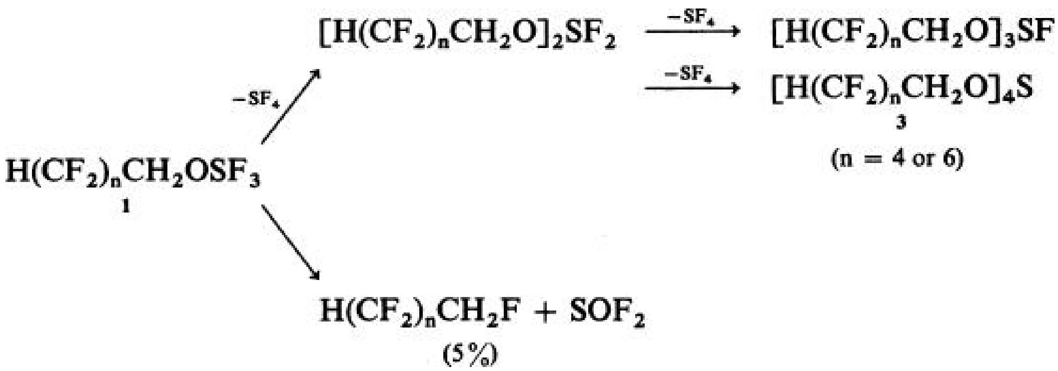
$$(75\text{–}85\%)\quad (n = 2, 4 \text{ or } 6)$$

hydrolyzed by atmospheric moisture to the corresponding alcohols, hydrogen fluoride, and sulfur dioxide. On controlled hydrolysis they are converted quantitatively into the fluorides of α , α, ω -trihydroperfluoroalkoxysulfurous acids **2**. (3)

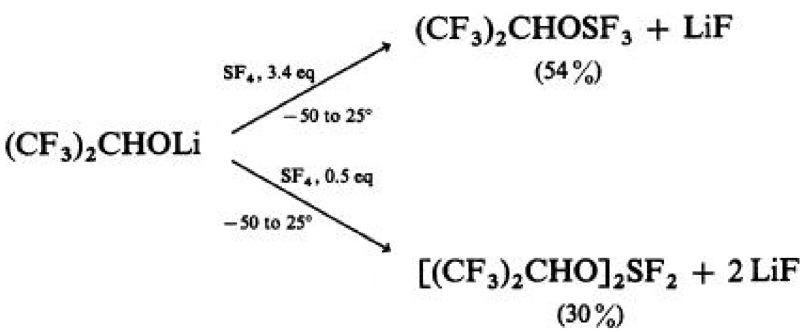
$$\underset{\mathbf{1}}{H(CF_2)_nCH_2OSF_3} + H_2O \longrightarrow \underset{\mathbf{2}}{H(CF_2)_nCH_2O_2SF} + 2HF$$

$$(n = 4 \text{ or } 6)$$

1,1,3-Trihydroperfluoropropoxysulfur trifluoride (**1**, n = 2) decomposes completely after a few minutes at 20° to form a complex mixture of unidentified products. Compounds **1** (n = 4 or 6), however, gradually disproportionate into sulfur tetrafluoride and tetrakis(α , α , ω -trihydroperfluoroalkoxy)sulfuranes (**3**) through the formation of unstable difluoro- and monofluorosulfuranes. α , α , ω -Trihydroperfluoroalkanes are formed in a side reaction in yields of less than 5%. (3) These results suggest that in the preceding reactions alkoxysulfur trifluorides are not precursors of fluorination products.

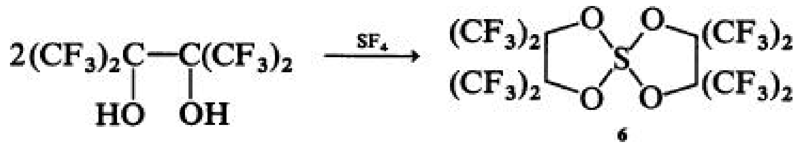


Lithium 1,1,1,3,3,3-hexafluoroisopropoxide, prepared from 1,1,1,3,3,3-hexafluoro-2-propanol and *n*-butyllithium, reacts with sulfur tetrafluoride in 1,3-dimethoxybenzene to afford either 2,2,2-trifluoro-1-(trifluoromethyl)-ethoxysulfur trifluoride or bis[2,2,2-trifluoro-1-(trifluoromethyl)ethoxy] sulfur difluoride as the major product, depending on the amount of sulfur tetrafluoride used. (3a) These two reagents have been used to replace hydroxy groups by fluorine. (3a)



Saturated tertiary polyfluoroalcohols usually give olefins on fluorination with sulfur tetrafluoride. However, exceptions are found in certain cases. For example, perfluorodialkyl sulfide **4** behaves as a typical diol in its reaction with sulfur tetrafluoride to give fluorinated product **5**. (4)

Reaction of sulfur tetrafluoride with perfluoropinacol at 20° yields the corresponding spirosulfurane **6**. (5)



6

(85%)

2.1.1.2. Hydroxyamines and Hydroxyamino Acids

Fluorination of alcohols by sulfur tetrafluoride is limited to those containing highly acidic hydroxy groups. The reactivity of sulfur tetrafluoride with many alcohols is dramatically increased, and the chemoselectivity improved, by employing liquid hydrogen fluoride as a solvent. (6) On the other hand, the reactivity of sulfur tetrafluoride with carbonyl compounds and carboxylic acids is not concomitantly increased, and thus the sulfur tetrafluoride-hydrogen fluoride combination is a selective fluorinating system for alcohols. Hydrogen fluoride plays roles as both a catalyst and a solvent in the transformation of hydroxy amines and hydroxyamino acids into fluoroamines and fluoroamino acids, respectively. This procedure has been termed *fluorodehydroxylation*. (6) The method consists of reacting sulfur tetrafluoride with these alcohols in liquid hydrogen fluoride solution at low temperature, usually at –78°, and atmospheric pressure. In amino acids the amino group is protonated by hydrogen fluoride and thus protected against the electrophilic reagent. In the absence of this protection, the amino groups react with sulfur tetrafluoride to form iminosulfur difluorides. The results obtained with free amino acids indicate that there is no need to protect the carboxylic acid groups. Several examples of fluorodehydroxylation are given in Eqs. 1–4. (6, 7)

$$C_6H_5CHOHCH(NH_2)CO_2H \xrightarrow[-78^\circ]{SF_4,\ HF} \underset{(65\%)}{C_6H_5CHFCH(NH_2)CO_2H} \qquad (1)$$

$$HOCH_2CH(NH_2)CO_2H \xrightarrow[-78^\circ]{SF_4,\ HF} \underset{(51\%)}{FCH_2CH(NH_2)CO_2H} \qquad (2)$$

(52%)

(3)

$$(CH_3)_3\overset{+}{N}CH_2CH_2OH\ Cl^- \xrightarrow[-78^\circ]{SF_4,\ HF} \underset{(75\%)}{(CH_3)_3\overset{+}{N}CH_2CH_2F\ Cl^-} \quad (4)$$

A comparison of conventional fluorination by sulfur tetrafluoride with fluorodehydroxylation is shown in Table 1. (7, 8)

Table 1. Conventional Fluorination with SF_4 versus Fluorodehydroxylation

Substrate	Reaction Product Under Conventional Conditions[a]	Reaction Product in Fluorodehydroxylation[b]
C_6H_5CHO	$C_6H_5CHF_2$	No reaction
$C_6H_5COCH_2NH_2$	—	No reaction
$H_2NCH_2CO_2H$	$H_2NCH_2CF_3$	No reaction
$HOCH_2CH(NH_2)CO_2H$	No useful reaction	$FCH_2CH(NH_2)CO_2H$

[a]The reaction was carried out at 50–200° in a sealed system.

[b]The reaction was run in liquid HF solution at –78° and atmospheric pressure.

The mechanism of the reaction appears to involve initial generation of a leaving group at the alcoholic carbon atom. (7) This is followed by fluorine substitution that is mechanistically dependent on the structural type: S_N1 reactions of compounds that form carbonium ions easily, and S_N2 reactions of compounds with primary and secondary alkyl groups that usually require direct displacements (Eqs. 5–8).

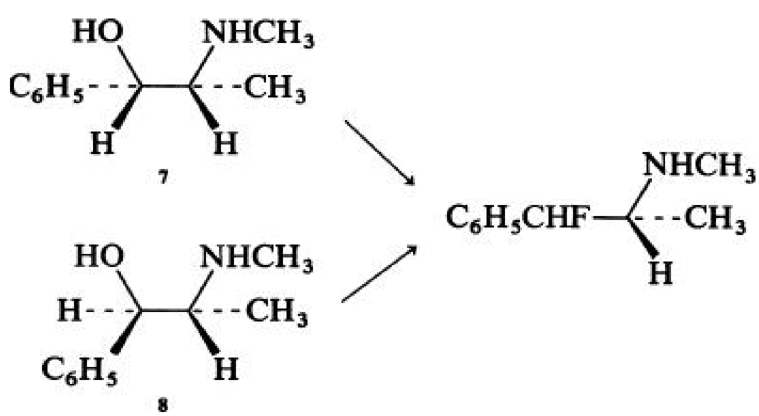
$$SF_4 + HF \longrightarrow SF_3^+ + HF_2^- \quad (5)$$

$$ROH + SF_3^+ \longrightarrow ROSF_3 + H^+ \quad (6)$$

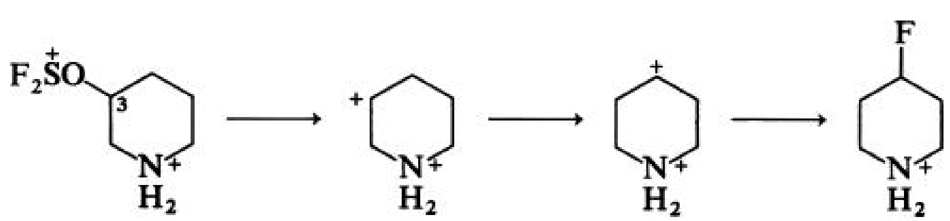
$$ROSF_3 + HF \longrightarrow ROSF_2^+ + HF_2^- \quad (7)$$

$$ROSF_2^+ + F^- \longrightarrow RF + SOF_2 \quad (8)$$

Evidence for the S_N1-type mechanism is provided by the following two examples. Fluorodehydroxylation of the diastereomeric benzylic alcohols *d*-ephedrine (**7**) and pseudoephedrine (**8**) afford, in 100% yields, the same ~2 : 1 mixture of 1-phenyl-1-fluoro-2-(methylamino)propanes. (7) This implies that bond breaking precedes bond making in those precursors that form

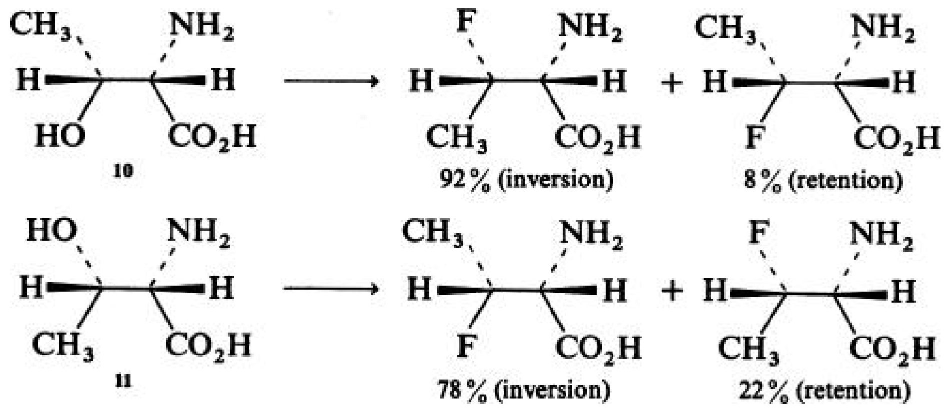


carbonium ions easily. Another example that involves a carbonium ion intermediate is the formation of 4-fluoropiperidine (**9**) on fluorodehydroxylation of both 3- and 4-hydroxypiperidines. (7)



A positive charge at position 3 of the protonated piperidine ring would be destabilized relative to one in the 4 position because the charge in the 4 position would be one additional bond away from the positively charged nitrogen; hence a migration to this position is expected.

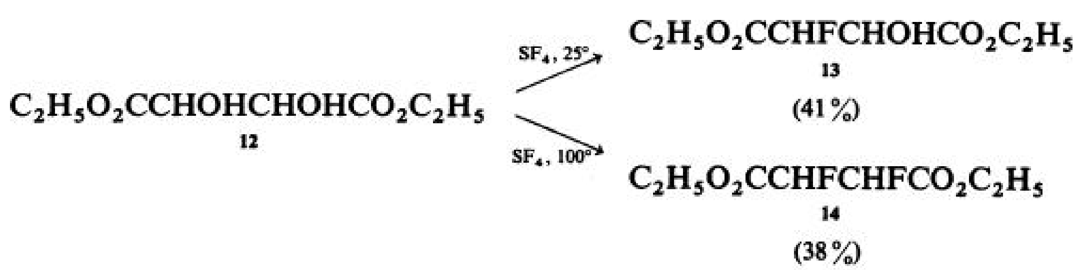
Evidence for an S_N2 displacement is based on the results of fluorodehydroxylation of L-threonine (**10**) and its C-3 epimer L-allothreonine (**11**). In both

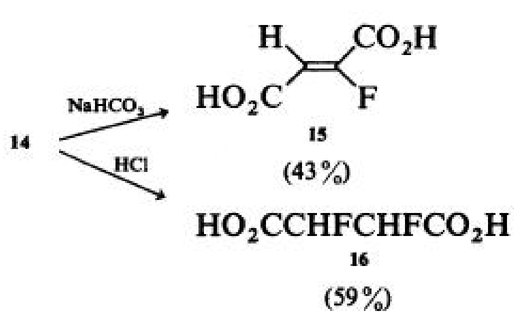


reactions a mixture is formed in which the major product is the one with an inverted configuration at C-3; threonine and allothreonine afford inverted products in yields of 92 and 78%, respectively. (7)

2.1.1.3. Hydroxyesters and Hydroxyacids

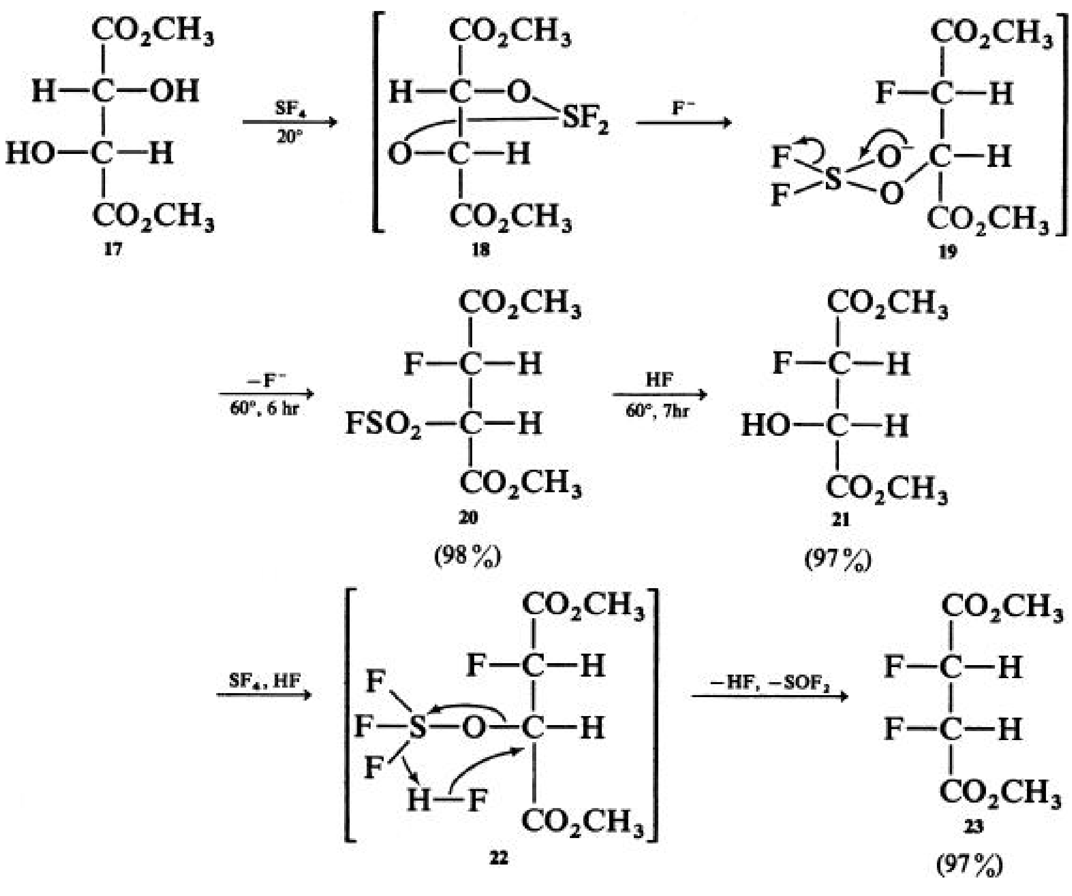
In the reaction of dialkyl tartrate **12** with sulfur tetrafluoride, one or two hydroxy groups can be substituted by fluorine, depending on the fluorination conditions. At 25° one hydroxy group in diethyl tartrate is replaced by fluorine, whereas at 100°, diethyl α , α′-difluorosuccinate is formed. (9) The ester **13** is unstable and readily eliminates hydrogen fluoride when stored or distilled under vacuum.



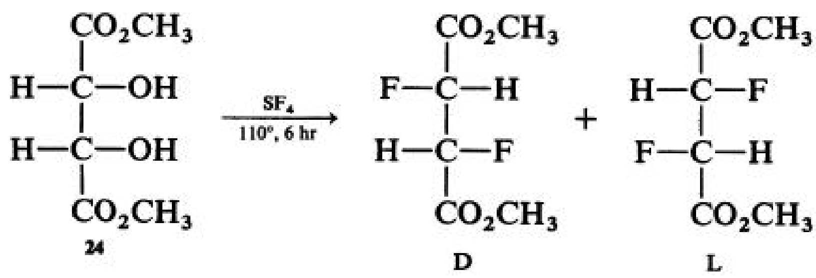


Treatment of **14** with sodium bicarbonate solution gives fluorofumaric acid (**15**), whereas acid hydrolysis affords α , α′-difluorosuccinic acid (**16**).

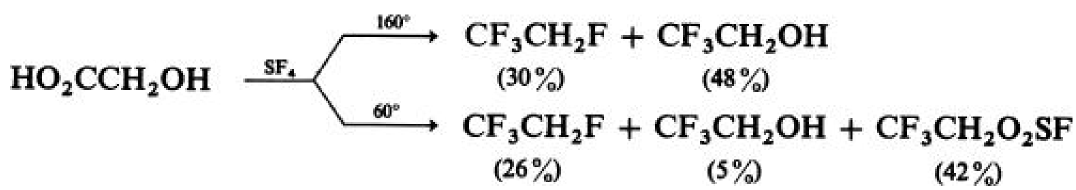
The mechanism and stereochemical outcome of this reaction have been studied in detail. (10, 11) Treatment of dimethyl(+)-L-tartrate (**17**) with sulfur tetrafluoride at 20° gives fluorosulfite **20** in 98% yield. (11) The first intermediate is believed to be the cyclic compound **18**, which is converted by an S_N2 reaction into anion **19** with inversion of configuration at one of the chiral carbon atoms. Loss of fluoride ion then results in the formation of fluorosulfite **20**. Cleavage of the latter by hydrogen fluoride gives the fluoroalcohol **21** in 97% yield. Further treatment of fluoroalcohol **21** with sulfur tetrafluoride in the presence of hydrogen fluoride proceeds by way of intermediate **22** to give dimethyl *meso*- α , α ′-difluorosuccinate (**23**) with retention of configuration at the second chiral center.



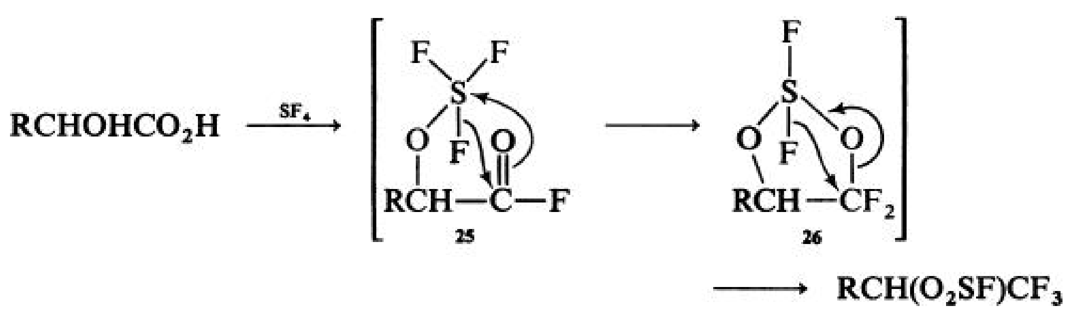
Similarly, dimethyl *meso*-tartrate (**24**) is converted by sulfur tetrafluoride into a racemic mixture of dimethyl D- and L- α , α ′-difluorosuccinates. (10)



The reactions of α -hydroxy acids with sulfur tetrafluoride have not been investigated extensively. It is reported that glycolic acid reacts with sulfur tetrafluoride at 160° to form a mixture of 1,1,1,2-tetrafluoroethane (48%) and fluoroacetyl fluoride (18%). (2) However, it has been shown that the second product of this reaction is trifluoroethanol rather than fluoroacetyl fluoride. (12) At 60°, 2,2,2-trifluoroethyl fluorosulfite is formed as the major product.



The carboxyl group is probably converted into a fluoroformyl group, and the alcohol group is converted into the trifluorosulfite with the formation of intermediate **25**. One fluorine atom of the trifluorosulfite group is then transferred to the carbonyl carbon, leading to a cyclic intermediate **26**. The



latter isomerizes to the trifluoroalkyl fluorosulfite. The formation of the fluorosulfite thus requires the presence of hydroxy and carbonyl groups adjacent to each other. This is confirmed by the reaction of alcohol **27** with sulfur tetrafluoride, in which a fluorosulfite is not obtained but rather substitution of the hydroxy group by fluorine occurs, accompanied by elimination of hydrogen fluoride. (12)

$$\underset{\mathbf{27}}{CF_3CH_2CHOHCF_3} \xrightarrow{SF_4} CF_3CH_2CHFCF_3 + CF_3CH{=}CHCF_3$$

The formation of trifluoroethanol in the reaction of glycolic acid with sulfur tetrafluoride at 160° can probably be explained by protonation of the ester oxygen in the trifluoroethyl fluorosulfite **28** by hydrogen fluoride with subsequent elimination of thionyl fluoride.

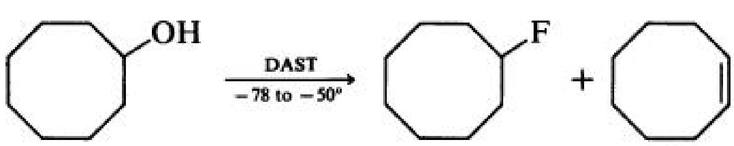
$$\underset{\mathbf{28}}{CF_3CH_2O_2SF} \xrightarrow{HF} [CF_3CH_2\overset{+}{O}(H)SOF\ F^-] \longrightarrow CF_3CH_2OH + SOF_2$$

2.1.1.4. An Alternative Method for Direct Replacement of Hydroxy Groups by Fluorine

Substitution of one of the fluorine atoms in sulfur tetrafluoride by a diethylamino group gives diethylaminosulfur trifluoride (DAST)[*]. (13, 14) This reagent is particularly useful for fluorination of alcohols. (15) The reaction

$$(C_2H_5)_2NSi(CH_3)_3 + SF_4 \xrightarrow{-65\ \text{to}\ -60^\circ} \underset{\text{DAST (84\%)}}{(C_2H_5)_2NSF_3} + FSi(CH_3)_3$$

of DAST with alcohols to replace the hydroxyl group with fluorine appears to be a general reaction, offering the following advantages compared with sulfur tetrafluoride: fluorinations of alcohols with the less reactive DAST are more selective, with fewer rearrangements or eliminations. In addition, DAST is a less volatile liquid, easy to work with and reactions under pressure are not necessary. However, dehydration reactions may occasionally predominate (14, 16)



(Ref. 14)

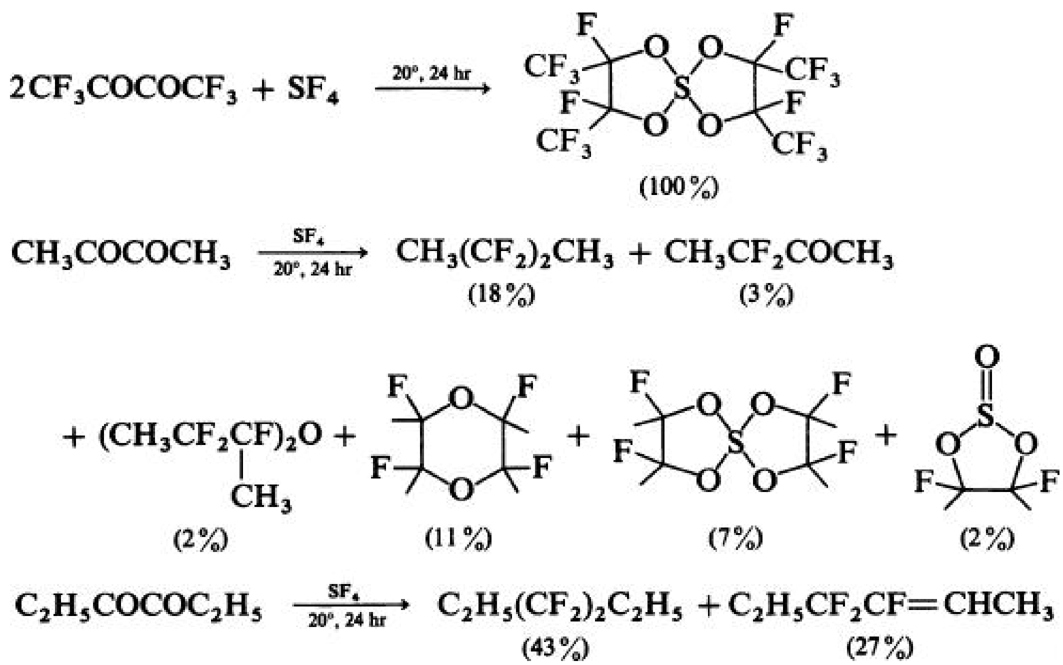
(70%) (30%)

in DAST fluorinations, and there are reports of explosions. (17, 18)

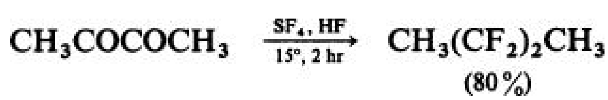
2.2. Aldehydes and Ketones

2.2.1.1. 1,2-Dicarbonyl Compounds

The reaction of perfluoro-2,3-butanedione with sulfur tetrafluoride proceeds by an unusual route to give perfluorobutylene glycol 2,3-orthosulfite in quantitative yield. (19) However, unfluorinated aliphatic α -diketones afford the corresponding tetrafluoroalkanes as the major products. (20)

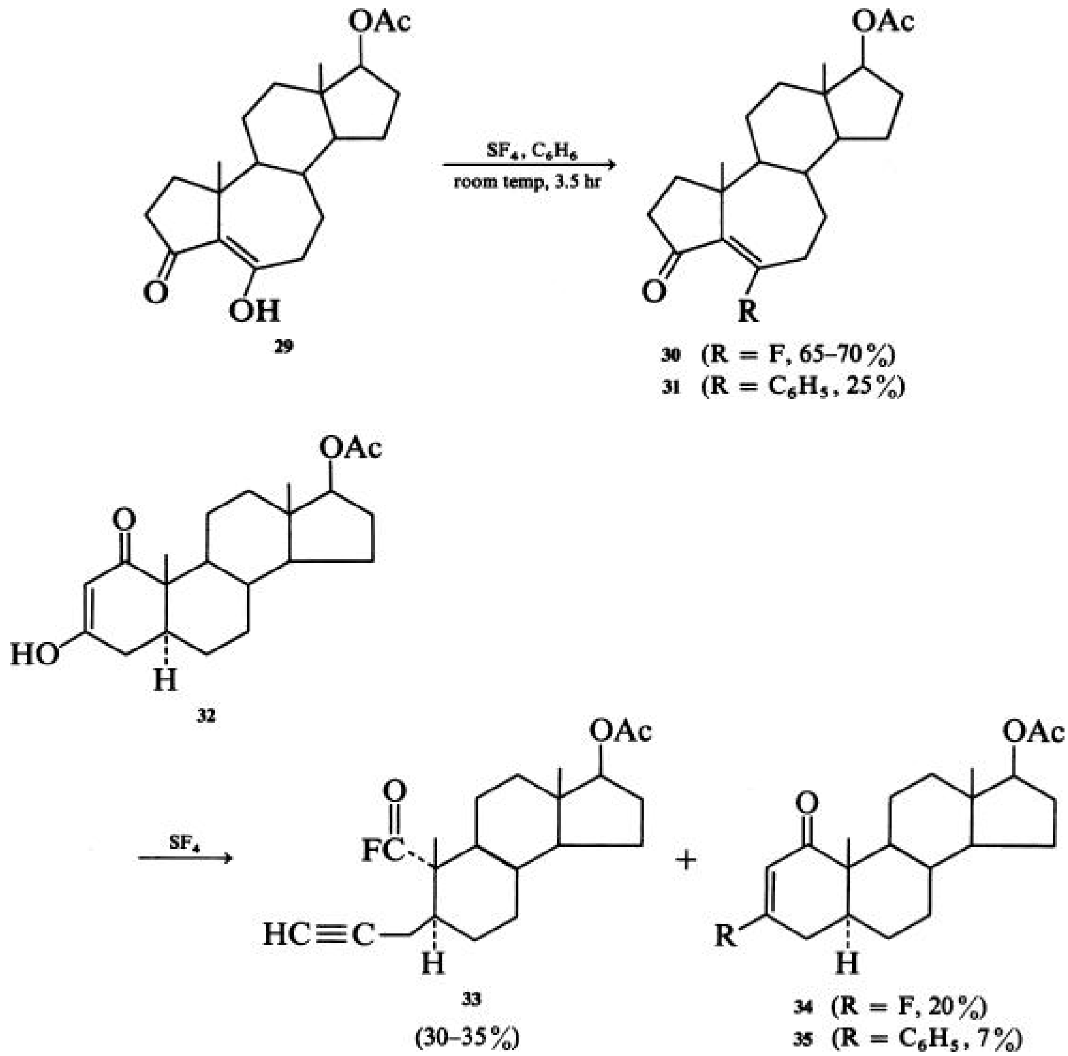


The yields of these tetrafluoroalkanes are greatly improved in anhydrous hydrogen fluoride. (20)



2.2.1.2. 1,3-Dicarbonyl Compounds

The reaction of enolizable 1,3-dicarbonyl compounds with sulfur tetrafluoride has not been well studied. A 1,3-diketo steroid (**29**) with a fixed *Z* configuration at the enolic double bond reacts with sulfur tetrafluoride in anhydrous benzene to give the β -fluoro- α , β -unsaturated ketone **30** and a minor product **31** containing a phenyl group at the β position. (21) The 17-acetoxy diketone **32**, with an *E* configuration at the enolic double bond, gives three products under the same conditions. (21)



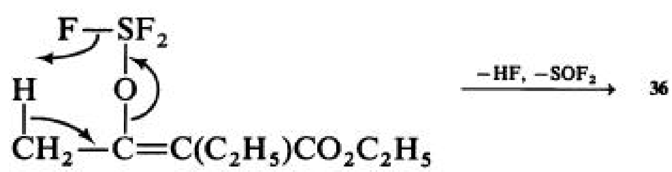
These results demonstrate that both types of β -diketones behave formally like vinylogous acids, with substitution of the enolic hydroxy group of the most stable tautomer by fluorine (i.e., **30** and **34**). Under the specific reaction conditions used, no further fluorination of the second carbonyl group takes place.

Fluorination of acetoacetic esters leads to products that depend on the α -substitution pattern. (22) For example, ethyl acetoacetate reacts with sulfur tetrafluoride at 100° to give ethyl 2-butynoate, *cis*- and *trans*-3-fluoro-2-butenoic esters, and ethyl 3,3-difluorobutanoate. (22, 23)

$$CH_3COCH_2CO_2C_2H_5 \xrightarrow[100^\circ]{SF_4} \underset{(38\%)}{CH_3C{\equiv}CCO_2C_2H_5} + \underset{(cis,\ 16\%;\ trans,\ 5\%)}{CH_3CF{=}CHCO_2C_2H_5} + \underset{(36\%)}{CH_3CF_2CH_2CO_2C_2H_5}$$

Ethyl α -ethylacetoacetate, which cannot be converted into an acetylene, gives the cumulene ester **36**. (22) The formation of cumulene **36** results from proton abstraction from the intermediate alkoxytrifluorosulfurane **37**. Sulfur tetrafluoride fluorination of ethyl α , α-diethylacetoacetate does not afford unsaturated compounds but gives ethyl 2,2-diethyl-3,3-difluorobutanoate in 31% yield. (22) In the presence of anhydrous hydrogen fluoride, however, all the preceding acetoacetates yield the corresponding β , β -difluoroderivatives in high yields. (22)

$$CH_3COCH(C_2H_5)CO_2C_2H_5 \xrightarrow[100^\circ]{SF_4} \underset{\mathbf{36}\ (33\%)}{CH_2{=}C{=}C(C_2H_5)CO_2C_2H_5} + \underset{(22\%)}{CH_3CF_2CH(C_2H_5)CO_2C_2H_5} + \underset{(cis,\ 13\%;\ trans,\ 6\%)}{CH_3CF{=}C(C_2H_5)CO_2C_2H_5}$$



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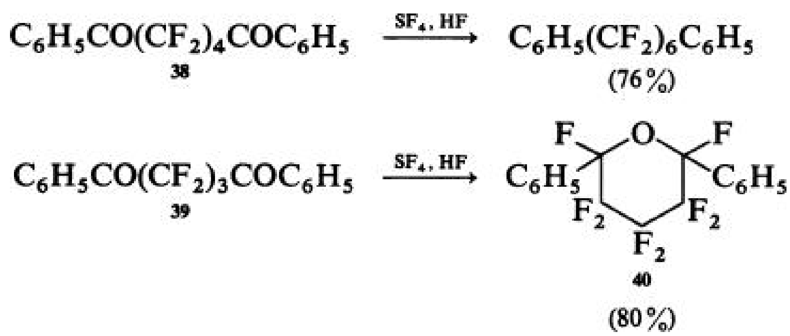
$$CH_3COC(C_2H_5)_2CO_2C_2H_5 \xrightarrow[100^\circ]{SF_4} \underset{(31\%)}{CH_3CF_2C(C_2H_5)_2CO_2C_2H_5}$$

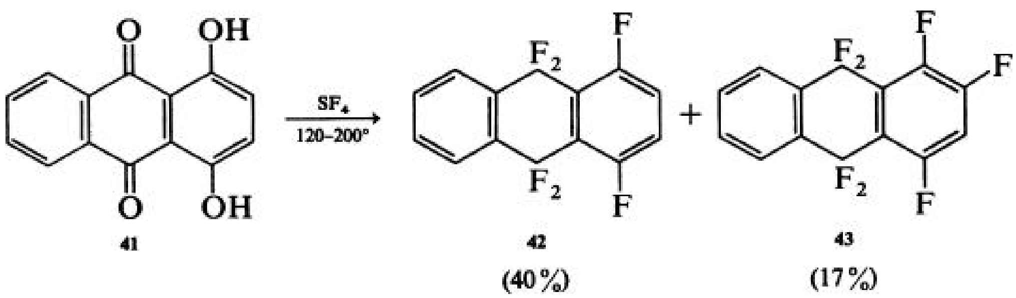
$$CH_3COCR^1R^2CO_2C_2H_5 \xrightarrow[20^\circ]{SF_4,\ HF} \underset{(76\text{–}85\%)}{CH_3CF_2CR^1R^2CO_2C_2H_5}$$

2.2.1.3. Abnormal Reactions

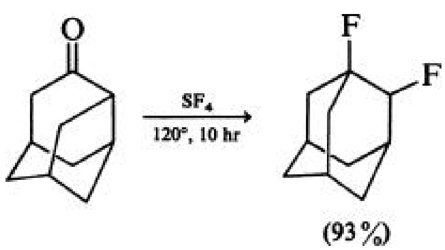
The diphenylperfluorodiketone **38** gives the normal fluorination product on treatment with sulfur tetrafluoride, whereas its lower homolog **39** forms a cyclic ether **40** instead. (24)



Fluorination of quinizarin (**41**) gives rise to not only the hexafluoro compound **42**, but also the heptafluoro compound **43** as the two principal products. (25)



Sulfur tetrafluoride fluorination of 4-protoadamantanone yields a rearrangement product, 1,2-difluoroadamantane. (26)



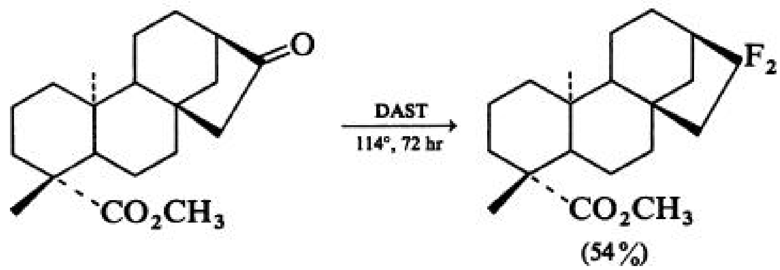
2.2.1.4. An Alternative Method for Replacement of Carbonyl Oxygen by Fluorine

A convenient reagent for replacement of the carbonyl oxygen of aldehydes and ketones with two fluorine atoms is DAST. Several examples are shown in the accompanying equations. (14, 27)

$$CH_3CH_2CHO \xrightarrow[25°]{DAST,\ CCl_3F} CH_3CH_2CHF_2 \ (95\%)$$

$$C_6H_5CHO \xrightarrow[25°]{DAST,\ CH_2Cl_2} C_6H_5CHF_2 \ (75\%)$$

$$(n\text{-}C_3H_7)_2CO \xrightarrow[25°]{DAST,\ CCl_3F} (n\text{-}C_3H_7)_2CF_2 \ (68\%)$$



This reagent is particularly useful for fluorinating aldehyes and ketones that are sensitive to acidic conditions. For example, pivaldehyde can be fluorinated by DAST in a nonpolar solvent such as pentane or fluorotrichloromethane. (14) Other fluorination methods result in rearrangement or trimerization.

$$t\text{-}C_4H_9CHO \xrightarrow[CCl_3F]{DAST} t\text{-}C_4H_9CHF_2 \ (88\%)$$

2.3. Carboxylic Acids

2.3.1.1. Aliphatic Carboxylic Acids

Aliphatic carboxylic acids react with sulfur tetrafluoride at low temperatures to give 1,1,1-trifluoroalkanes as well as the unexpected α , α , α ′, α′-tetrafluoroalkyl ethers. (28-30) The yields of tetrafluoroalkyl

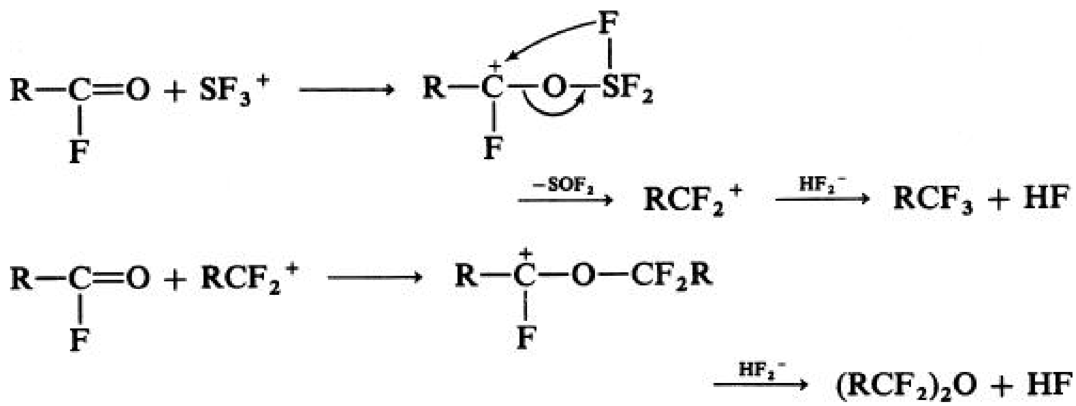
$$RCO_2H \xrightarrow{SF_4} RCOF \xrightarrow{SF_4} RCF_3 + (RCF_2)_2O$$

ethers depend primarily on their stability in the reaction medium because they

$$(RCF_2)_2O \xrightarrow{HF} RCOF + RCF_3$$

are subject to protolytic decomposition by hydrogen fluoride.

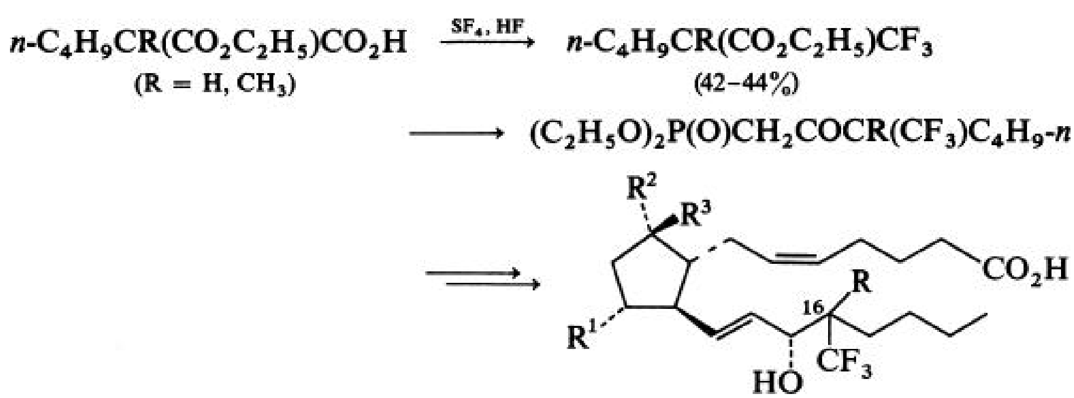
A mechanism for the formation of both 1,1,1-trifluoroalkanes and α , α , α′, α ′-tetrafluoroalkyl ethers has been proposed. (31) Support for this mechanism is



provided by the observation that α , α -difluorocarbocations are trapped by *p*-xylene or mesitylene in the reactions of chloroacetic and dichloroacetic acids with sulfur tetrafluoride. (32) The yields of *gem*-difluoroethylarenes range from 3 to 27%.

$$RCO_2H + ArH \xrightarrow{SF_4} RCF_3 + ArCF_2R + ArCOR$$
$$R = CH_2Cl, CHCl_2$$

The synthesis of a prostaglandin bearing a trifluoromethyl group at C-16 is based on an intermediate obtained by fluorination of a carboxylic acid with sulfur tetrafluoride. (33)



2.3.1.2. Aromatic Carboxylic Acids

In the sulfur tetrafluoride fluorination of *para*-substituted benzoic acids, the yields of the respective benzotrifluoride derivatives increase with increase in the electron-withdrawing character of the substituent. (34)

$$p\text{-}XC_6H_4CO_2H \xrightarrow[160°,\ 6\ hr]{SF_4,\ HF} p\text{-}XC_6H_4CF_3$$

X	OCH_3	CH_3	H	Br	Cl	F	CF_3	NO_2
Yield (%)	8	12	16.5	24	24	25	61	66

In the presence of an excess of hydrogen fluoride, the yields are substantially increased even under milder conditions. (35)

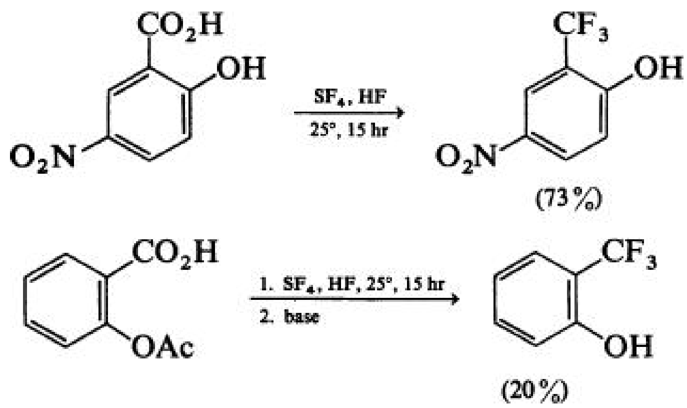
$$p\text{-}XC_6H_4CO_2H \xrightarrow{SF_4,\ HF} p\text{-}XC_6H_4CF_3$$

X	OCH_3	CH_3	H	Cl	NO_2
Reaction temperature	120–140°	120–140°	100–110°	90–100°	80°
Yield	55	80	93	70	92

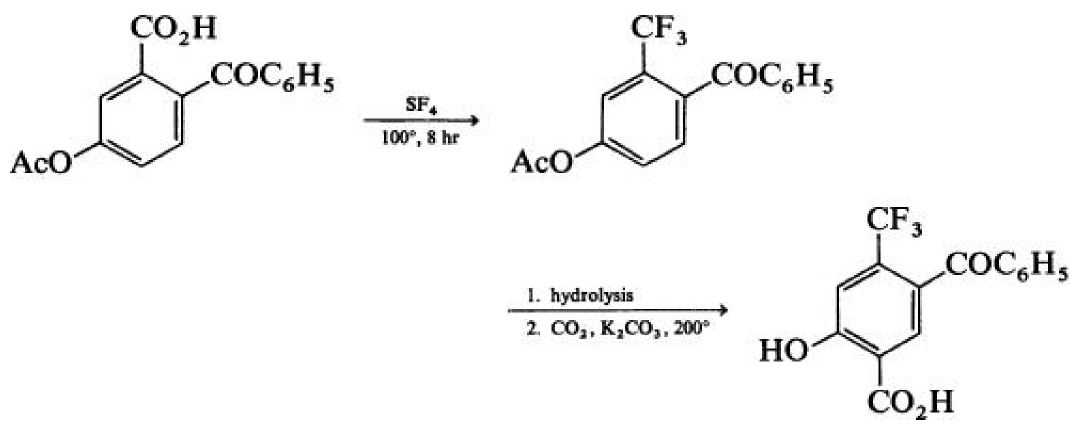
Hydroxybenzoic acids are also smoothly fluorinated by sulfur tetrafluoride in hydrogen fluoride solution to give good yields of the corresponding hydroxybenzotrifluorides. (36) An exception is salicylic acid, which resinifies under the reaction conditions. However, it is possible to fluorinate acetylsalicylic acid and then convert it to *o*-trifluoromethylphenol.

$$p\text{-}HOC_6H_4CO_2H \xrightarrow[85\text{–}90°,\ 110\ hr]{SF_4,\ HF} p\text{-}HOC_6H_4CF_3\ (80\%)$$

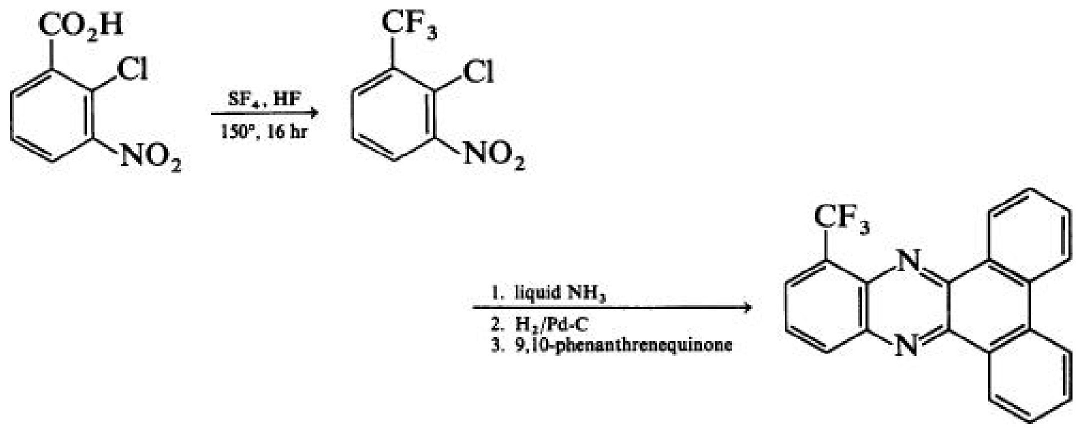
$$m\text{-}HOC_6H_4CO_2H \xrightarrow[25°,\ 15\ hr]{SF_4,\ HF} m\text{-}HOC_6H_4CF_3\ (75\%)$$



The fluorinated salicylic acids are of interest as anti-inflammatory agents, (37) and sulfur tetrafluoride fluorination of aromatic carboxylic acids is the method of choice for introducing the trifluoromethyl substituent.

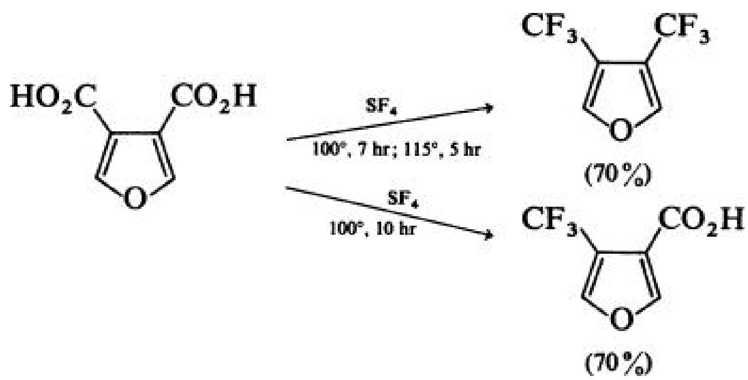


Recently, immunosuppressant agents have come into prominence because of their use during organ transplant operations. Some novel quinoxaline derivatives containing the trifluoromethyl moiety are useful as immune regulatory agents. (38) The synthesis of one of them, 10-(trifluoromethyl)-dibenzo[*a,c*]phenazine, is based on sulfur tetrafluoride fluorination.

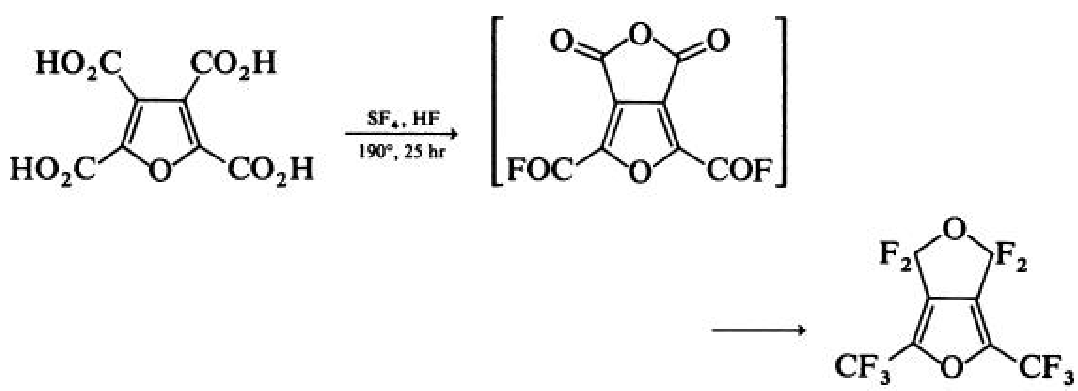


2.3.1.3. Furancarboxylic Acids

Furancarboxylic acids react with sulfur tetrafluoride to form the corresponding trifluoromethyl derivatives. (39, 40) An exception is furantetracarboxylic acid, which gives the bicyclic 1,1,3,3-tetrafluorofurofuran



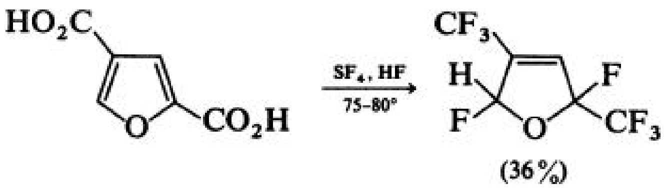
44 instead of tetrakis(trifluoromethyl)furan.



44

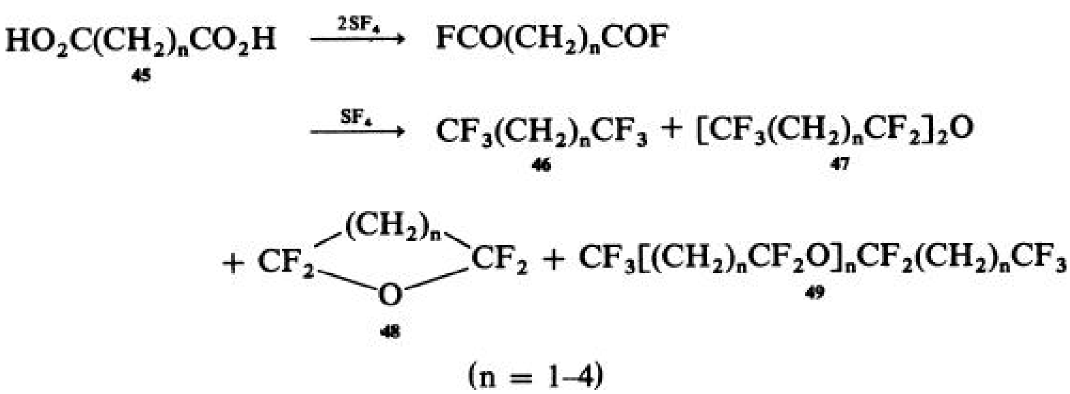
(54%)

An excess of sulfur tetrafluoride in hydrogen fluoride can convert furancarboxylic acids to highly fluorinated products. For example, 2,4-furandicarboxylic acid gives 2,5-difluoro-2,4-bis(trifluoromethyl)-2,5-dihydrofuran in 36% yield at 75–80°. (41)

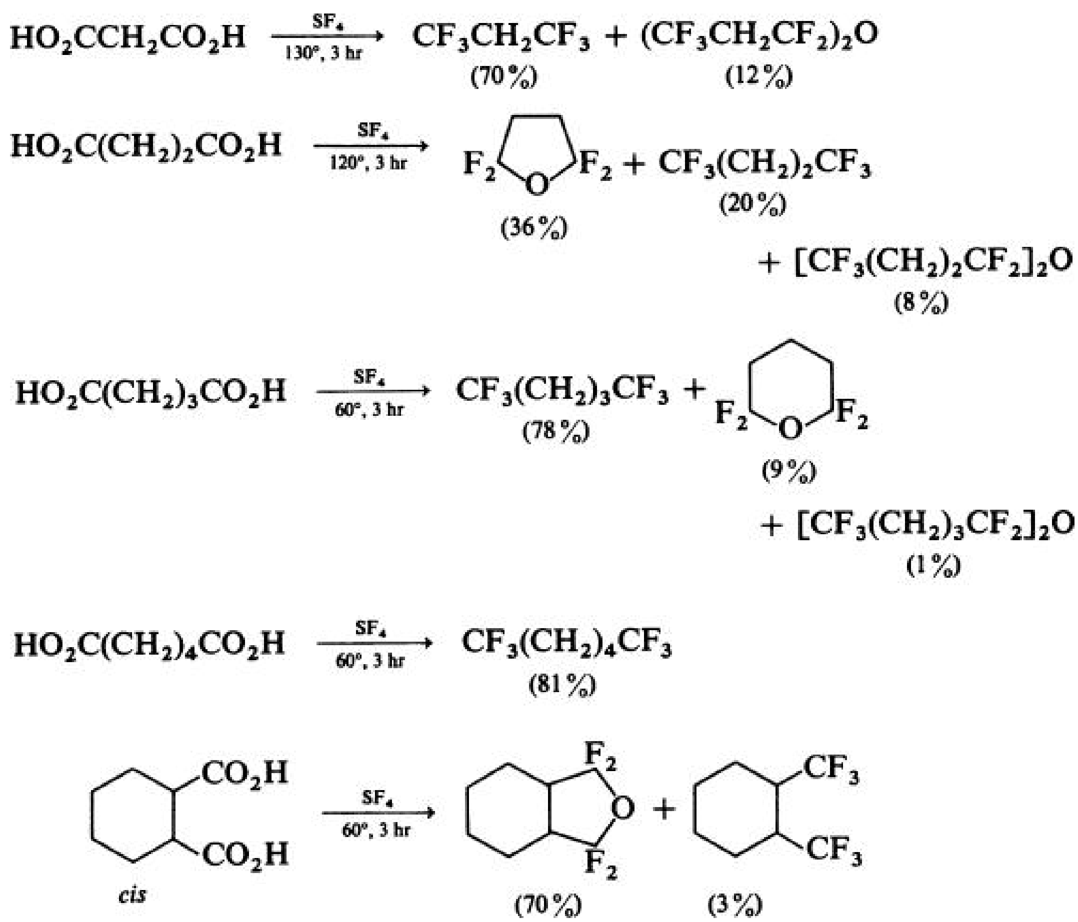


2.3.1.4. Polycarboxylic Acids

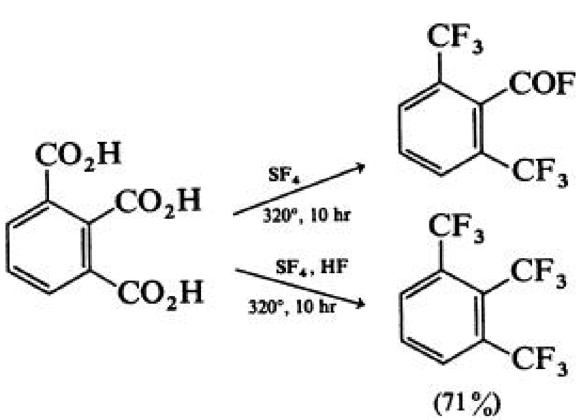
The reaction of sulfur tetrafluoride with alkanedicarboxylic acids **45** is more complicated than reported earlier and can afford simultaneously bis(trifluoromethyl)alkanes **46**, linear and cyclic α , α , α ′, α ′-tetrafluoroethers **47** and **48**, and small amounts of polyethers **49**. (42) The cyclic



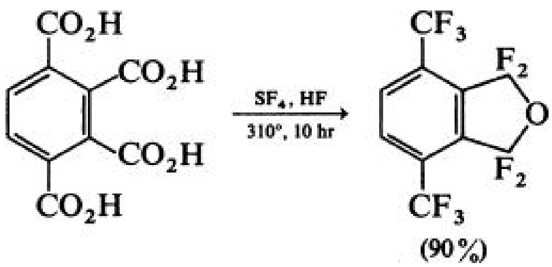
ethers constitute the major products of the reactions with alkane-1,2-dicarboxylic acids. They are also formed in the reactions with alkane-1,3-dicarboxylic acids, but not with 1,1- and 1,4-dicarboxylic acids.



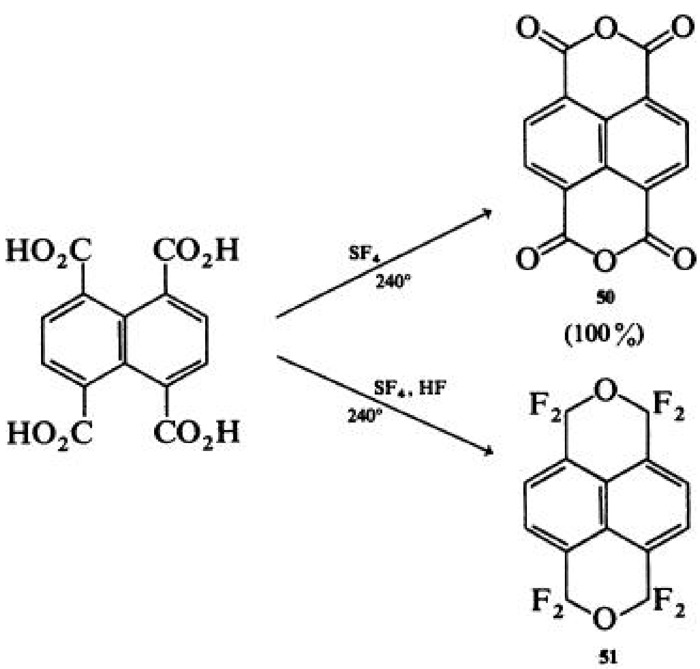
Sulfur tetrafluoride fluorination of the sterically hindered 1,2,3-benzenetricarboxylic acid gives 2,6-bis(trifluoromethyl)benzoyl fluoride. In the presence of hydrogen fluoride, 1,2,3-tris(trifluoromethyl)benzene becomes the major product. (43) However, fluorination of 1,2,3,4-benzenetetracarboxylic acid affords



4,7-bis(trifluoromethyl)-1,1,3,3-tetrafluorophthalan in the presence or absence of hydrogen fluoride. (43)



Reaction of naphthalene-1,4,5,8-tetracarboxylic acid with sulfur tetrafluoride forms dianhydride **50** quantitatively, which does not react further even under drastic conditions. In an excess of hydrogen fluoride, an octafluoro product **51** is isolated in 80% yield. (44)



2.4. Esters

In contrast to benzoic acids, methyl benzoates react with sulfur tetrafluoride only at temperatures above 300°. (1) However, like the acids, the methyl esters react with sulfur tetrafluoride in the presence of excess hydrogen fluoride at moderate temperatures to give the benzotrifluorides in good to excellent yields. (45)

$$C_6H_5CO_2CH_3 \xrightarrow[75\text{–}80°,\ 16\ \text{hr}]{SF_4,\ HF} C_6H_5CF_3 \quad (45\%)$$

$$p\text{-}O_2NC_6H_4CO_2CH_3 \xrightarrow[130°]{SF_4,\ HF} p\text{-}O_2NC_6H_4CF_3 \quad (92\%)$$

Perfluoroacyloxy-substituted methyl benzoates react with sulfur tetrafluoride at 75–80° in the presence of hydrogen fluoride to afford the corresponding α , α -difluoro ethers of benzotrifluorides in reasonable yields. (45)

$$p\text{-}R_FCO_2C_6H_4CO_2CH_3 \xrightarrow[75\text{–}80°,\ 16\ \text{hr}]{SF_4,\ HF} p\text{-}R_FCF_2OC_6H_4CF_3$$

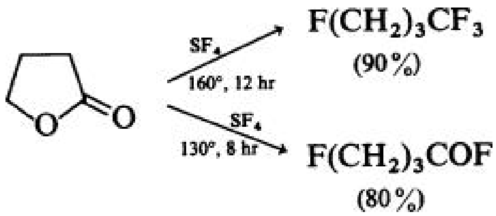
R_F	$n\text{-}C_3F_7$	$H(CF_2)_4$	$n\text{-}C_4F_9$	$H(CF_2)_6$	$n\text{-}C_6F_{13}$
Yield (%)	52	65	70	62	68

Hydrogen fluoride is the most effective catalyst for the synthesis of highly fluorinated ethers by sulfur tetrafluoride fluorination of the corresponding esters. The rate of reaction is higher when hydrogen fluoride is used as a solvent rather than in catalytic amounts. (46)

$$n\text{-}C_7F_{15}CO_2CH_2C_2F_5 \xrightarrow[150°,\ 15\ \text{hr}]{SF_4,\ HF} n\text{-}C_8F_{17}OCH_2C_2F_5 \quad (92\%)$$

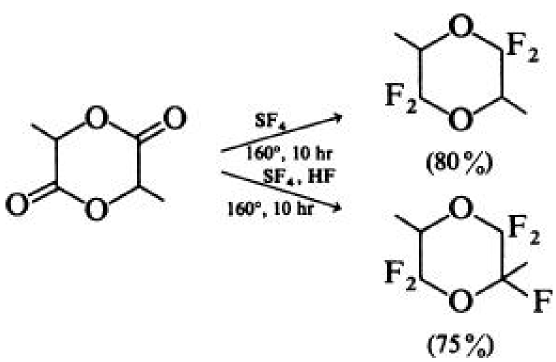
2.5. Lactones

The replacement of carbonyl oxygen by two fluorine atoms in lactones leads to fluorinated heterocyclic compounds. When γ -butyrolactone is treated with excess sulfur tetrafluoride at 160°, the isolated product is, however, the unexpected 1,1,1,4-tetrafluorobutane. At 130° and with only one equivalent of sulfur tetrafluoride, the main product is γ -fluorobutyryl fluoride. (47)



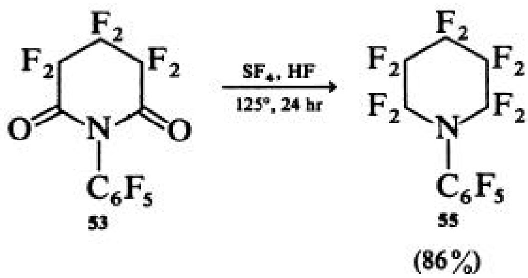
The γ -butyrolactone ring is apparently opened by traces of hydrogen fluoride that are usually present in sulfur tetrafluoride. In an excess of sulfur tetrafluoride, the resulting γ -fluorobutyric acid first gives γ -fluorobutyryl fluoride and then 1,1,1,4-tetrafluorobutane. In the absence of hydrogen fluoride (sodium fluoride-treated sulfur tetrafluoride), γ -butyrolactone does not react with sulfur tetrafluoride even at 230–240°, whereas decomposition occurs at higher temperatures. In anhydrous hydrogen fluoride, however, 1,1,1,4-tetrafluorobutane is obtained in high yield at 90–100°.

In contrast to γ -butyrolactone, the six-membered lactide reacts with sulfur tetrafluoride without ring opening. (47)

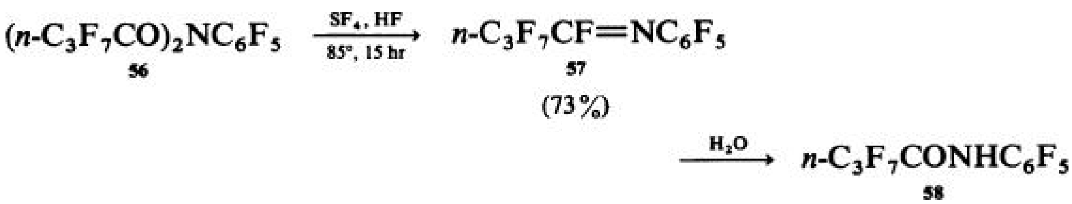


2.6. Amides and Imides

Polyfluorinated tertiary amines, which are commercially important as evaporation coolants, hydraulic fluids, and potential blood substitutes, can be prepared in high yields as sole products by treating amides or imides with sulfur tetrafluoride in the presence of hydrogen fluoride at moderate temperatures. (48) For example, the amide **52** and the cyclic imide **53** are completely converted into the amines **54** and **55** in 78 and 86% isolated yields, respectively.



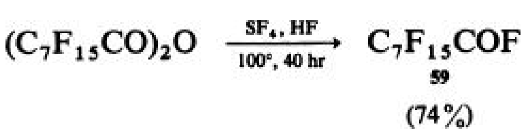
Treatment of the linear imide **56** with sulfur tetrafluoride under relatively mild conditions gives products resulting exclusively from acyl — nitrogen bond fission. The azaolefin **57** is extremely moisture sensitive and hydrolyzes to the amide **58** in solution or neat. (48)



The differences in reactivity and the products formed from the cyclic imide **53** and the linear imide **56** may be due to a preferred preliminary reaction between imide **56** and hydrogen fluoride to afford amide **58**, which subsequently is converted to azaolefin **57** in a relatively facile reaction.

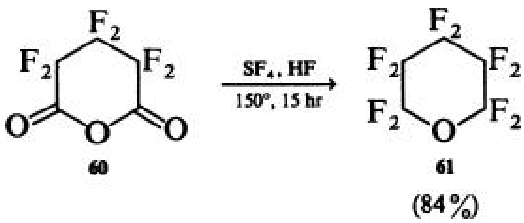
2.7. Acid Anhydrides

Acid anhydrides are converted by sulfur tetrafluoride to acyl fluorides and under extreme conditions to trifluoromethyl compounds. (2) In several instances an ether is obtained from an anhydride. In hydrogen fluoride solution, perfluorooctanoic anhydride reacts with sulfur tetrafluoride to afford only perfluorooctanoyl fluoride (**59**). (46) This result is attributed to cleavage of the



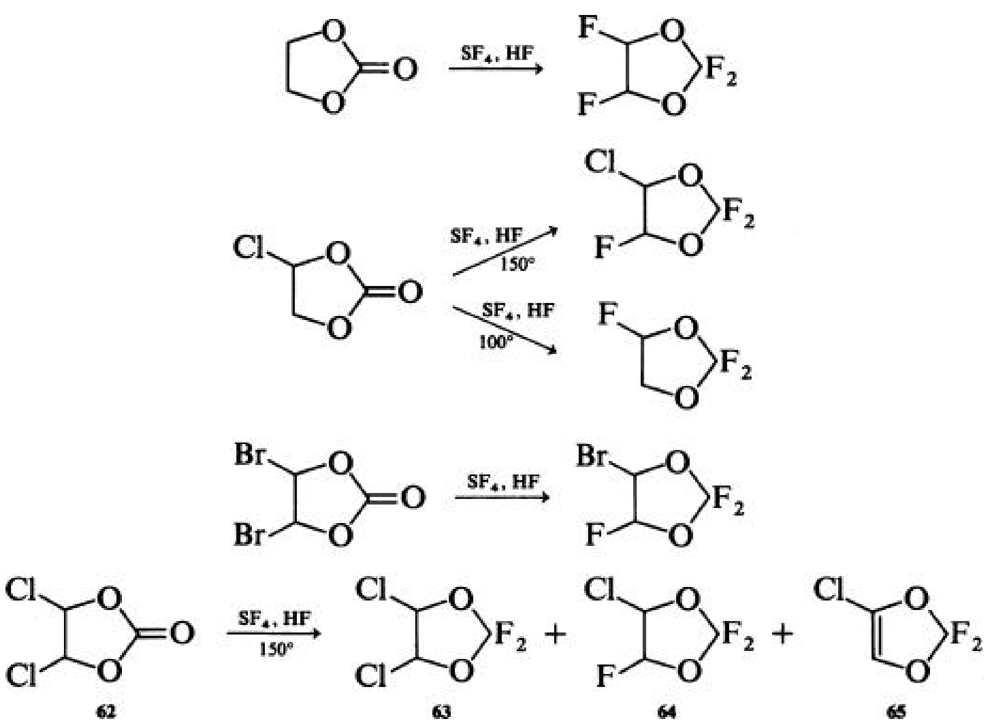
anhydride to an acyl fluoride–acid mixture by hydrogen fluoride, followed by sulfur tetrafluoride conversion of the acid to the acyl fluoride.

Cyclic anhydride **60** gives the normal product, the cyclic ether **61**. (46)



2.8. Carbonates

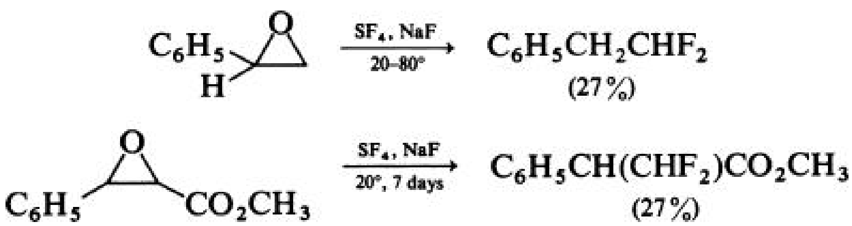
Although several fluorinated anesthetics are in clinical use today, all have disadvantages and possible hazards. Recent attention has been focused on using fluorinated ethers, such as fluorinated 1,3-dioxolanes, as volatile anesthetics. These compounds can be prepared by sulfur tetrafluoride fluorinations of cyclic carbonates. (49)



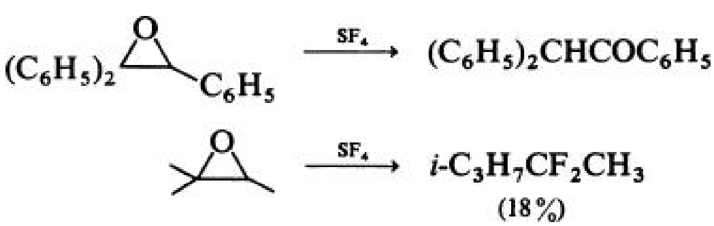
In the fluorination of 4,5-dichloroethylene carbonate (**62**), the ratio of the products depends on the hydrogen fluoride: sulfur tetrafluoride ratio. When the ratio is greater than 1:1, 4-chloro-2,2,5-trifluoro-1,3-dioxolane (**64**) is the major product.

2.9. Oxiranes

Monoaryloxiranes or unsymmetrical dialkyl- and diaryloxiranes react with sulfur tetrafluoride to give geminal difluoro compounds with the migration of alkyl or aryl groups. (50, 51)

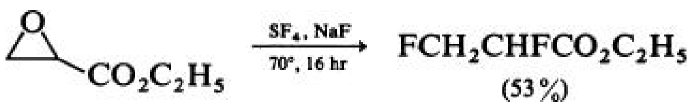


Fluorination of triphenyloxirane and tetraphenyloxirane by sulfur tetrafluoride at 20° leads only to isomerization of the starting materials. (51) This reaction course is evidently due to steric hindrance to the fluorination process. Trimethyloxirane forms 2,2-difluoro-3-methylbutane in 18% yield. (52)

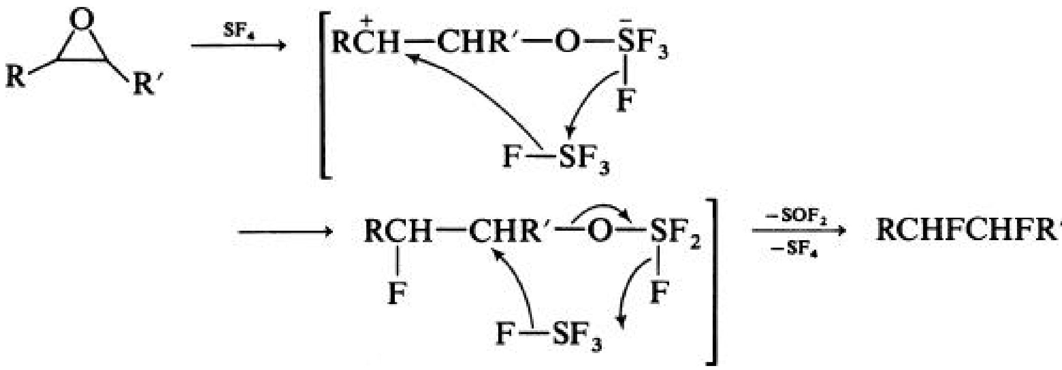


Monoalkyloxiranes give mainly polymerization products even at low temperatures. However, 1,2-difluorodecane can be isolated in 10% yield from sulfur tetrafluoride fluorination of octyloxirane in dilute methylene chloride solution. (52) (Ethoxycarbonyl)oxirane also gives a vicinal difluoro product,

ethyl 2,3-difluoropropionate. However, *trans*-2,3-bis(ethoxycarbonyl)oxirane does not react with sulfur tetrafluoride even at 200°.

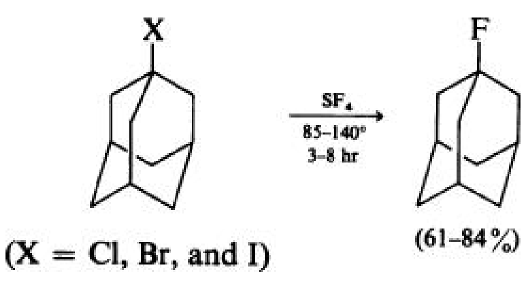


The mechanism of the fluorination of oxiranes leading to vicinal difluoro compounds is proposed as shown. (52)



2.10. Chlorides, Bromides, and Iodides

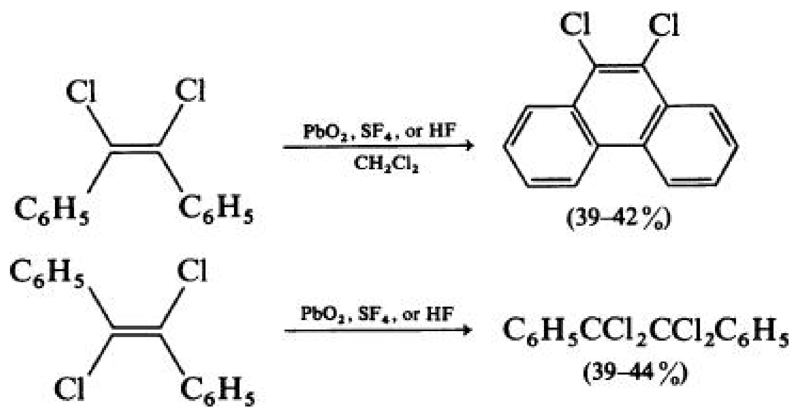
Sulfur tetrafluoride fluorination of organic chlorine, bromine, or iodine compounds often occurs only at relatively high temperatures. However, 1-chloro-, 1-bromo-, and 1-iodoadamantanes react with sulfur tetrafluoride under comparatively mild conditions to give 1-fluoroadamantane in high yields. (53) At 200°, 1-bromoadamantane or 1,3-dibromoadamantane gives a



mixture of 1,3-difluoroadamantane and 1,3,5-trifluoroadamantane. (54)

Addition of two fluorine atoms to olefinic double bonds has been accomplished by using lead dioxide in the presence of sulfur tetrafluoride or hydrogen fluoride. (1) An exception is the reaction of *cis*- or *trans*- α , β -dichlorostilbene with lead dioxide and sulfur tetrafluoride or hydrogen fluoride. (55) The *cis* isomer undergoes dehydrocyclization with the formation of

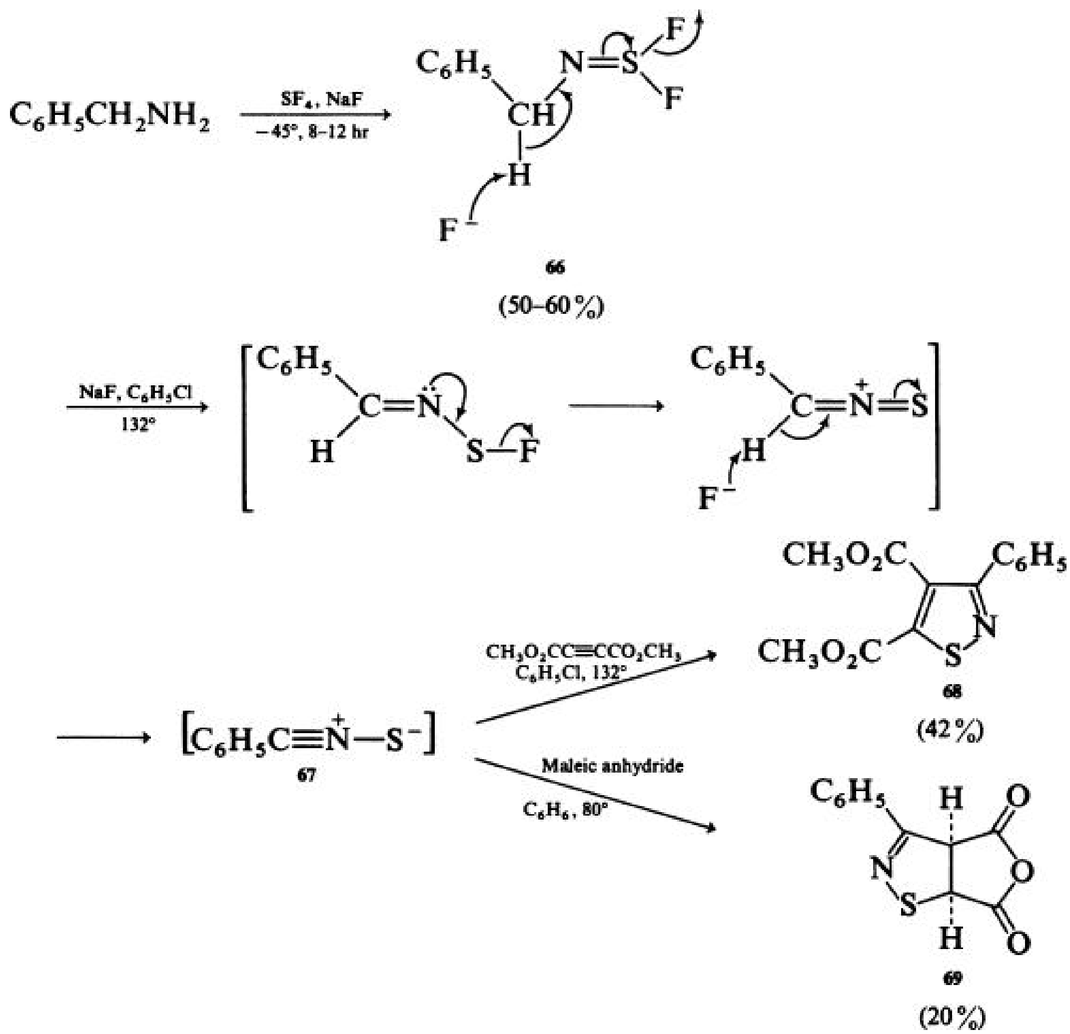
9,10-dichlorophenanthrene, and the *trans* isomer is converted into 1,2-diphenyltetrachloroethane.



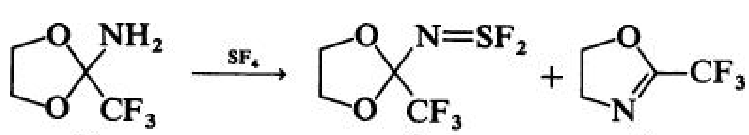
The free-radical nature of these reactions has been established by electron spin resonance (ESR) experiments. (55)

2.11. Amines

Benzonitrile-*N*-sulfide (**67**) is the first example of a molecule containing a coordinate covalent bond between elements of the fifth and sixth groups in which the element bearing a formal negative charge is less electronegative than the element bearing a formal positive charge. A novel generation of benzonitrile-*N*-sulfide is by the rare 1,3-elimination of two molecules of hydrogen fluoride from *N*-benzyliminosulfur difluoride (**66**), which is prepared by reacting benzylamine with sulfur tetrafluoride. (56) Benzonitrile-*N*-sulfide cannot be isolated but can be trapped by either dimethyl acetylenedicarboxylate or maleic anhydride to form dimethyl 3-phenylisothiazole-4,5-dicarboxylate (**68**) or *cis*-3-phenyl-4,5-isothiazoline-4,5-dicarboxylic acid anhydride (**69**).



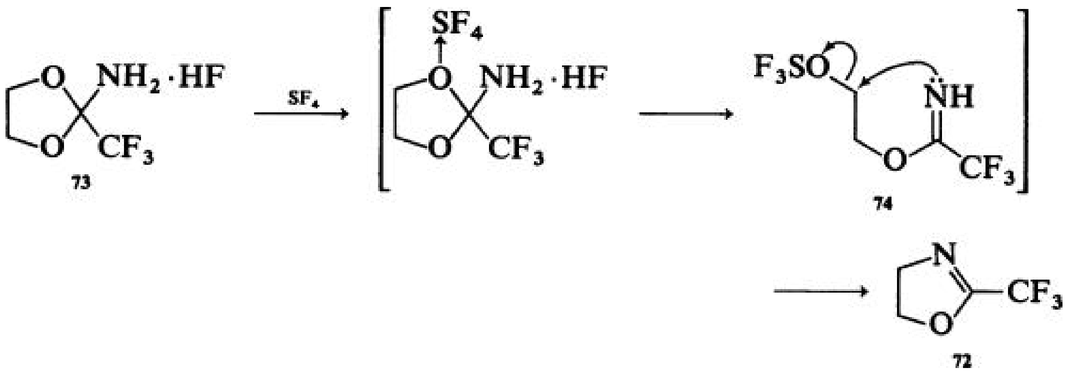
Reaction of 2-amino-2-trifluoromethyl-1,3-dioxolane (**70**) with sulfur tetrafluoride affords 2-trifluoromethyl-Δ^2-oxazoline (**72**), as well as the expected (2-trifluoromethyl-1,3-dioxol-2-yl)iminosulfur difluoride (**71**). (57) The ratio of



70 71 72

these products depends on the bases used. With trimethylamine, the reaction gives exclusively iminosulfur difluoride **71**, whereas the reaction using sodium fluoride affords a mixture of iminosulfur difluoride **71** and oxazoline **72** in a ratio of about 1:1.

The formation of oxazoline **72** can be explained in terms of cyclization of the ring-opened intermediate **74** formed by electrophilic attack of sulfur tetrafluoride at the dioxolane oxygen of the hydrogen fluoride salt **73** of dioxolane **70**.



2.12. Boron, Phosphorus, and Silicon Compounds

The reaction of sulfur tetrafluoride with tris(dimethylamino)borane affords a high yield of sulfonium tetrafluoroborate salt **75**. (58)

$$[(CH_3)_2N]_3B \xrightarrow{SF_4,\ SO_2} \underset{\mathbf{75}}{[(CH_3)_2N]_3\overset{+}{S}BF_4^-}$$

Sulfur tetrafluoride converts iminotriphenylphosphorane **76** to iminosulfur difluoride **77**. Similarly, bis(aminotriphenylphosphorane) **78** gives bis(iminosulfur difluoride) **79**. (59)

$$\underset{\mathbf{76}}{(C_6H_5)_3P{=}NC_6H_5} \xrightarrow{SF_4} \underset{\mathbf{77}}{F_2S{=}NC_6H_5} + (C_6H_5)_3PF_2$$

$$\underset{\mathbf{78}}{[(C_6H_5)_3PNHCH_2]_2^{2+}2Cl^-} \xrightarrow[20\text{–}25^\circ]{SF_4} \underset{\substack{\mathbf{79}\\(73\%)}}{(F_2S{=}NCH_2)_2} + (C_6H_5)_3PF_2$$

Aryloxytrimethylsilanes react readily with sulfur tetrafluoride to give products that depend on the nature of the aryl group and on the relative amounts of reactants. (60) For example, *p*-trifluoromethylphenoxytrimethylsilane is converted to bis(*p*-trifluoromethylphenoxy)sulfur difluoride by one equivalent of sulfur tetrafluoride, whereas phenoxytrimethylsilane gives phenoxysulfur trifluoride. With 0.5 equivalent of sulfur tetrafluoride, phenoxytrimethylsilane affords bis(phenoxy)sulfur difluoride instead.

$$p\text{-}CF_3C_6H_4OSi(CH_3)_3 \xrightarrow{SF_4} (p\text{-}CF_3C_6H_4O)_2SF_2 + (CH_3)_3SiF$$

$$C_6H_5OSi(CH_3)_3 \xrightarrow{SF_4,\ 1\ eq} C_6H_5OSF_3 + (CH_3)_3SiF$$

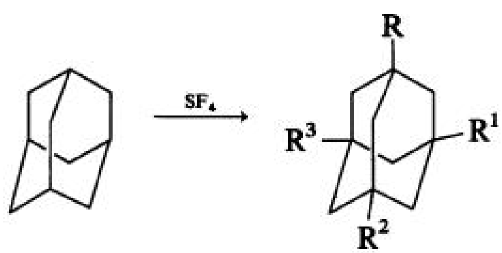
$$C_6H_5OSi(CH_3)_3 \xrightarrow{SF_4,\ 0.5\ eq} (C_6H_5O)_2SF_2 + (CH_3)_3SiF$$

As mentioned on page 328, treatment of diethylaminotrimethysilane with sulfur tetrafluoride yields DAST. Similarly, reaction of sulfur tetrafluoride with (dimethylamino)trimethylsilane gives rise to tris(dimethylamino)sulfonium trimethyldifluorosiliconate, which is a source of organic-solvent-soluble fluoride ion of high anionic reactivity. (60a) Fluoride ion from this salt has been used to displace other halogens. (60a)

$$3(CH_3)_3SiN(CH_3)_2 \xrightarrow[25^\circ]{SF_4,\ ether} [(CH_3)_2N]_3\overset{+}{S}\,F_2\overset{-}{Si}(CH_3)_3 + 2FSi(CH_3)_3 \quad (71\text{–}78\%)$$

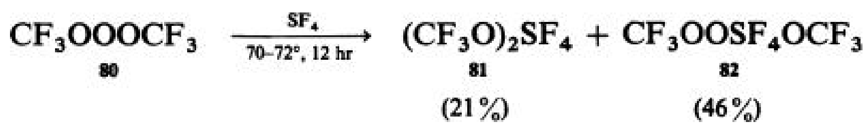
2.13. Miscellaneous Reactions

Fluorination of adamantane by sulfur tetrafluoride at 60, 100, and 200° gives monofluoro-, difluoro-, and trifluoroadamantanes, respectively. (54) In the presence of hydrogen fluoride at 140°, adamantane affords tetrafluoroadamantane.

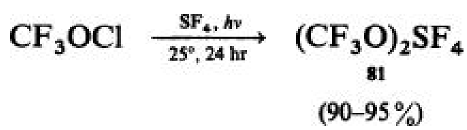


60°	$R = F, \quad R^1 = R^2 = R^3 = H$
100°	$R = R^1 = F, \quad R^2 = R^3 = H$
200°	$R = R^1 = R^2 = F, \quad R^3 = H$
HF, 140°	$R = R^1 = R^2 = R^3 = F$

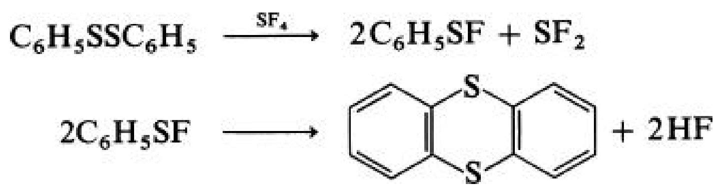
Bis(trifluoromethyl)trioxide (**80**) is a convenient source of both trifluoromethoxy and trifluoromethylperoxy groups; its reaction with sulfur tetrafluoride yields *cis*-tetrafluorobis(trifluoromethoxy)sulfur (**81**) and *cis*-tetrafluoro(trifluoromethoxy)(trifluoromethylperoxy)sulfur (**82**). (61) The photolytic



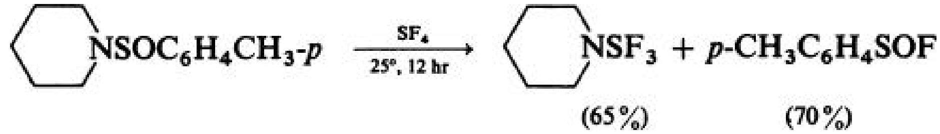
reaction of trifluoromethyl hypochlorite with sulfur tetrafluoride also provides the octahedral sulfur compound **81** in high yield. (62)



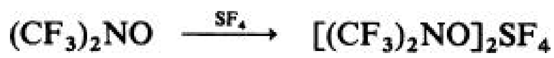
Sulfur tetrafluoride converts diphenyl disulfide into phenylsulfenyl fluoride, which dimerizes to give thianthrene. (63) Reaction of the piperidide of *p*-toluenesulfinic acid



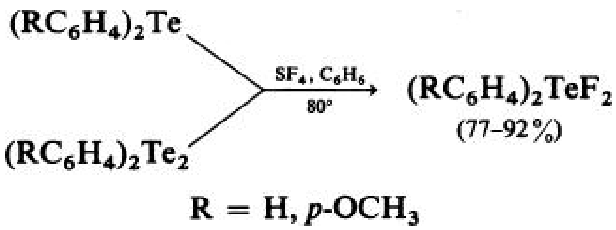
with sulfur tetrafluoride affords piperidinosulfur trifluoride and *p*-toluenesulfinyl fluoride. (64)



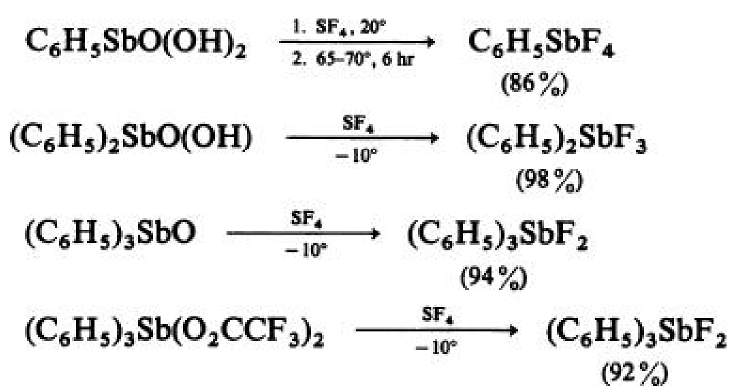
Treatment of hexafluorodimethylnitroxide with sulfur tetrafluoride at room temperature gives an almost quantitative yield of bis(hexafluorodimethylaminooxy)sulfur tetrafluoride. (65)



Sulfur tetrafluoride reacts with either diaryl tellurides or diaryl ditellurides to give diaryltellurium difluorides. (66) Phenylstibonic acid, diphenylstibinic acid,



and triphenylstibine oxide are converted by sulfur tetrafluoride to phenylantimony tetrafluoride, diphenylantimony trifluoride, and triphenylantimony difluoride, respectively. Similarly, triphenylantimony bis(trifluoroacetate) forms triphenylantimony difluoride. (67)



2.14. Polymers

Fluorination of polymers by sulfur tetrafluoride is a method of modifying their properties. The reaction of poly(vinyl alcohol) with sulfur tetrafluoride at 20° leads to substitution of the associated (via hydrogen bonding) hydroxy groups by fluorine atoms. (68) The properties of the fluorinated poly(vinyl alcohol) derivatives differ considerably from those of the original polymer. They react very slowly with formic, acetic, and chloroacetic acids. They have better resistance to alkalis and do not dissolve in water or organic solvents. In addition, when the fluorine content is greater than 10%, the polymer stops burning when removed from a flame.

Sulfur tetrafluoride fluorination of poly(acrylic acid) at 20–220° affords a fluorinated polymer with a total fluorine content of 50–52%, (69) The heat resistance of the fluorinated polymer is increased.

Polyacrylonitrile fibers are fluorinated by sulfur tetrafluoride at 180°. Elemental analysis of the fibers indicates that about 30% of the nitrile groups are converted to $CF_2N = SF_2$ groups. The fluorinated fibers show increased hydrophilic properties without a decrease in strength, and their flammability is decreased. (70)

3. Experimental Conditions

3.1.1.1. Properties (1)

Sulfur tetrafluoride is colorless in the gaseous, liquid, and solid states. It is thermally stable up to 500° but is hydrolyzed rapidly and exothermally by aqueous media at all pH values. Some of the physical properties of sulfur tetrafluoride are summarized here:

Melting point	–121.0 ± 0.5°
Boiling point	–38°
Density at –73°	1.9191 g/mL
Density at T (170–200 K)	2.5471 – 0.00314*T*
Vapor pressure (mm) at T (160–224 K), log P	8.8126 – 1381/*T*
Critical temperature	91°

Caution: Sulfur tetrafluoride and hydrogen fluoride are toxic and corrosive chemicals that should be handled with utmost care in a well-ventilated fume hood. Gloves and safety goggles should be used. Instructions of the suppliers for the safe handling of these reagents should be observed. First-aid treatment of hydrogen fluoride burns has been described. (71)

Sulfur tetrafluoride can be handled in a well-dried Pyrex glass apparatus up to about 30° with only nominal attack. Stainless steel, copper, and nickel are all inert to sulfur tetrafluoride at both ordinary and elevated temperatures.

Reactions with sulfur tetrafluoride are generally carried out in stainless steel or Hastelloy[*]-lined shaker tubes. Liquid or solid reactants are placed in the shaker tube under a nitrogen atmosphere, the head is screwed into place, the tube is cooled to solid carbon dioxide temperature, the nitrogen is removed with a vacuum pump, and gaseous reactants (HF, BF_3, SF_4, etc.) are condensed in the shaker tube. Sulfur tetrafluoride (17.5 mmol/mL at –78°) can be condensed into a graduated tube immersed in a dry ice–acetone bath and then introduced to the reaction vessel. After having been heated for the prescribed period, the shaker tube is allowed to cool. If the gaseous products are of interest, they are condensed in an evacuated stainless steel cylinder at liquid nitrogen temperature; otherwise, excess sulfur tetrafluoride and volatile byproducts are vented from the tube. Liquid or solid products are recovered when the tube is opened, and pure products are obtained by the usual processes of distillation, chromatography, recrystallization, or sublimation. When necessary, hydrogen fluoride is removed from the crude mixture by pouring the crude mixture into either (1) water and recovering the product by filtration, extraction, or steam distillation or (2) a suspension of sodium fluoride ($NaF + HF \rightarrow NaHF_2$) in an inert solvent such as methylene chloride, followed by filtration and fractional distillation. Sometimes removal of hydrogen fluoride from a solid or high-boiling liquid is accomplished by vaporizing the hydrogen fluoride and absorbing it in solid sodium fluoride or sodium hydroxide. Hydrogen fluoride can also be trapped with aqueous calcium hydroxide solution to precipitate innocuous calcium fluoride, which can be disposed of easily.

Some of the experimental procedures, as taken from the original literature, are vague in describing reaction vessels used in the experiments. Suggestions of this author that are inserted into those procedures are italicized in parentheses.

4. Experimental Procedures

4.1.1.1. 3-Fluoro-L-alanine (Fluorination of an Amino Acid in Liquid Hydrogen Fluoride) (7)

The flow diagram of the apparatus has been described but has been modified so that the fluoroxytrifluoromethane or fluorine cylinder is replaced by a sulfur tetrafluoride cylinder. (72) L-Serine (1.05 g, 10 mmol) was dissolved at –78° in 20 mL of anhydrous liquid hydrogen fluoride in a poly(chlorotrifluoroethylene) (Kel-F) reactor. Sulfur tetrafluoride (1.2 mL, 2.27 g, 21 mmol) was condensed into this solution, which was allowed to remain at –78° overnight. Nitrogen was introduced into the reactor until all hydrogen fluoride was evaporated from the reactor, and with the aid of a water aspirator the hydrogen fluoride was continuously flushed down the drain. (*The hydrogen fluoride should be trapped with solid sodium hydroxide or aqueous calcium hydroxide solution*.) The residue was taken up in concentrated hydrochloric acid, and the solution was evaporated to dryness *in vacuo*. This procedure of dissolution in hydrochloric acid and evaporation was repeated three times. The resultant hydrochloride was dissolved in 2 mL of water and 5 mL of 2-propanol, cooled to 0°, and treated with 0.81 mL of pyridine. Crystallization afforded, in two crops, 543 mg (51%) of 3-fluoro-L-alanine. A small sample recrystallized from water had mp 167–168°.

4.1.1.2. Diethyl α -Fluoro- α ′-hydroxysuccinate (Fluorination of a Hydroxy Ester) (9)

Diethyl tartrate (3.4 g, 16.5 mmol) was kept at 25° with sulfur tetrafluoride (3.9 mL, 7.4 g, 68.5 mmol) in an autoclave (*one can use a* 100-*mL stainless-steel or Hastelloy-lined vessel capable of containing* 20 *atm of pressure*) for 60 hours. The gaseous substances were released from the autoclave. The residue was extracted with ether. The ether extract was kept over sodium fluoride for 24 hours, and was then distilled, giving 1.5 g (41%) of diethyl α -fluoro- α ′-hydroxysuccinate, bp 144–145° (15 mm).

4.1.1.3. 2,2,2-Trifluoroethanol (Fluorination of a Hydroxy Acid) (12)

A mixture of 7.6 g (0.1 mol) of hydroxyacetic acid and 43.2 g (23 mL, 0.4 mol) of sulfur tetrafluoride was heated in an autoclave (*one can use a* 300-*mL stainless-steel or Hastelloy-lined vessel capable of containing* 50 *atm of pressure*) at 160° for 8 hours. The autoclave was cooled, and the gaseous products were passed through traps containing 20% potassium hydroxide solution and collected in a rubber chamber (*one can use a Kel-F vessel*), yielding 3 g (30%) of 1,1,1,2-tetrafluoroethane, bp –26°. The liquid from the autoclave was mixed in a quartz flask with 10.5 g (0.25 mol) of anhydrous sodium fluoride, and the products were distilled without heat under a vacuum of 50 mm. They were collected in a receiver cooled to –40° and distilled at atmospheric pressure to give 4.8 g (48%) of 2,2,2-trifluoroethanol, bp 73–74°.

4.1.1.4. 17 β -Acetoxy-5-fluoro-B-homo-A-norandrost-4-en-3-one (Fluorination of an Enolizable 1,3-Dicarbonyl Compound) (21)

A solution of 17 β -acetoxy-5-hydroxy-B-homo-A-norandrost-4-en-3-one (1 g, 2.89 mmol) in anhydrous benzene (150 mL) was placed in a glass hydrogenation vessel connected on one side to a sulfur tetrafluoride cylinder and on the other side, by means of a reduction valve, to an aspirator. A gentle stream of sulfur tetrafluoride was bubbled through the solution, and the progress of the reaction was monitored by thin-layer chromatography. After about 3 hours the gas supply was stopped and the closed vessel was shaken for another 30 minutes. The mixture was flushed with nitrogen, diluted with ether–benzene, washed with ice-cold saturated sodium bicarbonate solution and water, dried over sodium sulfate, and evaporated under vacuum. The crude product was purified by column chromatography on silica gel to give 17 β -acetoxy-5-fluoro-B-homo-A-norandrost-4-en-3-one (579 mg, 60%) after two recrystallizations from methylene chloride–ether, mp 156–157°.

4.1.1.5. 3,4,5-Tris(trifluoromethyl)nitrobenzene (Fluorination of a Polycarboxylic Acid) (73)

In a stainless-steel autoclave (*capable of containing* 90 *atm of pressure*) with a capacity of 70 mL was placed 3 g (11.7 mmol) of 5-nitrobenzene-1,2,3-tricarboxylic acid. After the autoclave had been evacuated and cooled with liquid nitrogen, 15 g (8 mL, 139 mmol) of sulfur tetrafluoride and 10 g of anhydrous hydrogen fluoride were condensed into it, and the mixture was heated at 250° for 50 hours. After cooling, the gaseous products were released from the autoclave, 25 mL of 25% aqueous ammonia was added, and the mixture was heated at 170° for 1.5 hours. The product was extracted with pentane and was purified on a column of aluminium oxide to afford 1.6 g (42%) of 3,4,5-tris(trifluoromethyl)nitrobenzene, mp 53°.

4.1.1.6. (Trifluoromethyl)benzene (Fluorination of an Ester) (45)

A 100-mL stainless-steel autoclave (*capable of containing* 50 *atm of pressure*) fitted with a needle valve was charged with 4 g (0.03 mol) of methyl benzoate and 15 mL (15 g, 0.75 mol) of anhydrous hydrogen fluoride. Then 16.2 g (8.7 mL, 0.15 mol) of sulfur tetrafluoride was condensed into it. The autoclave was heated at 75–80° for 16 hours and then cooled, and the volatile products were released. The reaction mixture was poured onto ice, and the products were extracted with ether. The ether extracts were washed with 5% sodium carbonate solution and water and dried over magnesium sulfate. The ether was evaporated, and the residue was distilled to afford (trifluoromethyl)benzene (2 g, 45%), bp 101–103°, n_D^{20} 1.4145.

4.1.1.7. 1,1-Difluoro-2-(4-nitrophenyl)ethane (Fluorination of an Oxirane) (50)

A mixture of (4-nitrophenyl)oxirane (3.3 g, 20 mmol) and sulfur tetrafluoride (2.5 mL, 4.6 g, 42.5 mmol) was kept in an autoclave (*one can use a* 100-*mL* *stainless-steel or Hastelloy-lined vessel capable of containing* 15 *atm of pressure*) at 85° for 3 hours. The gaseous products were released, the residue was dissolved in ether, and sodium fluoride was added to the ether solution. After 2 hours, the sodium fluoride was removed by filtration and the ether was evaporated. The reaction product was extracted with hot hexane. Removal of the hexane gave 1.78 g (47%) of 1,1-difluoro-2-(4-nitrophenyl)ethane, mp 55°.

4.1.1.8. 9,10-Dichlorophenanthrene (55)

A quartz reactor was charged with *cis*- α , β -dichlorostilbene (2.5 g, 0.01 mol), lead dioxide (2.4 g, 0.01 mol), and 40 mL of methylene chloride or carbon tetrachloride. The reactor was cooled to –50° technical sulfur tetrafluoride (3 mL, 5.4 g, 0.05 mol) was slowly added, and the mixture was stirred for 1 hour; the temperature was raised to –20°, and the precipitate was removed by filtration at room temperature. Anhydrous sodium fluoride (10 g) was added to the filtrate, and the mixture was left for 4–5 hours. The mixture was filtered, the filtrate was evaporated under vacuum, and the residue was treated two or three times with 20–30 mL of boiling hexane. The combined hexane extracts were evaporated to a volume of 5 mL and slowly cooled, the mixture of substances that had deposited was removed by filtration, and from this solid the cubic crystals of *trans*-stilbene were selected manually. The remaining acicular crystals of 9,10-dichlorophenanthrene were recrystallized from hexane to give 0.96–1.03 g (39–42%), mp 159–160°.

4.1.1.9. N-(Benzylimino)sulfur Difluoride (Fluorination of an Amine) (74)

Benzylamine (36 g, 0.34 mol), sodium fluoride (28 g), and trimethylamine (100 g) were placed into a dried flask with a condenser maintained at –75°. The flask was cooled to –45°. Sulfur tetrafluoride (30 mL, 56.7 g, 0.525 mol) was added over a period of 1 hour. The solution became yellow and a precipitate formed. The reaction mixture was stirred at –45° for 2 hours and then allowed to warm to room temperature to evaporate trimethylamine and any excess sulfur tetrafluoride. All gases exited the experiment through a trap containing an aqueous solution of sodium hydroxide. The residue was distilled directly from the reaction vessel to give 30 g (52%) of *N*-(benzylimino) sulfur difluoride, bp 30–35° (10^{-5} mm).

4.1.1.10. Diethylaminosulfur Trifluoride (14)

A solution of diethylaminotrimethylsilane (96 g, 0.66 mol) in fluorotrichloromethane (100 mL) was added dropwise to a solution of 40 mL (measured at –78°, 0.72 mol) of sulfur tetrafluoride in fluorotrichloromethane (200 mL) at –65 to –60°. The reaction mixture was warmed to room temperature and then distilled to give 88.9 g (84%) of diethylaminosulfur trifluoride as a pale yellow liquid, bp 46–47° (10 mm).

4.1.1.11. cis-Tetrafluorobis(trifluoromethoxy)sulfur (62)

Sulfur tetrafluoride (0.3 mL, 0.54 g, 5 mmol) was condensed into a 150-mL quartz vessel followed by 1.2 g (10 mmol) of trifluoromethyl hypochlorite. (75) The mixture was allowed to warm to 25° and was photolyzed for 24 hours with a Hanovia utility ultraviolet quartz lamp (310–1000 nm). After this period the remaining material was vacuum distilled, and *cis*-tetrafluorobis(trifluoromethoxy)sulfur was collected in a trap at –78°. The yield was 1.25–1.32 g (90–95%).

4.1.1.12. Difluorodiphenyltellurium (Fluorination of a Telluride) (66)

A moderately fast stream of sulfur tetrafluoride was passed through a boiling solution of diphenyl telluride (2.8 g, 10 mmol) in dry benzene (40 mL) in a two-necked 100-mL quartz flask for a period of 30 minutes. The contents of the flask were cooled, the solvent was evaporated under vacuum, and the residue was crystallized from petroleum ether to give 2.8 g (87%) of difluorodiphenyltellurium, mp 152°.

5. Tabular Survey

The following tables list the reactions of sulfur tetrafluoride reported from 1972 through 1982. Substrates are listed according to the functional group undergoing reaction as follows: Tables I, "Alcohols"; II, "Aldehydes and Ketones"; III, "Carboxylic Acids"; IV, "Acyl Halides"; V, "Esters"; VI, "Lactones"; VII, "Amides and Imides"; VIII, "Acid Anhydrides"; IX, "Carbonates"; X, "Oxiranes"; XI, "Chlorides, Bromides, and Iodides"; XII, "Amines"; XIII, "Boron, Phosphorus, and Silicon Compounds"; and XIV, "Miscellaneous Compounds".

A compound that has two or more different functional groups that undergo reaction appears in each appropriate table. Thus a hydroxy acid will appear in Table I ("Alcohols") if its hydroxyl group is replaced by a fluorine atom and in Table III ("Carboxylic Acids") if its carboxyl group is converted into CF_3 or COF.

Within each table, compounds are arranged by their empirical formulas according to the order of increasing number of carbon atoms and then in the order of increasing number of hydrogen atoms.

All reactions were carried out in sulfur tetrafluoride as the solvent unless otherwise specified. Yields are reported whenever available; a dash signifies that yields were not reported.

Table I. Alcohols

View PDF

Table II. Aldehydes and Ketones

View PDF

Table III. Carboxylic Acids

View PDF

Table IV. Acyl Halides

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Table V. Esters

View PDF

Table VI. Lactones

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Table VII. Amides and Imides

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Table VIII. Acid Anhydrides

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Table IX. Carbonates

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Table X. Oxiranes

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Table XI. Chlorides, Bromides, and Iodides

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Table XII. Amines

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Table XIII. Boron, Phosphorus, and Silicon Compounds

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Table XIV. Miscellaneous Compounds

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TABLE I. ALCOHOLS

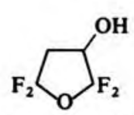
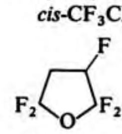
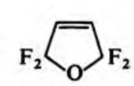
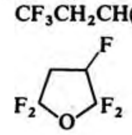
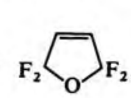
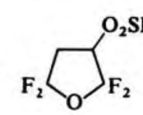
	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
C_2	$HOCH_2CO_2H$	160°, 8 hr	FCH_2CF_3 (30), $HOCH_2CF_3$ (48)	12
		60°, 15 hr	FCH_2CF_3 (26), $HOCH_2CF_3$ (5), $FSO_2CH_2CF_3$ (42)	12
C_3	$(CF_3)_2CHOH$	*n*-BuLi; SF_4, 3.4 eq, −50 to 25°	$(CF_3)_2CHOSF_3$ (54)	3a
		n-BuLi; SF_4, 0.5 eq, −50 to 25°	$[(CF_3)_2CHO]_2SF_2$ (30)	3a
	$(CF_3)_2C(OH)SH$	−78°	$(CF_3)_2CS$ (−)	4
	$H(CF_2)_2CH_2OH$	−60 to 20°, KF or NaF, ether	$H(CF_2)_2CH_2OSF_3$ (75–85)	3
	$CH_3CHOHCO_2H$	60°, 15 hr	CH_3CHFCF_3 (5), $CH_3CH(O_2SF)CF_3$ (40)	12
	$HOCH_2C(NO_2)_2CH_2OH$	80°, 4 days	$FCH_2C(NO_2)_2CH_2OH$ (20), $FCH_2C(NO_2)_2CH_2F$ (−)	76
	$HOCH_2CH(NH_2)CO_2H$	−78°, HF	$FCH_2CH(NH_2)CO_2H$ (51)	6
C_4	$CF_3CH_2CHOHCF_3$	120°, 6 hr	$CF_3CH_2CHFCF_3$ (49), *trans*-$CF_3CH{=}CHCF_3$ (35), *cis*-$CF_3CH{=}CHCF_3$ (5)	12
		120°, 10 hr	 (−),  (−)	12
	$(CF_3)_2COHCH_3$	90–95°, 18 hr	$(CF_3)_2C{=}CH_2$ (72)	77
	$CF_3COH(CHF_2)CH_3$	90–92°, 16 hr	$CF_3C(CHF_2){=}CH_2$ (35)	77
	$(CHF_2)_2COHCH_3$	95°, 16 hr	$(CHF_2)_2C{=}CH_2$ (38)	77
	$HO_2CCH_2CHOHCO_2H$	130°, 8 hr	$CF_3CH_2CHFCF_3$ (5), $CF_3CH{=}CHCF_3$ (4), $CF_3CH_2CH(O_2SF)CF_3$ (47),  (7),  (5),  (28)	12

TABLE I. Alcohols (*Continued*)

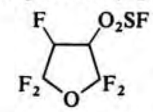
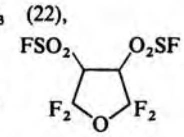
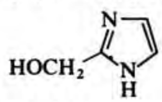
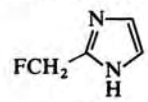
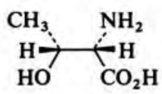
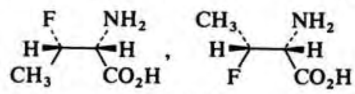
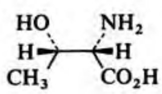
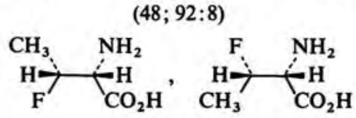
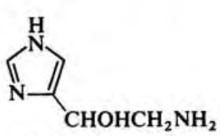
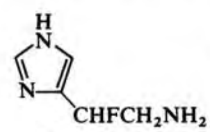
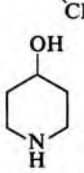
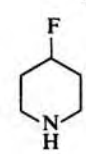
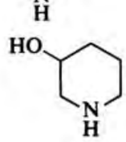
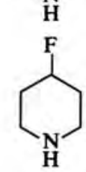
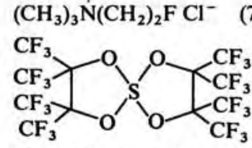
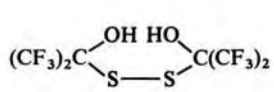
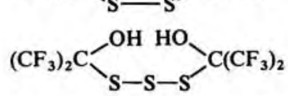
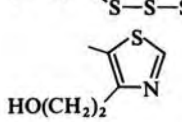
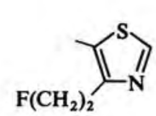
	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs.
	(−)-D-$HO_2CCHOHCHOHCO_2H$	HF, 20°, 48 hr	$CF_3CHFCH(O_2SF)CF_3$ (22),  (21),  (27)	78
	(−)-D- or (+)-L-$HO_2CCHOHCHOHCO_2H$	110°, 6 hr	*meso*-$HO_2CCHFCHFCO_2H$ (15)	10
		−78°, HF	 (32)	6
	$HO_2CCHOHCH(NH_2)CO_2H$	−78° to room temp, HF	$HO_2CCHFCH(NH_2)CO_2H$ (42–71)	7
	$CH_3CHOHCH(NH_2)CO_2H$	−78°, HF	$CH_3CHFCH(NH_2)CO_2H$ (85)	6
	$H_2NCH_2CHOHCH_2CO_2H$	−78° to room temp, HF	$H_2NCH_2CHFCH_2CO_2H$ (50)	7
	$HOCH_2C(CH_3)(NH_2)CO_2H$	−78° to room temp, HF	$FCH_2C(CH_3)(NH_2)CO_2H$ (18),  (28)	7
		−78° to room temp, HF	 (48; 92:8)	7
		−78° to room temp, HF	 (57; 78:22)	7
C_5	$H(CF_2)_4CH_2OH$	−60 to 20°, KF or NaF, ether	$H(CF_2)_4CH_2OSF_3$ (75–85)	3
		−78° to room temp, HF	 (71)	7
		−78°, HF	 (64)	6
		−78°, HF	 (46)	6
	$(CH_3)_3\overset{+}{N}(CH_2)_2OH\ Cl^-$	−78°, HF	$(CH_3)_3\overset{+}{N}(CH_2)_2F\ Cl^-$ (75)	6
C_6	$(CF_3)_2COHCOH(CF_3)_2$	20°	 (85)	5
		−78°	$(CF_3)_2C{=}S$ (−)	4
		−78°	" (−)	4
		−78°, HF	 (29)	6

TABLE I. ALCOHOLS (*Continued*)

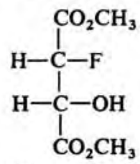
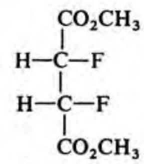
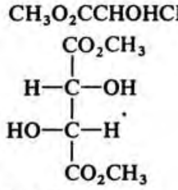
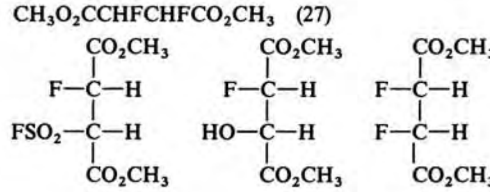
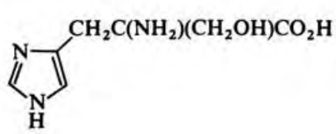
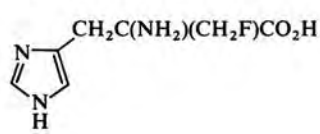
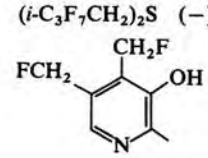
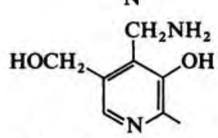
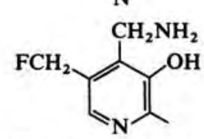
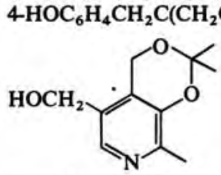
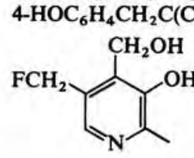
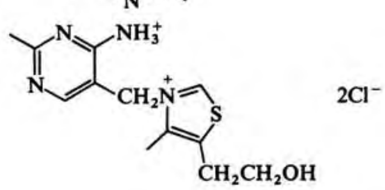
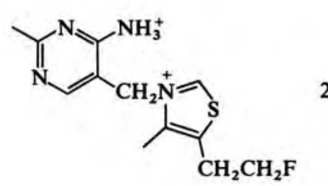
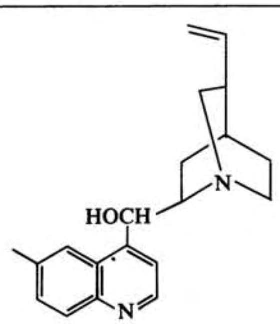
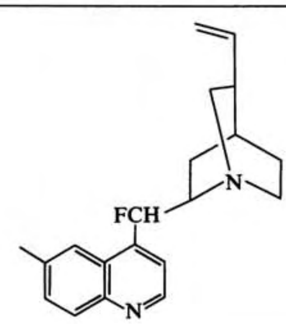
	Alcohol	Conditions	Product(s) and Yield(s) (%)	Refs
		60°, HF, 6 hr	 (97)	11
	$CH_3O_2CCHOHCHOHCO_2CH_3$	110°, 10 hr	$CH_3O_2CCHFCHFCO_2CH_3$ (27)	9
				
	(+)-L	20°, 2 hr	(98) (trace) (1)	11
		60°, 6 hr	(80) (7) (8)	11
		110°, 8 hr	(65) (5) (24)	10,11[a]
		40°, HF, 6 hr	(58) (2) (36)	11
		90°, HF, 6 hr	(trace) (trace) (96)	11
		20°, NaF, 24 hr	(97) (trace) (trace)	11
		110°, NaF, 8 hr	(92) (2) (3)	11
	$H_2N(CH_2)_3C(NH_2)(CH_2OH)CO_2H$	HF, BF_3	$H_2N(CH_2)_3C(NH_2)(CH_2F)CO_2H$ (−)	79
	t-$C_4H_9NH(CH_2)_2OH$	HF, −78°	t-$C_4H_9NH(CH_2)_2F$ (38)	6
C_7	$H(CF_2)_6CH_2OH$	−60 to 20°, KF or NaF, ether	$H(CF_2)_6CH_2OSF_3$ (75–85)	3
		HF, BF_3		79
C_8	$[(CF_3)_2COHCH_2]_2S$	25°	$(i$-$C_3F_7CH_2)_2S$ (−)	4
		HF, −78°	 (52)	7
		HF, −78°	 (49)	7
	$C_2H_5O_2CCHOHCHOHCO_2C_2H_5$	25°, 60 hr	$C_2H_5O_2CCHFCHOHCO_2C_2H_5$ (41)	9
		100°, 10 hr	$C_2H_5O_2CCHFCHFCO_2C_2H_5$ (38)	4
C_9	$C_6H_5CHOHCH(NH_2)CO_2H$	HF, −78°	$C_6H_5CHFCH(NH_2)CO_2H$ (65)	6
C_{10}	$3,4$-$(HO)_2C_6H_3CH_2C(CH_2OH)(NH_2)CO_2H$	HF, BF_3	$3,4$-$(HO)_2C_6H_3CH_2C(CH_2F)(NH_2)CO_2H$ (−)	79
	4-$HOC_6H_4CH_2C(CH_2OH)(NH_2)CO_2H$	HF, BF_3	4-$HOC_6H_4CH_2C(CH_2F)(NH_2)CO_2H$ (−)	79
C_{11}		HF	 (29)	7
C_{12}		HF, −78°	 (44)	7

TABLE I. ALCOHOLS (*Continued*)

Alcohol		Conditions	Product(s) and Yield(s) (%)	Refs.
C_{20}		HF, −78°	 (84)	7

[a] This reaction was also carried out with the (−)-D-isomer.

TABLE II. ALDEHYDES AND KETONES

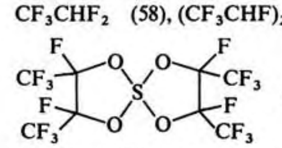
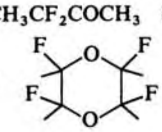
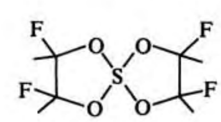
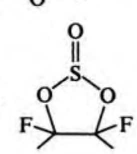
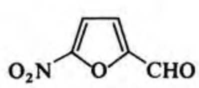
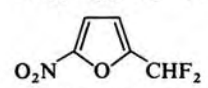
	Aldehyde or Ketone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_2	CCl_3CHO	Room temp, 16 hr	$CFCl_2CHFCl$ (57), $CHFClCCl_2OCHFCCl_3$ (13), $(CCl_3CHF)_2O$ (1)	80
	CF_3CHO	Room temp, 66 hr	CF_3CHF_2 (58), $(CF_3CHF)_2O$ (16)	80
C_4	$CF_3COCOCF_3$	Room temp, 24 hr	 (100)	19
	$CH_3COCOCH_3$	Room temp, 24 hr	$CH_3(CF_2)_2CH_3$ (18), $CH_3CF_2COCH_3$ (3), $(CH_3CF_2\underset{CH_3}{\underset{\mid}{C}}F)_2O$ (2),  (11),  (7),  (2)	20
		HF, 15°, 2 hr	$CH_3(CF_2)_2CH_3$ (80)	20
C_5		HF, 40°, 12 hr	 (86)	41
	$CH_3COCO_2C_2H_5$	100°, 10 hr	$CH_3CF_2CO_2C_2H_5$ (28)	81
		HF, 20°, 12 hr	„ (78)	81
	$CH_3COCOC_2H_5$	HF, 15°, 2 hr	$CH_3(CF_2)_2C_2H_5$ (82)	22
C_6	$CH_3COCH_2CO_2C_2H_5$	100°	$CH_3C{\equiv}CCO_2C_2H_5$ (38), $CH_3CF_2CH_2CO_2C_2H_5$ (36), $CH_3CF{=}CHCO_2C_2H_5$ (*cis*, 16; *trans*, 5)	23
		HF, 20°, 12 hr	$CH_3CF_2CH_2CO_2C_2H_5$ (85)	81

TABLE II. ALDEHYDES AND KETONES (*Continued*)

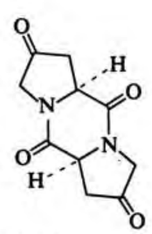
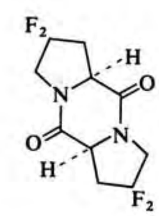
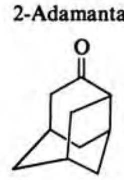
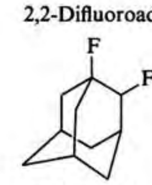
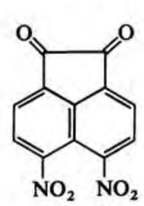
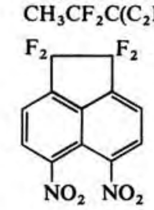
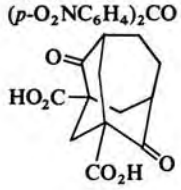
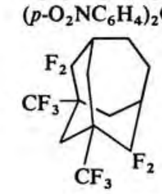
	Aldehyde or Ketone	Conditions	Product(s) and Yield(s) (%)	Refs.
	$C_2H_5COCOC_2H_5$	HF, 15°, 2 hr	$C_2H_5(CF_2)_2C_2H_5$ (84)	22
		20°, 24 hr	$C_2H_5(CF_2)_2C_2H_5$ (43), $C_2H_5CF_2CF{=}CHCH_3$ (27)	20
	$CH_3COCOC_3H_7$-*n*	HF, 15°, 2 hr	$CH_3(CF_2)_2C_3H_7$-*n* (86)	22
		20°, 24 hr	$CH_3(CF_2)_2C_3H_7$-*n* (40), $CH_3CF_2CF{=}CHC_2H_5$ (16), $CH_2{=}CFCF_2C_3H_7$-*n* (8)	20
C_7	C_6F_5CHO	140–150°, 8 hr, 160–170°, 3 hr	$C_6F_5CHF_2$ (51)	82
	$CO(CO_2C_2H_5)_2$	HF, 20°, 12 hr	$CF_2(CO_2C_2H_5)_2$ (−), $C_2H_5O(CF_2)_2CO_2C_2H_5$ (−)	81
	$C_2H_5COCH_2CO_2C_2H_5$	100°	$C_2H_5CF_2CH_2CO_2C_2H_5$ (22), $C_2H_5C{\equiv}CCO_2C_2H_5$ (32), $C_2H_5CF{=}CHCO_2C_2H_5$(*cis*, 11; *trans*, 6)	22
		HF, 20°	$C_2H_5CF_2CH_2CO_2C_2H_5$ (82)	22
	$CH_3CO(CH_2)_2CO_2C_2H_5$	HF, 20°, 12 hr	$CH_3CF_2(CH_2)_2CO_2C_2H_5$ (76)	81
C_8	$C_2H_5O_2CCH_2COCO_2C_2H_5$	HF, 20°, 12 hr	$C_2H_5O_2CCH_2CF_2CO_2C_2H_5$ (76)	81
	$CH_3COCH(C_2H_5)CO_2C_2H_5$	100°	$CH_2{=}C{=}C(C_2H_5)CO_2C_2H_5$ (33), $CH_3CF_2CH(C_2H_5)CO_2C_2H_5$ (22), $CH_3CF{=}C(C_2H_5)CO_2C_2H_5$ (*cis*, 13; *trans*, 6)	22
		HF, 20°	$CH_3CF_2CH(C_2H_5)CO_2C_2H_5$ (80)	22
	n-$C_3H_7COCOC_3H_7$-*n*	20°, 24 hr	*n*-$C_3H_7(CF_2)_2C_3H_7$-*n* (44), $C_3H_7CF_2{=}CHC_2H_5$ (29)	20
		HF, 15°, 2 hr	*n*-$C_3H_7(CF_2)_2C_3H_7$-*n* (92)	20
	$CH_3COCOC_5H_{11}$-*n*	HF, 15°, 2 hr	$CH_3(CF_2)_2C_5H_{11}$-*n* (82)	20
C_9	$CO(CH_2CO_2C_2H_5)_2$	HF, 20°, 12 hr	$CF_2(CH_2CO_2C_2H_5)_2$ (85)	81
	$CH_3COCH(C_3H_7$-*i*$)CO_2C_2H_5$	100°	$CH_2{=}C{=}C(C_3H_7$-*i*$)CO_2C_2H_5$ (33), $CH_3CF_2CH(C_3H_7$-*i*$)CO_2C_2H_5$ (22), $CH_3CF{=}C(C_3H_7$-*i*$)CO_2C_2H_5$ (*cis*, 19; *trans*, 8)	22
		HF, 20°	$CH_3CF_2CH(C_3H_7$-*i*$)CO_2C_2H_5$ (76)	22
C_{10}		HF, room temp, 3 days	 (70)	83
	2-Adamantanone	110°	2,2-Difluoroadamantane (75)	84
		120°, 10 hr	 (93)	26
	$CH_3COC(C_2H_5)_2CO_2C_2H_5$	100°	$CH_3CF_2C(C_2H_5)_2CO_2C_2H_5$ (31)	22
		HF, 20°	$CH_3CF_2C(C_2H_5)_2CO_2C_2H_5$ (78)	22
C_{12}		HF, 150°	 (100)	44
C_{13}	$(C_6F_5)_2CO$	235°, 6 hr	$(C_6F_5)_2CF_2$ (88)	85
	$C_6F_5COC_6H_5$	180°, 10 hr	$C_6F_5CF_2C_6H_5$ (40)	85
	$(p\text{-}O_2NC_6H_4)_2CO$	220–240°, 10 hr	$(p\text{-}O_2NC_6H_4)_2CF_2$ (90)	85
		HF, 130–135°, 10 hr	 (87)	26

TABLE II. ALDEHYDES AND KETONES (*Continued*)

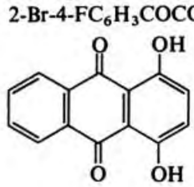
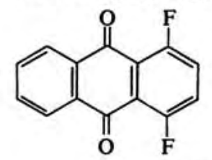
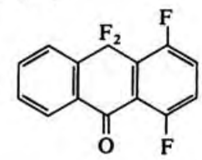
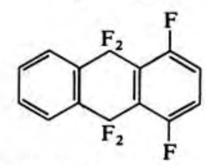
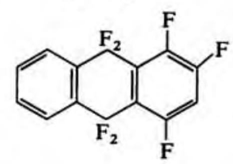
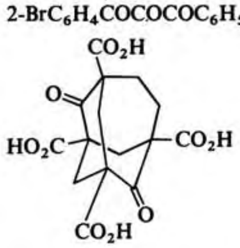
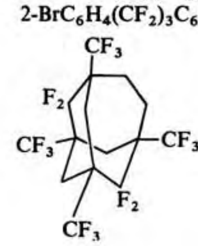
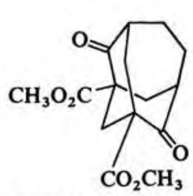
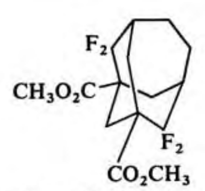
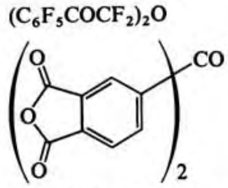
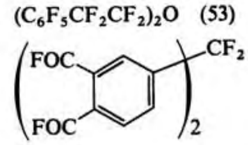
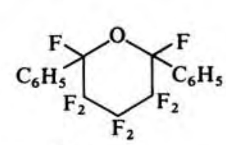
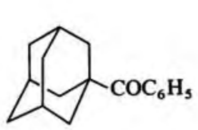
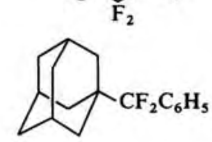
	Aldehyde or Ketone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{14}	2-Br-4-$FC_6H_3COCOC_6H_4F$-4		2-Br-4-$FC_6H_3(CF_2)_2C_6H_4F$-4 (−)	86
	2-$BrC_6H_4COCOC_6H_4F$-4		2-$BrC_6H_4(CF_2)_2C_6H_4F$-4 (−)	86
	2-Br-4-$FC_6H_3COCOC_6H_5$		2-Br-4-$FC_6H_3(CF_2)_2C_6H_5$ (−)	86
		120–200°	 (1),  (5),  (40),  (17)	25
	2-$BrC_6H_4COCOC_6H_5$		2-$BrC_6H_4(CF_2)_2C_6H_5$ (−)	86
C_{15}	2-Br-4-$FC_6H_3COCOCOC_6H_4F$-4		2-Br-4-$FC_6H_3(CF_2)_3C_6H_4F$-4 (−)	86
	2-$BrC_6H_4COCOCOC_6H_4F$-4		2-$BrC_6H_4(CF_2)_3C_6H_4F$-4 (−)	86
	2-Br-4-$FC_6H_3COCOCOC_6H_5$		2-Br-4-$FC_6H_3(CF_2)_3C_6H_5$ (−)	86
	2-$BrC_6H_4COCOCOC_6H_5$		2-$BrC_6H_4(CF_2)_3C_6H_5$ (−)	86
		HF, 125–135°, 15 hr	 (83)	26
		120–130°, 16 hr	 (89)	26
C_{16}	$(C_6F_5COCF_2)_2O$	165–170°, 14 hr	$(C_6F_5CF_2CF_2)_2O$ (53)	87
C_{17}		215–220°, 16 hr	 (63)	85
	$C_6H_5CO(CF_2)_3COC_6H_5$	HF	 (80)	24
		20°, 24 hr; 120–130°, 12 hr	 (−)	26

TABLE II. ALDEHYDES AND KETONES (*Continued*)

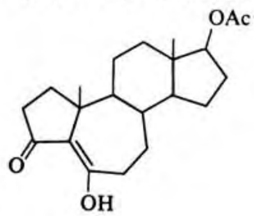
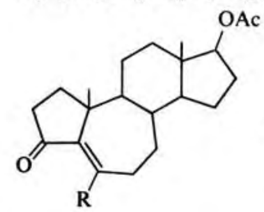
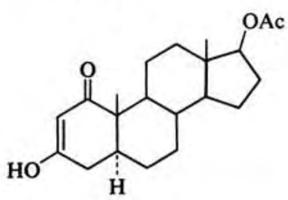
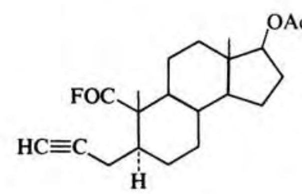
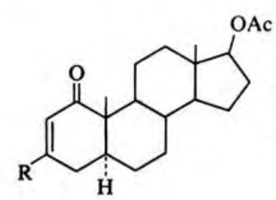
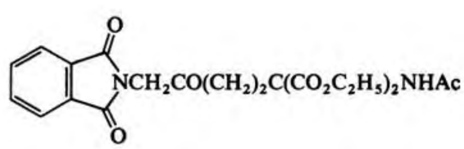
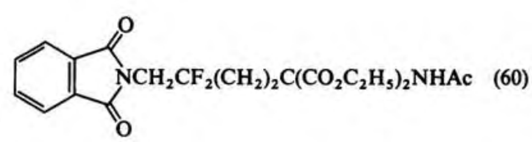
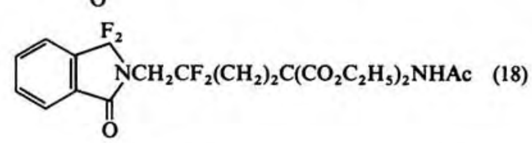
	Aldehyde or Ketone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{18}	$C_6F_5CO(CF_2)_4COC_6F_5$	175°, 70 hr	$C_6F_5(CF_2)_6C_6F_5$ (49–75)	87
	$[C_6F_5CO(CF_2)_2]_2O$	160°, 43 hr, 175°, 72 hr	$[C_6F_5(CF_2)_3]_2O$ (93)	87
	$C_6H_5CO(CF_2)_4COC_6H_5$	HF	$C_6H_5(CF_2)_6C_6H_5$ (76)	24
C_{21}	$C_6F_5COCF(CF_3)O(CF_2)_5COC_6F_5$	175°, 157 hr	$C_6F_5CF_2CF(CF_3)O(CF_2)_6C_6F_5$ (35)	87
		Room temp, dry C_6H_6	 ($R=F$, 65–70; $R=C_6H_5$, 25)	21
		Room temp, dry C_6H_6	 (30–35)  ($R=F$, 20; $R=C_6H_5$, 7)	21
		HF	 (60)  (18)	83

TABLE III. CARBOXYLIC ACIDS

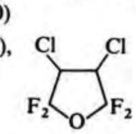
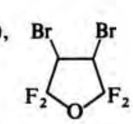
	Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
C_2	CF_3CO_2H	250°, 6 hr	CF_3COF (100)	29
	CCl_3CO_2H	250°, 6 hr	CCl_3COF (100)	29
	$CHCl_2CO_2H$	60°, 3 hr	$CHCl_2CF_3$ (65), $(CHCl_2CF_2)_2O$ (8)	29
		23°, 20 hr	" (27), " (4)	29
	CHF_2CO_2H	60°, 3 hr	CHF_2CF_3 (23), $(CHF_2CF_2)_2O$ (<1)	29
	FCH_2CO_2H	60°, 3 hr	FCH_2CF_3 (71), $(FCH_2CF_2)_2O$ (11)	29
		20°, 20 hr	" (16), " (7)	29
	$ClCH_2CO_2H$	65°, 3 hr	$ClCH_2CF_3$ (51), $(ClCH_2CF_2)_2O$ (24)	29
		16°, 18 hr	" (17), " (15)	29
	$BrCH_2CO_2H$	60°, 3 hr	$BrCH_2CF_3$ (67), $(BrCH_2CF_2)_2O$ (24)	29
		17°, 20 hr	" (17), " (18)	29
	ICH_2CO_2H	60°, 3 hr	ICH_2CF_3 (67), $(ICH_2CF_2)_2O$ (15)	29
		26°, 21 hr	" (35), " (17)	29
	CH_3CO_2H	60°, 3 hr	CH_3CF_3 (86)	29
		4°, 48 hr	" (78)	29
		−10°, 48 hr	" (29), $(CH_3CF_2)_2O$ (16)	29
	$HOCH_2CO_2H$	160°, 8 hr	FCH_2CF_3 (30), $HOCH_2CF_3$ (48)	12
		60°, 15 hr	FCH_2CF_3 (26), $HOCH_2CF_3$ (5), $FSO_2CH_2CF_3$ (42)	12
C_3	$ClCH_2CHClCO_2H$	60°, 3 hr	$ClCH_2CHClCF_3$ (55), $(ClCH_2CHClCF_2)_2O$ (9)	29
		23°, 20 hr	" (35), " (7)	29
	$BrCH_2CHBrCO_2H$	115°, 6 hr	$BrCH_2CHBrCF_3$ (69), $(BrCH_2CHBrCF_2)_2O$ (7)	29
		45°, 3 hr	" (25), " (7)	29
	$CH_3CCl_2CO_2H$	60°, 3 hr	$CH_3CCl_2CF_3$ (60)	29
		17°, 20 hr	" (12)	29
	$CH_2(CO_2H)_2$	70°, 3 hr	$CH_2(CF_3)_2$ (39), $(CF_3CH_2CF_2)_2O$ (10)	42
		130°, 3 hr	" (70), " (12)	42
	$Cl(CH_2)_2CO_2H$	70°, 3 hr	$Cl(CH_2)_2CF_3$ (45), $[Cl(CH_2)_2CF_2]_2O$ (21)	29
		18°, 18 hr	" (29), " (34)	29
	$Br(CH_2)_2CO_2H$	115°, 6 hr	$Br(CH_2)_2CF_3$ (80), $[Br(CH_2)_2CF_2]_2O$ (5)	29
		16°, 18 hr	" (46), " (28)	29
	$I(CH_2)_2CO_2H$	23°, 20 hr	$I(CH_2)_2CF_3$ (45), $[I(CH_2)_2CF_2]_2O$ (33)	29
	$CH_3CHClCO_2H$	75°, 6 hr	$CH_3CHClCF_3$ (48), $(CH_3CHClCF_2)_2O$ (20)	29
		20°, 20 hr	" (32), " (16)	29
	$CH_3CHBrCO_2H$	50°, 6 hr	$CH_3CHBrCF_3$ (58), $(CH_3CHBrCF_2)_2O$ (20)	29
		18°, 20 hr	" (35), " (16)	29
	$C_2H_5CO_2H$	20°, 20 hr	$C_2H_5CF_3$ (96)	29
		−15°, 48 hr	" (27), $(C_2H_5CF_2)_2O$ (16)	29
	$CH_3OCH_2CO_2H$	20°, 40 hr	$CH_3OCH_2CF_3$ (9)	30
		60°, 3 hr	" (35)	30
	$CH_3CHOHCO_2H$	60°, 15 hr	CH_3CHFCF_3 (5), $CH_3CH(O_2SF)CF_3$ (40)	12
C_4	$HO_2CC{\equiv}CCO_2K$	60°, 15 hr	$FCOC{\equiv}CCOF$ (48–70)	88
	$HO_2CCHClCHClCO_2H$	120°, 3 hr	$CF_3CHClCHClCF_3$ (5),  (25)	42
		150°, 6 hr	" (20), " (39)	42
		200°, 6 hr	" (20), " (52)	42
	$HO_2CCHBrCHBrCO_2H$	180°, 6 hr	$CF_3CHBrCHBrCF_3$ (30),  (37)	42
	cis-$HO_2CCH{=}CHCO_2H$	60°, 3 hr	*cis*-$CF_3CH{=}CHCF_3$ (20)	42
		120°, 6 hr	" (57)	42
	trans-$HO_2CCH{=}CHCO_2H$	60°, 3 hr	*trans*-$CF_3CH{=}CHCF_3$ (18)	42
		100°, 3 hr	" (72)	42
		150°, 6 hr	" (73)	42
	$CF_3(CH_2)_2CO_2H$	60°, 3 hr	$CF_3(CH_2)_2CF_3$ (71), $[CF_3(CH_2)_2CF_2]_2O$ (8)	30

TABLE III. Carboxylic Acids (*Continued*)

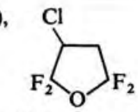
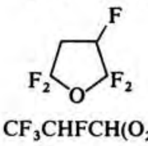
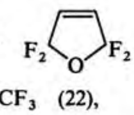
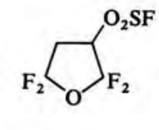
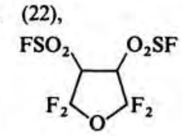
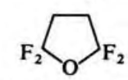
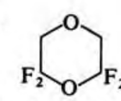
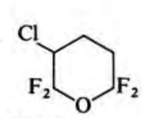
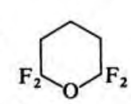
	Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
	$HO_2CCHClCH_2CO_2H$	55°, 3 hr	$CF_3CHClCH_2CF_3$ **A**(15),  **B**(24), $(CF_3CHClCH_2CF_2)_2O$ **C**(6)	42
		70°, 3 hr	**A**(22), **B**(19), **C**(6)	42
	$HO_2CCH_2CHOHCO_2H$	130°, 8 hr	$CF_3CH_2CHFCF_3$ (5), $CF_3CH{=}CHCF_3$ (4), $CF_3CH_2CH(O_2SF)CF_3$ (47),  (7),  (5),  (28)	12
	(−)-D-$HO_2CCHOHCHOHCO_2H$	20°, 48 hr	$CF_3CHFCH(O_2SF)CF_3$ (22),  (21),  (27)	78
	$HO_2C(CH_2)_2CO_2H$	20°, 20 hr	$CF_3(CH_2)_2CF_3$ **A**(11),  **B**(27), $[CF_3(CH_2)_2CF_2]_2O$ **C**(17)	42
		60°, 3 hr	**A**(11), **B**(35), **C**(12)	42
		120°, 3 hr	**A**(20), **B**(36), **C**(8)	42
	$(HO_2CCH_2)_2O$	45°, 3 hr	$(CF_3CH_2)_2O$ **A**(36),  **B**(16), $(CF_3CH_2OCH_2CF_2)_2O$ **C**(15)	52
		60°, 3 hr	**A**(43), **B**(14), **C**(15)	42
	$Cl(CH_2)_3CO_2H$	18°, 20 hr	$Cl(CH_2)_3CF_3$ (46), $[Cl(CH_2)_3CF_2]_2O$ (11)	30
		60°, 3 hr	" (63)	30
	n-$C_3H_7CO_2H$	−8°, 48 hr	n-$C_3H_7CF_3$ (19), $(n$-$C_3H_7CF_2)_2O$ (15)	30
		5°, 24 hr	" (8), " (12)	30
		20°, 24 hr	" (59)	30
		60°, 3 hr	" (85)	30
	i-$C_3H_7CO_2H$	−30°, 48 hr	i-$C_3H_7CF_3$ (16), $(i$-$C_3H_7CF_2)_2O$ (8)	30
		−10°, 48 hr	" (23), " (18)	30
		5°, 48 hr	" (25), " (13)	30
		17°, 24 hr	" (33), " (9)	30
		20°, 20 hr	" (83)	30
		60°, 3 hr	" (89)	30
	$C_2H_5OCH_2CO_2H$	0°, 48 hr	$C_2H_5OCH_2COF$ (high)	30
		22°, 22 hr	$C_2H_5OCH_2CF_3$ (41)	30
		30°, 20 hr	" (51)	30
C_5	$HO_2CCHCl(CH_2)_2CO_2H$	60°, 3 hr	$CF_3CHCl(CH_2)_2CF_3$ **A**(44),  **B**(6), $[CF_3CHCl(CH_2)_2CF_2]_2O$ **C**(11)	42
		120°, 3 hr	**A**(50), **B**(5), **C**(4)	42
	$HO_2C(CH_2)_3CO_2H$	5°, 48 hr	$CF_3(CH_2)_3CF_3$ **A**(34),  **B**(10), $[CF_3(CH_2)_3CF_2]_2O$ **C**(16)	42
		18°, 20 hr	**A**(42), **B**(7), **C**(18)	42
		60°, 3 hr	**A**(78), **B**(9), **C**(1)	42
	n-$C_4H_9CO_2H$	−5°, 48 hr	n-$C_4H_9CF_3$ (26), $(n$-$C_4H_9CF_2)_2O$ (6)	30
		5°, 42 hr	" (21), " (15)	30
		19°, 24 hr	" (32), " (7)	30
		20°, 24 hr	" (56)	30
		60°, 3 hr	" (70)	30
		90°, 3 hr	" (71)	30

TABLE III. Carboxylic Acids (*Continued*)

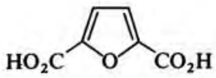
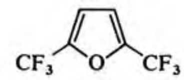
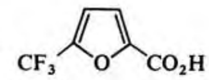
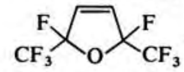
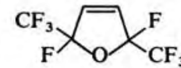
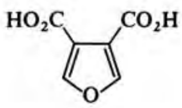
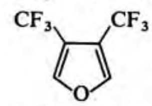
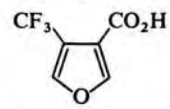
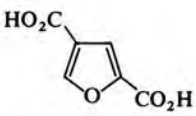
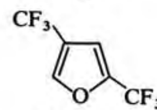
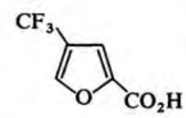
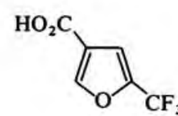
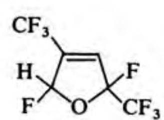
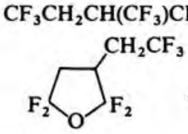
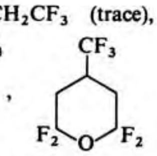
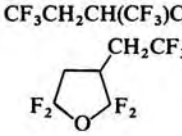
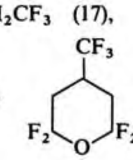
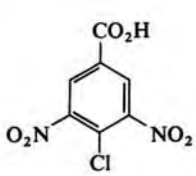
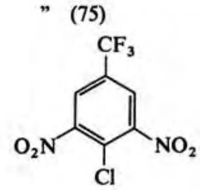
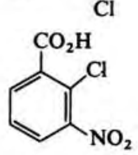
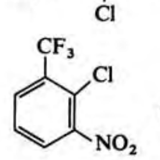
	Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
	$t\text{-}C_4H_9CO_2H$	60°, 3 hr	$t\text{-}C_4H_9COF$ (high)	30
		140°, 3 hr	$t\text{-}C_4H_9CF_3$ (10)	30
		160°, 3 hr	" (8)	30
C_6		185°, 45 hr	 (50),  (17)	39
		HF, 180–200°, 40 hr	,  (76)	41
		100°, 7 hr; 115°, 5 hr	 (70)	39
		100°, 10 hr	 (70)	39
		185°, 30 hr	 (69)	39
		140°, 4 hr; 175°, 12 hr; 185°, 20 hr	" (28),  (14),  (6)	39
		HF	 (36)	41
	$HO_2CCH_2CH(CO_2H)CH_2CO_2H$	60°, 3 hr	$CF_3CH_2CH(CF_3)CH_2CF_3$ (trace), ,  (28; 4:1)	42
		140°, 3 hr	$CF_3CH_2CH(CF_3)CH_2CF_3$ (17), ,  (63; 4:1)	42
	$HO_2C(CH_2)_4CO_2H$	5°, 48 hr	$CF_3(CH_2)_4CF_3$ (46), $[CF_3(CH_2)_4CF_2]_2O$ (20)	42
		18°, 20 hr	" (67), " (11)	42
		60°, 3 hr	" (81)	42
	$n\text{-}C_5H_{11}CO_2H$	15°, 16 hr	$n\text{-}C_5H_{11}CF_3$ (45), $(n\text{-}C_5H_{11}CF_2)_2O$ (7)	30
		22°, 20 hr	" (56)	30
		105°, 3 hr	" (75)	30
C_7		HF, 150°, 16 hr	 (—)	38
		HF, 150°, 16 hr	 (—)	38

TABLE III. CARBOXYLIC ACIDS (*Continued*)

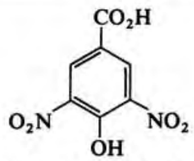
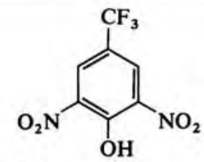
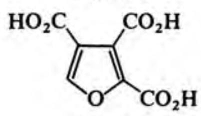
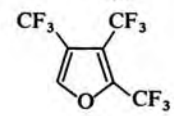
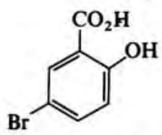
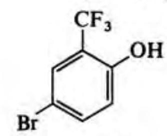
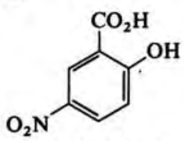
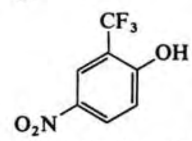
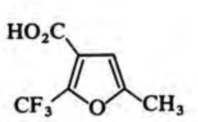
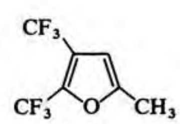
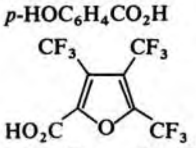
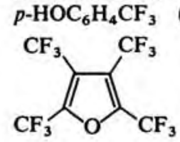
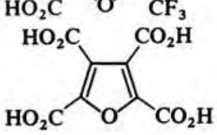
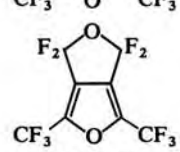
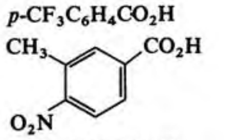
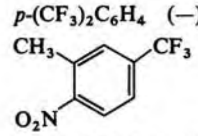
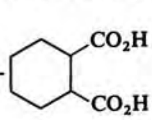
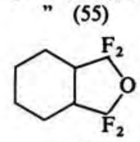
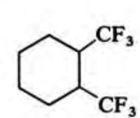
Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
	HF, 80°, 10 hr	 (92)	36
	HF, 175°, 15 hr	 (76)	40
	HF, 25°, 15 hr	 (45)	36
	HF, 25°, 15 hr	 (73)	36
o-$BrC_6H_4CO_2H$	HF, 190°, 2 days	*o*-$BrC_6H_4CF_3$ (52)	89
p-$FC_6H_4CO_2H$	160°, 6 hr	*p*-$FC_6H_4CF_3$ (25)	34
p-$ClC_6H_4CO_2H$	160°, 6 hr	*p*-$ClC_6H_4CF_3$ (24)	34
	HF, 90–100°	" (70)	35
p-$BrC_6H_4CO_2H$	160°, 6 hr	*p*-$BrC_6H_4CF_3$ (24)	34
p-$O_2NC_6H_4CO_2H$	160°, 6 hr	*p*-$O_2NC_6H_4CF_3$ (66)	34
	HF, 80°	" (80)	35
	130°, 12 hr	 (37)	39
$C_6H_5CO_2H$	HF, 100–110°	$C_6H_5CF_3$ (93)	35
	160°, 6 hr	" (17)	34
m-$HOC_6H_4CO_2H$	HF, 25°, 15 hr	*m*-$HOC_6H_4CF_3$ (75)	36
p-$HOC_6H_4CO_2H$	HF, 85–90°, 10 hr	*p*-$HOC_6H_4CF_3$ (80)	36
C_8 	HF, 120°, 20 hr	 (74)	41
	HF, 190°, 25 hr	 (54)	40
p-$CF_3C_6H_4CO_2H$	160°, 6 hr	*p*-$(CF_3)_2C_6H_4$ (—)	34
	140°, 8 hr	 (—)	90
p-$CH_3C_6H_4CO_2H$	160°, 6 hr	*p*-$CH_3C_6H_4CF_3$ (12)	34
	HF, 120–140°	" (80)	35
p-$CH_3OC_6H_4CO_2H$	160°, 6 hr	*p*-$CH_3OC_6H_4CF_3$ (8)	34
	HF, 120–140°	" (55)	35
cis- 	60°, 3 hr	 (70),  (3)	42
	100°, 3 hr	" (59), " (7)	42

TABLE III. CARBOXYLIC ACIDS (*Continued*)

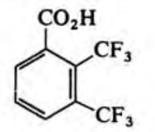
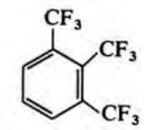
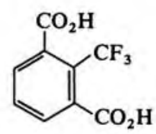
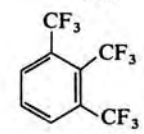
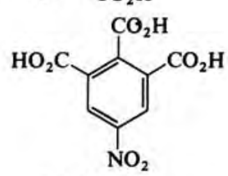
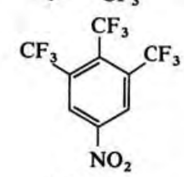
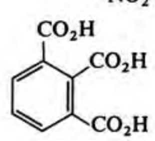
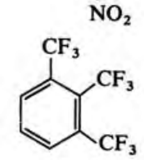
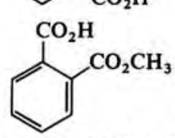
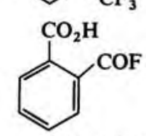
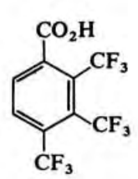
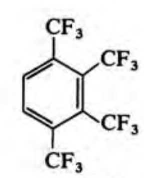
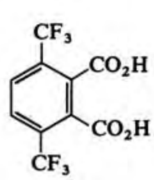
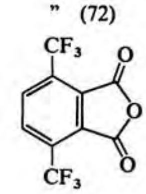
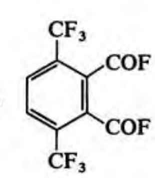
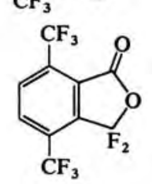
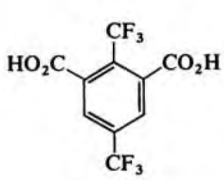
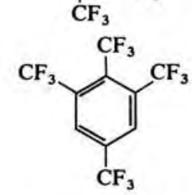
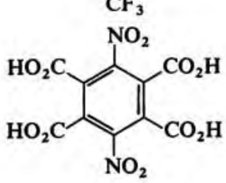
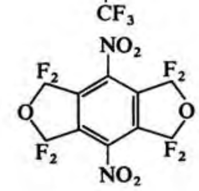
Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
C_9 	250–280°, 17 hr	 (25)	43
	HF, 250–280°, 17 hr	" (92)	43
	250°, 31 hr	 (17),  (60)	43
	HF, 250°, 50 hr	 (42)	73
	HF, 320°, 10 hr	 (71)	43
	140–145°, 48 hr	 (80–83)	91
$n\text{-}C_4H_9CH(CO_2C_2H_5)CO_2H$	HF, room temp, 13 days	$n\text{-}C_4H_9CH(CO_2C_2H_5)CF_3$ (44)	33
$n\text{-}C_8H_{17}CO_2H$	25°, 15 hr	$n\text{-}C_8H_{17}CF_3$ (41), $(n\text{-}C_8H_{17}CF_2)_2O$ (7)	30
	80°, 3 hr	" (71)	30
C_{10} 	320°, 10 hr	 (8)	43
	HF, 320°, 10 hr	" (72)	43
	60°, 10 hr	 (45),  (—),  (52)	92
	HF, 310°, 10 hr	 (55)	43
	HF, 160°, 15 hr	 (41)	73

TABLE III. CARBOXYLIC ACIDS (*Continued*)

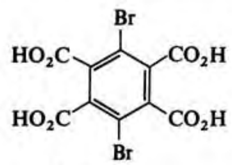
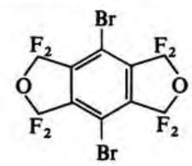
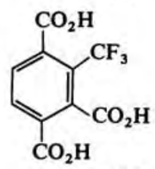
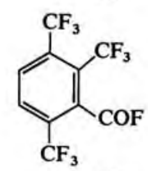
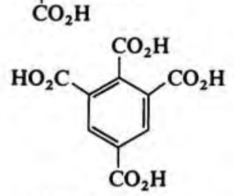
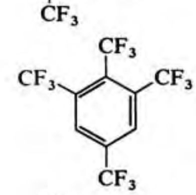
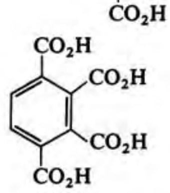
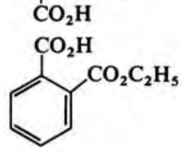
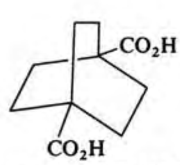
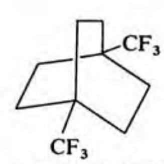
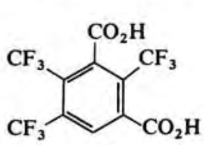
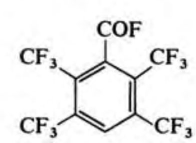
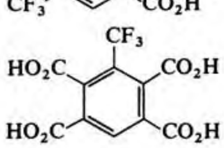
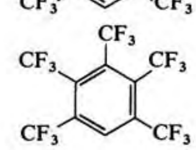
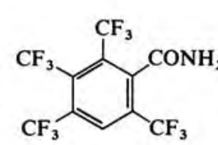
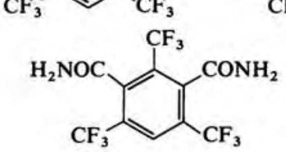
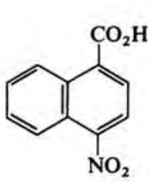
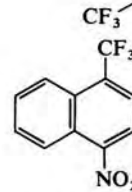
Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
	240–250°, 30 hr	 (84)	92
	100°, 1 hr; 150°, 3 hr; 170°, 5 hr; 220°, 10 hr	 (76)	92
	HF, 310°, 10 hr	 (37)	43
	HF, 310°, 10 hr	 (90)	43
	140–145°, 48 hr	 (80–83)	91
	75°, 1 hr; 100°, 1 hr; 125°, 8 hr	 (44)	93
n-$C_4H_9C(CH_3)(CO_2C_2H_5)CO_2H$	HF, room temp, 3 days; 60°, 3 days	n-$C_4H_9C(CH_3)(CO_2C_2H_5)CF_3$ (42)	33
C_{11} 	HF, 290°, 15 hr	 (71)	94
	HF, 300°, 100 hr, then NH_4OH	 (50),  (28),	73
		 (16)	73
	160°, 6 hr; 220–230°, 14 hr	 (53)	95
	HF, 40°	" (83)	35

TABLE III. CARBOXYLIC ACIDS (*Continued*)

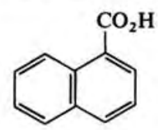
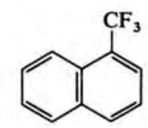
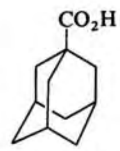
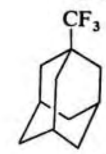
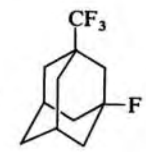
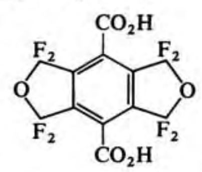
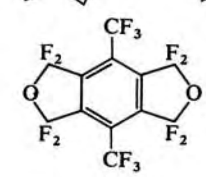
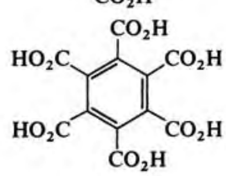
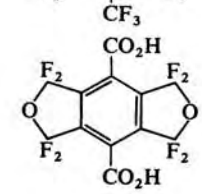
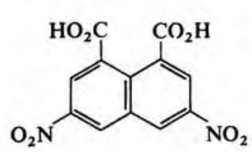
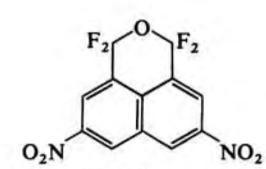
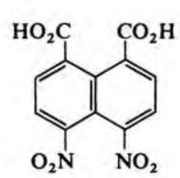
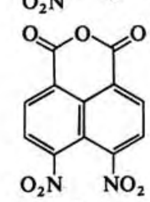
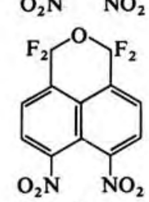
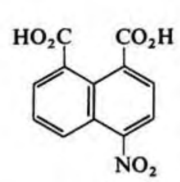
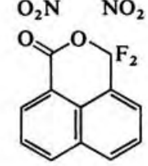
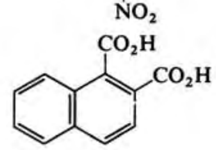
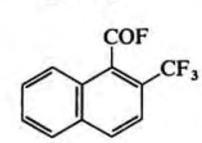
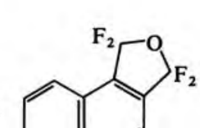
	Carboxylic Acid	Conditions	Product(s) and Yield(s) (%)	Refs.
		180°, 24 hr	 (7)	95
		160°, 4 hr; 220°, 14 hr; 250°, 12 hr	" (43)	95
		HF, 50°	" (60)	35
		50°, 1 hr; 75°, 1 hr; 100°, 1 hr; 125°, 1 hr	 (72),  (4)	93
C_{12}		260°, 40 hr	 (65)	92
		200°, 20 hr	 (17)	92
		HF	 (100)	44
		—	 (—)	44
		HF	 (—)	44
		150°, 8 hr	 (98)	44
		200–220°	 (—),  (—)	96

TABLE III. CARBOXYLIC ACIDS (*Continued*)

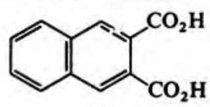
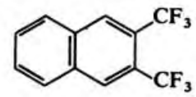
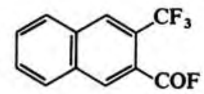
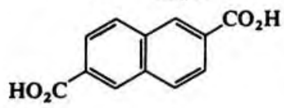
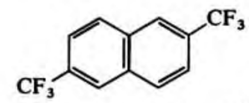
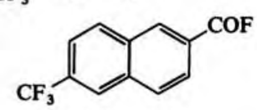
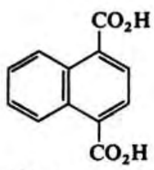
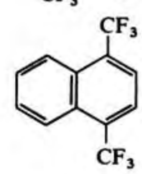
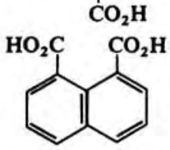
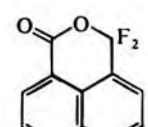
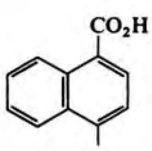
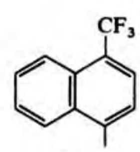
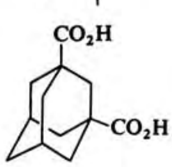
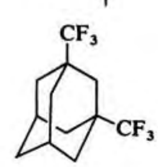
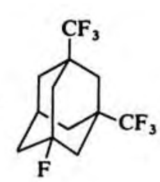
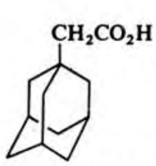
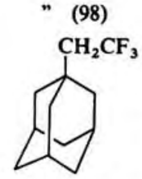
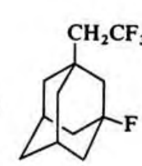
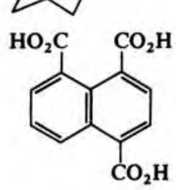
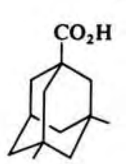
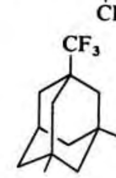
	Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
		—	 (—),  (—)	96
		—	 (—),  (—)	96
		HF, 50°	 (78)	35
		110–120°, 10 hr	 (68)	92
		220°, 10 hr	" (63)	92
		HF, 75°	 (70)	35
		75°, 1 hr; 100°, 1 hr; 125°, 8 hr	 (30),  (40)	93
		140°, 15 hr	" (98)	97
		75°, 1 hr; 100°, 1 hr; 125°, 8 hr	 (13),  (16)	93
C_{13}		—	 (—)	44
		75°, 1 hr; 125°, 3 hr	 (22)	93

TABLE III. CARBOXYLIC ACIDS (*Continued*)

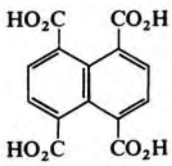
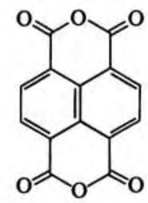
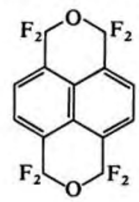
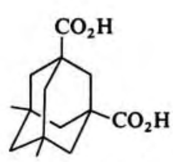
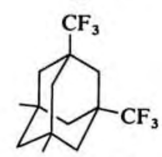
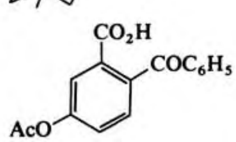
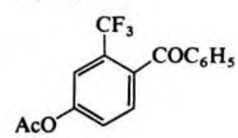
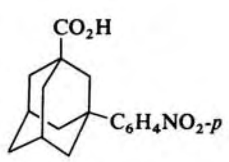
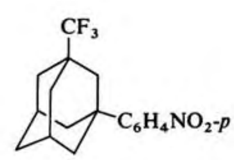
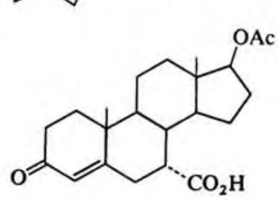
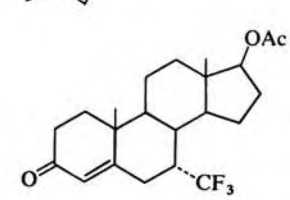
	Carboxylic Acid	Conditions	Product(s) and Yield(s)	Refs.
C_{14}		240°	 (100)	44
		HF, 240°	 (80)	44
		125°, 6 hr	 (64)	93
C_{16}		100°, 8 hr	 (—)	37
C_{17}		130–140°, 12 hr	 (90)	
C_{22}		HF, room temp	 (13)	

TABLE IV. ACYL HALIDES

	Acyl Halide	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3	$(O_2N)_3CCH_2OCOF$	HF, 80–90°	$(O_2N)_3CCH_2OCF_3$ (45)	99
	$FC(NO_2)_2CH_2OCOF$	"	$FC(NO_2)_2CH_2OCF_3$ (63)	99
C_4	$CH_3C(NO_2)_2CH_2OCOF$	"	$CH_3C(NO_2)_2CH_2OCF_3$ (73)	99
C_5	$CF_3OCH_2C(NO_2)_2CH_2OCOF$	"	$CF_3OCH_2C(NO_2)_2CH_2OCF_3$ (72)	99
	$FCO_2CH_2C(NO_2)_2CH_2OCOF$	SF_4, 1 eq, HF, 80°, 42 hr	$CF_3OCH_2C(NO_2)_2CH_2OCOF$ (52)	76

TABLE V. ESTERS

	Ester	Conditions	Product(s) and Yield(s) (%)	Refs.
C_8	*m*-$BrC_6H_4OCOCF_3$	HF, 100°, 2 hr	*m*-$BrC_6H_4OC_2F_5$ (75)	100
	p-$BrC_6H_4OCOCF_3$	HF, 50°, 4 hr	*p*-$BrC_6H_4OC_2F_5$ (75)	100
	p-$ClC_6H_4CO_2CH_3$	HF, 75–80°, 16 hr	*p*-$ClC_6H_4CF_3$ (70)	45
	p-$O_2NC_6H_4CO_2CH_3$	HF, 75–80°. 16 hr	*p*-$O_2NC_6H_4CF_3$ (20)	45
		HF, 130°	" (92)	45
	$C_6H_5CO_2CH_3$	HF, 75–80°, 16 hr	$C_6H_5CF_3$ (45)	45
C_9	*m*-$BrC_6H_4OCOCF_2OCF_3$	HF, 100°, 2 hr	*m*-$BrC_6H_4O(CF_2)_2OCF_3$ (76)	100
	m-$O_2NC_6H_4OCOCF_2OCF_3$	HF, 50°, 2 hr; 20°, 12 hr	*m*-$O_2NC_6H_4O(CF_2)_2OCF_3$ (84)	100
C_{11}	*n*-$C_7F_{15}CO_2CH(CF_3)_2$	HF, 185°, 15 hr	*n*-$C_8F_{17}OCH(CF_3)_2$ (81)	46
	n-$C_7F_{15}CO_2CH_2C_2F_5$	HF, 150°, 15 hr	*n*-$C_8F_{17}OCH_2C_2F_5$ (92)	46
	$C_2F_5O[(CF_2)_2O]_2CF_2CO_2CH_2C_2F_5$	HF, 150°, 15 hr	$C_2F_5O[(CF_2)_2O]_2(CF_2)_2OCH_2C_2F_5$ (83)	46
C_{12}	*n*-$C_7F_{15}CO_2C_4F_9$-*t*	HF, 180°, 100 hr	*n*-$C_8F_{17}OC_4F_9$-*t* (83)	46
	$(CF_3)_2CHO_2C(CF_2)_4CO_2CH(CF_3)_2$	HF, 185°, 16 hr	$(CF_3)_2CHO(CF_2)_6OCH(CF_3)_2$ (89)	46
	p-(*n*-$C_3F_7CO_2)C_6H_4CO_2CH_3$	HF, 75–80°, 16 hr	*p*-(*n*-$C_4F_9O)C_6H_4CF_3$ (—)	45
C_{13}	*p*-$(C_4F_9CO_2)C_6H_4CO_2CH_3$	HF, 75–80°, 16 hr	*p*-$(C_5F_{11}O)C_6H_4CF_3$ (70)	45
	p-$[H(CF_2)_4CO_2]C_6H_4CO_2CH_3$	HF, 75–80°, 16 hr	*p*-$[H(CF_2)_5O]C_6H_9CF_3$ (65)	45
C_{15}	*p*-$(C_6F_{13}CO_2)C_6H_4CO_2CH_3$	HF, 75–80°, 16 hr	*p*-$(C_7F_{15}O)C_6H_4CF_3$ (68)	45
	p-$[H(CF_2)_6CO_2]C_6H_4CO_2CH_3$	HF, 75–78°, 16 hr	*p*-$[H(CF_2)_7O]C_6H_4CF_3$ (62)	45

TABLE VI. LACTONES

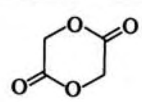
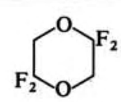
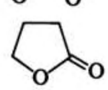
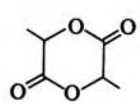
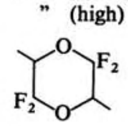
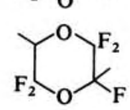
	Lactone	Conditions	Product(s) and Yield(s) (%)	Refs.
C_4		130°, 9 hr	 (85)	47
		130°, 8 hr	$F(CH_2)_3COF$ (80)	47
		160°, 12 hr	$F(CH_2)_3CF_3$ (90)	47
		HF, 90–100°	" (high)	47
C_6		160°, 10 hr	 (80)	47
		HF, 160°, 10 hr	 (75)	47

TABLE VII. AMIDES AND IMIDES

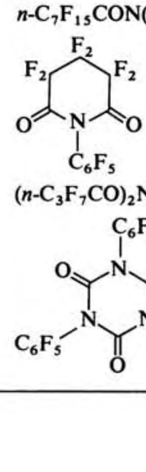
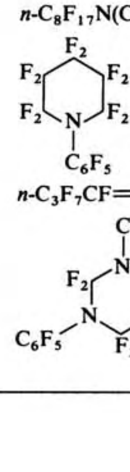
	Amide or Imide	Conditions	Product(s) and Yield(s) (%)	Refs.
C_{10}	n-$C_7F_{15}CON(CF_3)_2$	HF, 150°, 18 hr	n-$C_8F_{17}N(CF_3)_2$ (78)	48
C_{11}		HF, 125°, 24 hr	 (86)	48
C_{14}	$(n$-$C_3F_7CO)_2NC_6F_5$	HF, 85°, 15 hr	n-$C_3F_7CF{=}NC_6F_5$ (73), n-C_3F_7COF (—)	48
C_{21}		HF, 250°, 48 hr	(10)	48

TABLE VIII. ACID ANHYDRIDES

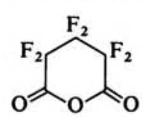
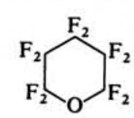
	Anhydride	Conditions	Product(s) and Yield(s) (%)	Refs.
C_5		HF, 150°, 15 hr	 (84)	46
C_{16}	$(n\text{-}C_7F_{15}CO)_2O$	HF, 100°, 40 hr	$n\text{-}C_7F_{15}COF$ (74)	46

TABLE IX. CARBONATES

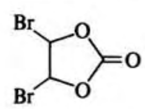
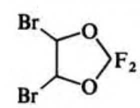
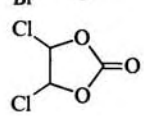
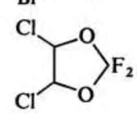
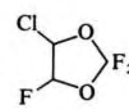
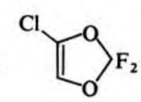
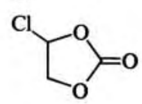
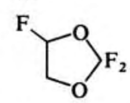
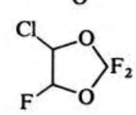
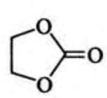
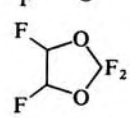
	Carbonate	Conditions	Product(s) and Yield(s) (%)	Refs.
C_3		HF	 (—)	49
		HF, 150°	 (—),  (—),  (—)	49
		HF, 100°	 (—)	49
		HF, 150°	 (—)	49
		HF	 (—)	49
C_9	$(t\text{-}C_4F_9O)_2CO$	HF, 250°, 48 hr	$(t\text{-}C_4F_9O)_2CF_2$ (—)	46

TABLE X. OXIRANES

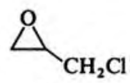
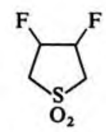
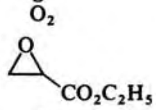
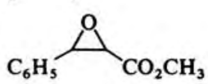
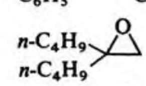
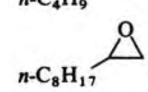
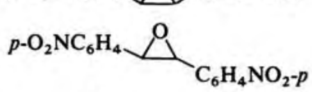
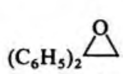
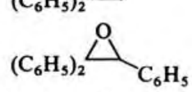
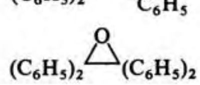
	Oxirane	Conditions	Product(s) and Yield(s)	Refs.
C_3		NaF, 75°, 6 hr	FCH_2CHFCH_2Cl (9)	51
C_4		100°, 4 days	 (50)	101
C_5		NaF, 70°, 16 hr	$FCH_2CHFCO_2C_2H_5$ (53)	52
		20°, 7 days	i-$C_3H_7CF_2CH_3$ (18)	52
C_{10}		NaF, CH_2Cl_2, 20°, 7 days	$C_6H_5CH(CHF_2)CO_2CH_3$ (27)	51
		NaF, CH_2Cl_2, 20°, 2 days	n-$C_4H_9CF_2C_5H_{11}$-n (40)	51
		NaF, CH_2Cl_2, 20°, 3 days	n-$C_8H_{17}CHFCH_2F$ (10)	52
C_{14}		NaF, CH_2Cl_2, 150°, 6 hr	*meso*-p-$O_2NC_6H_4CHFCHFC_6H_4NO_2$-$p$ (96)	51
		NaF, CH_2Cl_2, 150°, 8 hr	*dl*- " (50)	51
		NaF, CH_2Cl_2, 40°, 2 hr	$C_6H_5CF_2CH_2C_6H_5$ (15)	51
C_{20}		20°	$(C_6H_5)_2CHCOC_6H_5$ (—)	51
C_{26}		20°	$(C_6H_5)_3CCOC_6H_5$ (—)	51

TABLE XI. CHLORIDES, BROMIDES, AND IODIDES

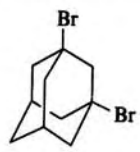
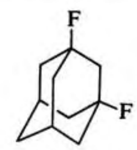
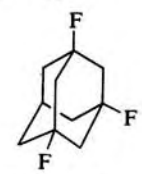
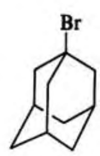
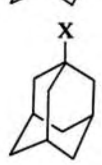
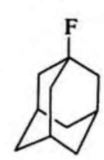
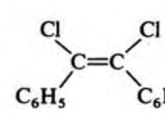
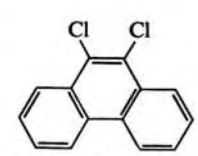
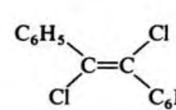
	Halide	Conditions	Product(s) and Yield(s)	Refs.
C_{10}		200°	 A(−),  B(−)	54
		200°	A(−), B(−)	54
	 (X = Cl, Br, I)	85–140°, 3–8 hr	 (61–84)	53
C_{14}		PbO_2, CH_2Cl_2, or CCl_4, −50 to −20°	 (39–42)	55
		PbO_2, CH_2Cl_2, or CCl_4, −50 to −20°	$C_6H_5CCl_2CCl_2C_6H_5$ (30–44)	55

TABLE XII. AMINES

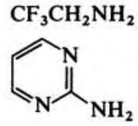
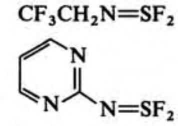
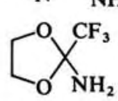
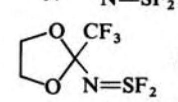
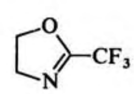
	Amine	Conditions	Product(s) and Yield(s)	Refs.
C_2	$C_2F_5NH_2$	CsF, −196 to 25°, 8 hr	$C_2F_5N{=}SF_2$ (40)	102
	$CF_3CH_2NH_2$	−45°, 2 hr	$CF_3CH_2N{=}SF_2$ (—)	103
C_4		NaF	 (15)	104
		CsF, room temp, 10 hr	 (67),  (14)	57
		NaF, room temp, 10 hr	" (36), " (31)	57
		$(C_2H_5)_3N$, room temp, 10 hr	" (79)	57
C_6	$C_6F_5NH_2$	NaF, 0–3°, 2 hr	$C_6F_5N{=}SF_2$ (33)	104

TABLE XIII. BORON, PHOSPHORUS, AND SILICON COMPOUNDS

	Reactant	Conditions	Product(s) and Yield(s) (%)	Refs.
C_2	$Cl_3P{=}NC_2Cl_5$	150°, 6 hr	$F_2S{=}NCF_2CCl_3$ (37), Cl_3F_6PS[a] (90)	105
C_3	$F_2POCH{=}CHNCO$	100–115°, 15 min	$F_4PCH{=}CHNCO$ (28)	106
C_5	$(CH_3)_3SiN(CH_3)_2$	Ether, 25°	$[(CH_3)_2N]_3S^+F_2\bar{S}i(CH_3)_3$ (71–78)	60a
C_6	$[(CH_3)_2N]_3B$	−196 to 10°	$[(CH_3)_2N]_3S^+BF_4^-$ (high)	58
C_7	$(C_2H_5)_2NSi(CH_3)_3$	$CFCl_3$, −65° to room temp	$(C_2H_5)_2NSF_3$ (84)	14
C_9	$C_6H_5OSi(CH_3)_3$	SF_4, 1 eq	$C_6H_5OSF_3$ (—)	60
		SF_4, 0.5 eq	$(C_6H_5O)_2SF_2$ (—)	60
C_{10}	p-$CF_3C_6H_4OSi(CH_3)_3$	SF_4, 1 eq	$(p$-$CF_3C_6H_4O)_2SF_2$ (—)	60
	o-$CH_3C_6H_4OSi(CH_3)_3$	SF_4, 1 eq	o-$CH_3C_6H_4OSF_3$ (—)	60
	m-$CH_3C_6H_4OSi(CH_3)_3$	SF_4, 1 eq	m-$CH_3C_6H_4OSF_3$ (—)	60
		SF_4, 0.5 eq	$(m$-$CH_3C_6H_4O)_2SF_2$ (—)	60
	p-$CH_3C_6H_4OSi(CH_3)_3$	SF_4, 1 eq	p-$CH_3C_6H_4OSF_3$ (—)	60
		SF_4, 0.5 eq	$(p$-$CH_3C_6H_4O)_2SF_2$ (—)	60
C_{38}	$[(C_6H_5)_3PNHCH_2]_2{}^{2+}2Cl^-$	20–25°, 2.5 hr	$F_2S{=}N(CH_2)_2N{=}SF_2$ (73)	59
C_{39}	$[(C_6H_5)_3PNH(CH_2)_3NHP(C_6H_5)_3]^{2+}2Cl^-$	20–25°, 2.5 hr	$F_2S{=}N(CH_2)_3N{=}SF_2$ (72)	59
	$[(C_6H_5)_3PNHCH_2CH(CH_3)NHP(C_6H_5)_3]^{2+}2Cl^-$	20–25°, 2.5 hr	$F_2S{=}NCH_2CH(CH_3)N{=}SF_2$ (71)	59
C_{40}	$[(C_6H_5)_3PNHCH_2C(CH_3)_2NHP(C_6H_5)_3]^{2+}2Cl^-$	20–25°, 2.5 hr	$F_2S{=}NCH_2C(CH_3)_2N{=}SF_2$ (69)	59
C_{42}	$[m$-$(C_6H_5)_3PNH)_2C_6H_4]^{2+}2Cl^-$	Room temp, 3 hr	m-$(F_2S{=}N)_2C_6H_4$ (67)	59

[a] The structure of this product has not yet been established. It is probably a saltlike substance of the type $[Cl_3PF]^+SF_5^-$, $[Cl_3PF_3]^-SF_3^+$, or $[PF_6]^-SCl_3^+$.

TABLE XIV. MISCELLANEOUS COMPOUNDS

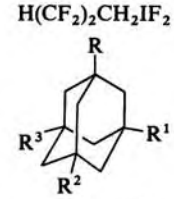
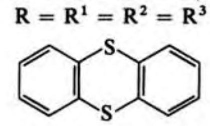
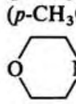
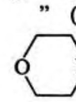
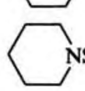
	Reactant	Conditions	Product(s) and Yield(s)	Refs.
C_1	CF_3OCl	$h\nu$, 25°, 24 hr	$(CF_3O)_2SF_4$ (90–95)	62
	CF_3OOF	−196° to room temp, 15 hr	CF_3OSF_5 (67), $CF_3OSF_4OSF_5$ (9)	107
C_2	CF_3OOOCF_3	70–72°, 12 hr	$(CF_3O)_2SF_4$ (21), $CF_3OOSF_4OCF_3$ (46)	61
	$(CF_3)_2NO$	Room temp, 20 days	$(CF_3)_2NOSF_4ON(CF_3)_2$ (95)	65
C_3	$(CH_3)_3SiOTeF_5$	—	$(CH_3)_3SiF$ (—), TeF_6 (—), SOF_2 (—)	108
C_6	$C_6H_5SbO(OH)_2$	20°; 65–70°, 6 hr	$C_6H_5SbF_4$ (86)	67
	$(CH_3)_3SiN{=}SF_2{=}NSi(CH_3)_3$	CsF, 100°, 12 hr	$F_2S{=}NSF_4N{=}SF_2$ (56)	109
C_7	$H(CF_2)_2CH_2I(O_2CCF_3)_2$	70°, 2 hr	$H(CF_2)_2CH_2IF_2$ (56)	110
C_{10}				54
		60°	$R = F$, $R^1 = R^2 = R^3 = H$ (—)	
		100°	$R = R^1 = F$, $R^2 = R^3 = H$ (—)	
		200°	$R = R^1 = R^2 = F$, $R^3 = H$ (—)	
		HF, 140°	$R = R^1 = R^2 = R^3 = F$ (—)	
C_{12}	$C_6H_5SSC_6H_5$	—	 (—)	63
	$(C_6H_5)_2Te$	80°, 30 min	$(C_6H_5)_2TeF_2$ (87)	66
	$(C_6H_5)_2Te_2$	80°, 45 min	" (77)	66
	$(C_6H_5)_2SbO(OH)$	−10°	$(C_6H_5)_2SbF_3$ (98)	67

TABLE XIV. MISCELLANEOUS COMPOUNDS (*Continued*)

	Reactant	Conditions	Product(s) and Yield(s)	Refs.
C_{14}	$[(CF_3CO_2)_2ICH_2(CF_2)_2]_2$	80°, 3 hr	$[F_2ICH_2(CF_2)_2]_2$ (high)	110
	$[H(CF_2)_4CH_2I(O_2CCF_3)]_2O$	70°, 2 hr	$H(CF_2)_4CH_2IF_2$ (15)	110
	$(p\text{-}CH_3OC_6H_4)_2Te$	80°, 30 min	$(p\text{-}CH_3OC_6H_4)_2TeF_2$ (92)	66
	$(p\text{-}CH_3OC_6H_4)_2Te_2$	80°, 45 min	" (84)	66
C_{15}	 $NSOC_6H_4CH_3\text{-}p$	25°, 12 hr	 NSF_3 (70), $p\text{-}CH_3C_6H_4SOF$ (73)	64
C_{17}	 $NSOC_6H_4CH_3\text{-}p$	25°, 12 hr	 NSF_3 (65), " (70)	64
C_{18}	$(C_6H_5)_3SbO$	−10°	$(C_6H_5)_3SbF_2$ (94)	67
	$(C_6H_5)_3Sb(O_2CCF_3)_2$	−10°	" (92)	67

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End

A chapter on fluorinations by DAST and related reagents is in preparation.

Notes

*

* Hastelloy is a chemically resistant alloy of nickel, iron, and molybdenum manufactured by the Union Carbide Corporation, 270 Park Avenue, New York, NY 10017.

References

1. G. A. Boswell, Jr., W. C. Ripka, R. M. Scribner, and C. W. Tullock, Org. React., **21**, 1 (1974).
2. W. R. Hasek, W. C. Smith, and V. A. Engelhardt, J. Am. Chem. Soc., **82**, 543 (1960).
3. L. N. Markovskii, L. S. Bobkova, V. E. Pashinnik, and S. V. Iksanova, J. Org. Chem. USSR (Engl. Transl.), **17**, 409 (1981).

3a. W. J. Middleton, U.S. Pat. 4,311,651 (1982) [C.A., **96**, 180785y (1982)].

4. Q.-C. Mir and J. M. Shreeve, Inorg. Chem., **19**, 1510 (1980).
5. L. Yu. Kryukova, L. N. Kryukov, A. F. Kolomiets, G. A. Sokolskii, and I. L. Knunyants, Bull. Acad. Sci. USSR, Div. Chem. Sci. (Engl. Transl.), **1979**, 1777.
6. J. Kollonitsch, S. Marburg, and L. M. Perkins, J. Org. Chem., **40**, 3808 (1975).
7. J. Kollonitsch, S. Marburg, and L. M. Perkins, J. Org. Chem., **44**, 771 (1979),
8. J. Kollonitsch, Israel J. Chem., **17**, 53 (1978).
9. A. M. Kozlova. L. N. Sedova, L. A. Alekseeva, and L. M. Yagupol'skii, J, Org. Chem. USSR (Engl. Transl.), **9**, 1447 (1973).
10. H. M. Bell and M. Hudlicky, J. Fluorine Chem., **15**, 191 (1980).
11. A. I. Burmakov, L. A. Motnyak, B. V. Kunshenako, L. A. Alexseeva, and L. M. Yagupol'skii, J. Fluorine Chem., **19**, 151 (1981).
12. A. I. Burmakov, L. A. Motnyak, B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **16**, 1204 (1980).
13. L. N. Markovskij and V. E. Pashinnik, Synthesis, **1973**, 787.
14. W. J. Middleton, J. Org. Chem., **40**, 574 (1975).
15. M. R. C. Gerstenberger and A. Haas, Angew Chem., Int. Ed. Engl., **20**, 647 (1981).
16. M. J. Green, H. J. Shue, M. Tanabe, D. M. Yasuda, A. T. McPhail, and K. D. Onan, J. Chem. Soc., Chem. Commun., **1977**, 611.
17. W. J. Middleton, Chem. Eng. News, **57** (21), 43 (1979).
18. J. Cochran, Chem. Eng. News, **57** (12), 4 (1979).
19. K. C. Hodges, D. Schomburg, J.-V. Weiss, and R. Schmutzler, J. Am. Chem. Soc., **99**, 6096 (1977).
20. A. I. Burmakov, I. V. Stepanov, B. V. Kunshenko, L. N. Sedova, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **18**, 1009 (1982).
21. H. Kaufmann, H. Fuhrer, and J. Kalvoda, Tetrahedron, **37**, Suppl. No. 1, 225 (1981).

22. F. A. Bloshchitsa, A. I. Burmakov, B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **18**, 679 (1982).
23. A. I. Burmakov, F. A. Bloshchitsa, B. V. Kunshenko, L. A. Alexeeva, and L. M. Yagupol'skii, Zh. Org. Khim., **16**, 2617 (1980) [C.A., **94**, 174265w (1981)].
24. J. A. Webster, J. M. Butler, and T. J. Morrow, Advan. Chem. Ser., **129**, 61 (1973).
25. B. G. Oksenenko, M. M. Shakirov, and V. D. Shteingarts, J. Org. Chem. USSR (Engl. Transl.), **12**, 1307 (1976).
26. A. M. Aleksandrov, A. E. Sorochinskii, and A. P. Krasnoshchek, J. Org. Chem. USSR (Engl. Transl.), **15**, 293 (1979).
27. B. E. Cross, A. Erasmuson, and P. J. Filippone, J. Chem. Soc., Perkin Trans. 1, **1981**, 1293.
28. W. Dmowski and R. A. Kolinski, J. Fluorine Chem., **2**, 210 (1972/73).
29. W. Dmowski and R. A. Kolinski, Rocz. Chem., **47**, 1211 (1973).
30. W. Dmowski and R. A. Kolinski, Rocz. Chem., **48**, 1697 (1974).
31. W. Dmowski and R. A. Kolinski, Pol. J. Chem., **52**, 547 (1978).
32. J. Wielgat and Z. Domagala, J. Fluorine Chem., **20**, 785 (1982).
33. G. W. Holland, J. L. Jernow, and P. Rosen, U.S. Pat. 4,256,911 (1981) [C.A., **89**, 146500x (1978)].
34. A. I. Burmakov, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **8**, 156 (1972).
35. B. V. Kunshenko, A. I. Burmakov, L. A. Alekseeva, V. G. Lukmanov, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **10**, 896 (1974).
36. A. N. Blakitnyi, I. M. Zalesskaya, B. V. Kunshenko, Yu. A. Fialkov, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **13**, 2000 (1977).
37. T.-Y. Shen, G. L. Walford, B. E. Witzel, and R. L. Bugianesi, U.S. Pat. 3,657,430 (1972) [C.A., **77**, 61604m (1972)].
38. J. B. Campbell, U.S. Pat. 4,024,142 (1977) [C.A., **86**, 190006c (1977)].
39. V. V. Lyalin, R. V. Grigorash, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR. (Engl. Transl.), **11**, 1073 (1975).
40. V. V. Lyalin, R. V. Grigorash, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **11**, 456 (1975).
41. R. V. Grigorash, V. V. Lyalin, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **14**, 2414 (1978).
42. W. Dmowski and R. A. Kolinski, Pol. J. Chem., **52**, 71 (1978).
43. V. G. Lukmanov, L. A. Alekseeva, A. L. Burmakov, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **9**, 1046 (1973).
44. B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **10**, 1715 (1974).

45. Y. A. Fialkov, L. I. Moklyachuk, M. M. Kremlev, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **16**, 1269 (1980).
46. R. J. DePasquale, J. Org. Chem., **38**, 3025 (1973).
47. N. N. Muratov, A. I. Burmakov, B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **18**, 1220 (1982).
48. R. J. DePasquale, J. Org. Chem., **43**, 1727 (1978).
49. D. D. Denson. E. T. Uyeno, R. L. Simon, Jr., and H. M. Peters, "Biochemistry Involving Carbon - Fluorine Bonds", in *ACS Symposium Series 28*, R. Filler, Ed., 1976, p.190.
50. L. M. Yagupol'skii, V. I. Golikov, L. A. Alekseeva, and A. M. Aleksandrov, J. Org. Chem. USSR (Engl. Transl.), **7**, 737 (1971).
51. V. I. Golikov, A. M. Aleksandrov, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **8**, 1088 (1972).
52. V. I. Golikov, A. M. Aleksandrov, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **10**, 297 (1974).
53. A. P. Khardin, A. D. Popov, and P. A. Protopopov, J. Org. Chem. USSR (Engl. Transl.), **11**, 2005 (1975).
54. A. P. Khardin, A. D. Popov, and P. A. Protopopov, Zh. Vses. Khim. Ova., **22**, 116 (1977) [C.A., **86**, 170933z (1977)].
55. Yu. A. Fialkov, M. M. Kremlev, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **10**, 2579 (1974).
56. J. R. Grunwell and S. L. Dye, Tetrahedron Lett., **1975**, 1739.
57. K. Tanaka and J. M. Shreeve, Inorg. Chem., **19**, 2612 (1980).
58. A. H. Cowley, D. J. Pagel, and M. L. Walker, J. Am. Chem. Soc., **100**, 7065 (1978).
59. R. Appel, J.-R. Lundehn, and E. Lassmann, Chem. Ber., **109**, 2442 (1976).
60. J. I. Darragh, S. F. Hossain, and D. W. A. Sharp, J. Chem. Soc., Dalton Trans., **1975**, 218.
60a. W. J. Middleton. U.S. Pat. 3,940,402 (1976) [C.A., **85**, 6388j (1976)].
61. F. A. Hohorst, D. D. DesMarteau, L. R. Anderson, D. E. Gould, and W. B. Fox, J. Am. Chem. Soc., **95**, 3866 (1973).
62. T. Kitazume and J. M. Shreeve, J. Am. Chem. Soc., **100**, 492 (1978).
63. F. Seel, R. Budenz, R. D. Flaccus, and R. Staab, J. Fluorine Chem., **12**, 437 (1978).
64. L. N. Markovskii, V. E. Pashinnik, and N. A. Kirsanova, J. Org. Chem. USSR (Engl. Transl.), **12**, 973 (1976).
65. M. D. Vorobév, A. S. Filatov, and M. A. Énglin, J. Org. Chem. USSR (Engl. Transl.), **10**, 1009 (1974).
66. I. D. Sadekov, A. Ya. Bushkov, L. N. Markovskii, and V. I. Minkin, J. Gen.

Chem. USSR (Engl. Transl.), **46**, 1617 (1976).
67. L. M. Yagupol'skii, N. V. Kondratenko, and V. I. Popov, J. Gen. Chem. USSR (Engl. Transl.), **46**, 618 (1976).
68. V. P. Bezsolitsen, B. N. Gorbunov, A. A. Nazarov, and A. P. Khardin, Vysokomol. Soedin., Ser. A, **14**, 950 (1972) [C.A., **77**, 75710e (1972)].
69. B. N. Gorbunov, T. I. Solomina, A. P. Khardin, and G. A. Berkova, Vysokomol. Soedin., Ser. B, **15**, 744 (1973) [C.A., **80**, 134000k (1974)].
70. A. P. Khardin, P. A. Protopopov, and V. E. Debrisher, Fiber Chem. USSR (Engl. Transl.), **1974**, 671.
71. A. J. Finkel, Adv. Fluorine Chem., **7**, 199 (1973).
72. J. Kollonitsch, S. Marburg, and L. M. Perkins, J. Org. Chem., **41**, 3107 (1976).
73. V. G. Lukmanov, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **13**, 1979 (1977).
74. M. J. Sanders, S. L. Dye, A. G. Miller, and J. R. Grunwell, J. Org. Chem., **44**, 510 (1979).
75. D. E. Young, L. R. Anderson, D. E. Gould, and W. B. Fox, J. Am. Chem. Soc., **92**, 2313 (1970).
76. H. M. Peters, R. L. Simon, Jr., L. O. Ross, D. L. Ross, and M. E. Hill, J. Chem. Eng. Data, **20**, 113 (1975).
77. E. E. Gilbert and R. E. A. Dear, U.S. Pat. 3,655,786 (1972) [C.A., **77**, 49093m (1972)].
78. L. A. Motnyak, A. I. Burmakov, B. V. Kunshenko, V. P. Sass, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **17**, 634 (1981).
79. J. Kollonitsch and S. Marburg, U.S. Pat. 4,288,601 (1981) [C.A., **91**, 21109m (1979)].
80. G. Siegemund, Justus Liebigs Ann. Chem., **1979**, 1280.
81. F. A. Bloshchitsa, A. I. Burmakov, B. V. Kunshenko, L. A. Alekseeva, A. L. Bel'ferman, Yu. A. Pazderskii, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **17**, 1260 (1981).
82. R. H. Mobbs, J. Fluorine Chem., **1**, 361 (1971).
83. F. N. Shirota, Ph.D. Dissertation, University of Minnesota, 1973 [C.A., **81**, 86035x (1974)].
84. R. E. Moore, U.S. Pat. 4,220,606 (1980) [C.A., **94**, 156420p (1981)].
85. E. P. Forkin, T. N. Gerasimova, T. N. Vasilevskaya, I. I. Baturina, and K. I. Matoshina, Izv. Sib. Otd. Akad. Nauk SSR, Ser. Khim. Nauk, **1971**, 135 [C.A., **77**, 61401t (1972)].
86. E. L. Engelhardt and M. E. Christy, Br. Pat. 1,265,053 (1972) [C.A., **76**, 153311w (1972)].

87. M. W. Buxton, R. H. Mobbs, and D. E. M. Wotton, J. Fluorine Chem., **2**, 231 (1972).
88. F. E. Herkes and H. E. Simmons, Synthesis, **1973**, 166.
89. R. A. Bekker, G. V. Asratyan, and B. L. Dyatkin, J. Org. Chem. USSR (Engl. Transl.), **9**, 1663 (1973).
90. G. Pissiotas and D. Duerr, Ger. Pat. 2,750,170 (1978) [C.A., **89**, 59765u (1978)].
91. Nihon Nohyaku Co., Ltd., Jpn. Pat. 80-59,135 (1980) [C.A., **93**, 185981g (1980)].
92. L. M. Yagupol'skii, A. I. Burmakov, L. A. Alekseeva, and B. V. Kunshenko, J. Org. Chem. USSR (Engl. Transl.), **9**, 710 (1973).
93. C. W. Tullock, U.S. Pat. 3,714,273 (1973) [C.A., **78**, 110713c (1973)].
94. L. M. Yagupol'skii, V. G. Lukmanov, V. N. Boiko, and L. A. Alekseeva, J. Org. Chem. USSR (Engl. Transl.), **13**, 2221 (1977).
95. B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **8**, 838 (1972).
96. B. V. Kunshenko, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **9**, 1971 (1973).
97. A. M. Aleksandrov, G. I. Danilenko, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **9**, 976 (1973).
98. G. H. Rasmusson, A. Chen, and G. E. Arth, J. Org. Chem., **38**, 3670 (1973).
99. H. M. Peters, R. L. Simon, Jr., L. O. Ross, D. L. Ross, and M. E. Hill, J. Chem. Eng. Data. **20**, 118 (1975).
100. V. M. Belous, L. M. Yagupol'skii, L. A. Alekseeva, S. V. Sokolov, A. I. Ponomarev, U.S. Pat. 4,093,655 (1978) [C.A., **89**, 6106y (1978)].
101. V. I. Golikov, A. M. Aleksandrov, L. A. Alekseeva, T. É. Benzmenova, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **9**, 2446 (1973).
102. R. C. Kumar and J. M. Shreeve, J. Am. Chem. Soc., **102**, 4958 (1980).
103. M. J. Sanders and J. R. Grunwell, J. Org. Chem., **45**, 3753 (1980).
104. A. V. Zibarev, I. R. Gol'ding, A. M. Sladkov, G. G. Furin, and G. G. Yakobson, Bull. Acad. Sci. USSR, Div. Chem. Sci. (Engl. Transl.) **11**, 2352 (1979).
105. L. N. Markovskii, E. A. Stukalo, and A. V. Kirsanov, J. Gen. Chem. USSR (Engl. Transl.), **42**, 2574 (1972).
106. L. N. Markovskii and E. A. Stukalo, Phosphorus, **4**, 237 (1974) [C.A., **82**, 86342r (1975)].
107. R. A. DeMarco and W. B. Fox, Inorg. Nucl. Chem. Lett., **10**, 965 (1974).
108. F. Sladky and H. Kropshofer, J. Chem. Soc., Chem. Commun., **1973**, 600.

109. R. Höfer and O. Glemser, Angew, Chem., **85**, 1105 (1973).

110. V. V. Lyalin, V. V. Orda, L. A. Alekseeva, and L. M. Yagupol'skii, J. Org. Chem. USSR (Engl. Transl.), **8**, 1027 (1972).

Reductions by Metal Alkoxyaluminum Hydrides

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1. Introduction

Since the discovery of the reducing properties of diborane (1939), (1) alkali metal borohydrides (1943), (2-5) and alkali metal aluminohydrides (1946) (6) by H. I. Schlesinger, H. C. Brown, W. G. Brown, and co-workers, considerable effort has been expended to enhance the versatility and selectivity of these widely used hydride reagents. Whereas diborane exhibits medium reaction (7, 8) large differences exist between sodium borohydride and lithium aluminum hydride. In contrast to the reducing action of sodium borohydride, limited originally to aldehydes, ketones, and acid chlorides, lithium aluminum hydride readily attacks almost all reducible groups. (9-21) The first progress in bridging this gap in reactivity can be traced to the availability of reagents that are easily prepared by addition of Lewis acids such as boron and aluminum halides to sodium borohydride and lithium aluminum hydride; in this manner diborane, (4, 7, 22) chloroaluminum hydrides, (23-28) and aluminum hydride (6, 16, 21, 25-27, 29-32) have been made accessible as reducing agents. Parallel development led to sodium alkoxyborohydrides (4, 8, 18-21, 33, 34) with generally higher reactivity than the parent hydride and to alkoxyaluminum hydrides, (21, 30, 32, 35-101) with markedly lower reactivity and increased chemoselectivity. On the other hand, the reducing capability of sodium borohydride (102-104) and lithium aluminum hydride (27, 104, 105) has been enhanced by the use of metal salt–hydride systems. A large number of other complex metal hydrides have gained importance as selective reducing agents: lithium aluminum hydride–nitrogen base complexes, (27) sodium cyanoborohydride, (106-109) lithium cyanoborohydride, (110) sulfurated sodium borohydride, (111) zinc borohydride, (112, 113) diisobutylaluminum hydride, (114-117) alkylaluminum compounds (118) such as triisobutylaluminum, (117) and tri-*n*-butyltin hydride. (119, 120) Sterically hindered organoboranes such as lithium tri-*sec*-butylborohydride (L-Selectride) exhibit excellent selectivity in reduction reactions. High asymmetric induction can be achieved with some chiral organoboranes. Lithium triethylborohydride (Super-Hydride) is a selective and exceptionally powerful reducing agent. (8, 47, 121-129) These complex metal hydrides often provide better regio- and stereoselectivities than those achieved with alkoxy-substituted hydrides; nevertheless, the alkoxyhydrides are readily available and continue to be widely used as reducing agents.

The properties of complex metal hydrides, including metal alkoxyaluminum hydrides, and their use in organic synthesis have been compared in a large number of papers, reviews, and monographs. (46, 129-144) Tables that indicate the choice of the most appropriate hydride agent for selective reductions of polyfunctional compounds have been published. (8, 21, 121, 134, 139) Asymmetric syntheses involving the use of chiral metal alkoxyaluminum hydride complexes have been reviewed. (145-152)

The purpose of this chapter is to present a critical review of reductions of the following compounds by metal alkoxyaluminum hydrides, alkoxyaluminum hydrides, and chiral metal alkoxyaluminohydride complexes: hydrocarbons, peroxides, ozonides, halogen compounds, unsaturated alcohols, aromatic alcohols, ethers, 1,2-oxides, aldehydes, ketones, quinones, acetals, and ketals. The literature is covered through December 1981. Important papers that appeared through September 1982 are also reviewed. Some reactions relating to other than reducing properties of these hydrides are included for completeness. The emphasis is on the scope, limitations, and synthetic utility of the hydrides in reduction reactions and on the optimum conditions for their application as reducing agents. Currently accepted views of reaction mechanisms are discussed. Comparisons with reductions by other complex metal hydrides are limited to the most important transformations of the functional groups.

2. Mechanism

2.1. Nature and Behavior of Metal Alkoxyaluminum Hydrides

Despite appreciable synthetic information accumulated during the last quarter century on reductions of organic substrates by metal alkoxyaluminum hydrides, little is known about the details of these processes. Lack of knowledge concerning the composition and structure of the reducing agents and their stability and the exact nature of the hydride–substrate complex or hydride–solvent species is an obstacle to a precise description of the reaction mechanism.

Of the great number of metal alkoxyaluminum hydrides, only a few are stable and have an exact composition. The formulas $MAlH_{4-x}(OR)_x$ (M = Li, Na; x = 1–3) used throughout the text for simplicity reflect the molar ratio of the parent complex metal hydride and alcohol and define composition only in special cases. The decreased stability of some metal alkoxyaluminum hydrides is due mainly to disproportionation; its extent and mechanism vary with the hydride type. Essentially the same stereoselectivity observed in reductions of cyclic ketones by $LiAlH_4$ and by lithium *sec*-alkoxyaluminum hydrides **1** (x = 1–3) (Eq. 1), where **R** is isopropyl, *sec*-butyl, or cyclohexyl, has been explained by rapid disproportionation to form the tetraalkoxides **2** and the parent hydride, which is the effective reducing agent. (39, 43, 153-155) Although a

$$4\underset{\mathbf{1}}{LiAlH_{4-x}(OR)_x} \rightleftharpoons (4-x)\,LiAlH_4 + x\,\underset{\mathbf{2}}{LiAl(OR)_4} \qquad (1)$$

great number of examples confirm this conclusion, (153-158) others deny its general validity. (155) A remarkable increase in the strength of aluminum–alkoxyl bonds has been achieved by complexing $LiAlH_4$ with amino-substituted *sec*-alcohols. The high enantiomeric excess (e.e.) obtained with the chiral $LiAlH_4$–(–)-*N*-methylephedrine–3,5-dimethylphenol (1:1:2) (159-161) and $LiAlH_4$–(–)-*N*-methylephedrine–*N*-ethylaniline (1:1:2) complexes (162, 163) confirm their resistance to disproportionation, which would lead to a decrease or even loss of complex chirality. (164, 165) The relationship between the hydride structure and stability is, however, very delicate, since reaction conditions used for the hydride preparation *in situ* can become a controlling factor; the $LiAlH_4$–(2*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol complex exhibits reverse stereoselectivity depending on age or thermal treatment of the reagent, presumably as a result of an intrinsic structure reorganization. (166, 167)

An example of a highly stable lithium aryloxyaluminum hydride is the chiral $LiAlH_4$–(*S*)-(–)-2,2′-dihydroxy-1,1′-binaphthyl–ethanol (1:1:1) complex, which is capable of inducing essentially complete enantioselectivity in reductions of some prochiral ketones. (168, 169) By contrast, the intermediate lithium aryloxyaluminum hydride arising from the reaction of $LiAlH_4$ with the hindered 2,4,6-tri-*tert*-butylphenol undergoes disproportionation to yield the tricoordinate bis(2,4,6-tri-*tert*-butylphenoxy)aluminum hydride (**3**) as the major product (Eq. 2). (170, 171) Similar disproportionation of

$$LiAlH_4 + 3\,ArOH \longrightarrow \longrightarrow LiOAr + \underset{3}{AlH(OAr)_2} + 3\,H_2 \qquad Ar = 2,4,6\text{-}(t\text{-}C_4H_9)_3C_6H_2 \tag{2}$$

$LiAlH(OCH_3)_3$ (158, 172) and $LiAlH(OC_4H_9\text{-}t)_3$, (157, 173, 174) which would lead to formation of $AlH(OCH_3)_2$ and $AlH(OC_4H_9\text{-}t)_2$, respectively, appears to be ruled out on the basis of IR and NMR spectra of the hydride solutions. (51, 175-178) Recently, $LiAlH(OCH_3)_3$ has been concluded to undergo total disproportionation, producing $LiAlH_4$ as the kinetically dominant reducing agent; (179, 180) however, this conclusion leaves unexplained the remarkably great difference in stereoselectivity encountered in some reductions with $LiAlH(OCH_3)_3$ and $LiAlH_4$. (51, 154, 173, 181, 182) The monoalkoxyhydride $LiAlH_3(OC_4H_9\text{-}t)$ formed by disproportionation is supposed to participate in those $LiAlH(OC_4H_9\text{-}t)_3$ reductions of ketones that proceed at a high rate. It has been suggested that mass transfer affects the product distribution in these reactions. (183)

On the basis of spectral studies, hydride disproportionation according to Eq. 3 is assumed to apply in the reaction of $LiAlH_4$ with an equimolar amount of ethanol in tetrahydrofuran, forming $LiAlH_4$ and $LiAlH(OC_2H_5)_3$ as the most stable lithium ethoxyaluminum hydride. Both $LiAlH_4$ and $LiAlH(OC_2H_5)_3$

$$3\,LiAlH_4 + 3\,C_2H_5OH \xrightarrow{-3H_2} 3\,LiAlH_3(OC_2H_5) \longrightarrow LiAlH(OC_2H_5)_3 + 2\,LiAlH_4 \tag{3}$$

also result, although in a different molar ratio, from the reaction of $LiAlH_4$ with two equivalents of ethanol. Use of the parent hydride and ethanol in a 1:3 ratio affords $LiAlH(OC_2H_5)_3$ as the sole product; (176) (see, however, Refs. 175, 184, and 185). The course of the latter reaction in diethyl ether is less straightforward. (43-45, 186, 187)

New evidence on the nature of metal alkoxyaluminum hydrides has emerged from ebullioscopic molecular weight and conductance measurements. When compared with $LiAlH_4$, $LiAlH_2(OCH_3)_2$ and $LiAlH(OCH_3)_3$ in tetrahydrofuran display substantially higher degrees of molecular association, which increases sharply with the hydride concentration. (178, 188) Chain-like structures involving methoxy or methoxy — hydrogen bridge bonds has been proposed for lithium methoxyaluminum hydrides. (188) In contrast, $LiAlH(OC_4H_9\text{-}t)_3$ (178, 188) appears to occur, like $LiAlH[OCH(C_6H_5)_2]_3$, (188) as a monomeric compound over a wide range of concentrations. For $NaAlH_2(OCH_2CH_2OCH_3)_2$, a monomeric structure has been suggested in which the four ethereal oxygen atoms are coordinated to the sodium atom. This coordination may be responsible for the markedly higher solubility of the hydride in aromatic hydrocarbons compared to $NaAlH_4$. (133, 137) Among the simple mono- and dialkoxyaluminum hydrides, $AlH_{3-x}(OR)_x$ (x = 1–2), which form mostly polymeric aggregates, only the 2-propoxy, *tert*-butoxy, and 2-methoxyethoxy derivatives are dimers or trimers soluble in ethers and aromatic hydrocarbons. (88, 89, 94, 95, 99, 100, 158, 189, 190) The views on hydride association as a factor influencing the stereochemistry of metal alkoxyaluminohydride reductions are not unambiguous. (51, 178, 183, 188) The equivalent molar conductance of $LiAlH(OCH_3)_3$ (2.32 mho/cm^2 at 0.1 *M*) is much greater than that of $LiAlH(OC_4H_9\text{-}t)_3$ (0.0124 mho/cm^2 at 0.1 *M*) and indicates considerably greater solvation of the former hydride. The greater solvation and thus higher steric requirements of $LiAlH(OCH_3)_3$ could be responsible for its greater stereoselectivity compared to $LiAlH(OC_4H_9\text{-}t)_3$ in some ketone reductions; (51, 154, 173) however, these patterns can change with the solvent used. (153) Stereoselectivity of reductions with metal alkoxyaluminum hydrides depending on the solvent type has frequently been interpreted in terms of greater or less hydride solvation. (167, 180, 181, 183, 191-195) For instance, a complete reversal of the stereochemistry has been observed by using $NaAlH_2(OCH_2CH_2OCH_3)_2$ in benzene and in tetrahydrofuran as the solvent. (196) This hydride forms 2:1 and 1:1 solvates in which the hydride: solvent ratio varies with the solvent type and the initial hydride concentration. (72, 197-199) The larger substituent alkoxy derivatives of $LiAlH_4$ appear to exist as ion pairs and triple ions in tetrahydrofuran. (188) Recent studies on the solvation effect suggest that complex hydrides present as solvent-separated ion pairs favor attack on cyclic ketones from the least hindered side of the carbonyl group. (51) Differences in the stereoselectivity of reductions with $LiAlH(OC_4H_9\text{-}t)_3$ in alkyl-substituted tetrahydrofurans having various steric requirements have been explained by complexing or steric hindrance to complexing of the lithium cation. (194) The results of experiments with some complexing agents appear to support this explanation. (200)

TABLE A. Preparation and Properties of some Metal Alkoxyaluminum Hydrides

Hydride	Method of Preparation	Remarks[a]	References
$LiAlH_3(OCH_3)$	$LiAlH_4$ + CH_3OH	Disproportionates[b]	43, 175, 176, 184, 185
$LiAlH_2(OCH_3)_2$	$LiAlH_4$ + 2 CH_3OH	Stable[c]	175, 176, 188
$LiAlH(OCH_3)_3$	$LiAlH_4$ + 3 CH_3OH	Temporarily stable[d]	43, 46, 175-177, 185, 188
$LiAlH_3(OC_2H_5)$	$LiAlH_4$ + C_2H_5OH	Disproportionates	176, 184, 185
$LiAlH_2(OC_2H_5)_2$	$LiAlH_4$ + 2 C_2H_5OH	Disproportionates	175, 176, 184-186
$LiAlH(OC_2H_5)_3$	$LiAlH_4$ + 3 C_2H_5OH	Stable[e]	176
$LiAlH_3(OC_4H_9\text{-}t)$	$LiAlH_4$ + $t\text{-}C_4H_9OH$	Disproportionates[f]	179, 180, 184, 201, 202
$LiAlH_2(OC_4H_9\text{-}t)_2$	$LiAlH_4$ + 2 $t\text{-}C_4H_9OH$	Disproportionates[g]	153, 179, 201, 202
$LiAlH(OC_4H_9\text{-}t)_3$	$LiAlH_4$ + 3 $t\text{-}C_4H_9OH$	Stable[h]	37, 40, 51, 178, 179, 183, 188, 202, 203
$NaAlH_2(OCH_3)_2$	$NaAlH_4$ + 2 CH_3OH	Disproportionates	176
$NaAlH(OCH_3)_3$	$NaAlH_4$ + 3 CH_3OH	Stable	176
$NaAlH(OC_2H_5)_3$	$NaAlH_4$ + 3 C_2H_5OH	Disproportionates	58, 176
$NaAlH(OC_4H_9\text{-}t)_3$	$NaAlH_4$ + 3 $t\text{-}C_4H_9OH$	Stable	58, 176
$NaAlH_3(OCH_2CH_2OCH_3)$	$NaAlH_4$ + $CH_3OCH_2CH_2OH$	Disproportionates[i]	72
$NaAlH_2(OCH_2CH_2OCH_3)_2$	$NaAlH_4$ + 2 $CH_3OCH_2CH_2OH$	Stable[j]	72, 176, 204
$NaAlH(OCH_2CH_2OCH_3)_3$	$NaAlH_4$ + 3 $CH_3OCH_2CH_2OH$	Stable	176, 190

[a]For opposite views on the stability or disproportionation of the hydrides, see footnotes [b–j].

[b]See Ref. 188.

[c]See Refs. 43 and 180.

[d]See Refs. 158, 172, and 180.

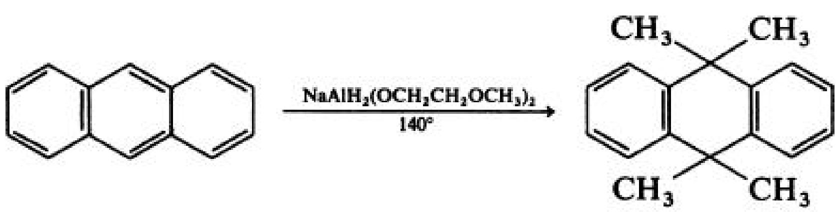
[e]See Refs. 43-45 and 175.

[f]See Refs. 40, 183, and 188.

[g]See Refs. 40, 43, 188, and 203.
[h]See Refs. 157, 173, 174, 180, and 201.
[i]See Ref. 176.
[j]See Ref. 190.

2.2. Single-Electron and -Proton Transfer Steps

The reduction of organic compounds by simple and complex metal hydrides has generally been considered to follow a polar mechanism. (134) Numerous examples now indicate involvement of radical intermediates in the hydride reduction of organic substrates. Radical anions have been suggested to occur in reactions of some diaryl ketones, (204-207) diarylalkanes, (204, 206) and diarylalkenes (208) with $NaAlH_2(OCH_2CH_2OCH_3)_2$ at elevated temperatures. Anthracene reacts with this hydride in aromatic hydrocarbon solutions to form, as confirmed by electronic absorption spectra, a blue radical anion, a green dianion, and an orange monoanion depending on temperature and age of the solution. Under forcing conditions, the intermediate species is trapped predominantly as the derivative **4** (Eq. 4). (205) Triphenylmethane undergoes a



4
(58%)

(4)

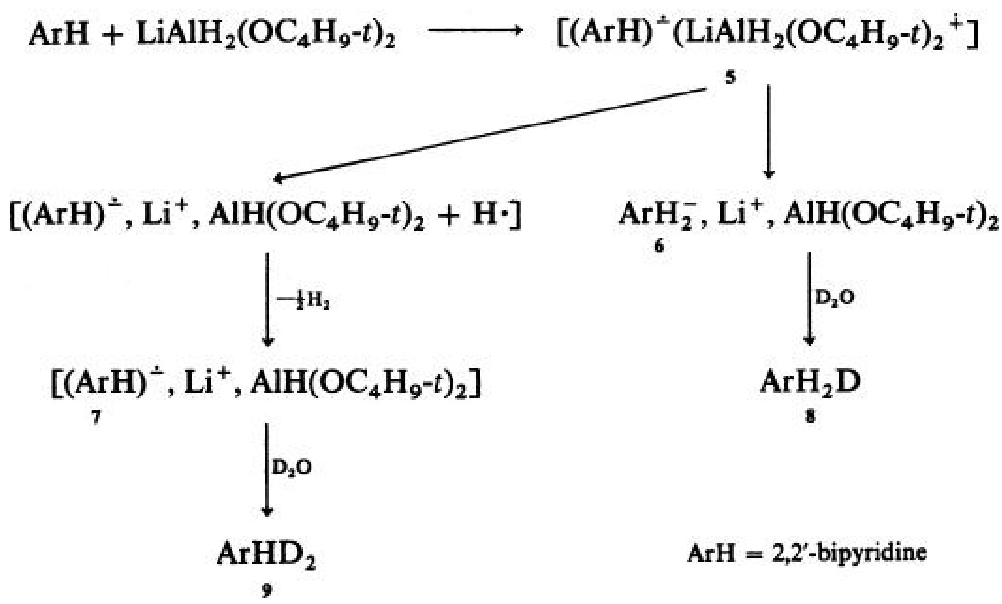
similar transformation (Eq. 5). (204) Although the mechanism of the reductive

$$(C_6H_5)_3CH \xrightarrow[177^\circ]{NaAlH_2(OCH_2CH_2OCH_3)_2} \underset{(98\%)}{(C_6H_5)_3CCH_3} \qquad (5)$$

methylation reaction is not known, isolation of ethylene glycol in the latter case (Eq. 5) suggests that it likely involves a cleavage of the carbon — oxygen bond in the methoxyl group of the hydride molecule. (204, 206)

Formation of radical intermediates (4–80%) in reactions of diaryl ketones (209, 210) and polynuclear aromatic hydrocarbons (210, 211) with $LiAlH_4$, lithium tetrakis(*N*-dihydropyridyl)aluminate, $NaAlH_4$, and other metal hydrides in tetrahydrofuran at ambient temperature has recently been evidenced by EPR spectra. Single-electron transfer is also operative in the reaction of complex metal hydrides with some heterocyclic nitrogen compounds. Most effective is

$LiAlH_2(OC_4H_9\text{-}t)_2$, which reacts with 2,2 -bipyridine to form the radical intermediate in 27% yield. The reaction has been proposed to proceed by way of the radical pair **5**, which gives either the reduction product **6** or



undergoes dissociation to afford the relatively stable radical anion **7**. Identification of **7** by EPR spectra and formation of both **8** and **9** as products of decomposition with deuterium oxide support this mechanism. An analogous mechanistic scheme has been suggested for the reaction of $LiAlH(OC_4H_9\text{-}t)_3$ with 1,10-phenanthroline and isoquinoline. (212)

The radical anion **10** generated by abstraction of hydrogen from $LiAlH(OC_4H_9\text{-}t)_3$ (Eqs. 6 and 7) reacts rapidly with *n*-propyl halides at low temperature to form *n*-propyl radicals (Eq. 8). (213)

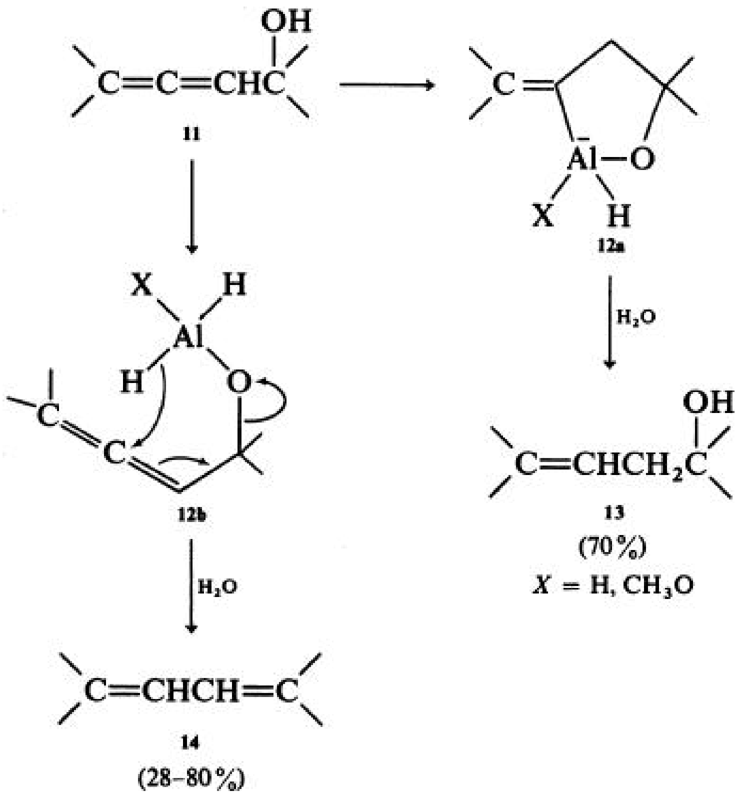
$$t\text{-}C_4H_9OOC_4H_9\text{-}t \xrightarrow{h\nu} 2\ t\text{-}C_4H_9O\cdot \qquad (6)$$

$$t\text{-}C_4H_9O\cdot + Al^{-}H(OC_4H_9\text{-}t)_3 \longrightarrow \underset{\mathbf{10}}{Al^{\dot{-}}(OC_4H_9\text{-}t)_3} + t\text{-}C_4H_9OH \qquad (7)$$

$$\mathbf{10} + n\text{-}C_3H_7X \underset{X\,=\,Cl,\ Br,\ I}{\longrightarrow} AlX(OC_4H_9\text{-}t)_3 + n\text{-}C_3H_7\cdot \qquad (8)$$

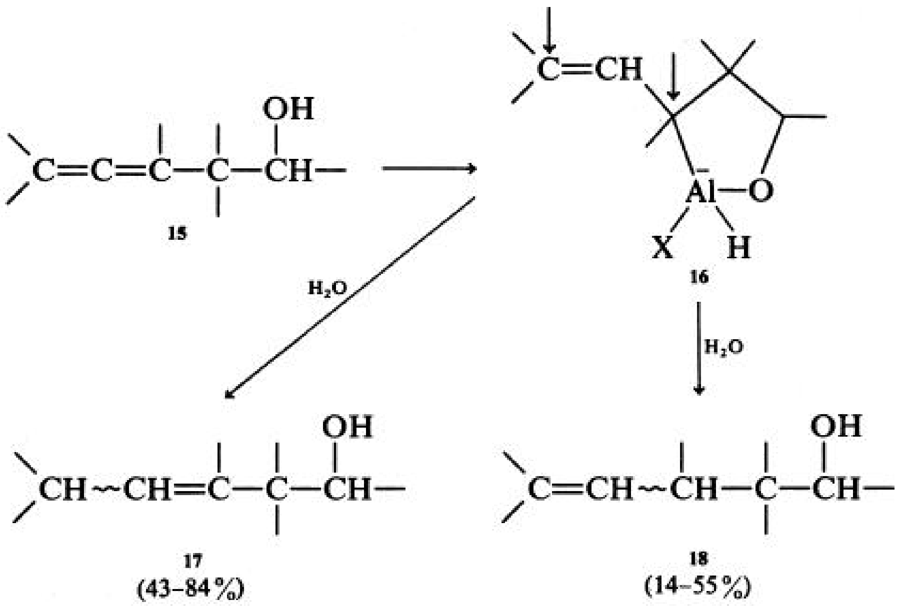
2.3. Intramolecular Hydride Transfer

The reduction of some functionalized organic compounds by complex metal hydrides follows an intra- rather than intermolecular mechanism. In a typical example, the reaction of α -allenic alcohols (2,3-alkadien-1-ols) **11** with $LiAlH_3(OCH_3)$ in tetrahydrofuran or with $LiAlH_4$ in diethyl ether involves formation of an alcoholate and an intramolecular hydride transfer to the



sp^2-carbon atom closest to the functional carbon giving the complex **12a**, which on decomposition affords homoallylic alcohols (3-alken-1-ols) **13**. Alternatively, intramolecular hydride attack at the allene central carbon atom and nucleophilic substitution of the hydroxyl group by a hydride ion, as shown by the structure **12b**, leads to 1,3-alkadienes **14**. Unlike $LiAlH_4$, which produces the diene hydrocarbons **14**, $LiAlH(OCH_3)_3$ favors the formation of alcohols **13**. Both hydrides behave similarly in the partial reduction of α -vinylallenic alcohols (2,4,5-alkatrien-1-ols), and the $OAlH_2$ group thus appears to be a better leaving group than $OAlH(OCH_3)$. (214)

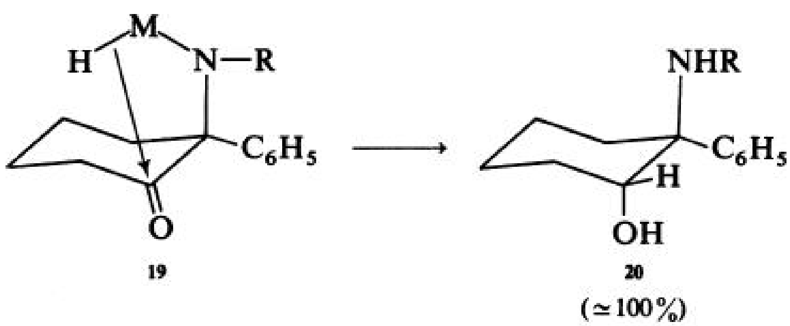
In the reduction of β -allenic alcohols (3,4-alkadien-1-ols) **15** by $LiAlH_3(OCH_3)$ and $LiAlH_4$, intramolecular hydride transfer involves formation of the cyclic complex **16**; this can be protonated at two sites (arrows) to



X = H, CH_3O

give either 3-alken-1-ols **17** or 4-alken-1-ols **18**, presumably depending on the relative stability of the corresponding intermediate carbanions. (214)

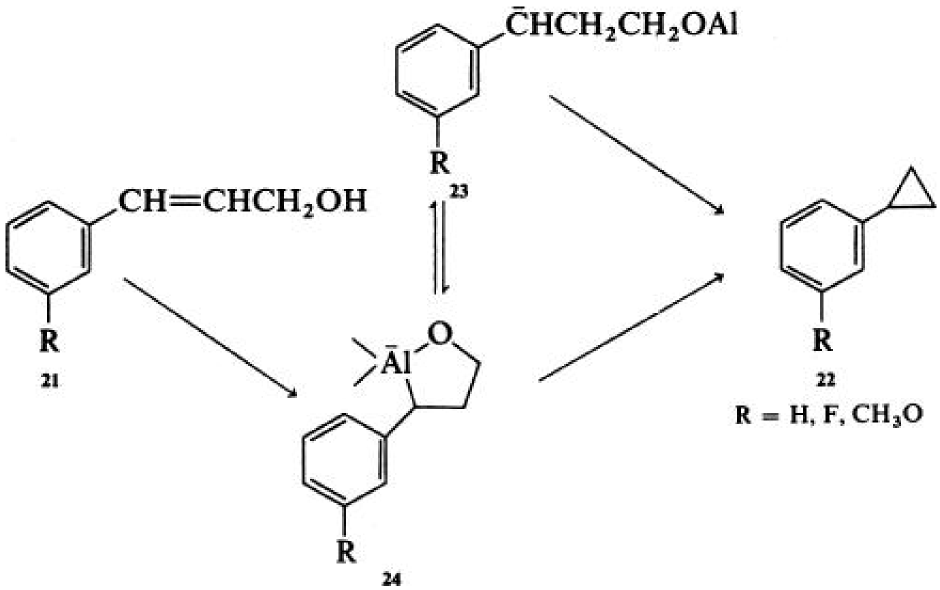
Intramolecular hydride transfer by way of the relatively stable intermediate complex **19** between an amino group and a complex metal hydride has been suggested to explain the essentially exclusive formation of *trans*-2-amino alcohols **20** from primary and secondary 2-aminocyclohexanones. The finding



R = H, alkyl

that reduction of tertiary 2-aminocyclohexanones proceeds with markedly decreased stereoselectivity is consistent with this idea. (215, 216) However, formation of an intermediate complex involving a nitrogen — aluminum bond and intramolecular hydride transfer has been suggested for the reduction of 2-(*N,N*-dimethylamino)cyclohexanone by $NaAlH_2(OCH_2CH_2OCH_3)_2$. (217, 218)

Cinnamyl alcohols **21** react with $LiAlH_2(OCH_3)_2$ in 1,2-dimethoxyethane to form phenylcyclopropanes **22** at elevated temperatures. The relatively high



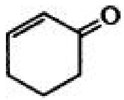
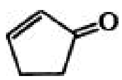
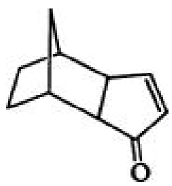
Hammett reaction constant, (219) the strong acceleration caused by the β -phenyl substituent in the formation of 1,1-diphenylcyclopropane from β -phenylcinnamyl alcohol with $LiAlH_4$ (220) or $NaAlH_2(OCH_2CH_2OCH_3)_2$ (221) and the stereochemistry of ring closure in reduction of α - or β -methyl-substituted cinnamyl alcohols, (219, 222) all support the formation of carbanions **23** in the transition state and disfavor the concerted mechanism via **24** **22**. (219)

2.4. Hydride Addition to α , β -Unsaturated Carbonyl Compounds

The formation of an allylic alcohol (charge-controlled process, 1,2 addition), a saturated ketone, or a saturated alcohol (frontier-orbital controlled process, 1,4 addition) in the reduction of conjugated carbonyl compounds by complex metal hydrides has been suggested to depend on the hardness and softness of the reactants defined in terms of coefficients of the lowest vacant molecular orbital (MO). (223) According to MO calculations and consideration of the fact that only orbital factors are operative, the 1,4 addition of a complex metal hydride to 2-cyclopenten-1-one should always be more favored than that to 2-cyclohexen-1-one. (224) In α , β -unsaturated carbonyl compounds such as cinnamaldehyde, conjugation with the phenyl group increases the frontierorbital control and renders the conjugated system more prone to 1,4 addition. (225) However, the course of reduction of conjugated carbonyl compounds is also significantly influenced by the nature of the metal hydride. According to Pearson's concept of soft and hard acids and bases, (226, 227) the hard metal hydrides should add preferentially to the 2 position and the soft metal hydrides to the **4** position of the conjugated system of α -enones. (223-225) As shown in Table B, this prediction agrees well with the representative experimental results of reductions by complex metal hydrides

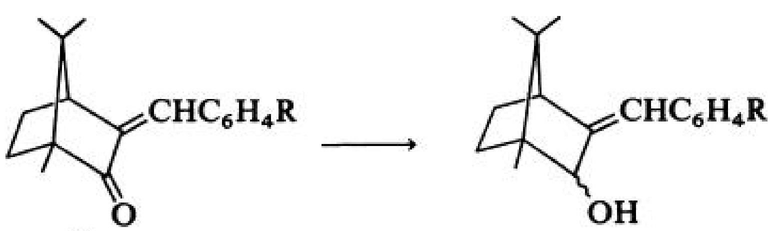
arranged in the order of increasing softness
[$LiAlH(OCH_3)_3$ ≤ $LiAlH(SC_4H_9\text{-}t)_3$].

TABLE B. Percentage of 1,4 Addition of Complex Metal Hydrides to α-Enones [a]

Ketone	LTMA[b]	LAH[c]	LTTMA[d]	LTBA[e]	LTTBA[f]
	5	22	56	78	95
	9.5[g]	86[g]	95	~100[g]	~100
	24[g, h]	~100[g]	—	~100[g]	—

[a]The ketones were added to the hydride in tetrahydrofuran and reduced at 0°; see Ref. 224.
b–f LTMA = $LiAlH(OCH_3)_3$; LAH = $LiAlH_4$; LTTMA = $LiAlH(SCH_3)_3$;
LTBA = $LiAlH(OC_4H_9\text{-}t)_3$; LTTBA = $LiAlH(SC_4H_9\text{-}t)_3$.
[g]See Ref. 228.
[h]Calculation was based on the ketone consumed.

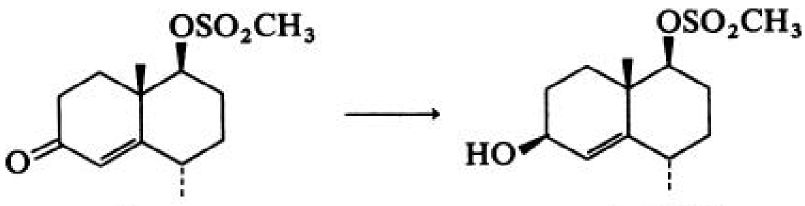
Frequent exceptions to preferential 1,4 addition of $LiAlH(OC_4H_9\text{-}t)_3$ to α-enones have been reported to result from other factors. 1,2 Addition (74–78%) (ρ = 0.79) predominates over 1,4 addition (ρ = 0.60) in the reduction of 3-benzylidene camphors **25** by this hydride. (229) In another example, the α-enone



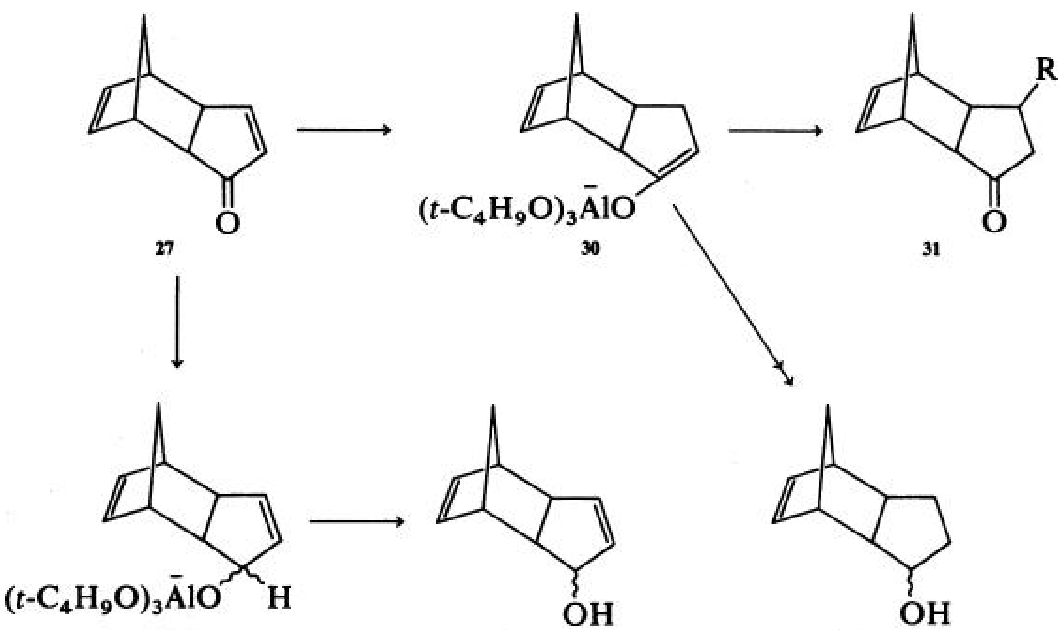
25

R = H, *m*-F, *p*-CH_3, *p*-CH_3O

26 is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to the equatorial allylic alcohol. (230)



The mechanism suggested for the 1,2 addition of $LiAlH(OC_4H_9\text{-}t)_3$ to α -enones such as **27** involves presumed formation of the intermediate **28**, which on decomposition yields the allylic alcohol **29**. The 1,4 addition of the same hydride presumably proceeds with predominating hydride attack at the C-5 position (99%) to give the enolate **30**, which affords the saturated ketone



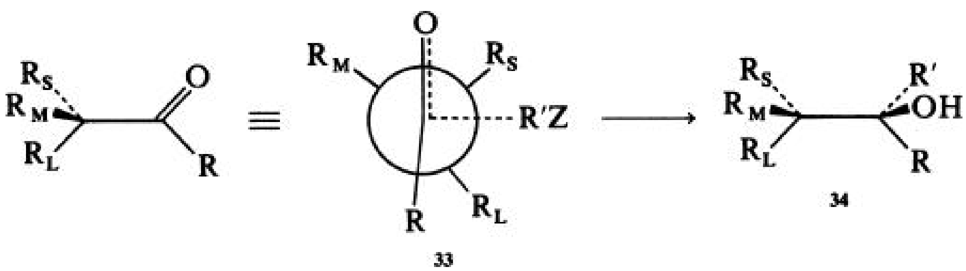
31 (R = H) (83%) as the major product. (231, 232) Reduction of the α -enone **27** by $LiAlD(OC_4H_9\text{-}t)_3$ gives the deuteriated ketone **31** (R = D) in high yield (80%); (233) (see also Ref. 232). Since the ketone **31** (R = H) reacts readily with $LiAlH(OC_4H_9\text{-}t)_3$ to give the saturated alcohol **32** (73%), the ketone **31** must not be formed until after decomposition of the enolate **30**. The saturated alcohol **32** (16%) is assumed to arise from intramolecular attack on the enolate **30** or its keto tautomer by $LiAlH(OC_4H_9\text{-}t)_3$. (231, 232)

2.5. Stereochemistry and Mechanism of Aldehyde and Ketone Reductions

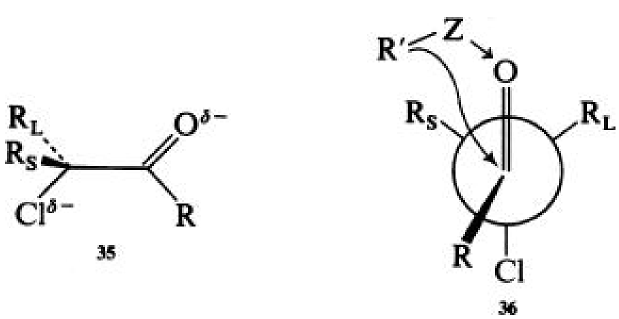
2.5.1.1. Acyclic Carbonyl Compounds

In the area of acyclic stereochemistry, the greatest effort has been devoted to understanding asymmetric induction in additions of achiral organometallic and complex hydride reagents to chiral aldehydes and ketones. Three models were developed to correlate the results of addition reactions of an acyclic carbonyl group attached to the asymmetric center (1,2-asymmetric induction).

The “open-chain model” **33** was proposed by Cram and co-workers (234, 235) to explain and predict the formation of the predominating diastereomer in noncatalytic (kinetically controlled) reactions of aldehydes and ketones carrying nonpolar groups. According to this model, the ketone will react preferentially in conformation **33** in which the carbonyl group is flanked by the smallest (R_S) and medium-sized (R_M) substituent, and the carbonyl double bond is attacked by the reagent R Z from the less hindered side to form predominately the *threo* diastereomer **34** (R_L denotes a large nonpolar substituent). (134, 148)

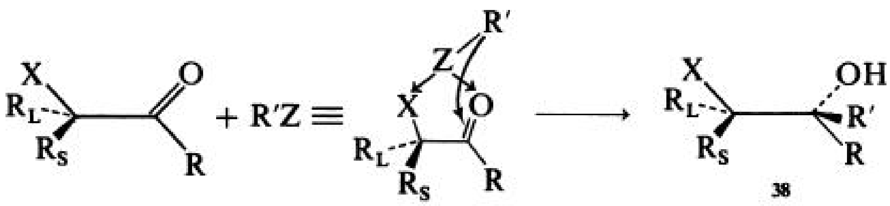


The “dipolar model” (**35** or **36**) was suggested by Cornforth and co-workers (236) to account for the stereochemical course in the nucleophilic addition reactions of aldehydes and acyclic ketones in which a halogen atom is on



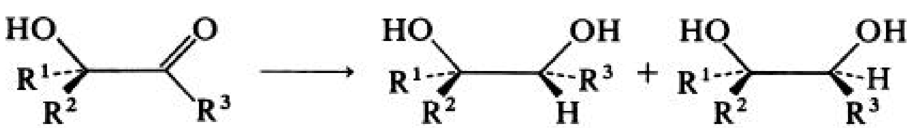
the asymmetric center adjacent to the carbonyl group. The substrate is considered to react largely in the *trans* dipolar conformation **35**; steric hindrance then operates to favor the approach of the reagent R Z from the less hindered side (**36**). (148)

The “cyclic model” **37** was introduced by Cram and co-workers (235, 237) for additions to aldehydes and ketones carrying a hydroxyl, alkoxyl, or amino group (X) on the asymmetric center alpha to the carbonyl group. Formation of the predominating diastereomer **38** is significantly influenced not only by



37 38

the substrate structure, but also by the reagent and reaction conditions. Reversal of the stereochemistry encountered often in this system has been explained by competition with the dipolar or open-chain models. (148, 238) In the reduction of substituted α -ketols **39** with $LiAlH_4$, $LiAlH(OCH_3)_3$, $AlH(C_4H_9\text{-}i)_2$, or $Al(C_4H_9\text{-}i)_3$, the predominant diastereomer was the *erythro* diol **40**, as predicted by Cram's cyclic model. However, the degree of stereoselectivity could

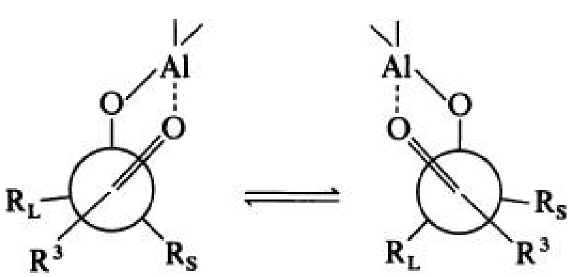


39 *erythro* *threo*

40

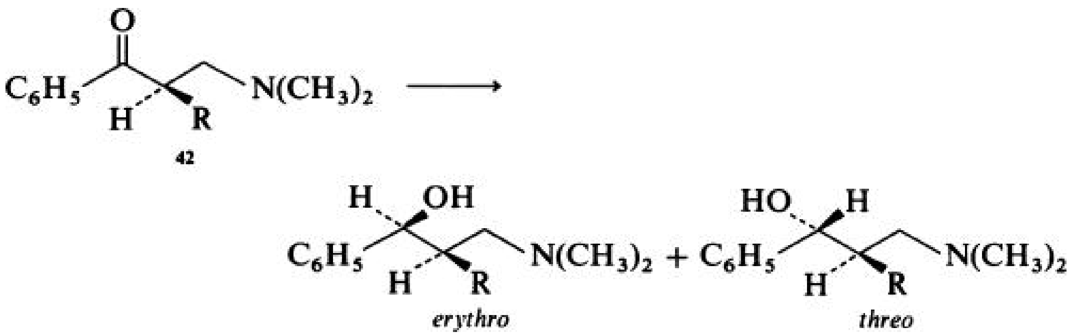
$R^1, R^3 = CH_3, n\text{-}C_5H_{11}, i\text{-}C_3H_7, t\text{-}C_4H_9, C_6H_5; R^2 = H, CH_3$

be correlated with the ketol structure only in reductions with the monomeric $Al(C_4H_9\text{-}i)_3$ in toluene. Cyclopentanoid half-chair conformations **41a** and **41b** (237) have thus been suggested to rationalize the dependence of the stereoselectivity on the effective bulk of the more associated reagents; surprisingly,



41a 41b

even this modification of Cram's cyclic model does not accommodate the variations in stereoselectivity characterizing reductions of phenyl-substituted α -ketols. Essentially the same conclusions hold for the formation of diols **40** from the corresponding α -diones ($R^1 + R^2 = R = n\text{-}C_5H_{11}$, $i\text{-}C_3H_7$, $t\text{-}C_4H_9$, C_6H_5). (239, 240) On the other hand, reductions of α -asymmetric β -dimethylaminopropiophenones **42** show a regular increase in stereoselective formation

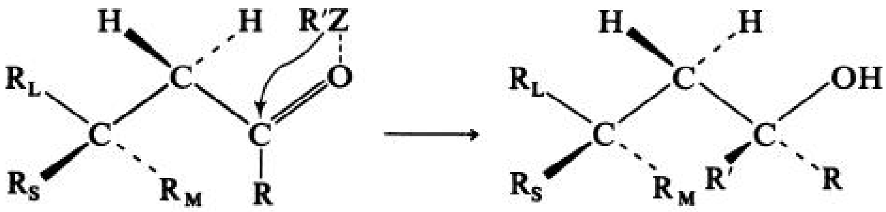


	Percentage of *erythro* Alcohol[a]		
R	$LiAlH_4$	$LiAlH(OCH_3)_3$	$LiAlH(OC_4H_9\text{-}t)_3$
CH_3	60	54	53
$C_6H_5CH_2$	64	79	85
C_6H_5	94	98	95

[a]Only one isomer of the racemic pair is shown; reactions were run in tetrahydrofuran at hydride concentrations of ~0.45 *M* and at 0°; the yields of isomeric alcohols are normalized to 100%.

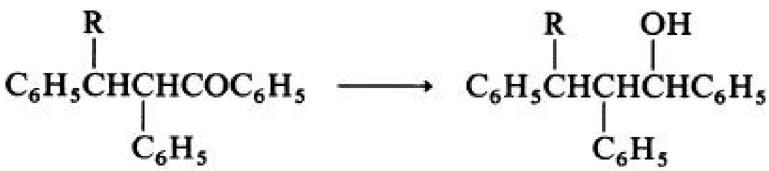
of the *erythro* alcohol with increasing relative bulk of the substituent R ($CH_3 < C_6H_5CH_2 < C_6H_5$) (see p. 89 in Ref. 148). However, replacement of the dimethylamino group in ketones **42** by a piperidyl group decreases the stereoselectivity, particularly when R is methyl or benzyl, and leads in some reactions to a reversal of the stereochemistry. (241)

In the model suggested (242, 243) for steric control of 1,3-asymmetric induction in additions to acyclic ketones (e.g., **43**), the carbonyl group is placed between the two least bulky groups on the adjacent carbon atom and the reagent R Z approaches preferentially over the smallest group (R_S) attached to the asymmetric center to form the predominant diastereomer **44**. A complex steric



43 44

course may occur in these systems. (241, 244, 245) For instance, the reduction of 3-alkyl-substituted *threo*-1,2,3-triphenyl-1-propanones **45a–45c** gives the *threo*-*erythro* diastereomers (TE) **46a–46c** as major products, in accordance with either the Cram 1,3 or 1,2 rule of asymmetric induction. However, the reduction of *erythro* ketones **45a–45b** to the *erythro*–*erythro* alcohols (EE) **46a–46b** is



45 46

Ketone	R	$LiAlH_4$[a]	$LiAlH(OC_4H_9\text{-}t)_3$[a]
		Diastereomer ratio,[b] TE-46:TT-46	
threo-**45a**	CH_3	78:22	70:30
-**45b**	C_2H_5	80:20	64:36
-**45c**	*i*-C_3H_7	72:28	61:39
		Diastereomer ratio,[b] EE-46:ET-46	
erythro-**45a**	CH_3	79:21	83:17
-**45b**	C_2H_5	72:28	70:30

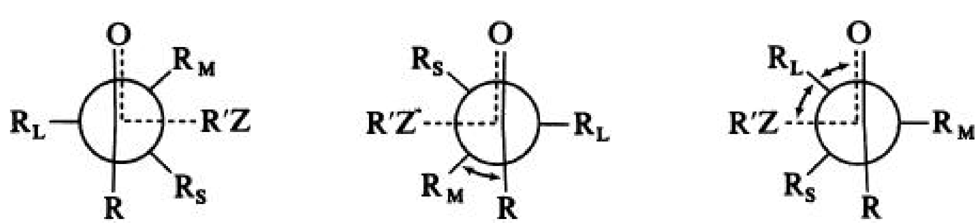
-**45c**	*i*-C_3H_7	25:75	45:55

[a]Reactions in diethyl ether at room temperature.

[b]The diastereomer yields were normalized to 100%.

consistent only with the Cram 1,2 rule, but not with the 1,3 rule. In contrast, formation of the *erythro–threo* alcohol (ET) **46c** as the predominating diastereomer in the reduction of the *erythro* ketone **45c** conforms only to the Cram 1,3 rule. In these cases $LiAlH(OC_4H_9\text{-}t)_3$ leads, with one exception, to increased formation of the minor diastereomer. Introduction of several models of the transition state was necessary to rationalize the contrasting effects of the size of substituents R on the stereochemistry. (246)

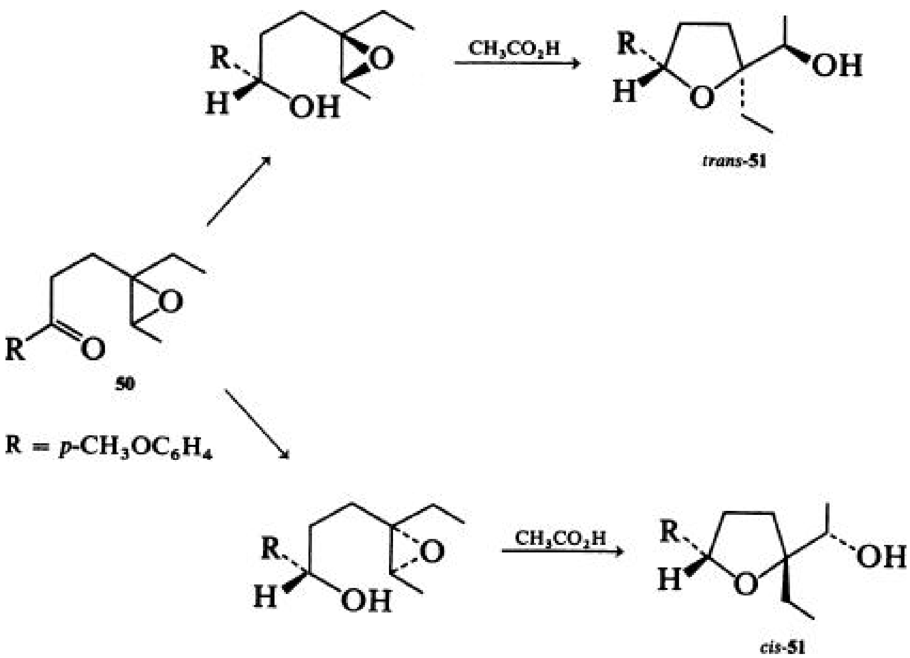
A more generalized rationalization aimed at predicting not only the major diastereomer but also the degree of stereoselectivity in reactions of aldehydes and ketones with complex metal hydrides (or organometallic reagents) has been proposed. (247, 248) This rationalization emphasizes the involvement of essentially reactant-like transition states, the importance of torsional strain (Pitzer strain) (249) involving partially formed bonds, and (in contrast to Cram (234) and Karabatsos (250)) the dominant role of transition-state interactions between the entering nucleophile (R Z) and the achiral group (R) attached to the carbonyl carbon atom. In the presence of polar effects, the preferred transition state will be the one that allows maximum separation between R Z and the electro-negative group (R_L, R_M, or R_S). The stereochemical course of metal hydride reductions of acyclic ketones is predicted by considerations of transition-state conformations **47–49**, which differ in the extent of steric interactions (indicated by arrows). In the absence of polar groups, the major diastereomer is formed by way of the preferred, relatively least strained conformation in transition state **47**. Increase in the size of R introduces greater steric strain into the conformation **48** and leads to decreased formation of the minor diastereomer and



47 48 49

thus to increased stereoselectivity. Similarly, increased size of either R_L or complex metal hydride R Z will destabilize conformation **49** in favor of **47** and cause the same effect. In reductions of ketones, where R_L is an alkyl and R_M a strongly electronegative group, the most stable and preferred conformation for the transition state is represented by the structure **49**. The variations in the effective size of complex metal hydrides, and presumably also in their capability of complexing with the substrate, can lead to dramatic changes in stereoselectivity, as illustrated by reductions of the racemic γ , δ -epoxy ketone **50**. (251)

The effort to establish models consistent with experimental results continues with theoretical treatment of asymmetric induction in acyclic systems. (252-254) The *ab initio* calculations of various transition-state geometries for addition of



Metal Hydride	Ratio *trans*-**51**: *cis*-**51**
$NaBH_4$[a] (room temp)	50:50
$LiBH(C_4H_9\text{-}s)_3$[b] (room temp)	50:50
$LiAlH_4$[b] (0°)	25:75
$LiAlH(OC_4H_9\text{-}t)_3$[b] (0°)	20:80
$LiAlH_4$–diamine[c] (–78°)[b]	8:92

[a]Reaction in methanol.

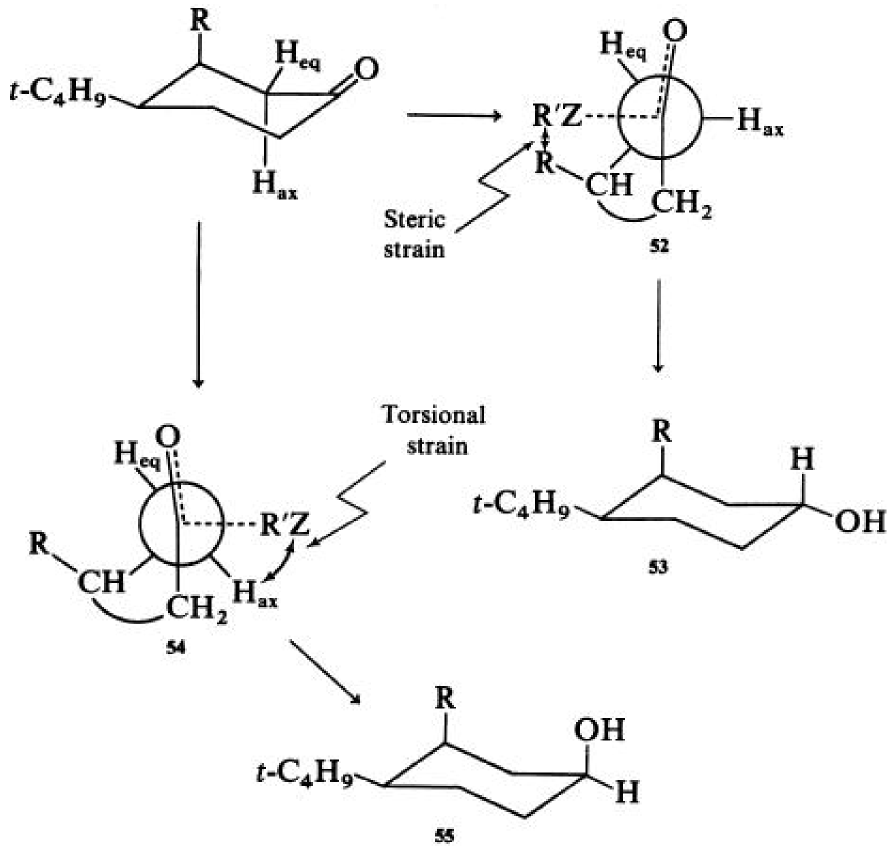
[b]Reaction in diethyl ether.

[c](de)-2-(*o*-Toluidinomethyl)pyrrolidine.

nucleophiles to nonpolar and polar carbonyl compounds provide support for the model **47–49**; according to these calculations, the most stable transition-state conformations in this model have the lowest relative energies, as a result of antiperiplanarity between the new bond being formed (nucleophile–carbonyl carbon atom) and the α -C —R_L bond. (255, 256)

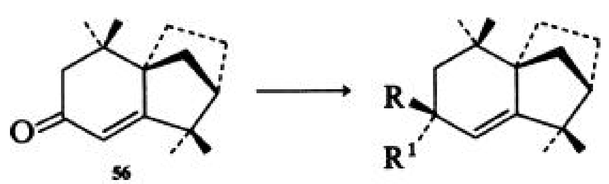
2.5.1.2. Cyclic Ketones

Since Barton's stereochemical analysis of the reduction of substituted cyclohexanones by $NaBH_4$ and $LiAlH_4$, (257) several rationalizations have been suggested to account for the predominating axial attack on a relatively unhindered (conformationally flexible) ketone to form the equatorial alcohol and the predominating equatorial attack on a relatively hindered (conformationally rigid) ketone to give the axial alcohol as the major isomer. Dauben and co-workers (258, 259) have introduced the concept of "product development control" (product-like transition state) for reductions of unhindered cyclohexanones and of "steric approach control" (reactant-like transition state) for reductions of hindered cyclohexanones. The latter concept has really never been questioned; arguments have been advanced for and against "product development control." (148, 154, 156, 260-270) The rationalizations by Chérest and Felkin (283-286) and Anh and co-workers (287-289) have found wider acceptance (134, 148, 269) than others. (51, 154, 173, 261, 269-282) According to the Chérest–Felkin interpretation, which is based on premises analogous to those suggested for open-chain ketones, (247) the stereochemistry is governed by the net difference between the steric strain in the transition state **52**, leading to the equatorial alcohol **53** and the torsional strain in the transition state **54**, which yields the axial alcohol **55**. Increase in the effective size of the axial substituent at C-3 and/or C-5 will raise the steric strain in **52** (R = alkyl), favoring the transition state **54** and hence formation of the axial alcohol **55**. The same effect would be attained by increasing the effective bulk of the hydride reagent. Use of the proper reducing agent can lead to profound changes in the stereochemical balance. Whereas eclipsing effects are likely to predominate in the



R'Z = entering complex metal hydride
R = hydrogen or alkyl group

NaBH$_4$ and LiAlH$_4$ reductions of 9-oxolongifolene (**56**) to form the thermodynamically more stable α alcohol **57a** as the major product, bulk steric



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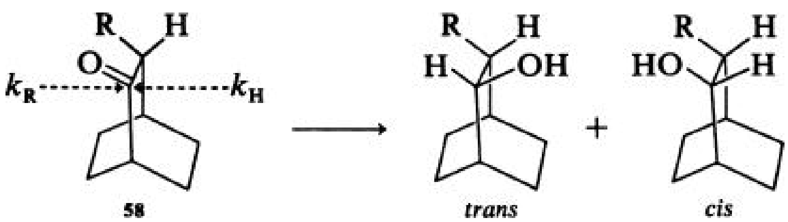
57a: R = H, R^1 = OH
57b: R = OH, R^1 = H

Metal Hydride	Ratio 57a:57b
LiAlH$_4$	76:24
NaBH$_4$	76:24

$NaAlH_2(OCH_2CH_2OCH_3)_2$	18:82

effects seem to determine the stereochemistry of reduction with $NaAlH_2(OCH_2CH_2OCH_3)_2$, favoring formation of the less stable β isomer **57b**. (290) A more complicated but illustrative example is provided by the reduction of 3-alkyl bicyclo[2.2.2]-2-octanones **58**. Unlike $LiAlH(OC_4H_9\text{-}t)_3$, which attacks ketones **58a–58d** from the less hindered side (k_R:k_H < 1) to



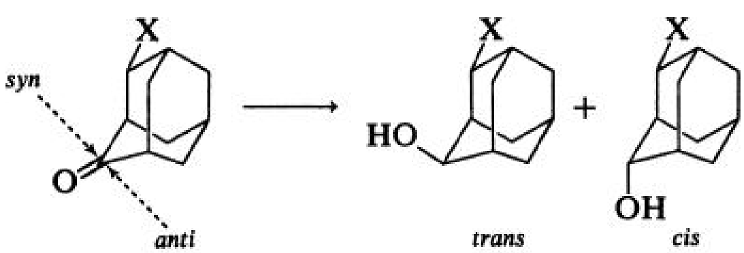
Ketone	R	Ratio *trans: cis* (k_R:k_H) LiAlH4	LiAlH(OC4H9-t)3[a]
58a	CH_3	50:50	25:75
58b	C_2H_5	68:32	30:70
58c	$i\text{-}C_3H_7$	72:28	40:60
58d	$t\text{-}C_4H_9$	15:85	5:95

[a]Approximate values calculated from log(k_R/k_H) as a function of substituent R. (293)

form predominately the *cis* alcohols, $LiAlH_4$ approaches the ketones **58b–58c** preferentially from the more hindered side (k_R:k_H > 1) and gives the *trans* alcohols as the major products. These patterns change only in the $LiAlH_4$ reduction of the *tert*-butyl ketone **58d**. (291-294) The gradually increasing *trans:cis* (k_R:k_H) ratio for both hydrides as the methyl is replaced by ethyl or isopropyl groups has been interpreted to arise from an anisotropic inductive effect of the alkyl groups. Increased steric hindrance of a *tert*-butyl group at C-3 is responsible for the sudden fall of k_R in the reduction of ketone **58d**. (293) It is noteworthy that the above effect of alkyl substituents can also be rationalized by the “twist angle approach” to the stereoselectivity of reduction of substituted cyclic ketones. (295)

Anh's concept of antiperiplanarity of the C-2 and C-6 axial hydrogens in the reduction of cyclohexanones represents a modification of the Chérest–Felkin model. According to this concept, the flexibility of the ring and hardness of the nucleophile should be considered in addition to steric and torsional factors to explain the competing axial and equatorial approaches of nucleophiles to cyclohexanones. (287-289)

The recently postulated generalized model of "charge-transfer stabilization of the transition state" derives from the consideration that "the feature of the transition state critical for stereoselectivity is the existence of a low-lying vacant orbital $\sigma^*_\ddagger$ associated with the σ bond being formed in the reaction. The stereochemistry of nucleophilic addition to cyclohexanones is thus determined by steric hindrance, which favors the equatorial approach, and by electron donation from the cyclohexanone σ_{CC} and σ_{CH} bonds into the $\sigma^*_\ddagger$ orbital facilitating the axial approach, because the carbon — hydrogen bonds are better electron donors." (296) The predominance of the more hindered approach of $LiAlH_4$ in the case of ketones **58b** and **58c** (293) is in accordance with this model. (296) The change in stereoselectivity of the reduction of 4-halogen-substituted 2-adamantanones **59** by $LiAlH(OC_4H_9\text{-}t)_3$ (295) correlates adequately



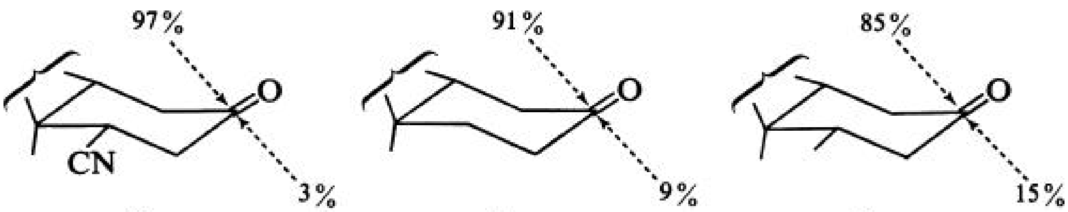
59

X	Ratio *trans*:*cis*
F	53:47
H	50:50
Cl	45:55
Br	43:57

I	34:66

with a net change of charge density in the σ $_{CC}$ bond as the fluorine atom is replaced by other halogen substituents; (296) interestingly, the same trend in stereoselectivity is predicted by the “twist angle approach.” (295)

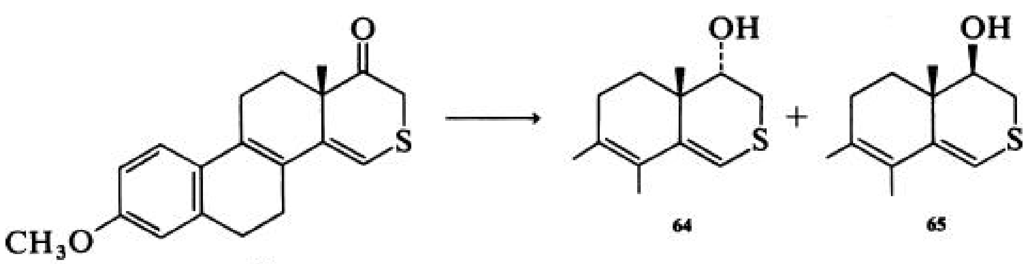
The $LiAlH(OC_4H_9\text{-}t)_3$ reduction of 1 β -cyano-10-methyl-*trans*-3-decalone (**60**) gives a greater proportion of the equatorial alcohol (97%) than is afforded by the unsubstituted ketone **61** (91%). (297, 298) In agreement with the model



60 61 62

prediction, the electron-withdrawing cyano group at C-1 decreases the value of ε (σ $_{CC}$) and the resulting decrease in the stabilization energy SE_{eq} then enhances the axial approach. The presence of the electron-donating methyl group at C-1 in the ketone **62** causes an opposite effect leading to a decreased formation of the equatorial alcohol (85%). (296-298)

Since the electron-donating power of the σ $_{CC}$ bond is lower than that of the σ $_{CS}$ bond, the equatorial hydride approach to a 3-thiacyclohexanone should be greater than that to an analogous carbocyclic cyclohexanone. (296) This prediction has been verified, for instance, by reductions of ketone **63**, which undergoes predominantely β attack by several hydrides, giving a greater proportion of the 17a α alcohol **64**. On the other hand,



63 64 65

Metal Hydride	Ratio 64:65

$LiAlH_4$	81:19
$LiAlH(OC_4H_9\text{-}t)_3$	73:27
$NaBH_4$	71:29
$LiAlH(OCH_3)_3$	67:33
$NaAlH_2(OCH_2CH_2OCH_3)_2$	26:74

$NaAlH_2(OCH_2CH_2OCH_3)_2$ evokes a predominance of α attack and leads to a reversal of the stereochemistry and to preferred formation of the 17a β alcohol **65**, which is usually the major product of the complex metal hydride reductions of the carbocyclic analog. (299)

The consideration that electron donation from the molecules solvating the transition state would raise the value of $\varepsilon(\sigma^*_\ddagger)$ and thus enhance the equatorial approach to cyclohexanones might explain many examples of the solvent effect on stereochemistry. (296) A typical example is given by the hydride reductions of 3,3,5-trimethylcyclohexanone in various solvents (Table C).

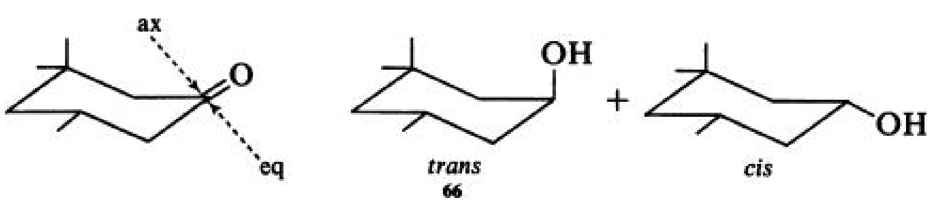


TABLE C. Effect of Solvents on the Stereoselectivity of Reduction of 3,3,5-Trimethylcyclohexanone

Metal Hydride	**Solvent**	**Percent of 66**	**Reference**
$NaBH_4$	$t\text{-}C_4H_9OH$	55	300
	$i\text{-}C_3H_7OH$	56–64	154, 300, 301

	C_2H_5OH	63–67	300
	CH_3OH	80–94	154, 300
$NaAlH_2(OCH_2CH_2OCH_3)_2$	C_6H_6	57	191
	$(C_2H_5)_2O$	57	192
	Tetrahydrofuran	68	192
$LiAlH_4$	$(C_2H_5)_2O$	55–71	51, 153, 154, 183, 302
	Tetrahydrofuran	74–83	51, 153, 180
$LiAlH(OCH_3)_3$	$(C_2H_5)_2O$	75	153
	Tetrahydrofuran	85–98	153, 154, 180
$LiAlH(OC_4H_9\text{-}t)_3$	2,2,5,5-Tetramethyl-tetrahydrofuran–C_6H_6	55	194
	C_6H_6	60–63	194
	$(C_2H_5)_2O$	73	153, 183, 194
	Tetrahydrofuran	88–96	153, 154, 178, 180, 200, 261, 263, 303

Mechanistic analysis taking into account the Hammett reaction constant (ρ), kinetic isotope effects (k_H/k_D), and activation parameters ($\triangle H^{\ddagger}$, $\triangle S^{\ddagger}$) determined for reductions by various hydride reagents (Table D) had led to the conclusion that the $NaBH_4$ reductions of cyclohexanones involve a product-like transition state. In contrast, the $LiAlH(OC_4H_9\text{-}t)_3$ reductions involve a midpoint-like, and the $LiAlH_4$ reductions a reactant-like transition state. (269, 270, 303, 304) Variation of the transition-state structure with the nature of the reducing agent follows from these considerations. (269, 270, 303) A four-center cycloaddition mechanism has been suggested for the $LiAlH(OC_4H_9\text{-}t)_3$ reductions of cyclohexanones; (303, 304) (see, however, Ref. 308).

TABLE D. Thermodynamic Parameters for Reduction of Ketones

Metal Hydride	ρ	k_H/k_D	$\triangle H^‡$ (kcal mol^{-1})	$\triangle S^‡$ (cal K^{-1} mol^{-1})
$NaBH_4$	3.06[a,b]	0.6–0.7[c–e]	5.5–11.0[c,f]	–36 to –48[c,f]
$LiAlH(OC_4H_9\text{-}t)_3$	2.13[g,h]	0.95[c,i,j]	6–8[c,k]	–33 to –42[c,k,l]
$LiAlH_4$[m]	1.95[n]	1.3–1.4[n,o]	10°	–26°
$NaAlH_4$	—	—	17.5	–5
AlH_3[g,h]	0.89	—	—	—
$Al_2H_3(OCH_2CH_2OCH_3)_3$[g,p]	0.34	—	15.5	–14

[a]This is the value for reduction of acetophenones.

[b]See Ref. 305.

[c]This is the value for reduction of alkyl cyclohexanones.

[d]See Ref. 306.

[e]See Ref. 307.

[f]See Ref. 301.

[g]This is the value for reduction of benzophenones.

[h]See Ref. 308.

[i]See Ref. 304.

[j]The value of k_H/k_D equal to 0.70–0.79 (±0.08) has been found for the highly hindered cyclohexanones. (309)

[k]See Ref. 303.

[l]See Ref. 310.

[m]This is the value for reduction of 2,4,6-trimethylbenzophenones, 2,2 -dimethylbenzophenone, and 2,2 -diethylbenzophenone.

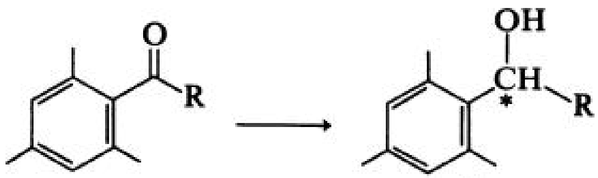
[n]See Ref. 179.

[o]See Ref. 311.

[p]See Ref. 312.

2.6. Asymmetric Reduction of Carbonyl Compounds

The high degree of sensitivity of asymmetric reductions of prochiral aldehydes and ketones by chiral lithium alkoxyaluminum hydride or deuteride complexes to changes in the substrate structure, reducing agent, and reaction conditions generally makes it difficult to rationalize the stereochemical outcome of these reactions. (148) The following examples illustrate at least some of these complexities. Reversal in the stereochemistry has been noted in the reduction of alkyl mesityl ketones by the $LiAlH_4$–(–)-quinine (1 : 1) complex; (313, 314) the change in the configuration of alcohols **67**, where R is isopropyl or *tert*-butyl has been explained by loss of coplanarity of the benzene ring and the carbonyl group. The same explanation evidently holds for the reversal of stereochemistry in reductions of isopropyl phenyl ketone and *tert*-butyl phenyl ketone by this hydride complex; whereas the former ketone is converted into the (*R*) alcohol, the latter gives the (*S*) enantiomer in excess. (314) By contrast, the asymmetric reduction of both ketones by $LiAlH_4$–(2*S*,3*S*)-(–)-1,4-bis(dimethylamino)-2,3-butanediol produces only the (*S*) alcohols (315) and that by the “fresh” $LiAlH_4$–(2*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol reagent gives predominantly the (*R*) alcohols. (166, 167) The

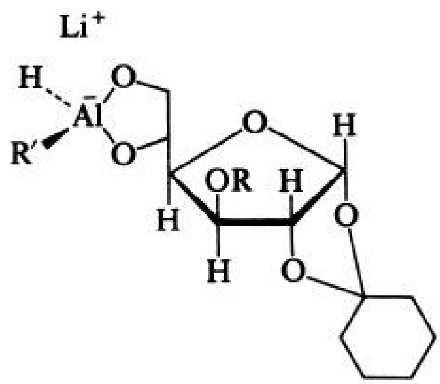


67

R	CH_3	C_2H_5	*i*-C_3H_7	*t*-C_4H_9
Configuration of **67**	(*R*)	(*R*)	(*S*)	(*S*)
Enantiomeric excess, %	41–45	—	20	27

reasons for this behavior, which has been encountered in many other reactions, are not obvious and require further exploration. Changes in solvents bring about a reversal in the expected stereochemistry of reductions with the $LiAlH_4$–(–)-quinine (316) and the “aged”

$LiAlH_4$–(2*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol complexes; (167) replacement of diethyl ether by tetrahydrofuran in an asymmetric reduction by $LiAlH_4$–(–)-*N*-methylephedrine–*N*-ethylaniline causes an 87% decrease in enantioselectivity. (162) Nonetheless, some chiral complex hydrides show systematic behavior and can be utilized for configurational correlations. For instance, $LiAlH_4$–3-*O*-benzyl-1,2-cyclohexylidene- α -D-glucofuranose (1:1) (**68a**) reacts uniformly with ketones to form (*S*) alcohols whereas the ethanol-modified complex (1:1:1) **68b** gives systematically (*R*) alcohols in excess. The



$R = C_6H_5CH_2$

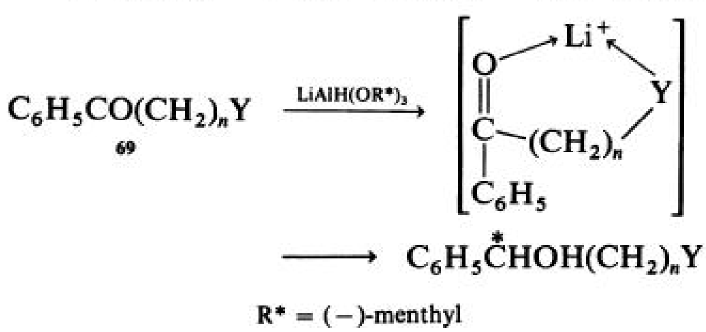
68a: R′ = H

68b: R′ = C_2H_5O

suggested model for the transition state accommodates convincingly the experimental results. (317-319) The kinetics of the asymmetric reduction of *meta*- and *para*-substituted benzophenones by $LiAlH_4$–1,2:5,6-di-*O*-isopropylidene- α-D-glucofuranose (1:1) indicate absence of any marked polar substituent effects. (320)

A comparison of the effect of various functional groups on the asymmetric induction in reductions of ketones **69** shows that the enantiomeric excess of the major isomer decreases in the following order:

$$OCH_3(n = 3) > OCH_3(n = 2) > N(CH_3)_2(n = 2) > SCH_3(n = 1\text{–}3) > C_2H_5(n = 1\text{–}3) > OCH_3(n = 4) > N(CH_3)_2(n = 1).$$

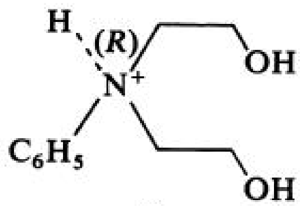


R* = (−)-menthyl

This trend parallels the decrease in the base strength and the coordinating capability of the functional groups, but it also reveals a clear dependence of enantioselectivity on the distance of the carbonyl from the functional group (except for the nonpolar SCH_3 and C_2H_5 groups). The results have been interpreted in terms of a cyclic transition state with lithium cation complexing the carbonyl oxygen, (321) as suggested for reductions by achiral complex metal hydrides. (51, 322, 323)

The effect of functional groups more or less remote from the carbonyl group of the substrate on the asymmetric reduction has some analogy in a similar effect of the structure of ligands used to modify $LiAlH_4$. This effect of substituents relatively distant from the site of ligand complexation with the hydride aluminum atom has been documented by comparing the asymmetric induction in ketone reductions with complexes of $LiAlH_4$ with (–)-quinine (CH_3O group at C-6) and (–)-cinchonidine (H at C-6) or (+)-quinidine (CH_3O group at C-6) and (+)-cinchonine (H at C-6). (313, 316, 324, 325) Systematic examination of the structural and stereochemical relationships in both substrate and chiral ligand has led in some reactions to a high degree of chiral induction and configurational unambiguity. (159-162, 168, 169, 326-330) Two examples illustrate this strategy. In the aminodiol **72** the weak (*S*)-directing induction of the (*R*)- α -methylbenzyl unit at nitrogen operates against the strong (*R*)-directing induction of the (*S,S*)-alcohol groups and the reduction of acetophenone with the $LiAlH_4$–**72** (1:2) complex gives the (*R*) alcohol in only low e.e. On the other hand, the (*S*) configuration at all three asymmetric centers of the aminodiol **73** leads to a substantial increase in the enantioselectivity and formation of the (*R*) alcohol in high e.e. (330)

Another approach utilizes the high degree of chiral recognition inherent in some conformationally rigid ligands; a typical example is the 1,1′-binaphthyl moiety in (*S*)-(–)-2,2′-dihydroxy-1,′-binaphthyl (331) and (*R*)-(+)-2,2 -dihydroxy-1,1 -binaphthyl. (332) Nonetheless, a careful structure stabilization of



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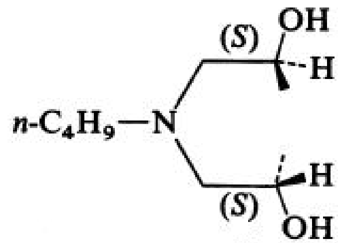

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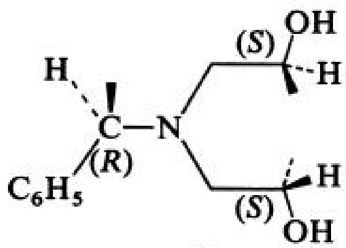

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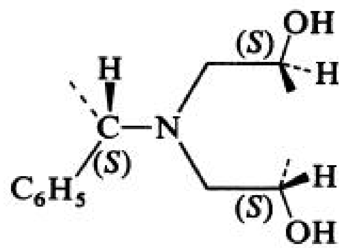
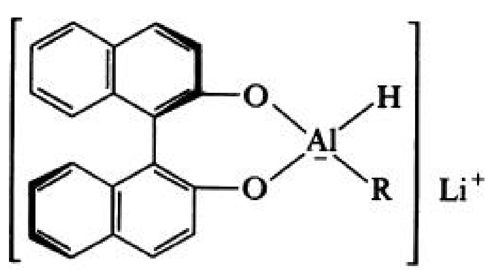


73

Ligand	1-Phenylethanol (e.e., %) (Configuration)
70	10(*S*)
71	44(*R*)
72	35(*R*)
73	82(*R*)

the $LiAlH_4$–chiral diol complex is necessary. Whereas reduction of acetophenone by $LiAlH_4$–(*R*)-(+)-2,2′-dihydroxy-1,1′-binaphthyl (1:1) [(*R*)-**74a**] proceeds presumably with almost complete disproportionation of the reagent,

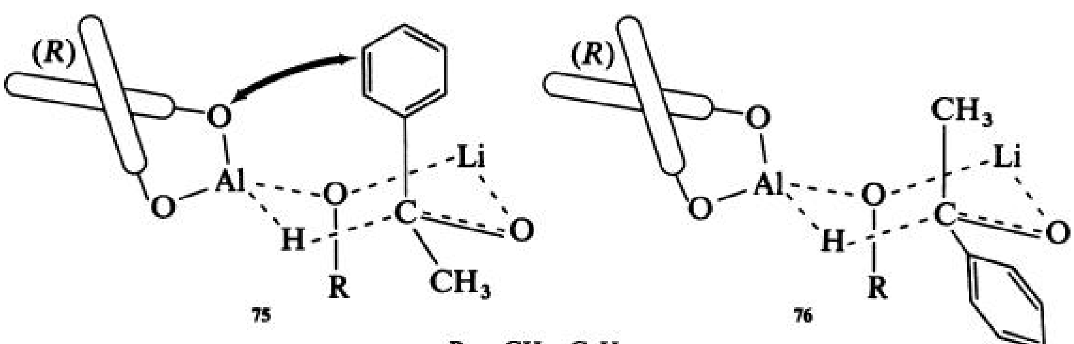


(*R*)-74

a: R = H
b: R = CH_3O
c: R = C_2H_5O

Reagent	Temperature (°C)	(*R*)-1-Phenylethanol (e.e., %)
(*R*)-**74a**	30	2
(*R*)-**74b**	30	73
(*R*)-**74c**	30	64
	–20	77
	–78	90

modification by methanol or ethanol to form the (*R*)-**74b** and (*R*)-**74c** complexes, respectively, enhances the stability of the reagent and brings about a high degree of enantioselectivity, which increases with decreasing temperature. (168) This temperature effect is in agreement with the rule that the proportion of the major isomer in the product increases with decreasing temperature and that raising the temperature increases the proportion of the minor isomer. (157, 162, 266, 271, 333) Most of the experimental results of reductions with the (*R*)-**74** complexes can be rationalized on stereoelectronic grounds. In the kinetically controlled asymmetric reduction of acetophenone with the reagents (*R*)-**74b** or (*R*)-**74c**, the methoxyl or ethoxyl oxygen has the highest basicity of the three oxygen atoms attached to aluminum and acts as the bridging atom



R = CH_3, C_2H_5

in the chair conformation of the intermediate six-membered cyclic complex. Existence of strong steric hindrance in the transition state **75** favors the transition state **76**, which leads, in accordance with experimental results, to formation of (*R*) alcohol as the predominating enantiomer. (168)

3. Scope and Limitations

3.1. Reactions of Hydrocarbons

3.1.1.1. Reduction of Carbon — Carbon Double Bonds

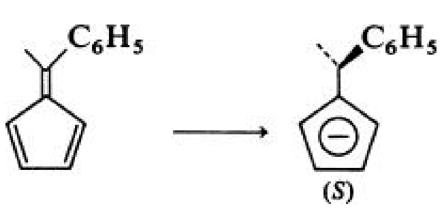
In the presence of bis(cyclopentadienyl)titanium dichloride as the catalyst, $AlH(OR)_2$ (R = CH_3, *i*-C_3H_7, *t*-C_4H_9) transforms 1-octene into the hydrometalation product, but at a substantially lower rate than bis(dialkylamino)aluminum hydrides. (334) On the other hand, the effectiveness of $NaAlH_2(OCH_2CH_2OCH_3)_2$ in the catalytic hydroalumination of terminal alkenes and internal alkynes is comparable with that of $LiAlH_4$, $NaAlH_4$, $LiAlH(CH_3)_3$, $NaAlH(CH_3)_3$, $LiAlH_2(NR_2)_2$, or $NaAlH_2(NR_2)_2$. (335) $NaAlH_2(OCH_2CH_2OCH_3)_2$ is a reagent of choice for transforming dicyclopentadienylzirconium dichloride into the hydride (η^5-$C_5H_5)_2Zr(Cl)H$, (336-339) which has been used for preparation of various C-1 functionalized alkanes by way of hydrozirconation of terminal or internal alkenes. (336, 340, 341) For instance, 1-octene (or *cis*- or *trans*-4-octene) can thus be converted to 1-bromooctane (Eq. 9). (336) A similar procedure has been

$$n\text{-}C_6H_{13}CH{=}CH_2 \xrightarrow[\text{2. } Br_2]{\text{1. } (\eta^5\text{-}C_5H_5)_2ZrCl_2,\ NaAlH_2(OCH_2CH_2OCH_3)_2,\ THF} \underset{(96\%)}{n\text{-}C_8H_{17}Br} \qquad (9)$$

applied to hydrozirconation of acetylenes yielding functionalized alkenes. (342) Reaction of dicyclopentadienylzirconium dichloride with the hydride and a long-chain internal alkene *in situ* followed by iodination leads almost exclusively to an 1-iodoalkane (Eq. 10). (338, 339)

$$n\text{-}C_{14}H_{29}CH{=}CHC_{14}H_{29}\text{-}n \xrightarrow[\text{2. } I_2\text{, room temp}]{\text{1. } (\eta^5\text{-}C_5H_5)_2ZrCl_2,\ NaAlH_2(OCH_2CH_2OCH_3)_2,\ C_6H_5CH_3\text{-THF, } 40^\circ} \underset{(74\%)}{n\text{-}C_{30}H_{61}I} \qquad (10)$$

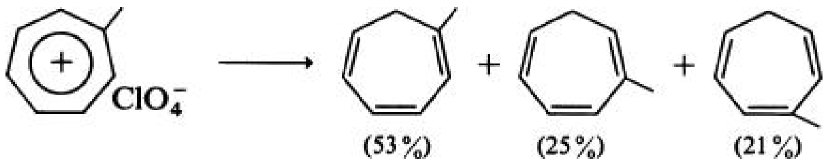
The asymmetric reduction of 6-methyl-6-phenylfulvene by the chiral $LiAlH_4$–(–)-quinine reagent (Eq. 11) is the first step in the preparation of



(11)

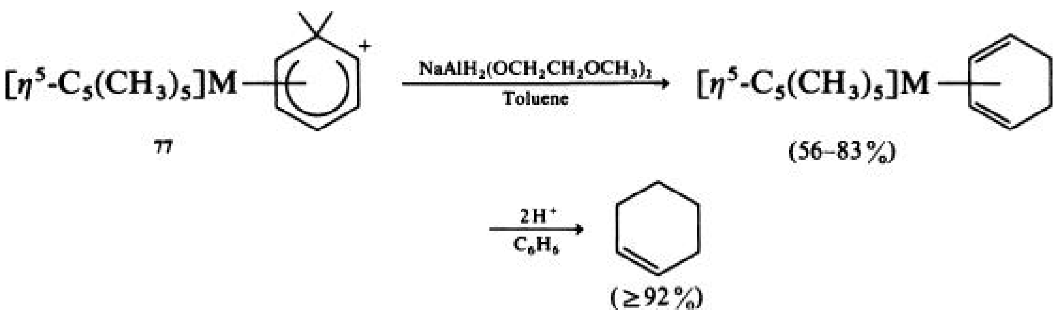
optically active titanocene complexes. (343) The *exo* double bond in 6,6-dimethylfulvene is not reduced by $LiAlH(OC_4H_9\text{-}t)_3$. (344)

The reduction of methyltropylium perchlorate with $LiAlH(OC_4H_9\text{-}t)_3$ affords a mixture of 1-, 2-, and 3-methyltropylidenes free of the 7-isomer (Eq. 12), in contrast to reductions with $LiAlH_4$, $NaBH_4$, or diphenylstannane. (345)



(12)

Reaction of $NaAlH_2(OCH_2CH_2OCH_3)_2$ with the η^5-cyclohexadienyl complex **77** (M = Rh, Ir) under forcing conditions represents one step in the selective reduction of benzene to cyclohexene involving regeneration and recycling of the initial complex. (346)



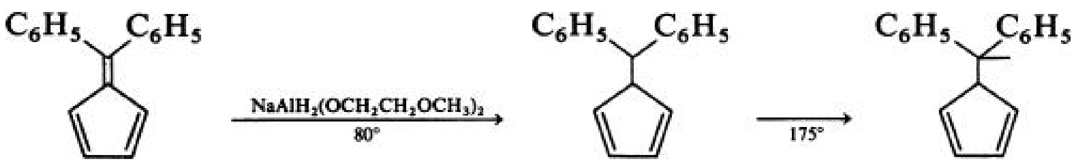
The lithium alkoxyaluminohydride resulting from interaction of $LiAlH_4$ with 2-(2-ethoxyethoxy)ethanol reduces acenaphthylene to acenaphthene in high yield. (35)

3.1.1.2. Reduction of Aryl-Conjugated Double Bonds with Methylation

$NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces double bonds with selective methylation at the more highly arylated carbon atom. The methyl group originates from the hydride methoxyl group. For example, 1,1-diphenylethylene (**78**, R = H)

$$\underset{\mathbf{78}}{(C_6H_5)_2C{=}CHR} \longrightarrow [(C_6H_5)_2CHCH_2R] \longrightarrow (C_6H_5)_2C(CH_3)CH_2R$$

and 1,1,2-triphenylethylene (**78**, R = C_6H_5) are converted into 2,2-diphenylpropane and 1,2,2-triphenylpropane, respectively, in excellent yields by reaction with this hydride at 140–180°. Reduction of 6,6-diphenylfulvene at 80° gives isomeric 5-(diphenylmethyl)cyclopentadienes; at higher temperatures 5-(1,1-diphenylethyl)cyclopentadienes are formed (Eq. 13). Reductive cleavage



(13)

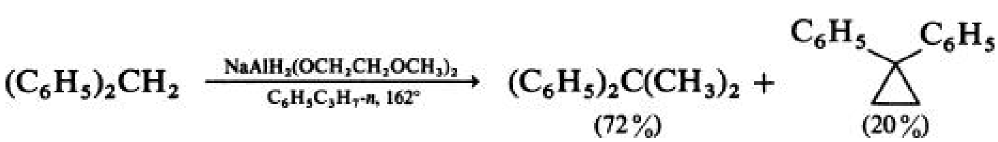
of carbon — carbon bonds occurs in the reductive methylation of the diene **79** with $NaAlH_2(OCH_2CH_2OCH_3)_2$ in *p*-cymene: 2,2-diphenylpropane along

$$\underset{\mathbf{79}}{(C_6H_5)_2C{=}CHCH{=}C(C_6H_5)_2} \xrightarrow{180^\circ} \underset{(50\%)}{(C_6H_5)_2C(CH_3)_2} + \underset{(6\%)}{(C_6H_5)_2C(CH_3)C_2H_5}$$

with a minor amount of 2,2-diphenylbutane and polymer are formed rather than the expected 2,2,5,5-tetraphenylhexane. (208)

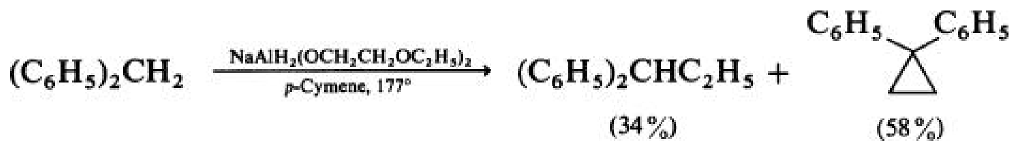
3.1.1.3. Methylation of Aryl-Activated Alkanes with $NaAlH_2(OCH_2CH_2OCH_3)_2$

Alkanes such as triarylmethanes or condensed aromatic hydrocarbons containing activated methylene groups can be methylated by reaction with $NaAlH_2(OCH_2CH_2OCH_3)_2$. In the reaction of diphenylmethane, the dimethylated product is accompanied by a minor amount of 1,1-diphenylcyclopropane (Eq. 14). (204, 206) 1,1-Diphenylpropane reacts with the same hydride to



(14)

give 2,2-diphenylbutane as the sole product. Another course of reaction is observed when the methoxyl groups in the hydride are replaced by ethoxyl groups (Eq. 15). (204) These reactions, particularly the reductive methylation and



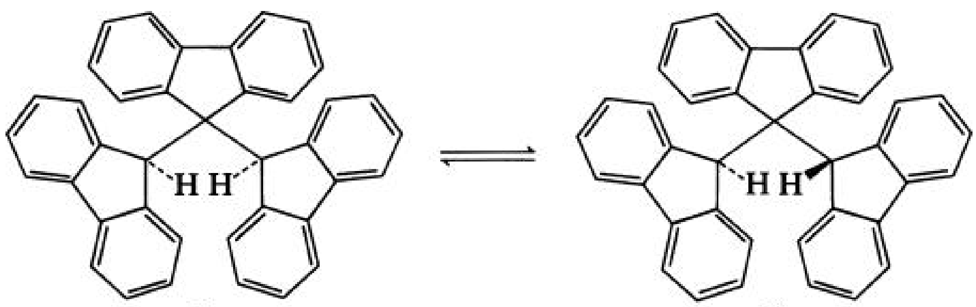
(15)

monoethylation, which proceed with high regioselectivity, are useful alternatives to reductive alkylation by lithium in ammonia and alkyl halides (347) or to methylation by $LiAlH_4$ in methyl ethers. (348-351)

3.1.1.4. Isomerization and Dehydrogenation of Aromatic Hydrocarbons

β -Methylstyrene isomerizes to allylbenzene (25%) in a base-catalyzed reaction with $NaAlH_2(OCH_2CH_2OCH_3)_2$. (352)

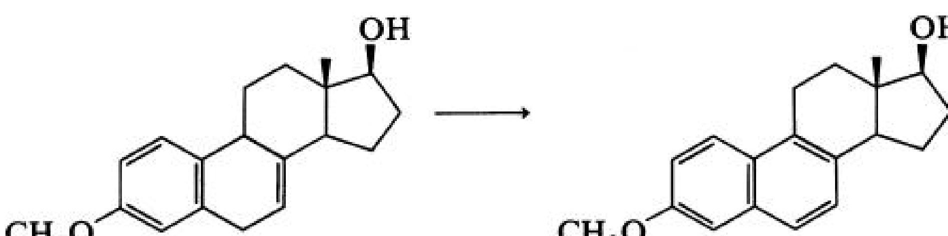
s-cis,s-cis-9,9¢:9¢,9²-Terfluorenyl (**80**) is isomerized, presumably by way of the 9-sodium derivative, to *s-cis,s-trans*-9,9¢:9¢,9²-terfluorenyl (**81**) (23%) as the major product on treatment with



80 81

$NaAlH_2(OCH_2CH_2OCH_3)_2$ in benzene; $LiAlH_4$ gives the isomer **81** in 36% yield. Reverse isomerization of **81** to **80** (13%) by $NaAlH_2(OCH_2CH_2OCH_3)_2$ is attributed to the high basicity of the hydride; in this case, $LiAlH_4$ gives only a small amount of 9,9¢-bifluorenyl. (353, 354)

$NaAlH_2(OCH_2CH_2OCH_3)_2$ can act as a dehydrogenating agent capable of transforming, for instance, the 1,3,5(10),7-estratetraene derivative **82** into the conjugated 1,3,5(10),6,8-estrapentaene **83**. (355-357)

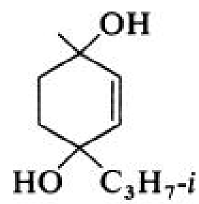


82 83

(73%)

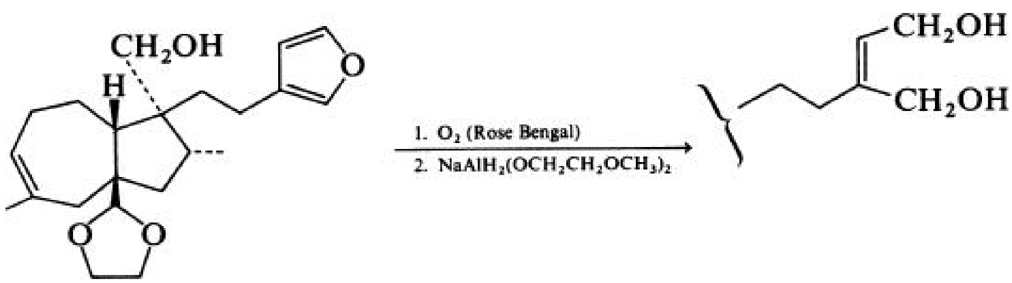
3.2. Reduction of Peroxides and Ozonides

1,3-Octadiene polyperoxide is reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ to 3,4-dihydroxy-1-octene, 1,2-dihydroxy-3-octene, and 1,4-dihydroxy-2-octene as the major products. Ascaridole, a transannular terpenic peroxide, reacts readily with the same hydride to give 1,4-dihydroxy-*p*-menthene (**84**) in 93% yield; (358) $LiAlH_4$ affords only 47% of the diol **84**, (359) and $NaBH_4$ does not



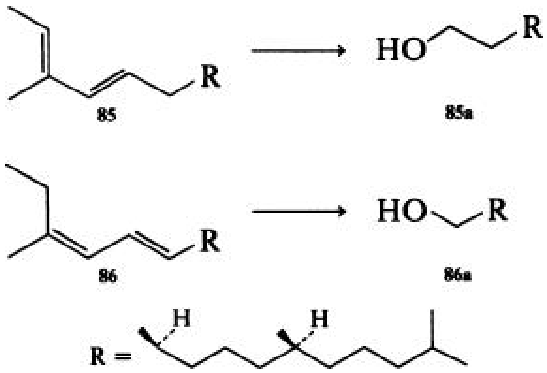
84

react with the peroxide. (360) Sensitized photooxidation of a furan derivative followed by hydride reduction produces an unsaturated diol (Eq. 16). (361, 362)

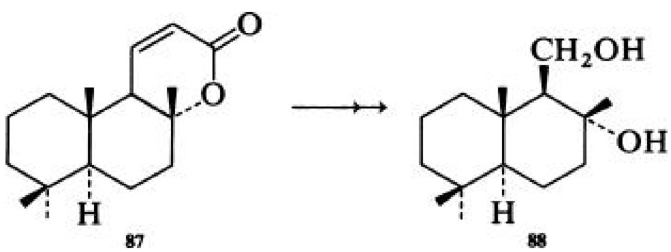


(16)

Ozonolysis of a mixture of 2,4-phytadiene (**85**) and 3,5-phytadiene (**86**) and subsequent reduction of the crude ozonides by $NaAlH_2(OCH_2CH_2OCH_3)_2$ leads to (3*R*,7*R*)-3,7,11-trimethyl-1-dodecanol (**85a**) and (2*R*,6*R*)-2,6,10-trimethyl-1-undecanol (**86a**). (363) Hexamethylcyclobutene ozonide undergoes reduction by $LiAlH_4$–(–)-1,4-bis(dimethylamino)-(2*S*,3*S*)-2,3-butanediol to



yield *meso*- and *dl*-3,3,5,5-tetramethyl-2,5-hexanediol in a 40:60 ratio; $LiAlH_4$ gives both products in a ratio of 91:9. (315) Ozonolysis of (+)-Δ^{11}-ambreinolide



(**87**) and reduction of the ozonide by $NaAlH_2(OCH_2CH_2OCH_3)_2$ produces (+)-8,11-dihydroxydrimane (**88**) in 85% overall yield; racemic **87** affords 87% of racemic **88**. (364)

3.3. Reduction of Halogen Compounds

Two areas of application of metal alkoxyaluminum hydrides can be distinguished in the great number of reactions with halogenated polyfunctional compounds: (a) preservation of the carbon — halogen bond with reduction of one or more functional groups by a less reactive and more selective alkoxyhydride and (b) reductive displacement of halide by using an alkoxyhydride with higher reducing power than $LiAlH_4$.

The reducing capability of $LiAlH(OCH_3)_3$ for haloalkanes is comparable with that of $LiAlH_4$ only in reductions of 1-iodoalkanes. Hydrogenolysis of 1-bromooctane is substantially slower, and that of 1-chlorooctane is incomplete even after 24 hours with use of the former hydride; $LiAlH(OC_4H_9\text{-}t)_3$ is far less reactive than $LiAlH(OCH_3)_3$ and does not react with 1-chlorooctane (365) or benzyl chloride. (40) The inertness of the carbon — chlorine bond toward lithium *tert*-butoxyaluminum hydrides (365) at ambient or lower temperatures permits selective reduction of the carbonyl group in chloroaldehydes. (40, 366) The capability of sodium alkoxyaluminum hydrides and alkoxyaluminum hydrides to transform 1-chloro- and 1-bromoalkanes into alkanes increases in the series

$NaAlH(OC_2H_5)_3$ [54,55]

< $NaAlH[OCH_2CH_2N(CH_3)_2]_3$ [367]

< $Al_2H_3(OCH_2CH_2OCH_3)_3$ [368]

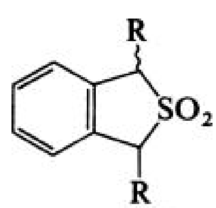
< $NaAlH_2(OCH_2CH_2OCH_3)_2$ [62,133,369,370]

< $NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$ [371]

< $NaAlH(OCH_3)(OCH_2CH_2OCH_3)_2$ [372]

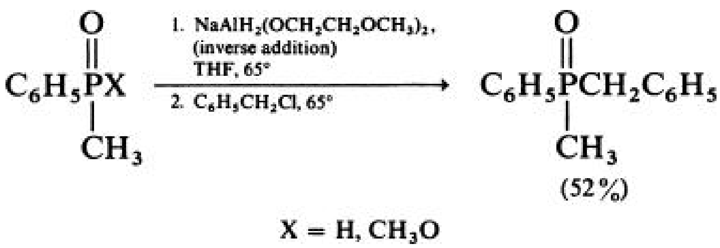
< $NaAlH(OH)(OCH_2CH_2OCH_3)_2$. [372]

A chloromethyl group is readily reduced to a methyl group by $NaAlH_2(OCH_2CH_2OCH_3)_2$; for instance, reductive dechlorination of 1,3-dihydro-1,3-bis(chloromethyl)benzo[*c*]thiophene 2,2-dioxide (**89**) by this hydride in refluxing benzene gives the 1,3-dimethyl derivative **90** in 91% yield. (373)



89:R = CH_2Cl
90:R = CH_3

The reactivity of $NaAlH_2(OCH_2CH_2OCH_3)_2$ in the dehalogenation of bromoalkanes, α , ω -dibromoalkanes, benzyl chloride, (370) *ortho*-substituted benzyl bromides, and *o*-xylylene dibromide at 65–135° has found an interesting application in a novel type of carbon — phosphorus bond formation (Eq. 17). (374-379) The procedure gives products in only moderate yields, but it is experimentally simple compared with other methods. (374, 375, 379)



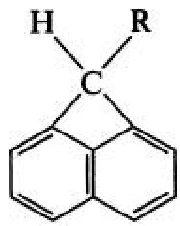
(17)

$NaAlH(OH)(OCH_2CH_2OCH_3)_2$ and $NaAlH(OCH_3)(OCH_2CH_2OCH_3)_2$ are both more powerful than $NaAlH_2(OCH_2CH_2OCH_3)_2$ in the reductive displacement of alkyl halides; a rapid reaction of 1-bromoheptane with these hydrides affords about 98% of *n*-heptane. (372)

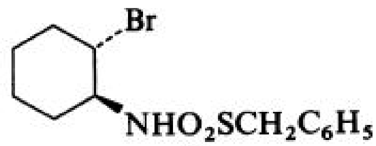
Secondary alkyl halides are usually less reactive than the primary halides. Reduction of 2-bromoheptane by $NaAlH_2(OCH_2CH_2OCH_3)_2$ gives 64% of *n*-heptane compared to 81% obtained from 1-bromoheptane under identical conditions. (369, 370)

Selective reduction of a carbonyl group in polycyclic fluoro, (380) chloro, (381, 382) and bromo ketones (383-388) with $LiAlH(OC_4H_9\text{-}t)_3$ has found wide synthetic application. The attractive feature is the preservation of the bromine configuration on the ring in cyclic α -bromo ketones, contrasting with epimerization of the bromine atom in the presence of $NaBH_4$ or other hydrides. (383, 384, 387, 388) Treatment of 3 α -bromo-1-methyl-*cis*-bicyclo[4.4.0]-2-decanone with $LiAlH(OC_4H_9\text{-}t)_3$ thus produces the corresponding 3 α -bromo-2 α alcohol free of the 3 β -bromo isomer. (389)

$NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces *gem*-dihalocyclopropanes in refluxing benzene to give preferentially *anti* or *trans* monohalides accompanied by variable quantities of the corresponding hydrocarbons. (390-392) Reduction of the tricyclic monobromide **91** by $NaAlH_2(OCH_2CH_2OCH_3)_2$ in diethyl ether gives more than 80% of 1,8-methanonaphthalene (**92**). (393) However, debromination of *trans*-2-bromo-1-benzylsulfonamidocyclohexane (**93**) by the



91: R = Br
92: R = H



93

same hydride is accompanied by removal of the sulfonyl group (352) and yields cyclohexylamine. (394)

In the reduction of vicinal dihalides, hydrogenolysis competes with elimination. Treating of 1,2-dibromoheptane with $NaAlH_2(OCH_2CH_2OCH_3)_2$ produces 1-heptene (74%) as the major product along with 2-bromoheptane (16%) and *n*-heptane (3%); reduction of 1,2-dibromocyclohexane yields 42% of cyclohexene. (370)

Chlorobenzene is inert toward $AlH(OC_2H_5)_2$, $AlH(OC_4H_9\text{-}n)_2$, (87) $Al_2H_3\text{-}(OCH_2CH_2OCH_3)_3$, (368) $NaAlH(OC_2H_5)_3$, (54) $NaAlH[OCH_2CH_2\text{-}N(CH_3)_2]_3$, (367) or $NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$. (371) $LiAlH_2(OC_2H_5)_2$, $LiAlH_4$, and $NaAlH_2(OCH_2CH_2OCH_3)_2$ are effective reagents for replacing fluorine atoms by hydrogen in trichlorotrifluorobenzene. (395) Reduction of *p*-bromotoluene in refluxing tetrahydrofuran with $LiAlH_4$ or $LiAlH_2(OCH_3)_2$ produces 7% and 59% of toluene, respectively. Use of the latter hydride in place of $LiAlH_4$ under otherwise identical conditions for reduction of 8-bromo-1-naphthylmethanol increases the yield of the debrominated product from 19 to 77%. 396a The generally low rate of dehalogenation of aromatic halides can be markedly improved by using $NaAlH_2(OCH_2CH_2OCH_3)_2$, (370, 397, 398) or even better, $NaAlH(OCH_3)(OCH_2CH_2OCH_3)_2$ at elevated temperatures. Reduction of bromobenzene by the latter hydride in refluxing xylene (1 hour) yields 99% of benzene, (372) whereas $LiAlH_4$ gives only 24% of benzene at 100° for 24 hours; 396a reduction of 3-bromochlorobenzene with $NaAlH(OCH_3)\text{-}(OCH_2CH_2OCH_3)_2$ affords 94% of chlorobenzene. (372) The yields of dehalogenated products in $LiAlH_4$ reductions can be increased by using either homogeneous hydride solutions in tetrahydrofuran 396b or ultrasonic waves and heterogeneous hydride–halide mixtures. 396c In the presence of catalytic amounts of bis-(phenylcyano)palladium dichloride, $NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces 1-chloronaphthalene nearly quantitatively to naphthalene; fluorobenzene gives only 12% of benzene. The bis(benzylcyano)palladium dichloride-assisted reduction of bromobenzene and chlorobenzene by $NaAlH_2(OCH_2\text{-}CH_2OCH_3)_2$ yields approximately 100% and 52% of benzene, respectively. (397, 399) By comparison, the $LiAlH_4$– $NiCl_2$

complex effects essentially quantitative conversion of chlorobenzene to benzene. (400)

$NaAlH_2(OCH_2CH_2OCH_3)_2$ is a reagent of choice for converting 1,1-difluoroalkenes $RR^1C=CF_2$ (R = alkyl, C_6H_5; R^1 = H, CH_3) to monofluoro derivatives $RR^1C=CHF$ (predominantly *trans*) in 78–96% yields. (401) The relatively high stability of the chloroallyl group toward $LiAlH(OCH_3)_3$ at low temperatures makes it possible to reduce the keto group in α -(β -chloroallyl)deoxybenzoin with high stereoselectivity. (402, 403)

Whereas reduction of bromoalkynes RC ≡ CBr [R = C_6H_5, CH_3OCH_2, $(C_2H_5)_2NCH_2$, $CH_2=C(CH_3)$, $HOCH_2$, $CH_2=CHC(OH)(CH_3)$, $(CH_3)_2C(OH)$, $(CH_3)_2C(OH)CH_2$] by $LiAlH_4$ gives mixtures of the debrominated alkynes, alkenes, and alkanes, the $LiAlH_4$– $AlCl_3$ complex produces 40–60% of the *trans* alkenes RCH = CH; $NaAlH_2(OCH_2CH_2OCH_3)_2$ gives the alkynes RC ≡ CH as the major products. (404) Reduction of (*R*)-(+)-2-bromo-3-decyne with $LiAlH_4$ yields 3-decyne (75%) along with small amounts of 2,3-decadiene; $LiAlH(OCH_3)_3$ gives, in addition to 23% of 3-decyne, 54% of nearly racemic 2,3-decadiene, and AlH_3 affords (*S*)-(+)-2,3-decadiene (25–74%) in 45–53% enantiomeric excess. (405)

Complex hydrides useful for the reductive displacement of organic halides have been discovered; their effectiveness has been compared in several papers and reviews. 121,122,130,134,365,396b,406–410 Lithium triethylborohydride (“Super Hydride”) arising from interaction of $LiAlH(OC_4H_9\text{-}t)_3$ with triethylborane reduces simple primary alkyl bromides such as 1-bromooctane completely in 2 minutes; allylic and benzylic bromides are reduced almost instantly. Bromocyclooctane gives 99% of cyclooctane. Nearly the same effect can be achieved by using lithium hydride in the presence of catalytic amounts of triethylborane; bromocyclohexane thus gives 95% of cyclohexane, and bromocycloheptane yields cycloheptane almost quantitatively. (365, 411)

The complex formed from $LiAlH(OCH_3)_3$ and copper(I) iodide reduces primary alkyl chlorides; primary and secondary alkyl bromides; neopentyl, allyl, vinyl, cycloalkyl, and aryl bromides; and 9,9-dibromobicyclo[6.1.0]-nonane to the corresponding hydrocarbons in 85–100% yields; the reactions are complete at room temperature in less than 2.5 hours. Although chlorides require longer reaction times and an excess of the reagent, hydrocarbon yields >90% are obtained. (412)

The complex $LiCuH(C_4H_9\text{-}n)$ reacts with 2-bromononane, 1-bromoadamantane, or 1-bromonaphthalene to give the corresponding hydrocarbons in 70–95% yield and does not attack the ester group in bromoesters. (413)

3.4. Reactions of Active Hydrogen Compounds

Primary, secondary, and tertiary alcohols, thiols, phenols and primary or secondary amines react rapidly with $LiAlH(OCH_3)_3$ (30, 46) and $NaAlH_2(OCH_2CH_2OCH_3)_2$ (72, 133, 191, 361, 372) with evolution of the theoretical amount of hydrogen. In contrast to 1-hexanethiol, benzenethiol evolves very rapidly one equivalent of hydrogen in contact with $LiAlH(OC_4H_9\text{-}t)_3$. (30, 414)

3.4.1.1. Reduction of Unsaturated Alcohols

The rate of hydrogen liberation and formation of alcoholates in reactions of α -allenic, β -allenic, and α -vinylallenic alcohols with $LiAlH_3(OCH_3)$ and $LiAlH_4$ appears to coincide with the overall rate of reduction; primary and secondary alcohols react more rapidly than the tertiary and sterically hindered alcohols. The course of partial reductions of α -allenic alcohols (2,3-alkadien-1-ols) by these hydrides (see pp. 9–10) depends on the structure of the starting alcohol and the nature of the hydride used. An example of stereospecific reaction forming a homoallylic alcohol (3-alkenol) exclusively in the *trans* configuration along with stereoisomeric dienes is given by Eq. 18. (214)

$$CH_3CH{=}C{=}CHC(CH_3)_2OH \xrightarrow{LiAlH_3(OCH_3)} \underset{trans\ (43\%)}{CH_3CH{=}CHCH_2C(CH_3)_2OH} + \underset{(54\%)}{CH_3CH{=}CHCH{=}C(CH_3)_2} \quad (18)$$

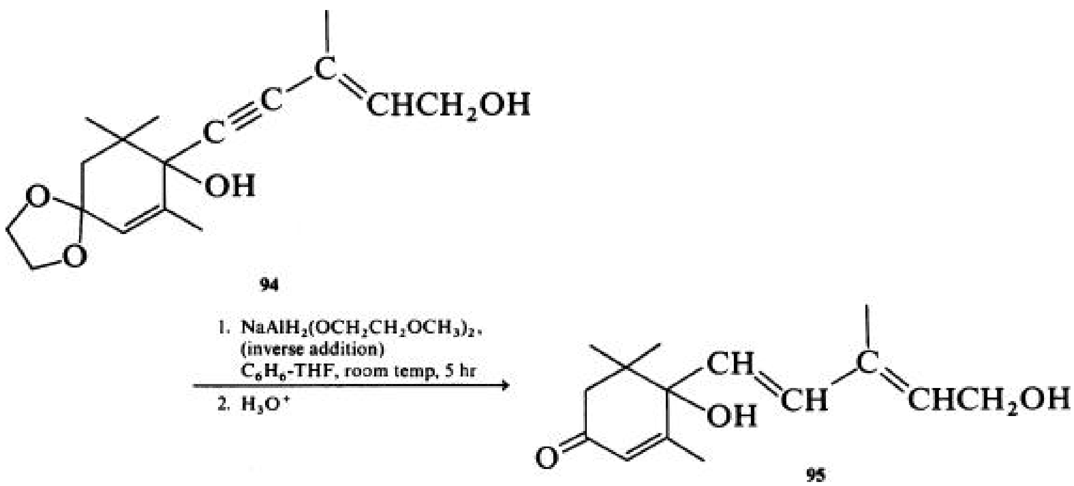
α -Vinylallenic alcohols (2,4,5-alkatrien-1-ols) undergo partial reduction by $LiAlH_3(OCH_3)$ or $LiAlH_4$ to yield 3,5-alkadien-1-ols (0–70%) and 1,3,5-alkatrienes (29–81%). Two examples of stereospecific reactions in this series are: (214)

$$(CH_3)_2C{=}C{=}CHCH{=}CHCOH(C_6H_5)CH_3 \xrightarrow{LiAlH_3(OCH_3)} \underset{cis\ \ (47\%)}{(CH_3)_2C{=}CHCH{=}CHCH_2COH(C_6H_5)CH_3} + \underset{(51\%)}{(CH_3)_2C{=}CHCH{=}CHCH{=}C(C_6H_5)CH_3} \quad (19)$$

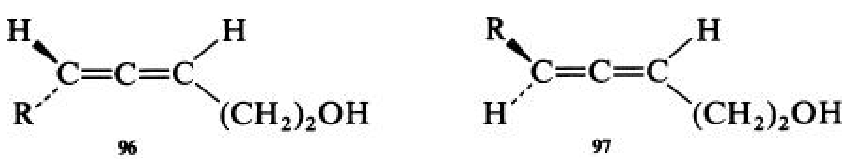
$$t\text{-}C_4H_9C(CH_3){=}C{=}CHCH{=}CHCOH(CH_3)C_4H_9\text{-}t \xrightarrow{LiAlH_3(OCH_3)} \underset{3\text{-}cis,5\text{-}cis,7\text{-}trans}{t\text{-}C_4H_9C(CH_3){=}CHCH{=}CHCH{=}C(CH_3)C_4H_9\text{-}t} \quad (20)$$

In the reaction of β -allenic alcohols (3,4-alkadien-1-ols) with $LiAlH_4$ or $LiAlH_3(OCH_3)$ (see p. 10), no polyene hydrocarbons are formed as byproducts. (214)

$NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces α -acetylenic alcohols to *trans*-allylic alcohols with high selectivity. Addition of this hydride to (4*S*, 6*R*)-(–)-6,10-dimethyl-2-undecyn-4-ol gives 84% of (4*S*, 6*R*)-(–)-*trans*-6,10-dimethyl-2-undecen-4-ol free of the *cis* isomer; $LiAlH_4$ gives the *trans* product in lower yield. (415) With the use of $NaAlH_2(OCH_2CH_2OCH_3)_2$, the *cis*-2-en-4-yne-1,6-diol **94** can be converted into the *cis*-2-*trans*-4-diene-1,6-diol **95** isolated after deketalization in 69% yield. (416)



Asymmetric reduction of 2-alken-4-yn-1-ols by the $LiAlH_4$–monosaccharide complex **68a** has been shown to give (*R*)-(–)- β -allenic alcohols **96** in excess. (417-420) By contrast, (*S*)-(+)- β -allenic alcohols **97** predominate in the

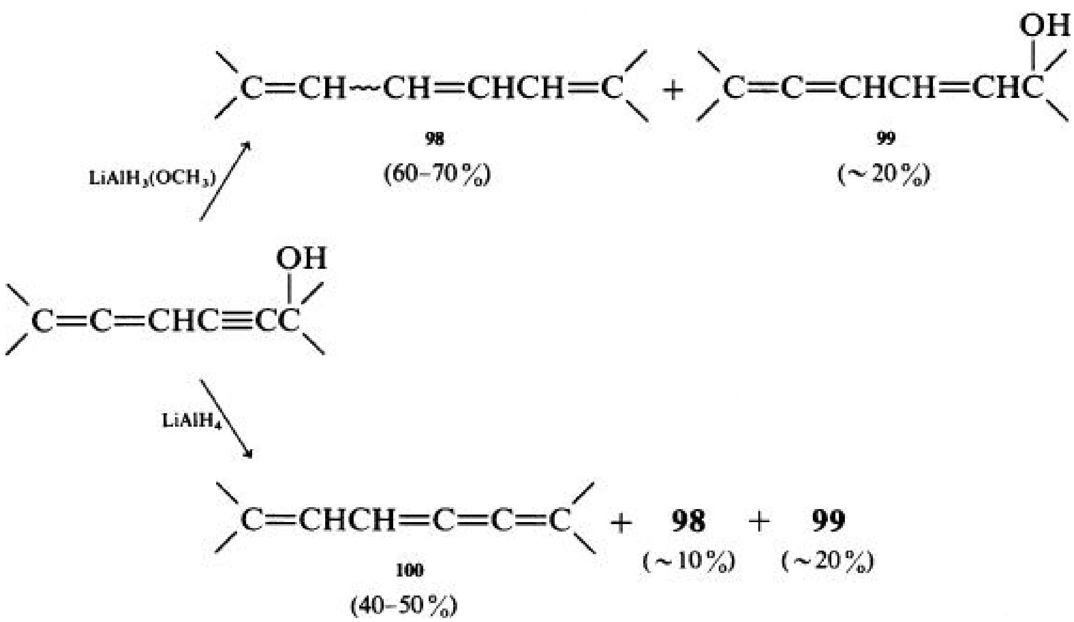


R = alkyl

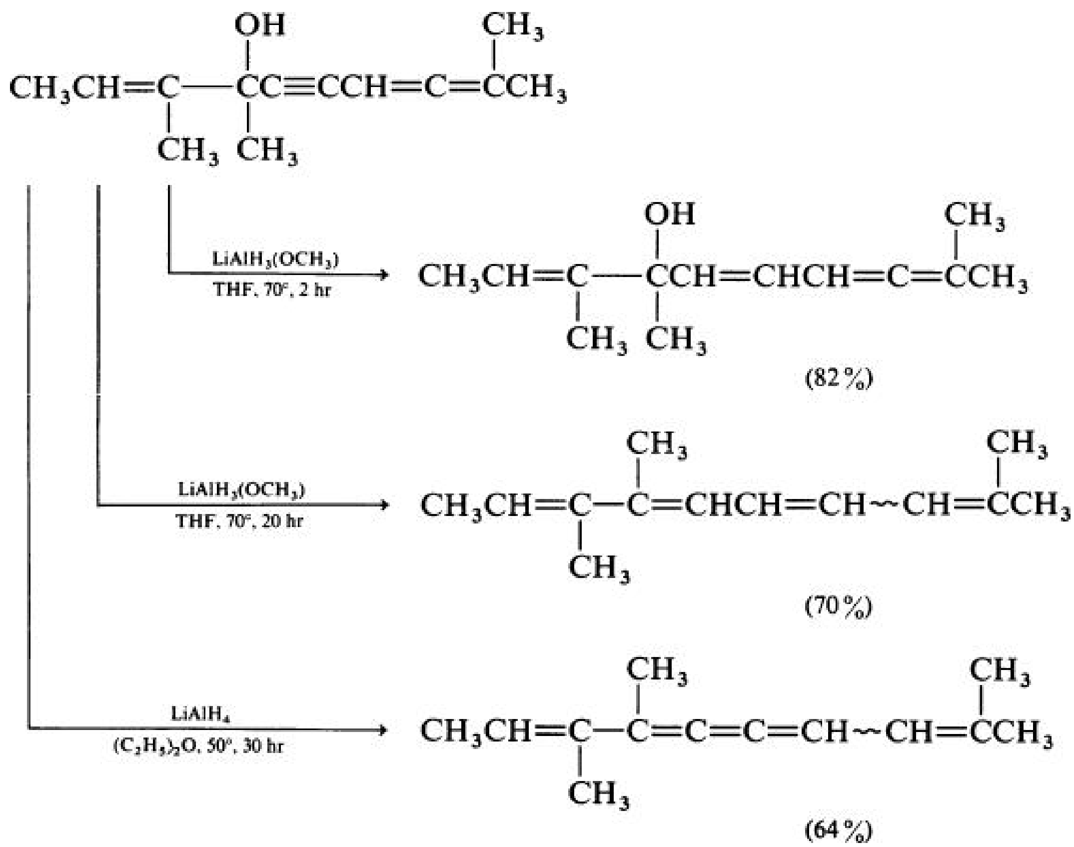
enantiomer mixture resulting from the reduction of 2-alken-4-yn-1-ols with $LiAlH_4$-(–)–menthol (1:2). (421, 422) *trans*- α -Vinylallenic alcohols (2,4,5-alkatrien-1-ols) are easily accessible in up to 90% yields by contacting 4,5-alkadien-2-yn-1-ols with $LiAlH_3(OCH_3)$; 1,3,5-alkatrienes are formed as byproducts. (423) This method has been used for the preparation of a vinylallenic pheromone, *trans*-2,4,5-tetradecatrien-1-ol (Eq. 21). (424) Prolonged treatment of 4,5-alkadien-2-yn-1-ols with

$$n\text{-}C_8H_{17}CH{=}C{=}CHC{\equiv}CCH_2OH \xrightarrow[\text{THF, 70°, 90 min}]{LiAlH_3(OCH_3)} \underset{(80\%)}{n\text{-}C_8H_{17}CH{=}C{=}CHCH{=}CHCH_2OH} \quad (21)$$

$LiAlH_3(OCH_3)$ leads to 1,3,5-alkatrienes **98** as major products accompanied by minor quantities of *trans*- α -vinylallenic alcohols **99**; $LiAlH_4$ is less selective producing mixtures of 1,2,3,5-alkatetraenes (vinylcumulenes) **100**, *trans*- α -vinylallenic alcohols **99**, and 1,3,5-alkatrienes **98**; (423) (see, however, Ref. 425).

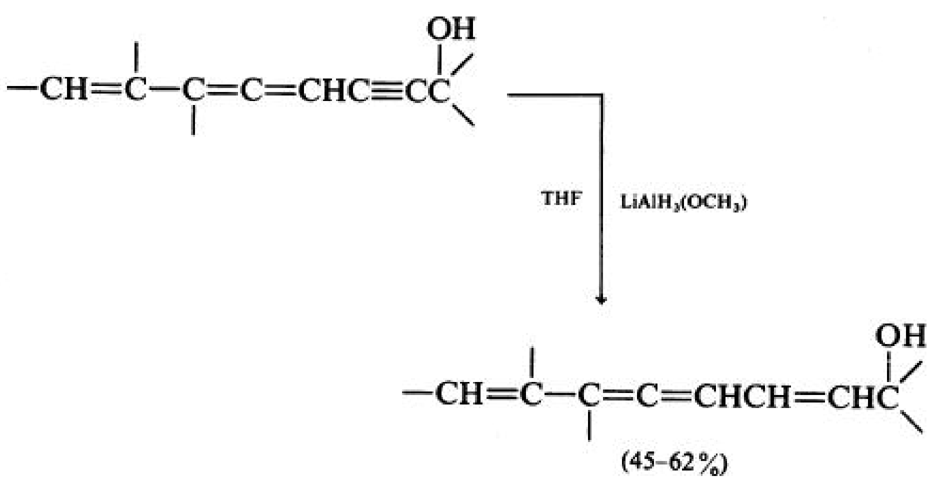


The transformation of 1,6,7-alkatrien-4-yn-3-ols by use of $LiAlH_4$ or $LiAlH_3(OCH_3)$ can be similarly oriented to one of the three possible products by proper choice of reaction conditions. As illustrated by Eq. 22, 3,4,9-trimethyl-2,7,8-decatrien-5-yn-4-ol

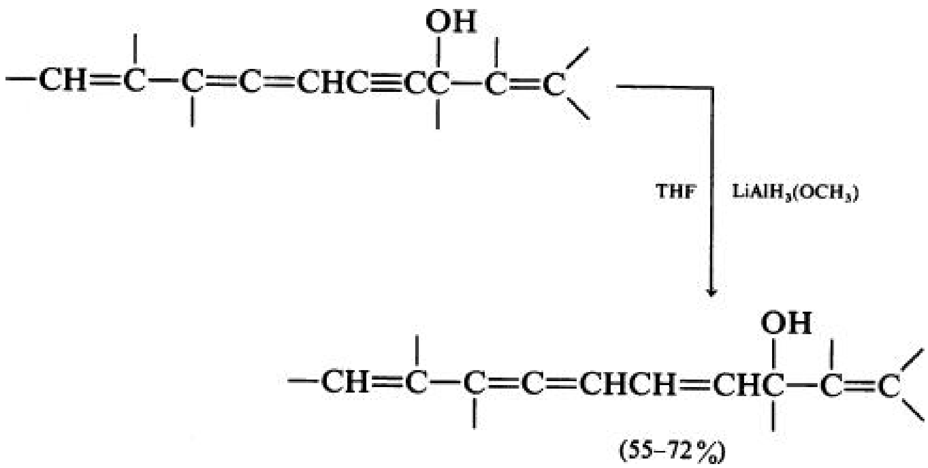


(22)

can be converted preferentially to the *trans*-tetraenol, to the unstable isomeric tetraenes, or to isomeric pentaenes (divinylcumulenes). The method used for the selective reduction of the triple bond in 1,6,7-alkatrien-4-yn-3-ols can also be applied to the unsaturated homologs. Thus $LiAlH_3(OCH_3)$ reduces 4,5,7-alkatrien-2-yn-1-ols to the fragile 2,4,5,7-alkatetraen-1-ols (Eq. 23), and 1,6,7,9-alkatetraen-4-yn-3-ols to 1,4,6,7,9-alkapentaen-3-ols (Eq. 24). (423)

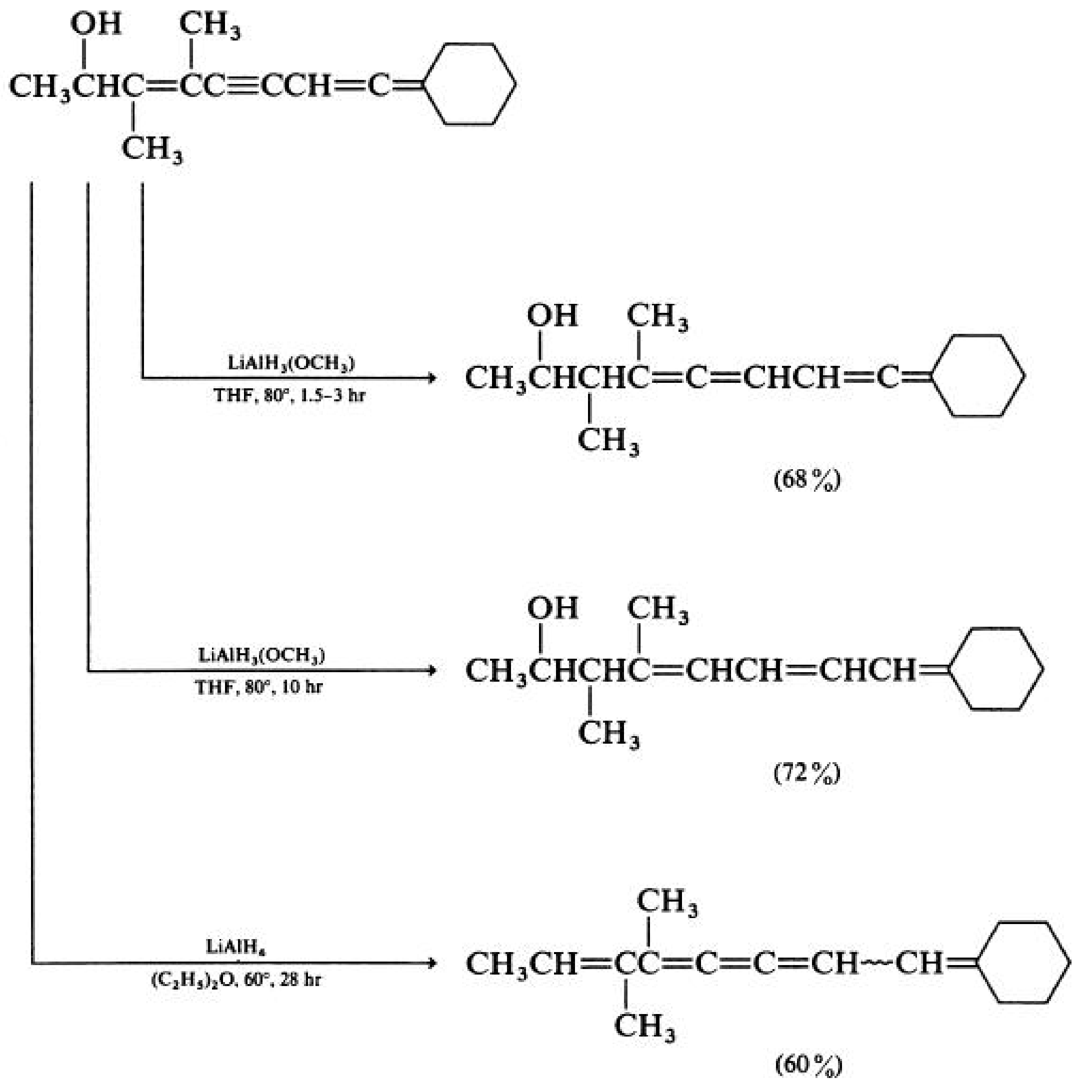


(23)



(24)

The partial reduction of 2,6,7-alkatrien-4-yn-1-ols by $LiAlH_4$ and $LiAlH_3(OCH_3)$ constitutes a new approach to the 3,4,6,7-alkatetraen-1-ols (β -diallenic alcohols) (³78%); alternatively, 3,5,7-alkatrien-1-ols (0–75%) and/or 1,3,4,5,7-alkapentaenes (divinylcumulenes) (0–60%) can be obtained as the major products. Thus $LiAlH_3(OCH_3)$ is a more suitable reagent than $LiAlH_4$ for reductions of hindered 2,6,7-alkatrien-4-yn-1-ols to β -diallenic alcohols. The factors that control the formation of β -diallenic alcohols, alkatrienols, or divinylcumulenes are illustrated in Eq. 25. (426-428)



(25)

The reduction of 2-alkene-4,6-diyn-1-ols by $LiAlH_4$ gives 3,5,6-alkatrien-1-ols (allenenols) as the major products and minor amounts of 3,4-alkadien-6-yn-1-ols (allenynols); $LiAlH_2(OCH_3)_2$ and $LiAlH_2(OC_2H_5)_2$ exhibit higher selectivity and afford allenynols such as **101** in higher yield (Eq. 26). The

$$t\text{-}C_4H_9C{\equiv}CC{\equiv}CCH{=}CHCH_2OH \; (trans) \xrightarrow{LiAlH_2(OCH_3)_2} \underset{\mathbf{101}\ (54\%)}{t\text{-}C_4H_9C{\equiv}CCH{=}C{=}CH(CH_2)_2OH} + \underset{\mathbf{102}}{t\text{-}C_4H_9CH{=}CHCH{=}C{=}CH(CH_2)_2OH} \quad (26)$$

LiAlH$_4$–2,3-butanediol complex is less active but shows higher selectivity in giving **101** (14%) free of allenenol **102**. (429)

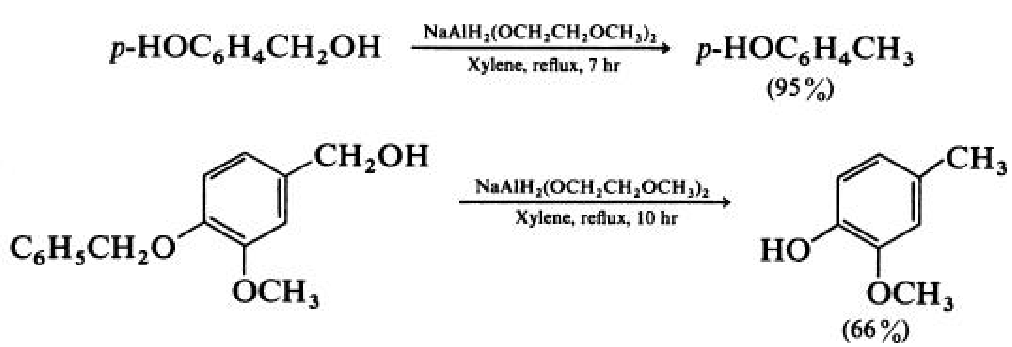
The 2-alkene-4,6,8-triyn-1-ol **103** can be reduced by LiAlH$_2$(OC$_2$H$_5$)$_2$ to yield 65% of a mixture containing 9% of *dl*-**104**, which is a racemic form of the naturally occuring (*R*)-marasin (Eq. 27); even though the yield of *dl*-marasin

$$\underset{\mathbf{103}}{HC{\equiv}CC{\equiv}CC{\equiv}CCH{=}CHCH_2OH} \xrightarrow{LiAlH_2(OC_2H_5)_2} HC{\equiv}CCH{=}CHCH{=}C{=}CH(CH_2)_2OH + CH_2{=}CHC{\equiv}CCH{=}C{=}CH(CH_2)_2OH + \underset{\mathbf{104}}{HC{\equiv}CC{\equiv}CCH{=}C{=}CH(CH_2)_2OH} \quad (27)$$

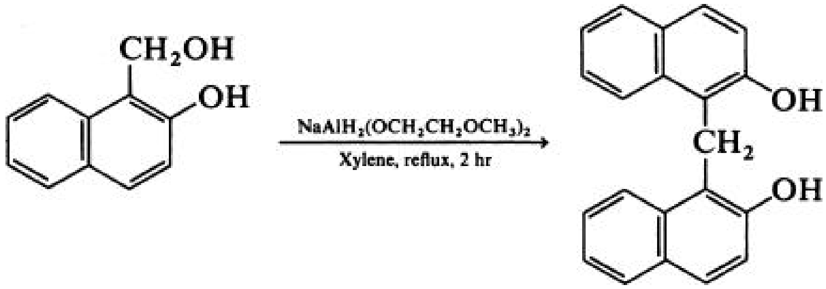
(**104**) is low, it is still 10 times as high as that obtained by the LiAlH$_4$ reduction. (429) Reaction of **103** with the LiAlH$_4$–monosaccharide complex **68a** produces (*R*)-(–)-marasin (12%) (417, 420)

3.4.1.2. Hydrogenolysis of Aromatic Alcohols

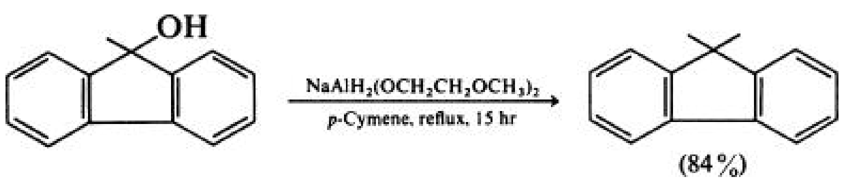
Benzyl alcohols substituted in the *ortho* or *para* position by electron-donor groups readily undergo hydrogenolysis on treatment with NaAlH$_2$(OCH$_2$CH$_2$OCH$_3$)$_2$ at 120–140° to give the corresponding *ortho*- or *para*-substituted toluenes. The reactivity of the hydride often parallels or is even higher than that of LiAlH$_4$– AlCl$_3$ or diborane in these reactions. (430-433)



Hydrogenolysis of 1-hydroxymethyl-2-naphthol (434) unexpectedly affords di-(2-hydroxy-1-naphthyl)methane. (435, 436) 2-Aminobenzyl alcohol is reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ to form *o*-toluidine (95%) at a rate more



than 30 times as high as that using $LiAlH_4$. (431) Benzyl alcohols with a tertiary amino group in the *ortho* or *para* position are less reactive than the corresponding derivatives with a primary amino group. (431, 437) Benzhydrols undergo rapid hydrogenolysis on treatment with $NaAlH_2(OCH_2CH_2OCH_3)_2$ at elevated temperatures, but the hydrogenolysis product reacts further to form hydrocarbons methylated at the benzylic carbon atom. (206-208) An unexpected



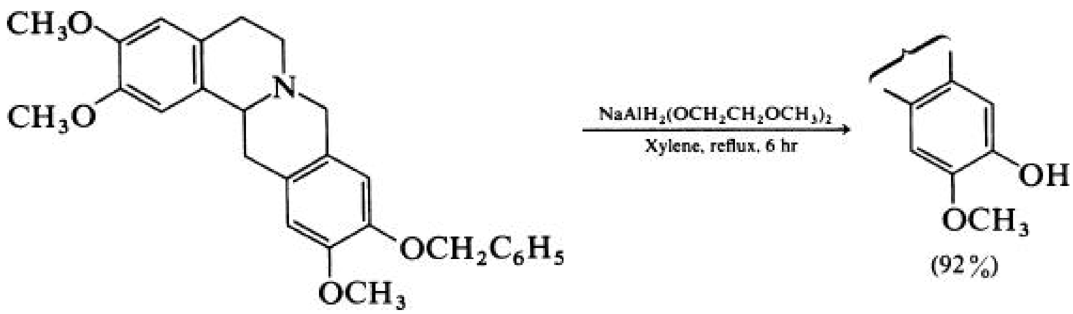
reaction course has been observed in the reaction of 3-phenyl-2-propen-1-ol with $LiAlH_2(OCH_3)_2$, which gives almost quantitatively phenylcyclopropane. (219)

3.5. Reductive Cleavage of Ethers

Dialkyl ethers, alkyl aryl ethers, diaryl ethers, and cyclic ethers are usually stable toward lithium and sodium alkoxyaluminum hydrides at temperatures below 100°. However, cleavage of the ether linkage accompanies reduction and hydrogenolysis of the aldehyde group in *o*-methoxybenzaldehyde and *p*-methoxybenzaldehyde by $NaAlH_2(OCH_2CH_2OCH_3)_2$ at 140°; *o*- and *p*-cresols are thus formed as byproducts (6–32%). *p*-Methoxytoluene alone gives 8% of *p*-cresol under the same conditions.

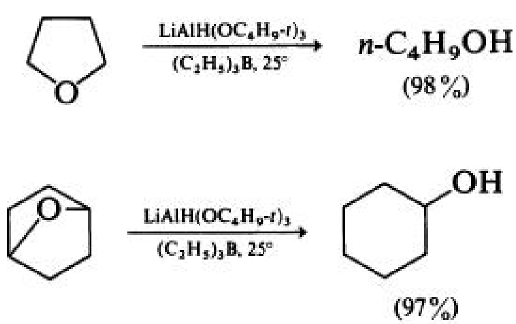
3,4-Methylenedioxybenzaldehyde is reduced readily by this hydride at 70° to give 98% of 3,4-methylenedioxybenzyl alcohol; however, a cleavage (21%) of the methylenedioxy group was observed at 143°; (432) (see also Refs. 348-351).

$NaAlH_2(OCH_2CH_2OCH_3)_2$ is a useful reagent for debenzylation and deallylation of aryl benzyl ethers and allyl aryl ethers at elevated temperatures. The reaction is markedly enhanced by a vicinal methoxyl group (Eq. 28). The


(28)

method is recommended for debenzylation and deallylation of phenolic ethers that are labile to acid or catalytic hydrogenolysis, (433) it also provides a useful alternative to the reductive cleavage of benzyl phenyl and allyl phenyl ethers by $LiAlH_4$ in the presence of cobalt or nickel salts (see pp. 45–46 in Ref. 27). Moreover, $LiAlH_4$ in refluxing benzene or heptane is an effective reagent for selective demethylation and debenzylation of methyl phenyl and benzyl phenyl ethers that have at least one additional ether function in the vicinity of the reaction site. (438)

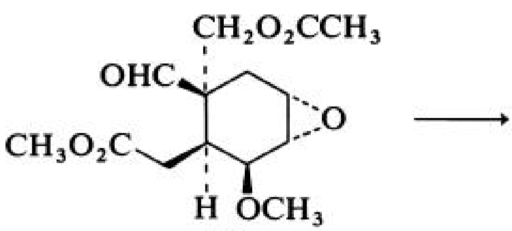
Addition of an equimolar or even catalytic amount of triethylborane to a solution of $LiAlH(OC_4H_9\text{-}t)_3$ in tetrahydropyran results in rapid formation of a reagent, presumably a lithium triethylborohydride–aluminum *tert*-butoxide complex, which is more effective than diborane or aluminum hydride in the cleavage of some cyclic ethers. Methyl *n*-alkyl ethers are less reactive;



diethyl ether, 2,2-dimethyltetrahydrofuran, tetrahydropyran, and oxepane undergo the reductive opening slowly, and 4,5-dihydro-2-methylfuran or anisole do not react at all. (439-442) Lithium bis(2,6-di-*tert*-butylphenoxy)-aluminum hydride can effect reductive cleavage of tetrahydrofuran to *n*-butyl alcohol on prolonged heating; lithium diphenoxyaluminum hydride does not cleave tetrahydrofuran. (171)

3.6. Reduction of 1,2-Oxides

1,2-Butylene oxide, 1,2-cyclohexene oxide, and styrene oxide all react relatively slowly with $LiAlH(OC_4H_9\text{-}t)_3$ (30) utilizing only 34, 7, and 9%, respectively, of the hydride after 1 hour at 0°; (414) 1-methyl-1,2-cyclohexene oxide requires 96 hours to attain 66% conversion. (30) Thus $LiAlH(OC_4H_9\text{-}t)_3$ is less effective than $LiAlH_4$, which reduces these oxides within 0.5–1 hour. (47, 443) This resistance of the 1,2-oxide ring toward $LiAlH(OC_4H_9\text{-}t)_3$ can be used for selective reduction of the more reactive formyl or keto groups in the presence of the 1,2-oxide group, (251) particularly in the alicyclic series. However, an unusual cleavage of the 1,2-oxide ring has been reported by Danishefsky and co-workers: (444) reduction of the aldehyde oxide **105** by $LiAlH(OC_4H_9\text{-}t)_3$ gives the hydroxy ester **106** as the major product and only lesser amounts of the expected lactone oxide **107**. Formation of the compound **106** has been attributed to an intramolecular oxide opening by the intermediate lithium alkoxide generated during reduction of the formyl group.



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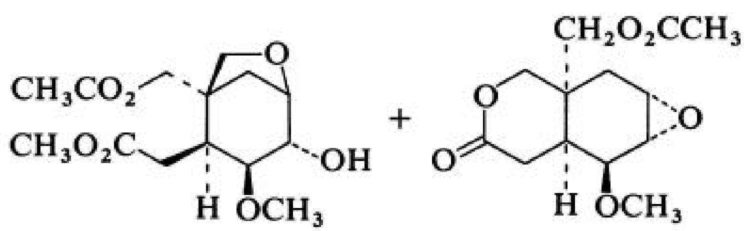
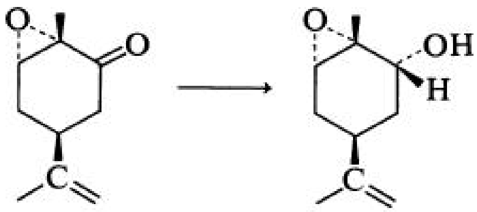


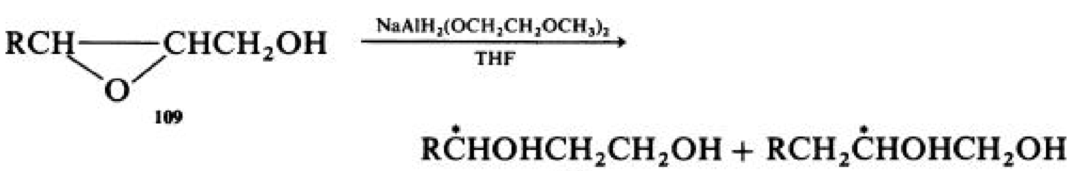
106 (46%) 107 (20%)

The reactivity of $LiAlH(OCH_3)_3$, measured by the rate of hydride utilization in reductions of 1,2-butylene oxide, 1,2-cyclohexene oxide, and styrene oxide, lies between that of $LiAlH(OC_4H_9\text{-}t)_3$ and $LiAlH_4$. (30, 46) An ester group can thus be reduced selectively by $LiAlH(OCH_3)_3$ in the presence of 1,2-oxide. (445) In the reaction with (+)-carvone oxide, however, $LiAlH(OCH_3)_3$ behaves similarly as $LiAlH_4$ and $NaBH_4$ and gives the hydroxy oxide **108**, along with four diols resulting from the cleavage of the oxide ring. (446)



108

Unsymmetrical 1,2-oxides are attacked by lithium or sodium alkoxyaluminum hydrides and some other strong nucleophilic hydride reagents predominantly at the least-substituted carbon atom to yield the more highly substituted alcohol as the major product (see, e.g., p. 53 in Ref. 27, p. 103 in Ref. 134, and p. 149 in Ref. 21a). (30, 46, 47, 443) $NaAlH_2(OCH_2CH_2OCH_3)_2$ yields a greater proportion of the secondary alcohol than does $LiAlH_4$ or $LiBH_4$ in the reduction of styrene oxide, 1,2-propylene oxide, and 1,2-butylene oxide. (447) Reductions with $LiAlH_4$ are, however, strongly solvent dependent. For instance, the ratio of 1-phenylethanol to 2-phenylethanol formed in the reduction of styrene oxide changes from 79 : 21 in benzene (447) to 95 : 5 in diethyl ether (448) and to 99 : 1 in tetrahydrofuran solution. (447) $NaAlH_2(OCH_2CH_2OCH_3)_2$ in boiling benzene gives both products in a ratio of 98 : 2, (447) and $LiAlH(OCH_3)_3$ affords 97% of a product containing 99% of 1-phenylethanol and 1% of the primary alcohol. (46) The $NaAlH_2(OCH_2CH_2OCH_3)_2$ reduction of hydroxy 1,2-oxides **109**, where R is an alkyl, cycloalkyl, aryl, or ethereal substituent alpha and/or beta to the oxide ring, produces almost exclusively the 1,3 diols **110**; 449a,449b,450a,450b thus the 1,3-diol **112a** can be prepared from



109

110

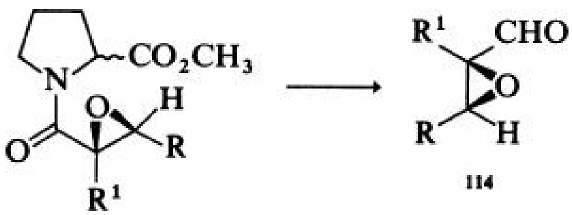
111a in greater than 99% isomeric purity. In contrast, diisobutylaluminum hydride gives preferentially the 1,2 diols; the 1,3 diol **112a** and its 1,2 isomer

111a: R = $C_6H_5CH_2$, R^1 = H
111b: R = $C_6H_5CH_2$, R^1 = CH_3
111c: R = H, R^1 = $C_6H_5CH_2$

112a:
R = $C_6H_5CH_2$, R^1 = H

can thus be obtained in a ratio of 7:93. 450b $LiAlH_9$ is substantially less stereoselective. 449a,449b,450b The high regioselectivity of the $NaAlH_2(OCH_2CH_2OCH_3)_2$ reductions appears to be determined by the presence of the hydroxyl group alpha to the 1,2-oxide ring, since the 1,2-oxide **111b** is recovered unchanged under the same conditions and the 1,2-oxide **111c** gives almost exclusively the corresponding 1,2 diol. 450b

Nevertheless, the 1,2-oxide ring can be preserved by using $NaAlH_2(OCH_2CH_2OCH_3)_2$ at 0°; reductive cleavage of the proline moiety in epoxyamides **113** (R, R^1 = alkyl, aryl) gives (2*R*,3*S*)- α , β-epoxyaldehydes

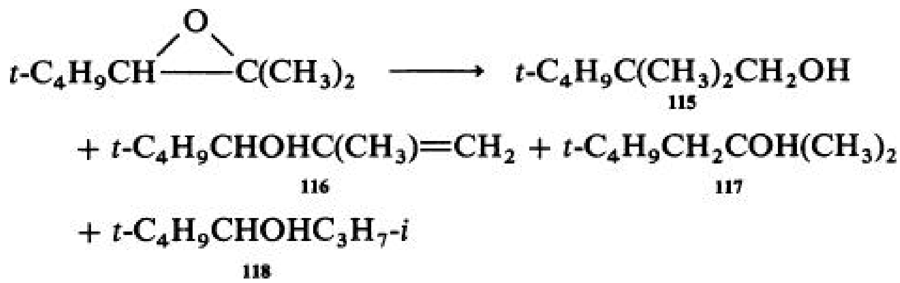


113

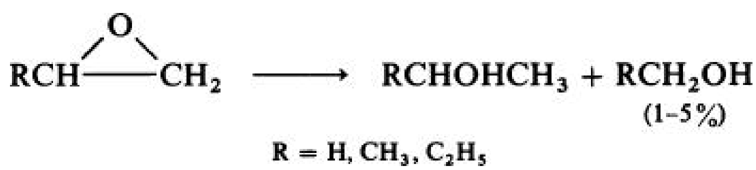
114

114 in up to 85% chemical and high optical yields (84 to ~100% e.e.). (451, 452) 1,2-Cyclooctatetraene oxide is not reduced by either $NaAlH_2(OCH_2CH_2OCH_3)_2$ in refluxing benzene or by $NaBH_4$ in methanol; $LiAlH_4$ produces a mixture of 3,5-cyclooctadien-1-ol and 2,4,6-octatrien-1-al. (453)

As shown by the reduction of β -diisobutylene oxide, alkoxyaluminum hydrides (100) are substantially less reactive than the “mixed hydrides” (24, 100, 454, 455) but more reactive than $LiAlH_4$; (100) the extent of oxide cleavage and the product distribution have been found to be a function of the Lewis acidity of the hydride reagent. However, increased Lewis acidity leads at the same time to increased formation of 2,2,3,3-tetramethylbutanol (**115**) resulting from the opening of the oxide ring and subsequent migration of the *tert*-butyl group (see pp. 55–56 in Ref. 27); thus AlH_3, H_2AlCl , and $HAlCl_2$ give product mixtures containing 5, 60, and 74% of the alcohol **115**, respectively. (24, 100, 455) On the other hand, complex hydrides that are weak Lewis acids, such as $AlH_2(OC_4H_9\text{-}t)$ and $AlH(OC_4H_9\text{-}t)_2$, form the unsaturated alcohol **116** as the major product. (100) Unlike $LiAlH_4$, which gives the alcohol **117** (21%) as the sole product, AlH_3 affords a product mixture in which the alcohol **118** predominates. (100, 455)



Reduction of some alkene 1,2-oxides by $NaAlH_2(OCH_2CH_2OCH_3)_2$ (447) or $LiAlH_4$ (456) also effects carbon–carbon cleavage, forming minor amounts of primary alcohols along with secondary alcohols as major products (Eq. 29).



(29)

Whereas the reagent formed from LiAlH(OC$_4$H$_9$-*t*)$_3$ and triethylborane converts, for example, 1-methylcyclohexene oxide to a mixture of the tertiary (90%) and secondary alcohols (10%) (*cis*-2-methylcyclohexanol), $LiBH(C_2H_5)_3$ gives exclusively the tertiary alcohol. As a powerful nucleophile, the latter hydride also reduces highly hindered, labile 1,2-oxides rapidly and produces the more highly substituted alcohols with high regio- and stereoselectivity. 129a,442,457

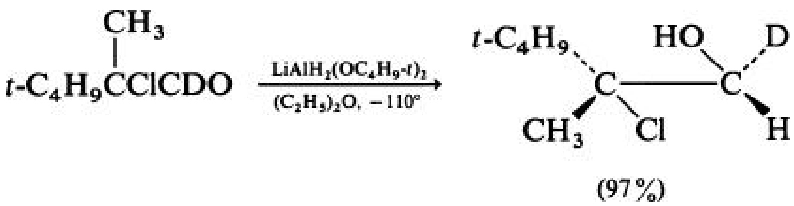
The $LiAlH(OCH_3)_3$ – copper(I) iodide reagent reduces cyclohexene oxide quantitatively to cyclohexanol. (412)

The reduction of styrene oxide, α -methylstyrene oxide, and 1,1-diphenylethylene oxide with diborane–boron trifluoride mixture at 0° produces almost quantitatively the corresponding primary alcohols; 1-phenylcyclopentene oxide yields selectively the less substituted alcohol, 2-phenylcyclopentanol, as a mixture of the *trans* (82%) and *cis* (18%) isomers. (458) The “mixed hydride” $LiAlH_4$– $(AlCl_3)_4$ appears to be a less selective reagent. (26, 448)

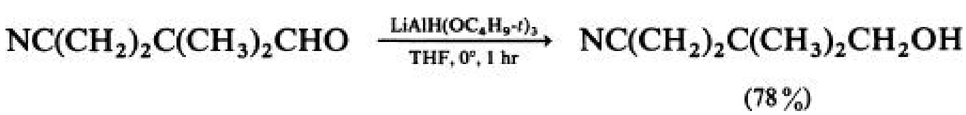
3.7. Reduction of Aldehydes

Simple saturated aldehydes are reduced by $LiAlH(OCH_3)_3$, (30, 46, 47) $LiAlH(OC_4H_9\text{-}t)_3$, (30, 40, 47, 414) and $NaAlH_2(OCH_2CH_2OCH_3)_2$ (369, 459) at 0–30° as rapidly as by $LiAlH_4$ (30, 443) to the primary alcohols in high yields; $NaAlH(OC_2H_5)_3$ gives lower yields. (54) The synthetic utility of $LiAlH_2(OC_4H_9\text{-}t)_2$, (40, 366) $LiAlH(OC_4H_9\text{-}t)_3$, and $NaAlH_2(OCH_2CH_2OCH_3)_2$ can be compared by their capability of reducing selectively the formyl group in the presence of other reducible functions.

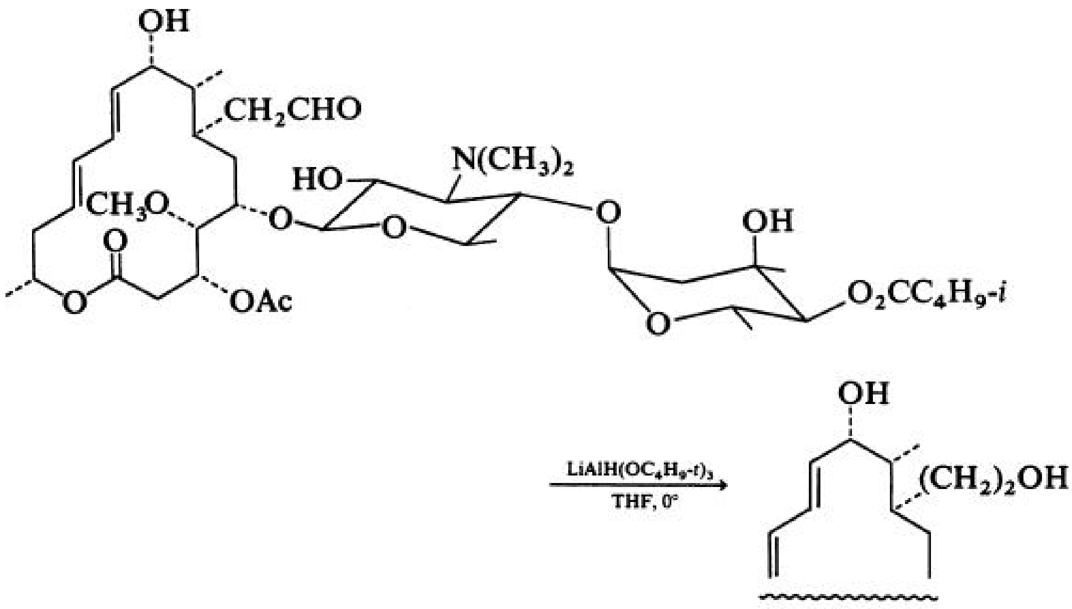
α -Chloroaldehydes can be transformed by $LiAlH(OC_4H_9\text{-}t)_3$ or $LiAlH_2(OC_4H_9\text{-}t)_2$ at low temperatures into the corresponding chloro alcohols (Eq. 30), (40, 366) cyanoaldehydes can be reduced to cyano alcohols (Eq. 31), (460) and aldehyde lactones can be reduced to hydroxy lactones (Eq. 32). (461, 462)



(30)



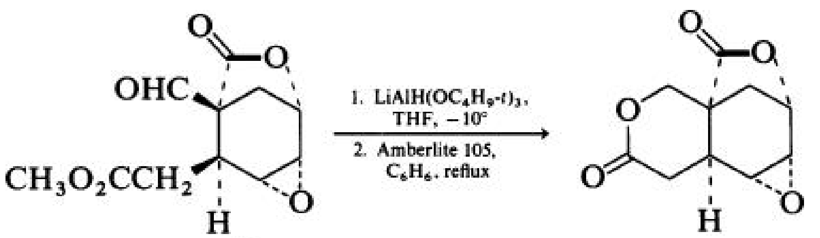
(31)



(92%)

(32)

Reduction of the aldehyde ester **119** with the same hydride and the subsequent treatment of the resulting hydroxymethyl ester with an Amberlite resin leads

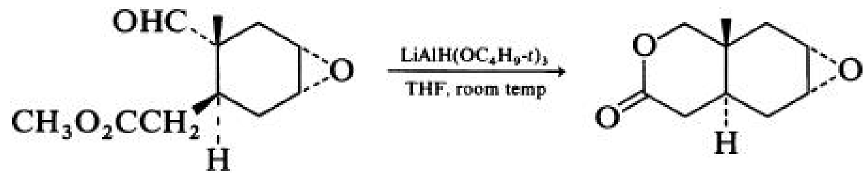


119

120 (95%)

to the dilactone **120**. (462, 463) The aldehyde derivatives **121** and **122** both undergo spontaneous reductive cyclization on treatment with $LiAlH(OC_4H_9\text{-}t)_3$ to give the *trans*-fused lactones **123** and **124**, respectively. (444)

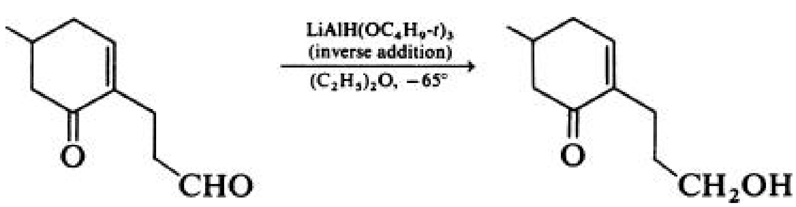
121 123 (63%)



122 124 (61%)

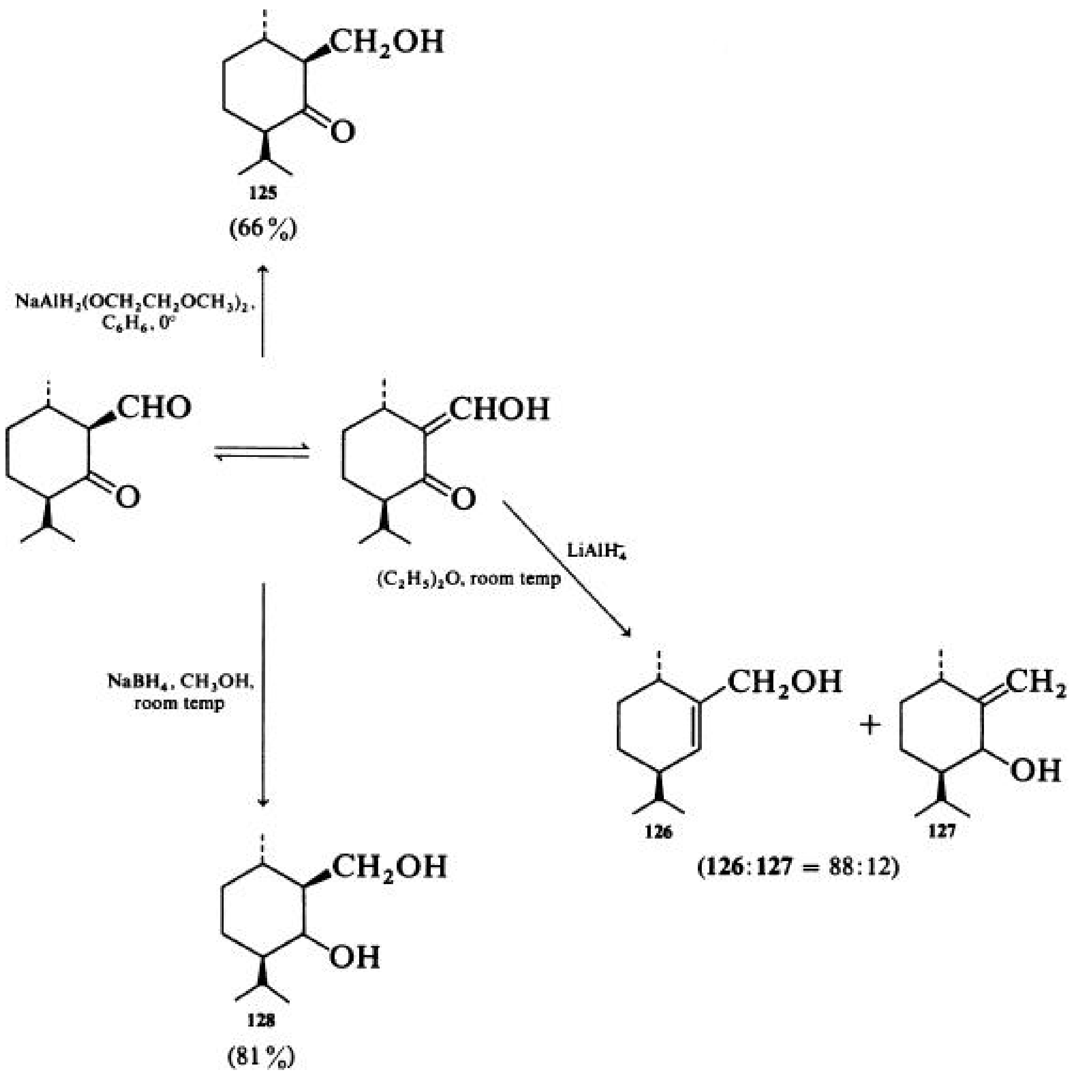
Reductions of a mixture of 1-hexanal and 2-heptanone (1:1) by $LiAlH[OC(C_2H_5)_3]_3$, $LiAlH[OCCH_3(C_2H_5)_2]_3$, $LiAlH[OCC_2H_5(CH_3)_2]_3$, and $LiAlH(OC_4H_9\text{-}t)_3$ proceed with excellent selectivity, giving 1-hexanol and 2-heptanol in a ³99.5 : £0.5 ratio (conversion ³90%). (464) In a similar reaction, $LiAlH(OC_4H_9\text{-}t)_3$ reduces a mixture of 1-butanal and 2-butanone to form *n*-butyl alcohol and *sec*-butyl alcohol in a ratio of 99:1; $NaBH_4$ yields greater amounts of the secondary alcohol (4%). (465) The above alkoxy hydrides (464) and $NaBH_4$ (465) are equally effective in reducing selectively benzaldehyde (³99%) in the presence of acetophenone (attack £1%); $LiAlH_4$, $LiBH_4$, and $LiBH_3(CN)$ show lower selectivity and produce benzyl alcohol along with 9–31% of 1-phenylethanol. (465) High capability to reduce preferentially an aldehyde in the presence of a ketone is also shown by sodium triarylborohydrides (selectivity 93–99%) (466) and lithium di-*n*-butyl-9-borabicyclo[3.3.1]nonane (selectivity 95%). (467)

Through the use of $LiAlH(OC_4H_9\text{-}t)_3$, the low reactivity of the α -enone grouping can be utilized for transforming α -enone aldehydes essentially quantitatively into α -enone alcohols (Eq. 33). (468)

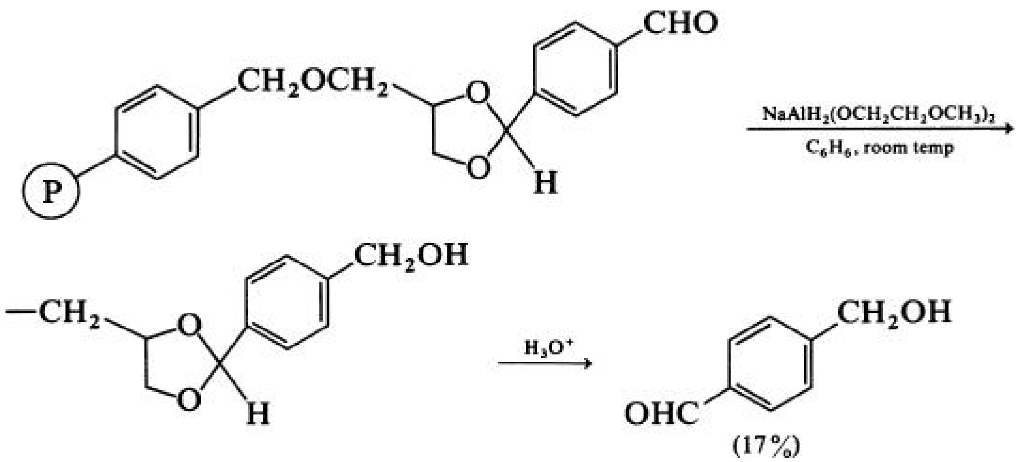


(33)

The formyl group in 3-oxo-*p*-menthane-2-carbaldehyde can be reduced selectively with $NaAlH_2(OCH_2CH_2OCH_3)_2$ to yield the ketol **125** as the sole product; $LiAlH_4$ gives a mixture of the allylic alcohols **126** and **127**, and $NaBH_4$ affords the diol **128**. (469)

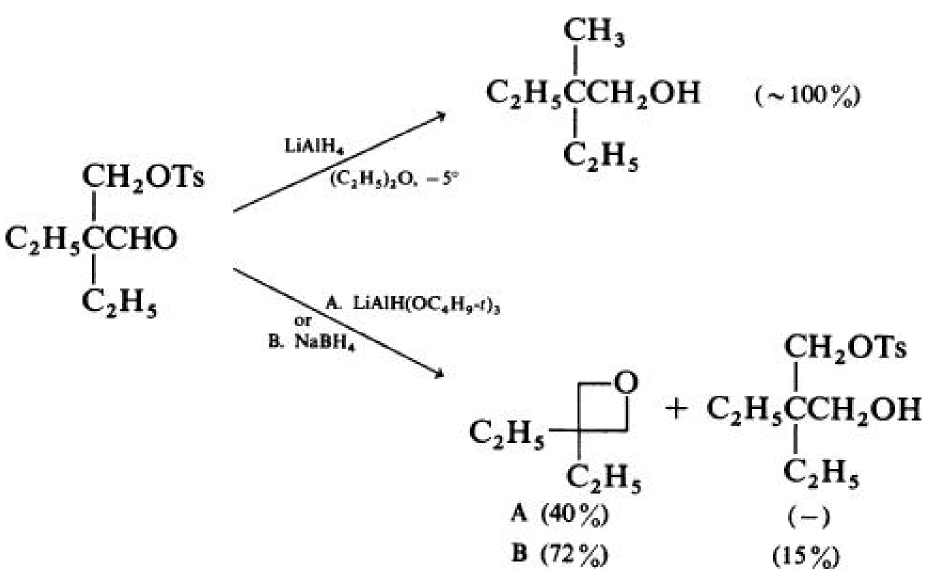


Selective reduction of one formyl group in an aromatic dialdehyde such as terephthalaldehyde can be achieved by reaction with a Merrifield polymer (P) incorporating a vicinal diol function available for acetal formation. The polymer-bonded acetal aldehyde is then reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ to give the polymer-bonded acetal alcohol, which on hydrolysis yields *p*-hydroxymethylbenzaldehyde (Eq. 34). Isophthalaldehyde can similarly be transformed into *m*-hydroxymethylbenzaldehyde (8%). (470, 471)



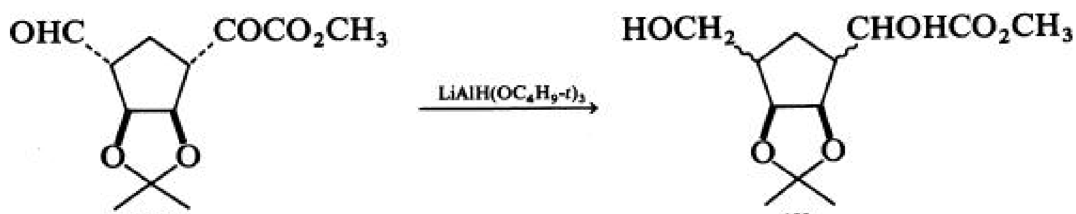
(34)

The *p*-toluenesulfonyl group can be cleaved in the reduction of aldehydes (Eq. 35). (472)



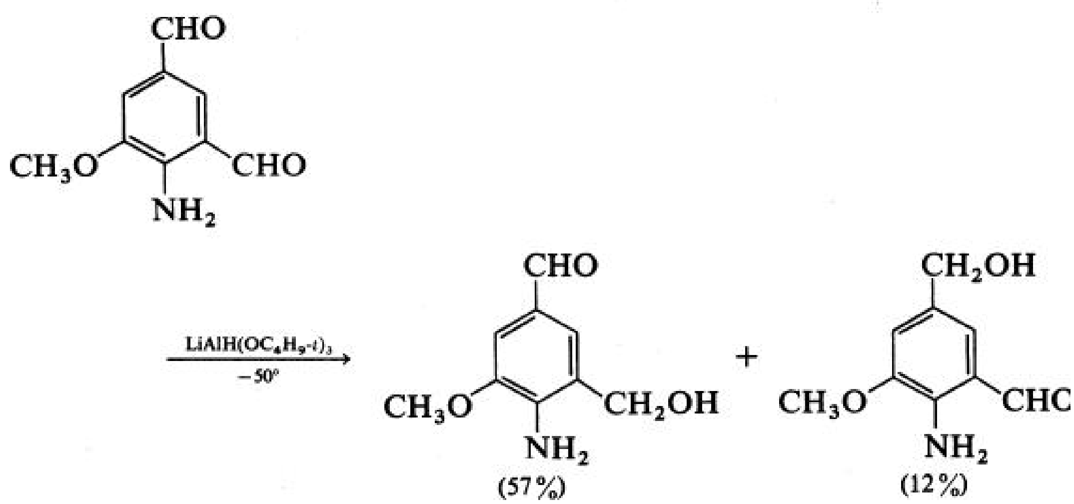
(35)

The attempted selective reduction of a formyl group in the presence of an α -keto ester function in the compound **129** by $LiAlH(OC_4H_9\text{-}t)_3$ does not succeed and gives only a mixture of epimeric diols **130**. (473) Similarly, the



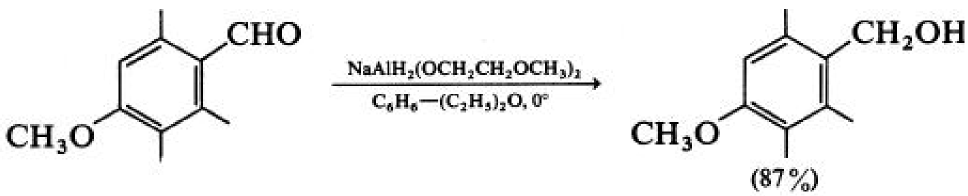
129 → 130 (70%)

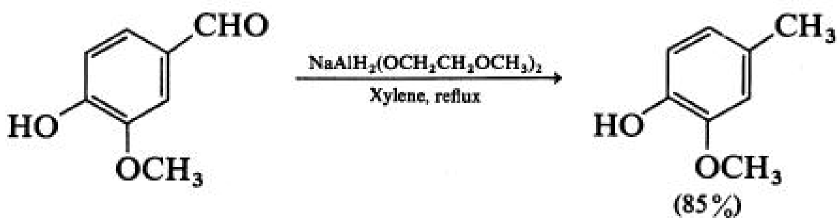
attempt to reduce selectively one formyl group in 4-amino-5-methoxyisophthalaldehyde by using $LiAlH(OC_4H_9\text{-}t)_3$ in bis(2-methoxyethyl) ether gives a mixture of aldehyde alcohols in which 4-amino-3-hydroxymethyl-5-methoxy-benzaldehyde predominates (Eq. 36). (474)

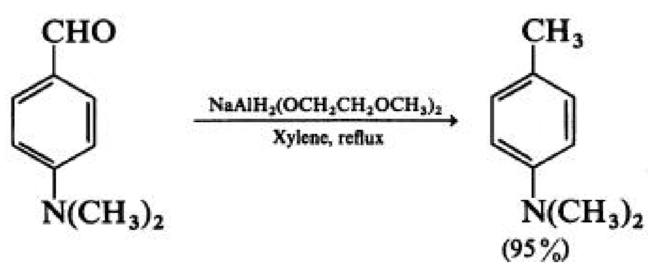


(36)

Benzaldehydes substituted in the *ortho* or *para* positions by hydroxyl, alkoxyl, or amino groups react with $NaAlH_2(OCH_2CH_2OCH_3)_2$ to form either the corresponding benzyl alcohols or cresols and toluidines in high yield, depending on temperature. (430-432, 434, 475)







4-Benzyloxybenzaldehyde undergoes a double hydrogenolysis on treatment with $NaAlH_2(OCH_2CH_2OCH_3)_2$ to form *p*-cresol. (433)

Chiral primary deuterio alcohols can be prepared by reacting aldehydes with chirally modified lithium alkoxyaluminodeuteride reagents. Reductions of benzaldehyde by the $LiAlD_4$–(–)-quinine (476) (Eq. 37, *x* = 1) and $LiAlD_4$–(2*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol (167, 477, 478) complexes (Eq. 37, *x* = 2) give (*S*)-(+)-benzyl-1-d_1 alcohol in

$$C_6H_5CHO \xrightarrow[2.\ H_3O^+]{1.\ LiAlD_{4-x}(OR^*)_x} C_6H_5\overset{*}{C}HDOH \qquad (37)$$

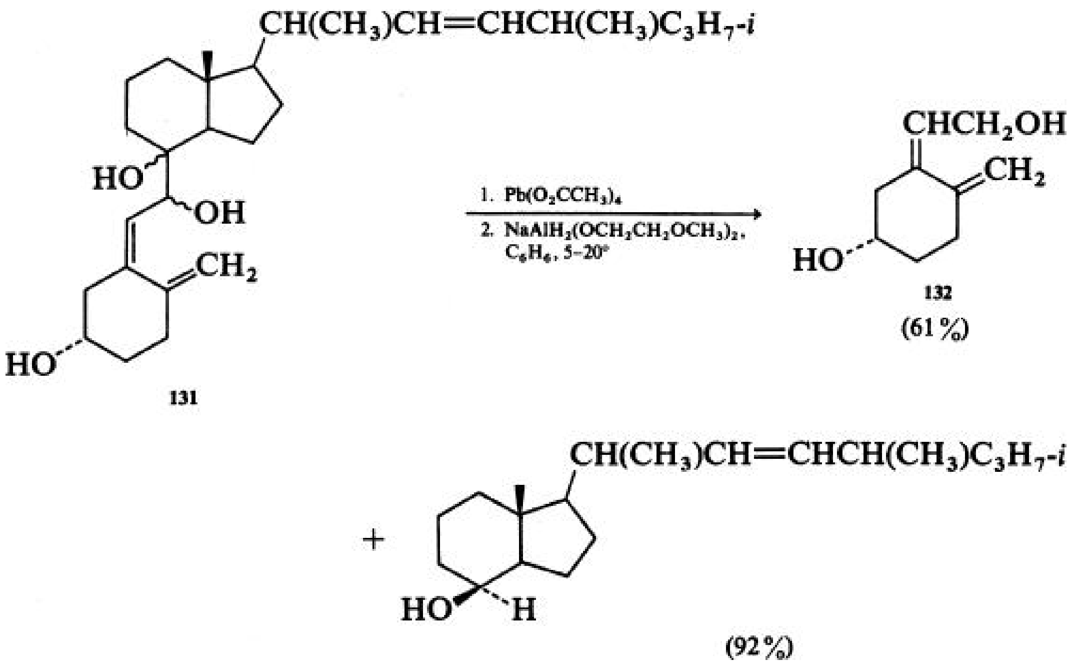
up to 43% e.e. With *p*-tolualdehyde, *p*-methylbenzyl-d_1 alcohol containing only 16% excess of the (*S*)-(+) enantiomer is obtained by use of the former hydride; somewhat better enantioselectivity (20–32% e.e.) is achieved in reductions of furfural and α-thienylaldehyde. (476) In reductions of aliphatic, alicyclic, and aromatic aldehydes by the latter complex hydride the enantiomeric excess of the corresponding (*S*)-(+)-1-deuterio alcohols varies between 15 and 66%. (477, 478) (*R*)-(–)-Benzyl-d_1 alcohol (21% e.e.) can be prepared by reducing benzaldehyde with the $LiAlD_4$–1,4-bis(dimethylamino)-(2*S*,3*S*)-(–)-2,3-butanediol complex (Eq. 37, *x* = 1). (315)

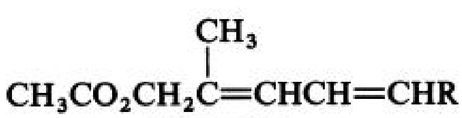
A dramatic increase in the optical yields is achieved by using the $LiAlH_4$–(*R*)-(+)-2,2¢-dihydroxy-1,1¢-binaphthyl-ethanol reagent (1:1:1), which reduces benzaldehyde-d_1 at –100° to form (*R*)-(–)-benzyl-d_1 alcohol in 82% e.e. (168, 479)

3.8. Reduction of α , β -Unsaturated Aldehydes

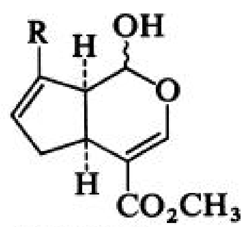
Reduction of a conjugated aldehyde by complex metal hydrides can afford either an unsaturated or a saturated primary alcohol or a mixture of both. Addition of 3-phenyl-2-propenal to $NaAlH_2(OCH_2CH_2OCH_3)_2$ in benzene gives 97% of 3-phenylpropanol, and inverse addition yields 94% of 3-phenyl-2-propenol; (369, 459) in this case, the hydride resembles $LiAlH_4$ in being capable of producing either alcohol. Inverse addition of $Al_2H_3(OCH_2CH_2OCH_3)_3$ to 3-phenyl-2-propenal gives 3-phenyl-2-propenol in 84% yield; (368) $LiAlH(OC_4H_9$-*t*) reduces the carbonyl group in 3-phenyl-2-propenal without affecting the carbon — carbon double bond. (30, 47, 414) On the other hand, the formyl group as well as the conjugated double bond are attacked by $LiAlH(OCH_3)_3$, producing 98% of 3-phenylpropanol; (30, 46, 47) $NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$ reacts similarly. (371)

Aliphatic and alicyclic α , β -unsaturated aldehydes can be reduced to allylic alcohols by $LiAlH(OC_4H_9\text{-}t)_3$ or $NaAlH_2(OCH_2CH_2OCH_3)_2$. For instance, reduction of 2-butenal by the latter hydride gives 97% of 2-butenol. (459) The products obtained by cleavage of the triol **131** with lead tetraacetate are reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ to give the diene diol **132** along with des-AB-ergost-22-en-8 β -ol. (480) The conjugated aldehyde **133** can be converted by $LiAlH(OC_4H_9\text{-}t)_3$ to the unsaturated alcohol **134**, an intermediate in the synthesis of (*R,S*)-lyratol. (481) Reduction of the unsaturated aldehyde lactol **135** by the same hydride in diethyl ether gives racemic genipin (**136**). (482)



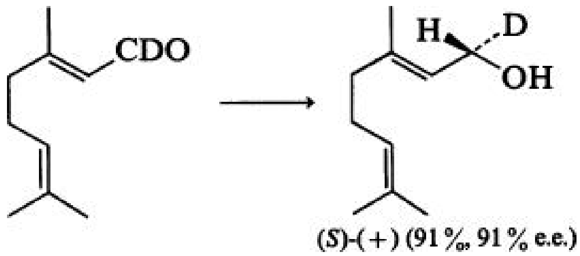


133: R = CHO
134: R = CH_2OH



135: R = CHO
136: R = CH_2OH

Asymmetric reduction of geranial-d_1 by the $LiAlH_4$–(*S*)-(–)-2,2¢-dihydroxy-1,1¢-binaphthyl–ethanol complex produces (*S*)-(+)-geraniol-d_1 (Eq. 38);



(38)

the enantioselectivity in reductions of related terpenic aldehydes varies between 72 and 88% e.e. (483)

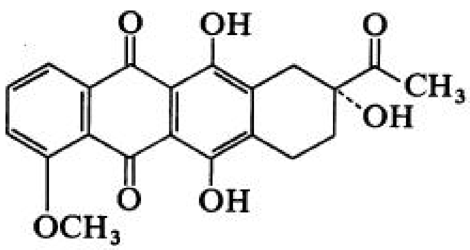
The effectiveness of aluminum hydride, (30) diisobutylaluminum hydride, (117, 139) sodium cyanoborohydride, (106, 107, 484) and tetrabutylammonium cyanoborohydride (484) in selectively reducing conjugated aldehydes to allylic alcohols is well documented. (139) Exceptionally high selectivity is found in reductions with 9-borabicyclo[3.3.1]nonane, which is capable of converting 2-butenal and 3-phenyl-2-propenal to 2-butenol and 3-phenyl-2-propenol, respectively, in 99% yields. (8, 485) The inertness of nitro, halogen, epoxide, carboxyl, ester, amido, cyano, and other reducible groups toward this reagent makes it more selective when compared with other reducing agents, (8, 485) including diisobutylaluminum hydride. (117)

3.9. Reduction of Alkyl and Aryl Ketones

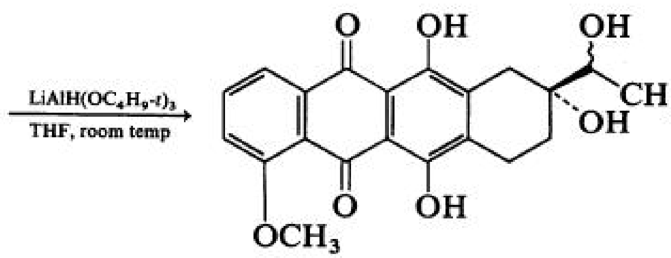
Simple alkyl and aryl ketones such as 2-heptanone, 4,4-dimethyl-2-pentanone, acetophenone, and benzophenone react with $LiAlH(OCH_3)_3$, (30, 46, 47) $LiAlH(OC_4H_9\text{-}t)_3$, (30, 40, 47, 308, 414) and $NaAlH_2(OCH_2CH_2OCH_2)_2$ (369, 459) very rapidly at 0–30° to form secondary alcohols, usually in excellent yields; $AlH(OC_3H_7\text{-}i)_2$, (87, 98) $Al_2H_3(OCH_2CH_2OCH_3)_3$, (312, 368) $NaAlH_3(OCH_3)$, (59) and $NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$ (371) all are less reactive, and $NaAlH(OC_2H_5)_3$ requires several hours for an incomplete reaction. (54) Competitive reduction of aldehyde–ketone mixtures by complex metal hydrides reveals that ketones are reduced less readily than the related aldehydes; (464-467) however, selective reduction of a ketone group in the presence of an aldehyde group can be accomplished by masking the aldehyde group by reaction with *tert*-butylamine, reduction of the ketone with $LiAlH(OC_4H_9\text{-}t)_3$, and subsequent cleavage of the aldimine. (486) Use of $LiAlH(OC_4H_9\text{-}t)_3$ makes it possible to reduce selectively a keto function in the presence of ester, lactone, amide, (414) halogen, (381, 389) 1,2-oxide, (251, 414) *O*-alkyloxime, (414, 487) azide, (488) and cyano groups (Eq. 39). (414, 489-491)

$$i\text{-}C_4H_9COC(CH_3)_2CH_2CN \xrightarrow{LiAlH(OC_4H_9\text{-}t)_3} \underset{(88\%)}{i\text{-}C_4H_9CHOHC(CH_3)_2CH_2CN} \quad (39)$$

The 9-acetyl group in 7-deoxydaunomycinone (**137**) is attacked preferentially by $LiAlH(OC_4H_9\text{-}t)_3$ leaving intact the 1,4-quinone moiety and giving



137



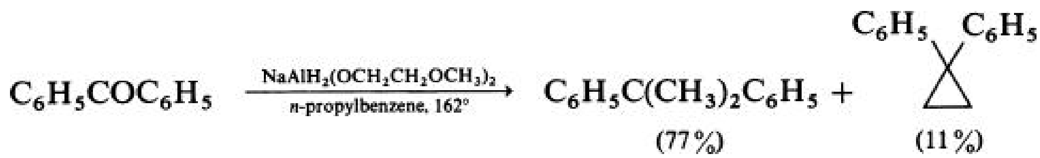
138

(80%)

the epimeric tetrols **138**. (492, 493) $LiAlH(OC_2H_5)_3$ can be used to reduce selectively a keto group in a keto diester (Eq. 40); $LiAlH_4$ gives 48% of the hydroxy diester. (494)

$$C_2H_5O_2CCH(CH_3)COCH(CH_3)CH_2CH(CH_3)CO_2C_2H_5 \xrightarrow{LiAlH(OC_2H_5)_3} \underset{(71\%)}{C_2H_5O_2CCH(CH_3)CHOHCH(CH_3)CH_2CH(CH_3)CO_2C_2H_5} \quad (40)$$

1-Acetyl- and 2-acetylnaphthalene are converted rapidly by $NaAlH_2(OCH_2CH_2OCH_3)_2$ in refluxing benzene to the corresponding carbinols (~96%); reaction of the latter ketone with the same hydride at 140° produces 2-ethylnaphthalene (37%) along with *meso*- and *dl*-2,3-bis(2-naphthyl)butane (43%). (495) Aryl alkyl ketones and diaryl ketones substituted in the *ortho* and *para* positions by hydroxyl or amino groups undergo hydrogenolysis by $NaAlH_2(OCH_2CH_2OCH_3)_2$ under forcing conditions to form the corresponding cresols, toluidines, and hydroxy- or amino-substituted diarylmethanes, respectively; high yields can be obtained even in cases where $LiAlH_4$ fails to react at an acceptable rate. (431, 432, 437) Diaryl ketones and condensed aromatic ketones such as benzophenone and 9-fluorenone undergo hydrogenolysis and subsequent alkylation at the benzylic carbon atom on treatment with $NaAlH_2(OCH_2CH_2OCH_3)_2$ (Eq. 41). (206, 207, 496)



(41)

Carbonyl groups in polymers are reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ in toluene-*N*-methylmorpholine solution; poly(methyl vinyl carbinol) is thus obtained from poly(methyl vinyl ketone) in 82% yield. (497) The same hydride, $LiAlH_4$, or $NaBH_4$ transforms the terminal benzoyl group attached to a polystyrene–divinylbenzene copolymer into the phenylhydroxymethyl group. (498)

Typical asymmetric reductions of dialkyl, alkyl cycloalkyl, and alkyl aryl ketones with chiral lithium alkoxyaluminum hydrides (499) are summarized in Table E.

TABLE E. Asymmetric Reductions of Prochiral Ketones by Some $LiAlH_4$-Chiral Agent Complexes (Percent Enantiomeric Excess and Alcohol Configuration)

		Chiral Agent[a]											
Entry	Ketone	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	$CH_3COC_2H_5$	0	—	45(*R*)	—	2(*S*)	—	—	—	8(*S*)	14(*S*)	—	—
2	$CH_3COC_3H_7$-*i*	6(*S*)	—	—	—	—	—	—	—	25(*S*)	41(*S*)	—	—
3	$CH_3COC_4H_4$-*n*	—	11(*S*)	13(*R*)	—	—	—	—	—	—	19(*S*)	—	—
4	$CH_3COC_4H_9$-*i*	—	30(*S*)	17(*R*)	—	16(*S*)	—	—	—	—	20(*S*)	—	—
5	$CH_3COC_4H_9$-*t*	11(*S*)	4(*S*)	19(*R*)	—	12(*S*)	—	28(*R*)	21(*S*)	—	21(*S*)	—	—
6	$CH_3COCH_2C_4H_9$-*t*	—	19(*S*)	4(*R*)	—	—	—	—	—	52(*S*)	—	—	—
7	$C_6H_5COCH_3$	48(*R*)	34(*S*)	71(*R*)	31(*R*)	42(*S*)	65(*R*)	75(*R*)	75(*S*)	—	84(*R*)	88(*S*)	—
8	$C_6H_5COC_2H_5$	42(*R*)	38(*S*)	46(*R*)	—	44(*S*)	62(*R*)	—	—	76(*S*)	85(*R*)	90(*S*)	98(*S*)
9	$C_6H_5COC_3H_7$-*n*	46(*R*)	—	—	—	—	—	62(*R*)	59(*S*)	—	89(*R*)	—	100(*S*)
10	$C_6H_5COC_4H_9$-*n*	47(*R*)	—	—	36(*R*)	47(*S*)	—	—	—	—	78(*R*)	80(*S*)	100(*S*)

11	$C_6H_5COC_3H_7$-*i*	25(*R*)	—	—	—	27(*S*)	43(*R*)	30(*R*)	20(*S*)	—	17(*R*)	78(*S*)	71(*S*)
12	$C_6H_5COC_4H_9$-*t*	30(*S*)	—	—	—	21(*S*)	—	36(*R*)	28(*R*)	—	31(*S*)	—	—
13	$C_6H_5COC_4H_9$-*i*	34(*R*)	18(*S*)	—	—	—	—	—	—	—	84(*R*)	—	—
14	$C_6H_5COC_6H_{11}$	26(*R*)	—	—	—	53(*S*)	—	—	—	—	11(*R*)	—	—
15	Mesityl-$COCH_3$	41(*R*)	—	—	—	75(*S*)	—	—	—	—	—	—	—

[a]Agent:

I (–)-Quinine (313, 316, 324, 325, 500, 501)

II 3-*O*-Benzyl-1,2-*O*-cyclohexylidene- α -D-glucofuranose (317, 318)

III 3-*O*-Benzyl-1,2-*O*-cyclohexylidene- α -D-glucofuranose-ethanol (319)

IV (2*R*,3*R*)-(+)-1,4-Bis(dimethylamino)-2,3-butanediol (315)

V (2*S*,3*S*)-(–)-1,4-Bis(dimethylamino)-2,3-butanediol (315)

VI (4*S*,5*S*)-(–)-2-Ethyl-4-hydroxymethyl-5-phenyl-2-oxazoline (502)

VII (2*S*,3*R*)-(+)-4-Dimethylamino-3-methyl-1,2-diphenyl-2-butanol(“fresh reagent”) (166, 167)

VIII (2*S*,3*R*)-(+)-4-Dimethylamino-3-methyl-1,2-diphenyl-2-butanol(“aged reagent”) (166, 167)

IX (2*R*,3*S*)-(–)-4-Dimethylamino-3-methyl-1,2-diphenyl-2-butanol(“fresh reagent”) (503)

X (1*R*,2*S*)-(–)-*N*-Methylephedrine-3,5-dimethylphenol (159, 160)

XI (1*R*,2*S*)-(–)-*N*-Methylephedrine-*N*-ethylaniline (163)

XII (*S*)-(–)-2,2¢-Dihydroxy-1, 10-binaphthyl-ethanol (168)

Of the chiral $LiAlH_4$–amino alcohol complexes, the reagent prepared by complexing $LiAlH_4$ with (+)-3-*exo*-phenylamino-2-*exo*-hydroxybornane reduces alkyl aryl ketones to form secondary alcohols (26–43% e.e.) with (*R*) configuration; (504) (*S*) alcohols (8–87% e.e.) can be obtained by reducing alkyl aryl ketones, aryl cycloalkyl ketones, and diaryl ketones with $LiAlH_4$–(2*S*,3*S*)-1,4-dipyrrolidino-2,3-butanediol. (505) Asymmetric synthesis with only modest e.e. is observed with complexes of $LiAlH_4$ with various chiral monosaccharide derivatives, (317, 320, 506-508) secondary alcohols, (422, 509) and diols; (510, 511) thus $LiAlH_4$–(+)-1-hydroxycarvomethol-ethanol transforms acetophenone into the (*R*) alcohol in 24–30% e.e. (511)

The $LiAlD_4$–(–)-quinine complex reduces *o*-tolyl and *p*-tolyl phenyl ketone to the (*R*) deuterio alcohols in 46–56% e.e. (476)

In the reduction of substituted aliphatic α -ketols **39** $LiAlH(OCH_3)_3$ and particularly triisobutylaluminum show the highest stereoselectivity and give the *erythro* and *threo* diols in ratios of 78:22 to 95:5, respectively. (239, 240)

Reduction of monosubstituted α -(phenylalkylamino)propiophenones (**139a–b**) gives only *erythro* alcohols with any of $LiAlH_4$, $LiAlH(OC_4H_9\text{-}t)_3$, $NaBH_4$, $Al(OC_3H_7\text{-}i)_3$, or $AlCl(OC_3H_7\text{-}i)_2$ as the reducing agent. On the other hand, the course of reduction of the disubstituted derivatives **139c–d** depends on the reductant; $LiAlH_4$ reduces **139c** to form a mixture of *erythro* and *threo* alcohols, whereas a bulky hydride such as $LiAlH(OC_4H_9\text{-}t)_3$ gives exclusively *threo* alcohols. (512)

$C_6H_5COCH(CH_3)NRR^1$

139

	R	R^1
a	H	— $CH(CH_3)C_6H_5$
b	H	— $(CH_2)_{1-4}C_6H_5$
c	CH_3	— $(CH_2)_{2-4}C_6H_5$
d	—$CH_2C_6H_5$	— $(CH_2)_{1-4}C_6H_5$

Erythro alcohols are major products of reduction of α-(acylamino)propiophenones (**140**) by various reducing agents. The proportion of *threo* alcohol

$C_6H_5COCH(CH_3)NHCOR$

140

R = alkyl, haloalkyl, aryl, $(C_6H_5)_2CH$, $(C_6H_5)_3C$

is influenced by the reducing agent, and the order of increasing effectiveness is $Al(OC_3H_7\text{-}i)_3 \sim AlCl(OC_3H_7\text{-}i)_2 < NaBH_4 \sim LiAlH(OC_4H_9\text{-}t)_3$. (513) Unlike

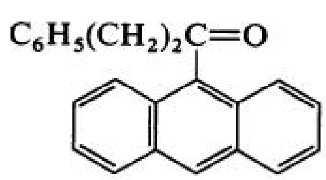
$NaBH_4$, $NaAlH_2(OCH_2CH_2OCH_3)_2$, or sodium in *n*-propanol, $LiAlH_4$ reduces racemic isomethadone (**141**) with high stereoselectivity. (514)

$$\underset{\mathbf{141}}{C_2H_5COC(C_6H_5)_2CH(CH_3)CH_2N(CH_3)_2} \xrightarrow{LiAlH_4} \underset{\substack{2S,4R/2R,4S \\ (94\%)}}{C_2H_5CHOHC(C_6H_5)_2CH(CH_3)CH_2N(CH_3)_2}$$

The reduction of normethadone (**142**) by the $LiAlH_4$–*cis*-pinanediol–benzyl alcohol complex produces predominantly (*S*)-(–)-normethadol. (515)

$$\underset{\mathbf{142}}{C_2H_5COC(C_6H_5)_2CH_2CH_2N(CH_3)_2} \longrightarrow \underset{\substack{(S)\text{-}(-) \\ (33\%\ e.e.)}}{C_2H_5CHOH(C_6H_5)_2CH_2CH_2N(CH_3)_2}$$

Alkoxyaluminum hydrides fail to reduce some highly hindered ketones. The hindered ketones **143** and **144** can be converted into the alcohols by $LiAlH_4$



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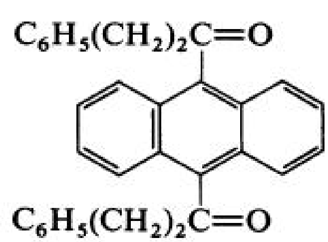
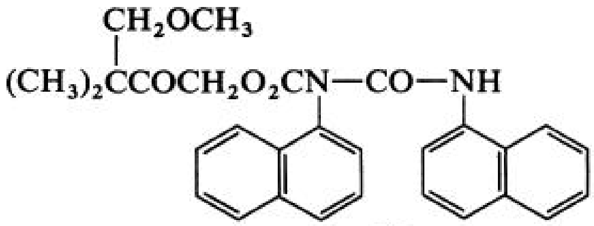


144

or AlH_3, but not by $LiAlH(OC_4H_9\text{-}t)_3$ or $NaBH_4$. (516) The keto group in the allophanate **145** is not affected by $LiAlH(OC_4H_9\text{-}t)_3$ nor by $NaBH_4$. (517) 2,4,6-Trimethylacetophenone treated with $NaAlH_2(OCH_2CH_2OCH_3)_2$ under forcing conditions yields only 10% of the alcohol; in contrast, $LiAlH_4$ reduces this



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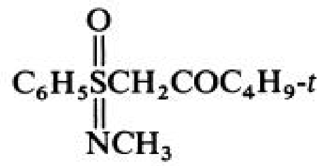


146

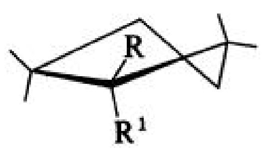
ketone to the alcohol in 80% yield. (459) Unlike $LiAlH(OC_4H_9\text{-}t)_3$, $NaBH(OC_3H_7\text{-}i)_3$, or $KBH(C_4H_9\text{-}s)_3$, which do not react with β -ketosulfoximines **146**, diborane gives the corresponding diastereomeric alcohols in high yield. (518)

3.10. Reduction of Cyclic Ketones

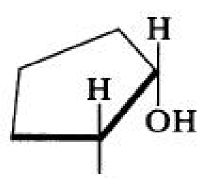
3.10.1.1. Monocyclic Ketones

Reductions of simple alkyl cyclohexanones have been studied extensively, and the stereochemical outcome of reductions has been tabulated in relation to ketone structure, nature of the reducing agent, and reaction conditions (see e.g., pp. 27–29 in Ref. 27; pp. 60–70 in Ref. 134; and pp. 119, 121, 123, and 135 in Ref. 148). 8,21a,47,51,124,136,153,154,173,261,263,269,272,301,303,519–524 Principal synthetic interest has centered on the reducing systems that enhance formation of the thermodynamically less stable epimeric alcohol.

There has been relatively little investigation of reductions of substituted cyclobutanones by metal alkoxyaluminum hydrides. 1,1,5,5-Tetramethylspiro[2,3]hexan-4-one is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to give nearly equal proportions of the less stable alcohol **147a** and its more stable epimer **147b**;



147a: R = OH, R¹ = H (47.5%)
147b: R = H, R¹ = OH (52.5%)

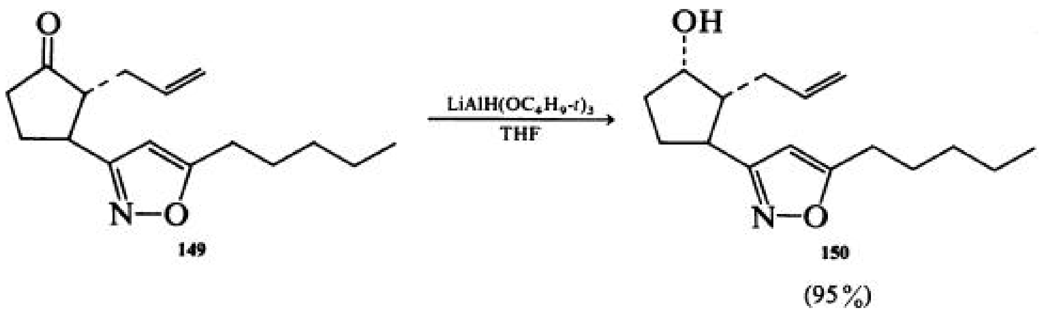


148

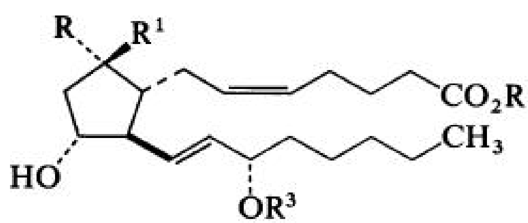
$NaBH_4$ and $LiAlH_4$ produce **147a** and **147b** in 43.3:56.5 and 36.2:63.8 ratios, respectively. (525)

Formation of the less stable *cis*-2-methylcyclopentanol **148** in the reduction of 2-methylcyclopentanone increases on going from $LiAlH(OC_2H_5)_3$, (173) $LiAlH_4$, (51, 173, 526) $NaBH_4$, (148) or $LiAlH(OC_4H_9\text{-}t)_3$, (~25%) (173, 520) to $LiAlH(OCH_3)_3$(46%) (173, 520, 526) and lithium dimesitylborohydride–bis(1,2-dimethoxyethane), (523) lithium tri-*sec*-butylborohydride, (522) or lithium trisiamylborohydride (98–99%). (524) In the reduction of 2-ethyl-, 2-isopropyl-, 2-cyclopentyl-, and

2-phenylcyclopentanone the proportion of the *trans* alcohol in the epimer mixture decreases for the given sequence of substituents from 76–81% to 59% with $LiAlH_4$ and from 71 to 52% with $LiAlH(OC_4H_9\text{-}t)_3$; $LiAlH(OCH_3)_3$ gives the *cis* alcohols as major products (60–76%). (526) Unlike $NaBH_4$, $LiAlH(OC_4H_9\text{-}t)_3$ and potassium tri-*sec*-butyl borohydride are highly selective in the reduction of ketone **149** and give the 1 α alcohol **150** as the sole product. (527)



$NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces the cyclic oxo group in the prostaglandin methyl PGE_2 15-acetate to give the $PGF_{2\alpha}$ derivative **151a** ($R^2 = CH_3$, $R^3 = CH_3CO$)(59%) along with a lesser amount of the β isomer



151a:R = OH, R¹ = H
151b:R = H, R¹ = OH

$R^2 = H, CH_3; R^3 = H, CH_3CO$

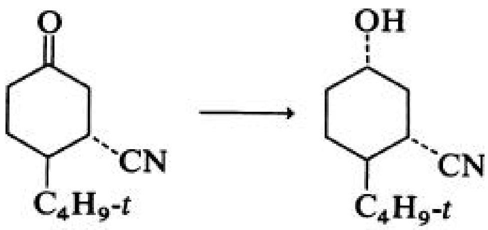
151b ($R^2 = CH_3$, $R^3 = CH_3CO$)(30%). (528) However, lithium tri-*sec*-butyl-borohydride reduces PGE_2 with excellent selectivity, yielding $PGF_{2\alpha}$ (**151a**; $R^2 = R^3 = H$) free of $PGF_{2\beta}$(**151b**; $R^2 = R^3 = H$). (139)

The proportion of the less stable *cis*-2-methylcyclohexanol (89%) in the product of a slow and incomplete reaction (69%) of 2-methylcyclohexanone with lithium [neopentyloxy-bis(2,6-di-*tert*-butylphenoxy)]aluminum hydride (193) can be raised to 99% by using lithium dimesitylboro hydride-bis(1,2-dimethoxyethane), (523) lithium tri-*sec*-butylborohydride, (522, 524) or lithium trisiamylborohydride; (524) $AlH(OC_4H_9\text{-}t)_2$ produces the *cis* epimer in only 56% yield. (178) 4-*tert*-Butyl-2,2-dimethylcyclohexanone is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to give almost exclusively the stable *trans* alcohol. (154, 262, 263) In the reduction of 2-isopropylcyclohexanone by various complex metal hydrides, the yield of the *trans* alcohol varies between 48 and

84%; (218, 266) $NaAlH_2(OCH_2CH_2OCH_3)_2$ gives 65% of this product. (218) 2-Methyl-, 2-ethyl- and 2-*n*-butylcyclohexanone, or 2-isopropyl-5-methylcyclohexanone react with $LiAlH(OC_4H_9\text{-}t)_3$ to give the corresponding *trans* and *cis* alcohols in about 65:35 ratio. (51, 173, 259, 261, 303) The highest yield (60–64%) of the less stable *cis*-2-*tert*-butylcyclohexanol with the use of lithium alkoxyaluminohydrides results from reductions of the ketone with $LiAlH(OCH_3)_3$ in tetrahydrofuran and $NaAlH_2(OCH_2CH_2OCH_3)_2$ in benzene. (173, 459) $LiAlH(OC_4H_9\text{-}t)_3$ does not react with 2-*tert*-butyl-5,5-dimethylcyclohexanone or 2-trimethylsilyl-5,5-dimethylcyclohexanone. (529)

In the reduction of 3-methylcyclohexanone, $LiAlH_4$ (260) and $LiAlH(OC_4H_9\text{-}t)_3$ (261, 303) show essentially identical stereoselectivity and afford the more stable *cis* alcohol in 85–87% yield. On the other hand, lithium [neopentyloxy-bis(2,6-di-*tert*-butylphenoxy)]aluminum hydride gives an 85% yield of the less stable *trans* epimer. (193) Reduction with lithium trisiamylborohydride is again more effective, producing the *trans* alcohol essentially quantitatively in 99.6% isomeric purity. (524) (*R*)-(+)-3-Methylcyclohexanone undergoes reduction by $LiAlH(OCH_3)_3$ to form (1*S*, 3*R*)-(–)-3-methylcyclohexanol (68%) and (1*R*, 3*R*)-(–)-3-methylcyclohexanol (32%). (503)

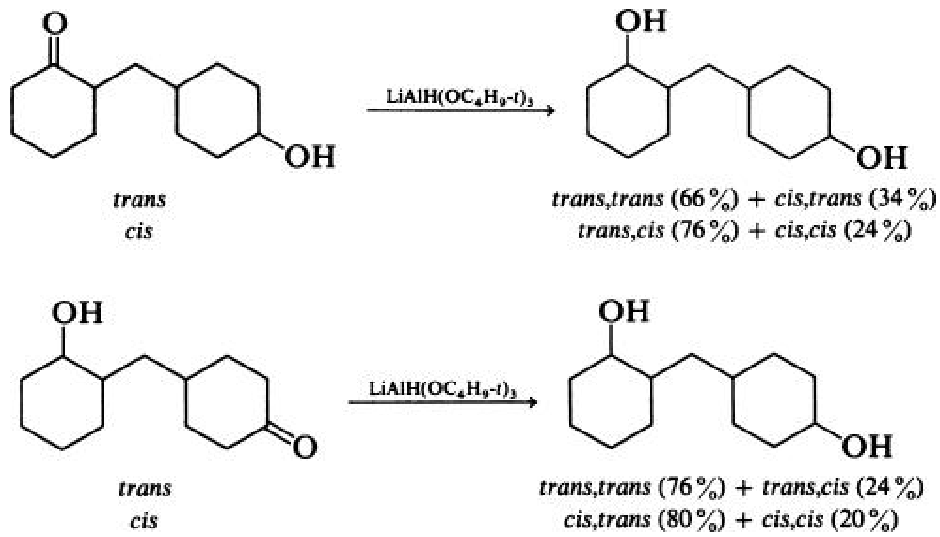
Whereas $LiAlH_4$, (258, 260) $NaBH_4$, (258) $NaAlH_2(OCH_2CH_2OCH_3)_2$, (459) and $LiAlH(OC_4H_9\text{-}t)_3$ (261, 303, 519) convert 4-methylcyclohexanone predominantly to the more stable *trans* alcohol (75–85%), lithium trisiamylborohydride gives a 99% yield of the *cis* epimer. (524) When 4-*tert*-butylcyclohexanone is reduced by hydrides of the general formula $LiAlH(OR)_3$, where R is 2,6-dimethylphenyl, 2,6-diisopropylphenyl, or 2,6-di-*tert*-butylphenyl, the percentage of the less stable axial *cis*-4-*tert*-butylcyclohexanol in the epimer mixture increases from 21 to 72 to 85%, respectively. (193) The course of the reduction of 4-*tert*-butylcyclohexanone by lithium bis(2,6-di-*tert*-butylphenoxy)aluminum hydride in tetrahydrofuran is strongly temperature dependent. Whereas the reaction proceeds in a normal manner at 0°, forming 53% of the *cis* and 47% of the *trans* alcohol, heating to reflux temperature gives the unchanged ketone and *n*-butyl alcohol from the reductive cleavage of tetrahydrofuran. (171) Reduction of the ketone with lithium [neopentyloxy-bis(2,6-di-*tert*-butylphenoxy)]-aluminum hydride affords the *cis* and *trans* alcohols in a 93:7 ratio. (193) Highest stereoselectivity is achieved with lithium trisiamylborohydride, which produces the *cis* alcohol (99.4% isomeric purity) in 98% yield; (524) the enzymatic reduction of this ketone proceeds with only 95% stereoselectivity. (522) The $LiAlH(OC_4H_9\text{-}t)_3$ reduction of the cyano ketone **152** gives the diaxial cyano alcohol **153** as the sole product. (530)



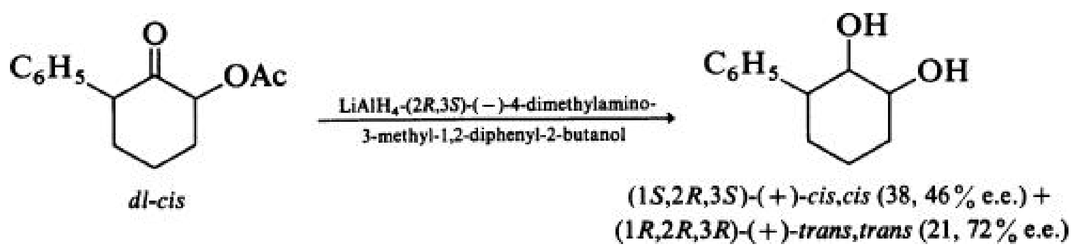
152 → 153 (83%)

2,6-Dimethylcyclohexanone, 3,3-dimethylcyclohexanone, and 3,3,5,5-tetramethylcyclohexanone are reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to form the corresponding *cis* alcohols in a proportion increasing from 46 to 89 to 95%, respectively. (303) 3,5-Dimethylcyclohexanone reacts with $LiAlH_4$ and $LiAlH(OC_4H_9\text{-}t)_3$ to give the *cis* and *trans* alcohols in about 85:15 ratio, (154, 263) which changes to 53:47 by using $LiAlH(OCH_3)_3$. (154) Of the various lithium alkoxyaluminum hydrides used to reduce 3,3,5-trimethylcyclohexanone, (153, 155, 170, 178, 183, 191, 192, 275) only $LiAlH(OCH_3)_3$ (153, 154, 180) or $LiAlH(OC_4H_9\text{-}t)_3$, (153, 154, 178, 180, 194, 200, 261, 263, 303) both in tetrahydrofuran, and $LiAlH(OCH_2CH_2OCH_2CH_2OC_2H_5)_3$; (531) $LiAlH[OCH(C_4H_9\text{-}t)_2]_3$; (155) lithium[neopentyloxy-bis(2,6-di-*tert*-butylphenoxy)]aluminum hydride; (193) or the $LiAlH_4$–2,3-dimethyl-2,3-butanediol complex (183) afford the less stable *trans* alcohol **66** with ^{3}90% stereoselectivity; lithium tri-*sec*-butylborohydride gives the same product in 99.8% isomeric purity. (522)

Comparable stereoselectivity is shown by $LiAlH(OC_4H_9\text{-}t)_3$ and $LiAlH_4$ in reductions of oxohydroxydicyclohexylmethanes. (158)

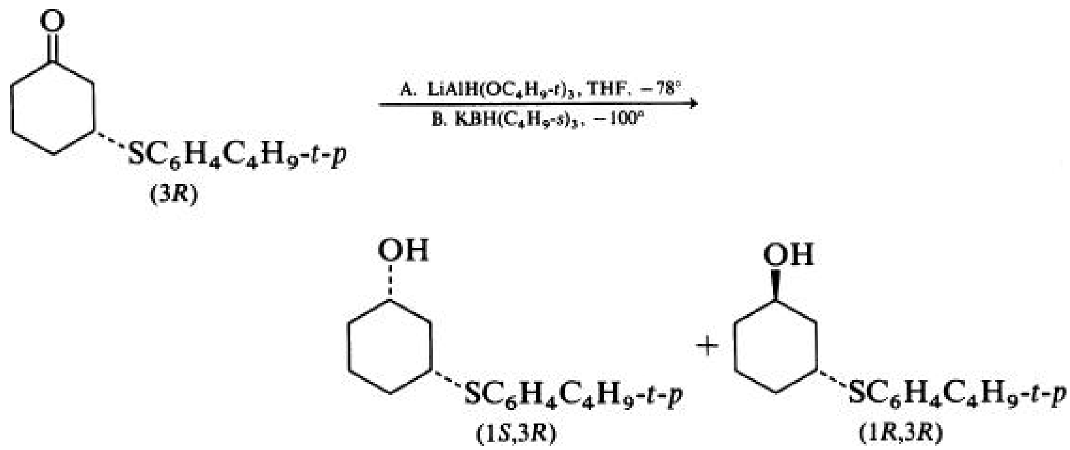


4-Acetoxy-3,3,5-trimethylcyclohexanone undergoes reduction by $LiAlH(OC_4H_9\text{-}t)_3$ producing the less stable axial alcohol monoacetate in 52% yield. (532) A mixture of enantiomers results on reduction of *dl-cis*-2-acetoxy-6-phenylcyclohexanone with the Mosher–Yamaguchi complex. (151, 533, 534)



Whereas $LiAlH_4$, $NaBH_4$, and $NaAlH_2(OCH_2CH_2OCH_3)_2$ reduce 2-*N,N*-dimethylaminocyclohexanone to form predominantly the *trans* alcohol (53–76%), (217, 218) lithium bis(*trans*-2-*N,N*-dimethylaminocyclohexyloxy)aluminum hydride or $NaAlH_4$ yield 56–64% of the *cis* epimer. (218) 2-*N,N*-Di-*n*-propylaminocyclohexanone is reduced by $NaAlH_2(OCH_2OCH_3)_2$, $NaBH_4$, and $LiAlH_4$ to form the *cis* and *trans* alcohols in 40 : 60, 25 : 75, and 10 : 90 ratios, respectively. (217) The *N-p*-toluenesulfonyl derivative of 2-aminocyclohexanone is converted to the *trans* alcohol (90%) by $LiAlH(OC_4H_9\text{-}t)_3$. 535a

(3*R*)-3-(*p-tert*-Butylphenylthio)-1-cyclohexanone can be transformed either into the *cis* or the *trans* alcohol with essentially complete enantioselectivity by



A. (1*S*,3*R*):(1*R*,3*R*) = 98:2 (overall yield 85%)
B. —"—:—"— = 4:96 (—"— —"— 95%)

using $LiAlH(OC_4H_9\text{-}t)_3$ or $KBH(C_4H_9\text{-}s)_3$, respectively, as reducing agents; other complex metal hydrides are less stereoselective. 535b

3.10.1.2. Bicyclic Ketones

In the reduction of 3-oxobicyclo[3.1.0]hexanes **154**, $LiAlH(OC_4H_9\text{-}t)_3$ produces predominantly the less stable *cis* alcohols **155**; $LiAlH_4$ is less stereoselective. (536, 537)

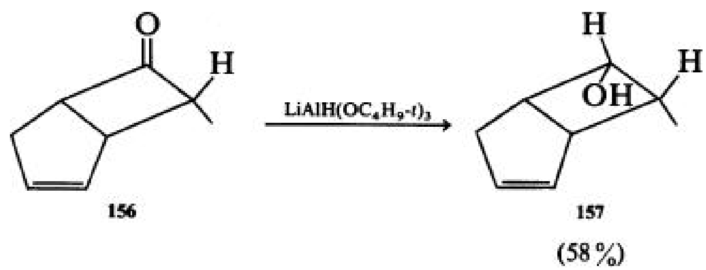
154

155

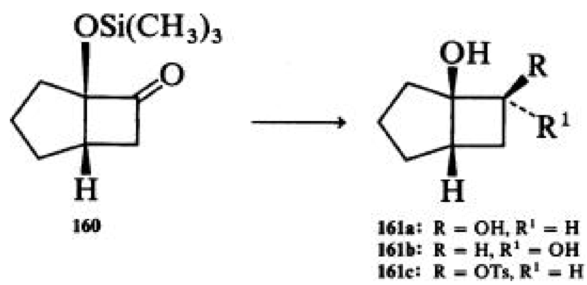
R,R[1],R[2],R[3],R[4],R[5] = H,alkyl

(78–99.5%)

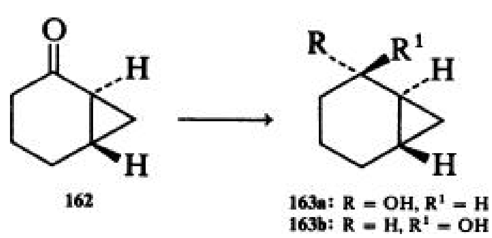
Reduction of the α -methyl ketone **156** with $LiAlH(OC_4H_9\text{-}t)_3$ gives selectively the *endo* alcohol **157**. (538) In contrast the α -chloro ketone **158** reacts with the same hydride to yield the *exo* alcohol **159** and its *endo* isomer in the ratio of 93 : 7. (381)



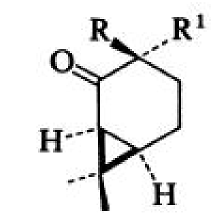
The bicyclic ketone **160** is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to form the *cis* diol **161a** as the major product along with a lesser amount of the *trans* epimer **161b** (overall yield 88%). When the tosylate **161c** is treated with potassium *tert*-butoxide,



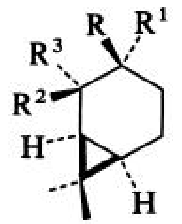
2-oxo-*trans*-bicyclo[4.1.0]heptane (**162**) is obtained in 83% yield; if the rearrangement is carried out in the presence of $KAlH(OC_4H_9\text{-}t)_3$, the ketone **162** undergoes reduction to give the *trans* alcohol **163a** and its *cis* epimer **163b** in a 67 : 33 ratio. (539)



The steric course of ketone reductions in the *trans*-bicyclo[4.1.0]heptane series depends on the ketone structure and nature of the reducing agent. (–)-2-Isocaranone (**164**) reacts with $LiAlH(OCH_3)_3$ to give (+)-2-neoisocaranol (**165a**) and (–)-2-isocaranol (**165b**) in a ratio of 96 : 4; $LiAlH_4$ affords a reverse proportion of the alcohols **165a** and **165b** (33 : 67). Reduction of (–)-caranone (**166**) with aluminum isopropoxide produces the epimeric alcohols (86%), (–)-2-caranol (**167a**) and (+)-2-neocaranol (**167b**), in a ratio

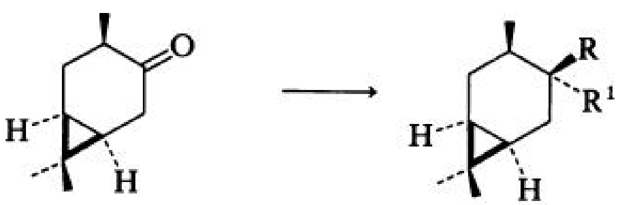


164: R = CH_3, R^1 = H
166: R = H, R^1 = CH_3



165a: R = CH_3, R^1 = H, R^2 = OH, R^3 = H
165b: R = CH_3, R^1 = H, R^2 = H, R^3 = OH
167a: R = H, R^1 = CH_3, R^2 = OH, R^3 = H
167b: R = H, R^1 = CH_3, R^2 = H, R^3 = OH

of 21 : 79; in contrast, $LiAlH_4$ or $LiAlH(OCH_3)_3$ yield the same epimers (86%) in an 88 : 12 ratio. (540) (–)-4-Isocaranone (**168**) is reduced by $LiAlH(OCH_3)_3$ to give (+)-4-neoisocaranol (**169a**) and (–)-4-isocaranol (**169b**) (overall yield

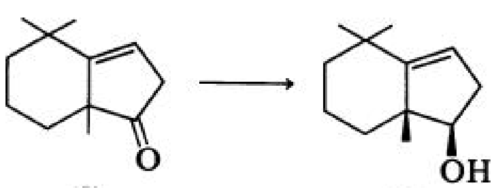


168

169a: R = OH, R^1 = H
169b: R = H, R^1 = OH

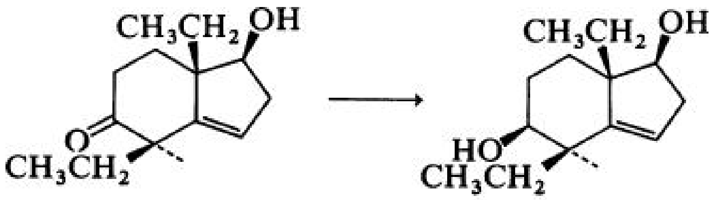
89%) in a ratio of 79 : 21, which changes to 41.4 : 58.6 (overall yield 92%) by using $LiAlH(OC_4H_9\text{-}t)_3$. (541)

Reduction of the bicyclic ketone **170** by $LiAlH_4$ or $LiAlH(OC_4H_9\text{-}t)_3$ in diethyl ether affords the alcohol **171** as the sole product. (542) The latter hydride



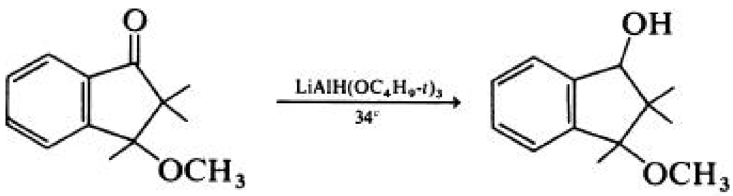
170 **171**

reduces the ketol **172** stereoselectively to give the diol **173**. (543) In the reduction



172 173

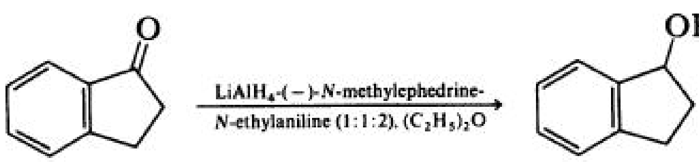
of the methoxyindanone **174** by $LiAlH(OC_4H_9\text{-}t)_3$, the *trans* alcohol is the predominating isomer; $LiAlH_4$ is less stereoselective and forms the *trans* and *cis* alcohols in a reverse ratio (32:68). (182)



174

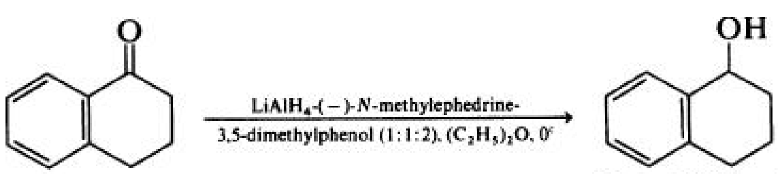
trans:*cis* = 90:10

Chiral lithium alkoxyaluminohydride complexes can be used for the asymmetric reduction of 1-indanone and α - or β -tetralones and their *gem*-dimethyl derivatives to give the corresponding (*S*) and (*R*) alcohols (160, 163, 314, 502, 503, 505, 544) (Eqs. 42 (163) and 43. (160))



(*S*)-(+) (88%, 71% e.e.)

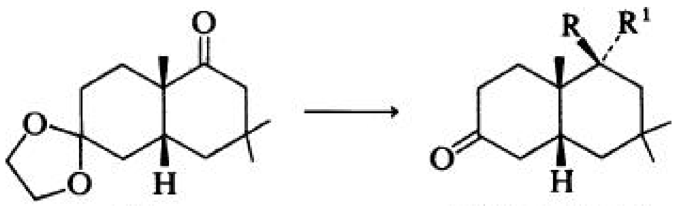
(42)



(*R*)-(−) (68% e.e.)

(43)

High stereoselectivity is noted in the reduction of the *cis*-1-decalone ketal **175** with $LiAlH[OC(CH_3)_2C_2H_5]_3$ affording, after deketalization, the β -hydroxy ketone **176a** as the single product; $LiAlH_4$, $NaBH_4$, and sodium in 2-propanol give **176a** and **176b** in ratios of 60:40, 50:50, and 10:90, respectively. (545)



175

176a: R = OH, R[1] = H
176b: R = H, R[1] = OH

Reduction of the 2-bromo-1-decalone **177** with $LiAlH(OC_4H_9\text{-}t)_3$ proceeds without bromine epimerization at C-2. (389)

177

(55%)

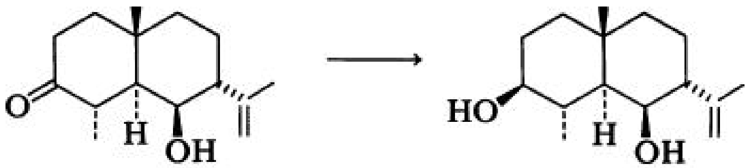
The reaction of the *cis*-2-decalone **178** with complex metal hydrides leads to a mixture of the 2 β - (**179a**) and 2 α -hydroxy (**179b**) decalins. Increasing the

178

179a: R = OH, R[1] = H(70%)
179b: R = H, R[1] = OH (30%)

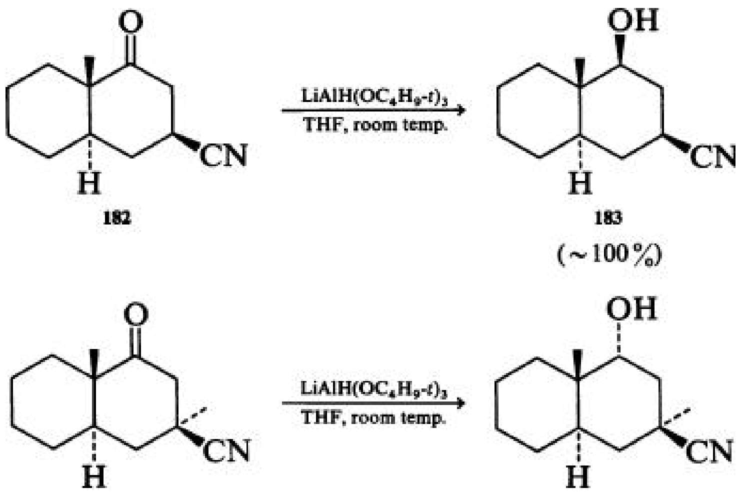
steric requirements of the metal hydride has little effect: the use of $LiAlH[OC(C_2H_5)_3]_3$ or $LiAlH[OC(CH_3)_2C_2H_5]_3$ changes the proportion of the alcohol **179a** to only 72%. (546) Lithium perhydro-9*B*-boraphenalylhydride (547) shows similar stereoselectivity, giving 68% of the 2 β alcohol. (546)

In the *trans*-decalin series, (+)-6 β -hydroxy-4 β , 7 β (H)-eudesm-11-en-3-one (**180**) is converted by treatment with $LiAlH(OC_4H_9\text{-}t)_3$ to the 3 β , 6 β diol **181**. (548) Whereas reduction of the cyano ketone **182** gives the equatorial alcohol



180 → 181

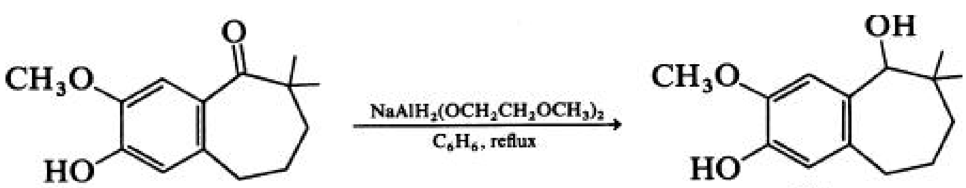
183, that of the ketone **184** with an axial methyl group at C-3 produces the axial alcohol **185**. (549)



182 → 183 (~100%)

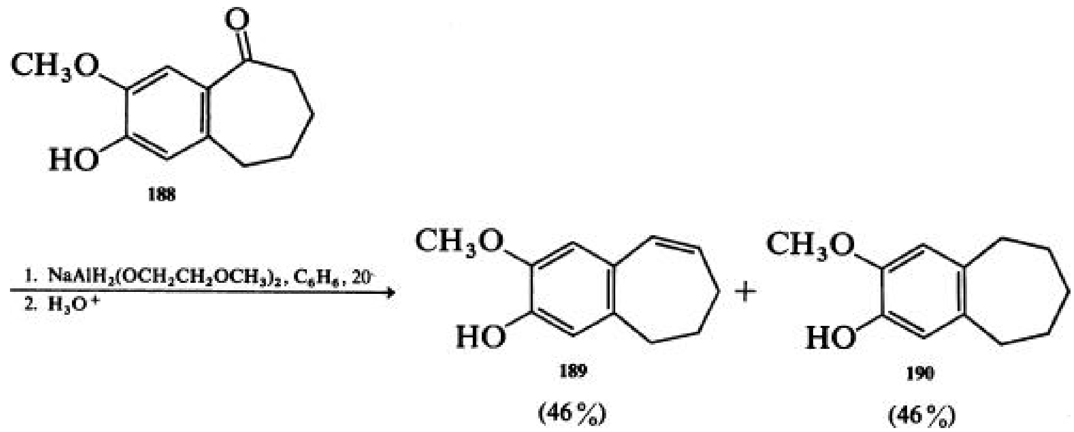
184 → 185 (~100%)

Whereas the benzocycloheptanone **186** is readily converted by $NaAlH_2(OCH_2CH_2OCH_3)_2$ into the 2,5-diol **187**, the ketone **188** without the

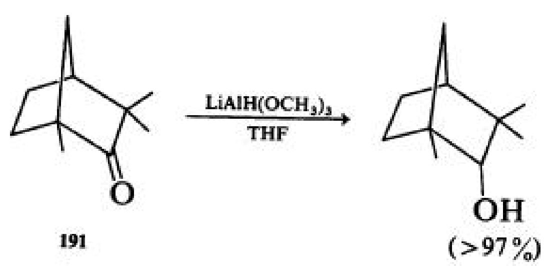


186 → 187 (88%)

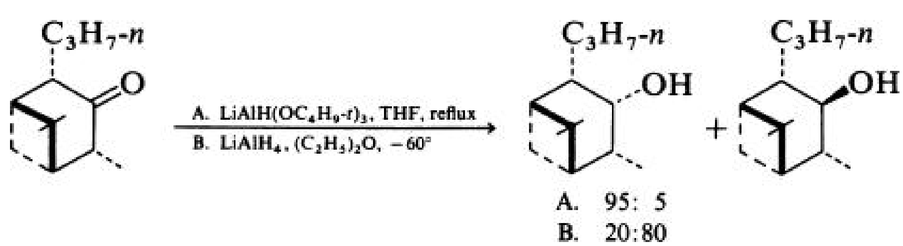
gem-dimethyl groups at C-6 is transformed by the same hydride, presumably by way of the 2,5-diol, into a 1 : 1 mixture of the unsaturated compound **189** and the fully reduced product **190**; $LiAlH_4$ behaves similarly in these reactions. (550)



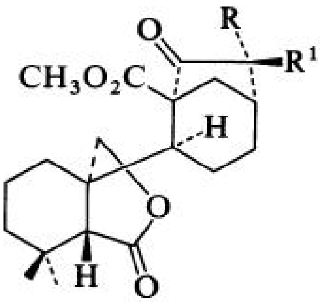
In the reduction of bridged bicyclic ketones, the formation of the predominating isomeric alcohol, which results from the attack by $LiAlH_4$, $LiAlH(OC_4H_9\text{-}t)_3$, or $NaAlH_2(OCH_2CH_2OCH_3)_2$ from the less hindered side of the carbonyl group, can be enhanced in many instances by using $LiAlH(OCH_3)_3$. Thus fenchone (**191**) gives *endo*-fenchyl alcohol, (173, 551) and (+)-isopinocamphone (**192**) yields (+)-neoisopinocampheol as the major



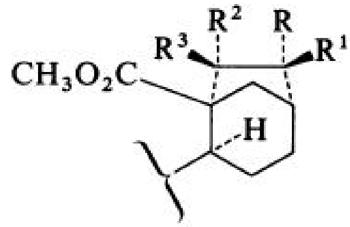
product. (173, 552) In some reactions, a reversal of the stereochemistry is observed when $LiAlH(OC_4H_9\text{-}t)_3$ is used in place of $LiAlH_4$. (196)



Whereas the $NaBH_4$ reduction of the keto lactone ester **193**, a derivative of enmein, in a methanol–water solution gives only the *trans*- β alcohol **194a**,



193: R = CH_3, R^1 = H
195: R = H, R^1 = CH_3



194a: R = CH_3, R^1 = R^2 = H, R^3 = OH
194b: R = CH_3, R^1 = R^3 = H, R^2 = OH
196: R = R^3 = H, R^1 = CH_3, R^2 = OH

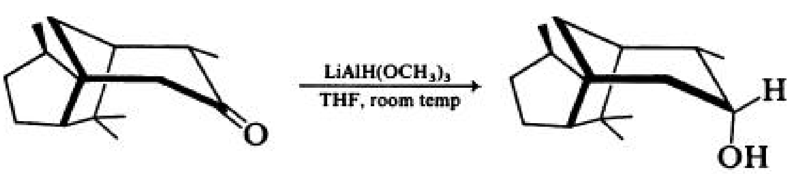
$LiAlH(OC_4H_9\text{-}t)_3$ affords the *cis*- α alcohol **194b** as the sole product. The isomeric keto lactone ester **195** is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ to yield the *trans* alcohol **196**. (553, 554)

3.10.1.3. Polycyclic Ketones

Only a few examples of the use of $LiAlH(OCH_3)_3$ in reductions of polycyclic ketones are known. (–)-3-Thujopsanone reacts with this hydride to form (+)-3-neothujopsanol (**197a**) and (+)-3-thujopsanol (**197b**) in a 96 : 4 ratio, compared with the 81 : 19 ratio obtained with $LiAlH_4$. (555)

197a: R = H, R^1 = OH
197b: R = OH, R^1 = H

The reduction of (–)-isocedran-2-one with $LiAlH(OCH_3)_3$ proceeds almost exclusively from the *exo* side and gives (–)-neoisocedran-2-ol (**198**) in 99% isomeric purity; $LiAlH_4$ yields 93.6% of this product. (556)

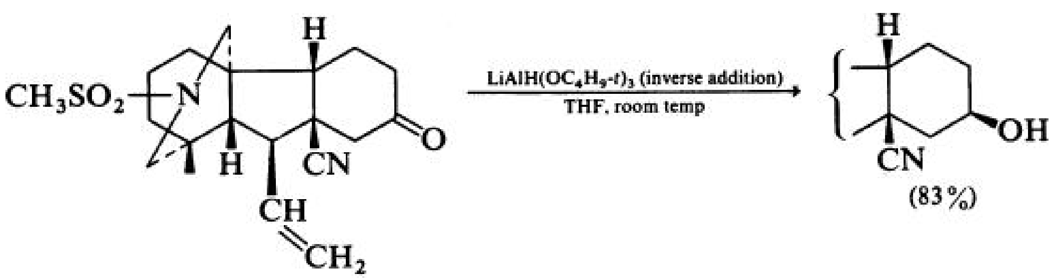


198

Use of $LiAlH(OC_4H_9\text{-}t)_3$ or $NaAlH_2(OCH_2CH_2OCH_3)_2$ provides good stereoselectivity in reductions of polycyclic ketones. For instance, reaction of *endo*-tricyclo[3.2.2.0^{2,4}]nonan-6-one with the former hydride gives the 6-*endo* alcohol **199** as the sole product (79%). (557) Stereospecific reduction of the

199

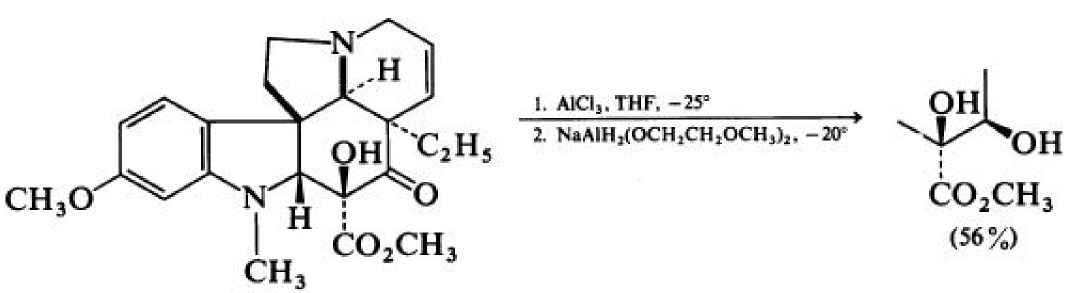
cis-cyano ketone **200** with $LiAlH(OC_4H_9\text{-}t)_3$ yields the 7 β -hydroxycarbonitrile,



200

which on treatment with *p*-toluenesulfonic acid can be readily converted into the corresponding imino lactone (95%). (558)

The reaction of various hydrides with the 3 β -hydroxy ketone ester **201**, an intermediate in the total synthesis of the alkaloid vindoline, produces mixtures of epimeric diols and triols; on the other hand, prior addition of aluminum trichloride to **201** followed by reduction with $NaAlH_2(OCH_2CH_2OCH_3)_2$

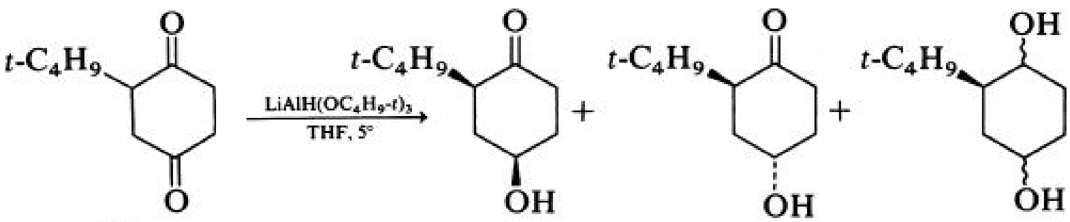


201

gives the 4 β -hydroxy epimer as the sole product. (559) Similar reduction by $NaAlH_2(OCH_2CH_2OCH_3)_2$ of compounds differing from the ketol **201** by the absence of the C_6–C_7 double bond fails to exhibit this stereoselectivity. (560, 561) The high selectivity achieved in the reduction of the ketol **201**–aluminum trichloride complex by this hydride has been attributed to the possible involvement of the C_6 — C_7 double bond rather than of the 3 β -hydroxyl group in the complex formation. (560)

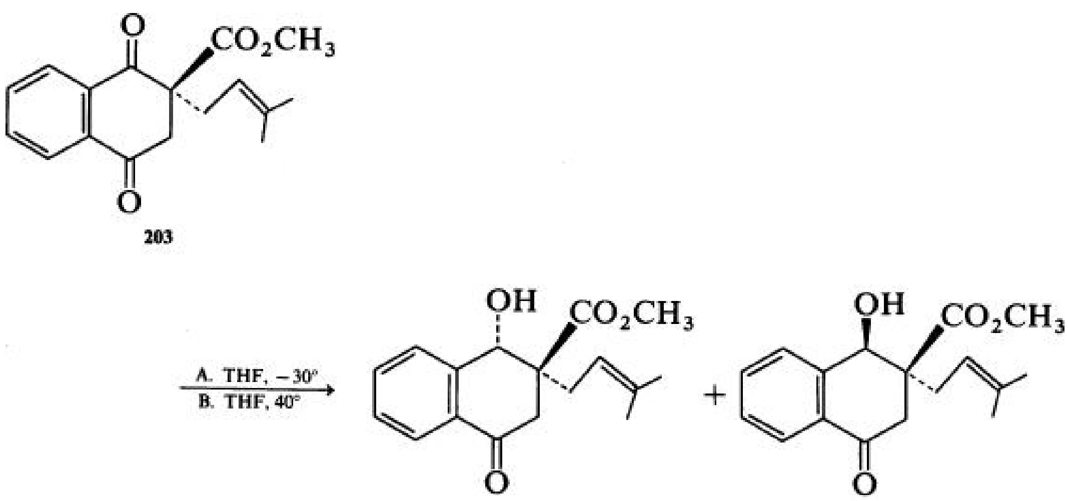
3.11. Reduction of Polyketones

Diketones can be transformed by complex metal hydrides into diols and/or ketols. (158, 172) The capability of $LiAlH(OC_4H_9\text{-}t)_3$ to reduce only one carbonyl group in cyclic diketones is reported (562) and used in the steroid series (383, 384) (see p. 84 in Ref. 135). The regio- and stereoselectivity in the formation of ketols depends markedly, however, on the diketone structure and reaction conditions as well. Thus treatment of the diketone **202** gives a mixture of isomeric ketols and diols. (563) In reduction of the ester diketone **203** by



202 (75%) (15%) (10%)

$LiAlH(OC_4H_9\text{-}t)_3$ the proportion of the stereoisomeric ester ketols **204** and **205** can be influenced by reaction temperature. (564) Whereas $NaBH_4$ transforms

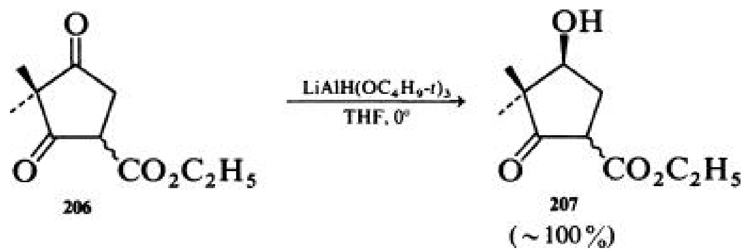


203 204 205

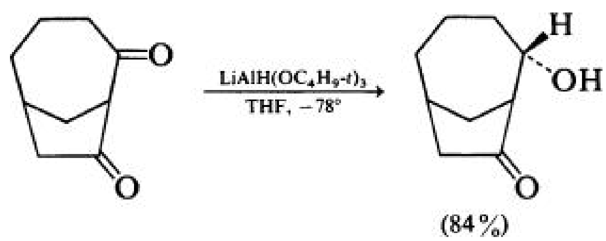
A **204:205** = 34:66

B **204:205** = 95:5

the ester diketone **206** into four isomeric diols in nearly equal proportions, $LiAlH(OC_4H_9\text{-}t)_3$ yields selectively the ester ketol **207**. Formation of an

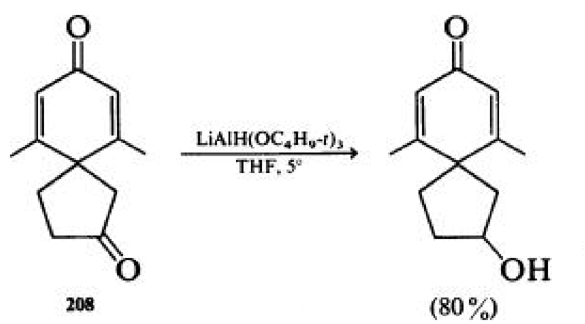


aluminohydride–enolate complex is presumed to prevent hydride attack on the C-2 keto group. (565) Another example of a partial regio- and stereoselective

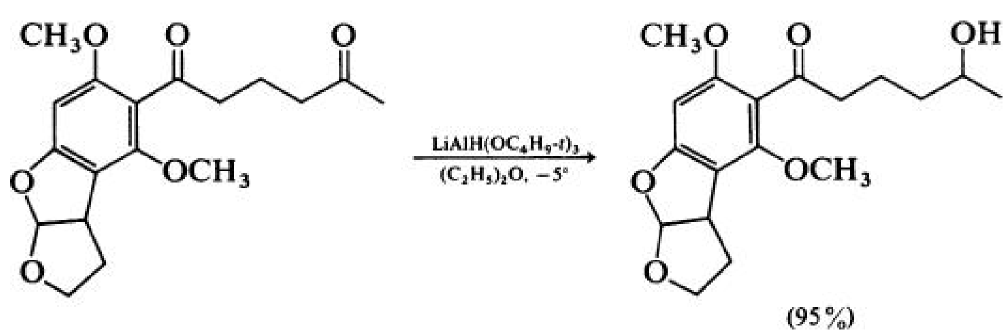


(44)

reduction is shown in Eq. 44. (566) The partial reduction of the diketone **208** is enhanced by lower reactivity of the conjugated keto group. (567)

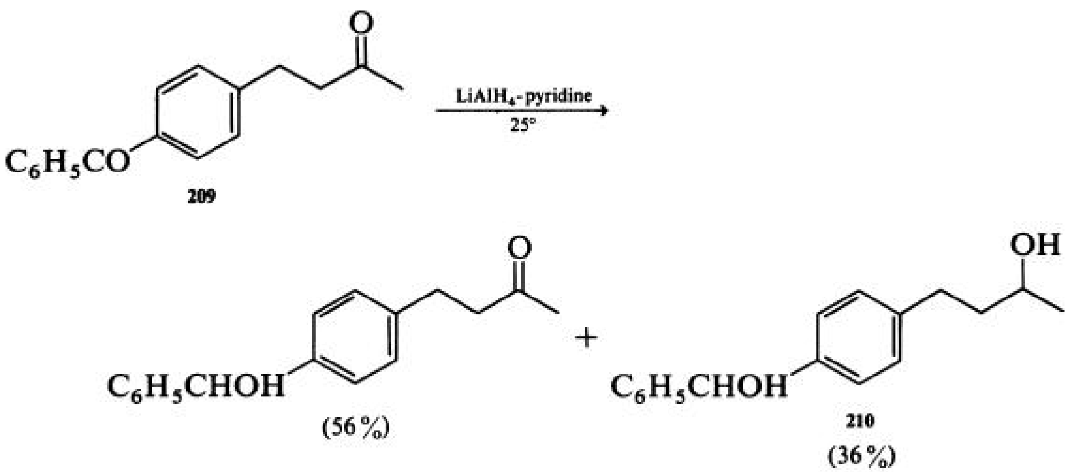


$LiAlH(OC_4H_9\text{-}t)_3$ can also be used for regioselective reduction of aryl aliphatic diketones (Eq. 45); in this case, the hydride attacks predominantly the

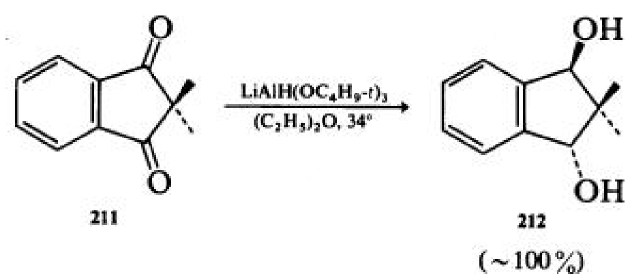


(45)

aliphatic keto group. (568) The $LiAlH_4$–pyridine complex reduces preferentially the aryl keto group in diketone **209** but gives also the diol **210** as byproduct (see pp. 69–70 in Ref. 134); $NaBH_4$ appears to be less selective, giving mainly the diol **210**.

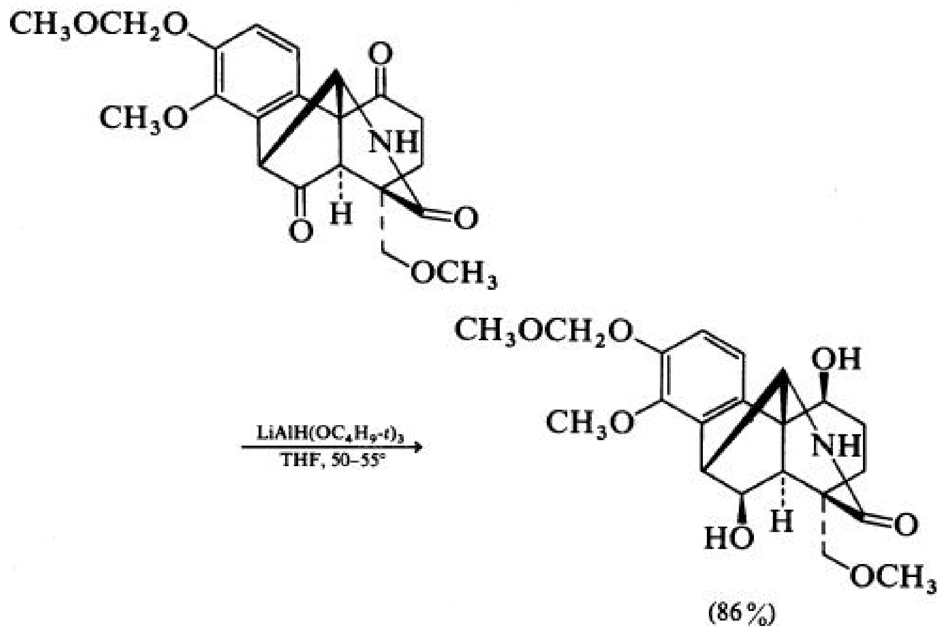


In some cases, cyclic diketones afford only diols, regardless of the reaction conditions. Thus reduction of the diketone **211** gives the *trans* diol **212** as the



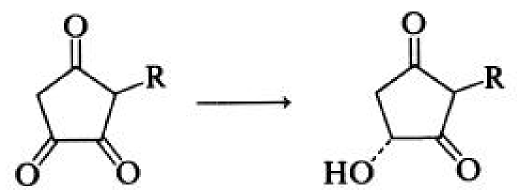
sole product; $LiAlH_4$ is markedly less stereoselective and yields mixtures of the *cis* and *trans* diols. (182, 569)

Another example is shown in Eq. 46. (570)



(46)

Asymmetric reduction of 1,3,4-cyclopentanetriones **213** by the $LiAlH_4$(–)-*N*-methylephedrine reagent leads to (*R*)-4-hydroxy-1,3,-diones **214** in 55–58%



R = *n*-C_3H_7, CH_2=$CHCH_2$, $CH_3O_2C(CH_2)_6$

213 214

e.e.; one of the diones [R = $CH_3O_2C(CH_2)_6$] is an intermediate in the synthesis of prostaglandin PGE_1, another (R = CH_2 = $CHCH_2$) is convertible to unnatural (*R*)-allethrolone. (571-573)

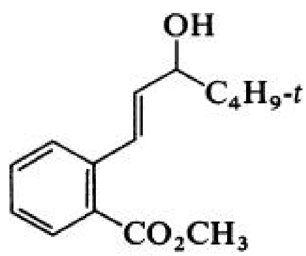
3.12. Reduction of α , β -Unsaturated Ketones

Structure of the α -enone, solvent effects, relative initial concentrations of the reactants, temperature, and softness or hardness of the hydride reagent all play important roles in controlling the ratio of 1,2 to 1,4 addition of metal hydrides to the α , β -unsaturated ketones. These reductions can be controlled to give either 1,2 (Eqs. 47 (574) and 48 (575)) or 1,4 addition with high selectivity.

$$(CH_3)_2C{=}CHCOCH_3 \xrightarrow{LiAlH_4} \underset{(99.6\%)}{(CH_3)_2C{=}CHCHOHCH_3} \quad (47)$$

$$t\text{-}C_4H_9CH{=}CHCOC_4H_9\text{-}t \xrightarrow{LiAlH(OCH_3)_3} \underset{(99\%)}{t\text{-}C_4H_9CH{=}CHCHOHC_4H_9\text{-}t} \quad (48)$$

As an example of the 1,2 addition of $LiAlH(OC_4H_9\text{-}t)_3$ to open-chain α -enones, methyl *o*-[(*trans*-3-oxo-4,4-dimethyl)-1-pentenyl]benzoate forms the allylic alcohol **215** in 86% isolated yield. (576) In the reduction of the *trans*



215

chalcone $C_6H_5CH = CHCOC_6H_5$, however, $LiAlH(OC_4H_9\text{-}t)_3$ is less selective than $LiAlH(OCH_3)_3$ (Eq. 49). (577, 578)

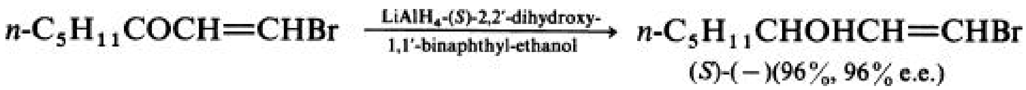
$$\underset{trans}{C_6H_5CH{=}CHCOC_6H_5} \xrightarrow[\text{or B. } LiAlH(OCH_3)_3 \text{ (inverse addition)}]{\text{A. } LiAlH(OC_4H_9\text{-}t)_3 \text{ (inverse addition)}} \underset{\text{A (38\%)} \quad \text{B (94\%)}}{C_6H_5CH{=}CHCHOHC_6H_5}$$

$$+ \underset{216}{C_6H_5(CH_2)_2COC_6H_5} + \underset{217}{C_6H_5(CH_2)_2CHOHC_6H_5} \quad (49)$$

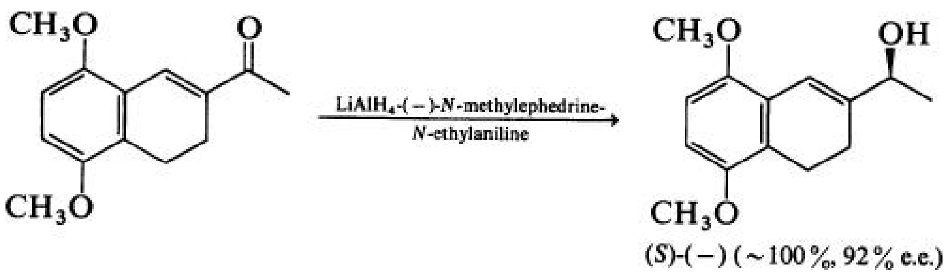
A **216** + **217** (62%)
B **216** + **217** (6%)

Chiral lithium alkoxyaluminohydride complexes can be used to form optically active allylic alcohols (Eqs. 50, (579, 580), 51, (169) and 52 (162, 163, 328)). The

$$C_6H_5CH{=}CHCOCH_3 \xrightarrow{LiAlH_4\text{-}(-)\text{-quinine}} \underset{(R)\text{-}(+)\ (85\%)}{C_6H_5CH{=}CHCHOHCH_3} + \underset{(R)\text{-}(-)\ (15\%)}{C_6H_5(CH_2)_2CHOHCH_3} \quad (50)$$

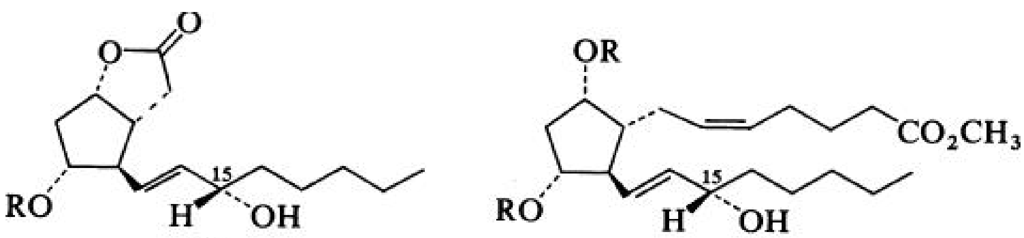


(51)



(52)

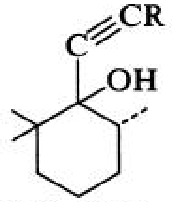
reductant of Eq. 51 can be applied to the side-chain α -enones in the prostaglandin series to prepare the corresponding allylic alcohols such as **218** (R = acetyl, tetrahydropyranyl) (96% yield, 99.4% e.e.) with the natural 15(*S*) configuration. Similarly, the $PGF_{2\alpha}$ derivative **219** (R = 2-tetrahydropyranyl) can be obtained as the single stereoisomer in 76% isolated yield. (169, 479)



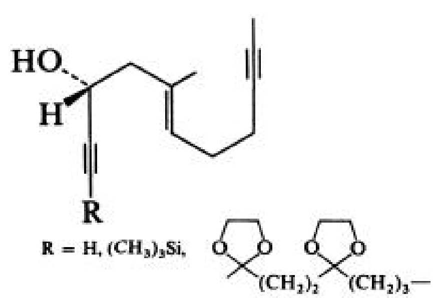
218 219

The $LiAlH_4$–polymer-supported diol and Landor's $LiAlH_4$–monosaccharide complexes, which can be used for transforming analogous prostaglandin α -enones, show substantially lower selectivity. (581)

Reduction of the acetylenic hydroxy ketone **220** with $LiAlH(OCH_3)_3$ leaves the carbon — carbon triple bond intact to give the acetylenic diol **221** in 90% yield. (582)



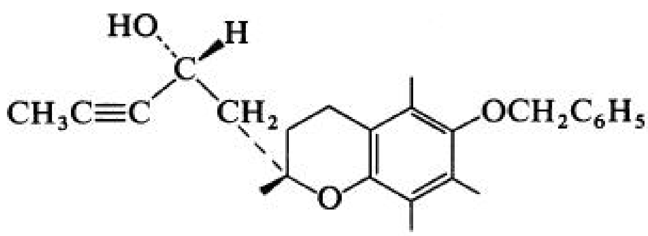
220: R = CH_3CO
221: R = CH_3CHOH



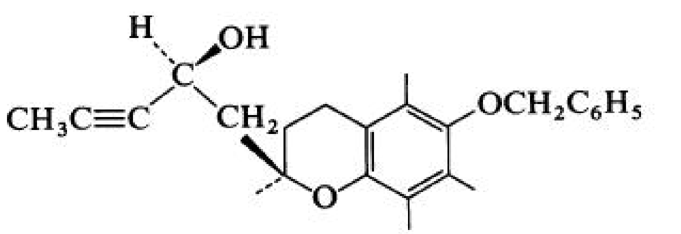
R = H, $(CH_3)_3Si$,

222

Asymmetric reduction of prochiral α , β -acetylenic ketones RC ≡ $CCOR^1$ by the “fresh” Mosher–Yamaguchi, (329, 583, 584) Vigneron–Jacquet, (161, 327, 585) and $LiAlH_4$–(*S*)-(–)- or $LiAlH_4$–*R*-(+)-2,2¢-dihydroxy-1,1¢-binaphthylmethanol (326) complexes as well as by using the reductant of Eq. 52 (328) constitutes an effective method of preparing optically active acetylenic alcohols RC ≡ $CCHOHR^1$ in high yield and high enantiomeric excess. Using the $LiAlH_4$-(2*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol reagent thus makes accessible a wide variety of acetylenic (*R*) alcohols [R = H, CH_3, $(CH_3)_3Si$; R^1 = *i*-C_4H_9, *n*-C_5H_{11}] (95%, 62–96% e.e.), intermediates in the synthesis of tocopherol and prostaglandins. Similarly, the (*R*) alcohols **222** useful in the synthesis of 11 α -hydroxyprogesterone are obtained in 70–95% yield and 78–84% e.e. (583, 584) The same method can be used for reduction of optically active α , β -acetylenic ketones; for instance, the (*R*) alcohol **223a** can be prepared with high enantioselectivity (93%, 90% e.e. referring to the carbinol center) by reduction of the corresponding (*R*)-chromanyl ketone. Reduction of the “natural” (*S*)-chromanyl ketone by $LiAlH_4$–(2*R*,3*S*)-(–)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol produces the (*S*) alcohol **223b** (96%,



223a

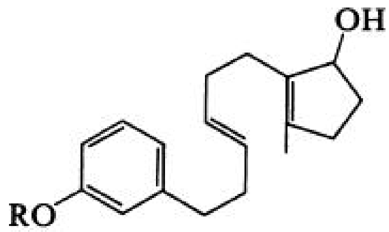


223b

90% e.e.). (329) Asymmetric synthesis (75–90% e.e.) of acetylenic alcohols (+)-RC ≡ $CCHOHR^1$, where R is H or CH_3 and R^1 is C_1 to C_{13} alkyl or cyclohexyl, can be effected by using the Vigneron–Jacquet complex as the chiral reducing agent. (161, 327, 585) Landor's chiral $LiAlH_4$–monosaccharide complexes are less selective and afford the acetylenic (*S*) alcohols in only 4–15% e.e., along with allylic alcohols. (317, 507, 586)

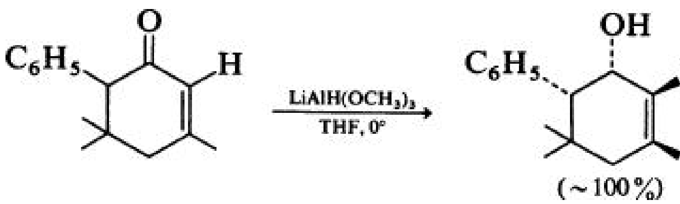
The reagent $NaAlH_2(OCH_2CH_2OCH_3)_2$ favors 1,2 addition to cyclic α -enones.

In the 2-cyclopentenone series, for instance, the allylic alcohols **224a** and **224b** are obtained in nearly quantitative yields by reduction of the

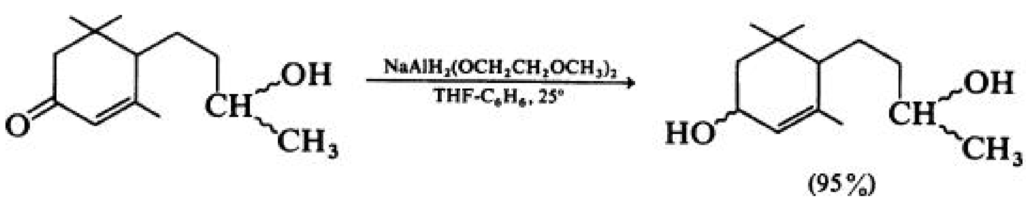


224a: R = H
224b: R = CH_3

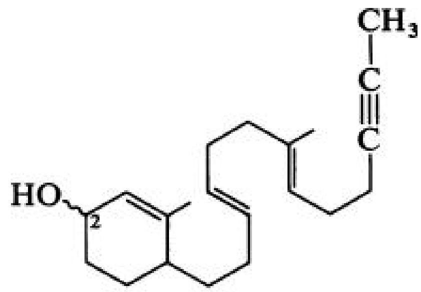
corresponding α -enones with this hydride. (587) The hydrides $LiAlH(OCH_3)_3$ (224) and AlH_3 (228) convert 2-cyclopentenone to 2-cyclopentenol (90%). The former hydride reduces 2-cyclohexenone to 2-cyclohexenol in 95% yield and 3,5,5-trimethyl-6-phenyl-2-cyclohexenone essentially quantitatively to the allylic alcohol (Eq. 53). (195) Reduction of 3,5,5-trimethyl-2-cyclohexenone by the same

 (53)

hydride leads, however, to formation of a mixture of the allylic alcohol (49%) and saturated ketone (45%); (575) on the other hand, $NaAlH_2(OCH_2CH_2OCH_3)_2$ gives the allylic alcohol in 89% yield. (588) Another example is shown in Eq. 54. (589) Essentially quantitative formation of the C-2 epimeric trienynols **225**

 (54)

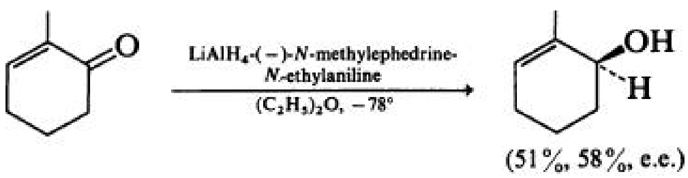
is obtained in the reaction of the corresponding trienyn-4-one with the same hydride. (590, 591) In some instances, such as in the reduction of 9-oxoisolongifolene (**56**) to the unsaturated 9 α and 9 β alcohols, a reversal of stereochemistry



225

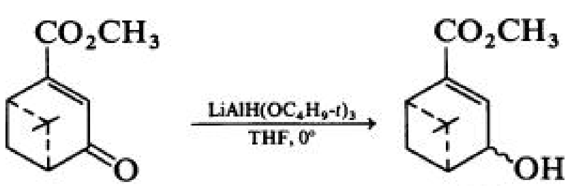
can occur if $NaAlH_2(OCH_2CH_2OCH_3)_2$ is used in place of $LiAlH_4$ or $NaBH_4$ (see pp. 19–20). (290)

Optically active 2-cyclohexenols can be prepared by reduction of prochiral 2-cyclohexenones with a chiral lithium alkoxyaluminohydride complex (Eq. 55). (328)



(55)

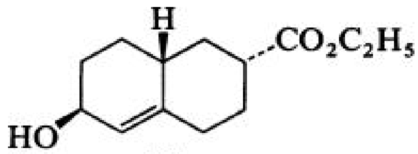
While 2-cyclohexenone is reduced by $LiAlH(OC_4H_9\text{-}t)_3$ predominantly to the saturated ketone (78%), (224) a bridged α -enone ester, methyl 4-oxomyrtenate, is transformed by this hydride nearly quantitatively into a mixture of epimeric allylic alcohols **226**. (592) In the $\triangle^{1,9}$-octalin series, reduction of 6-carbethoxy- $\triangle^{1,9}$-2-octalone by $LiAlH(OC_4H_9\text{-}t)_3$ produces the pseudo-equatorial alcohol



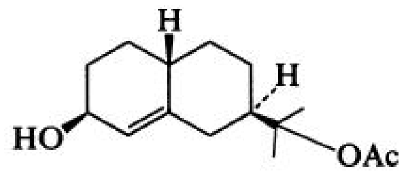
226

(~100%)

227 in 91% yield. (593) The β -allylic alcohol **228** is the product of a stereoselective reduction of the corresponding α -enone by the same hydride. (594) The 10 β

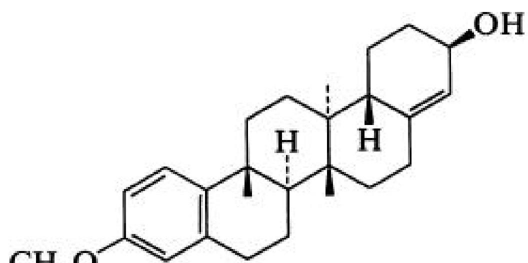


227



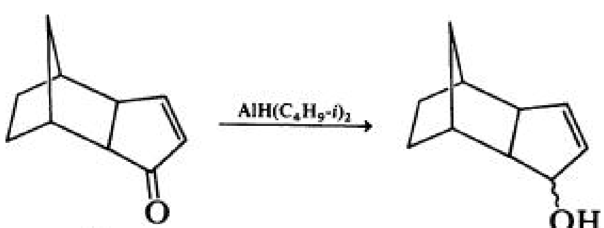
228

alcohol **229** is obtained in 85% yield by reduction of the triterpenic ketone with $LiAlH(OC_4H_9\text{-}t)_3$. (595)



229

Of the other hydride reagents, diisobutylaluminum hydride, (117, 189, 223) 9-borabicyclo[3.3.1]nonane, (125) and aluminum hydride (228) have been used for reductions of α , β -unsaturated ketones to allylic alcohols. For example, 2-cyclopentenone and the tricyclic α -enone **230** are transformed by the former



230

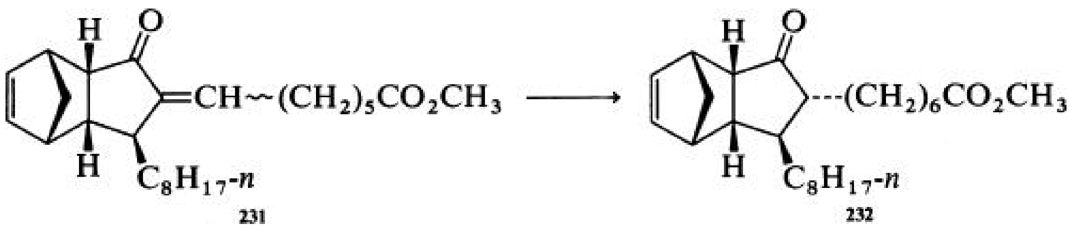
(98 %)

hydride into unsaturated alcohols in 98–99% yields. (596) 2-Cyclopentenone and 2-cyclohexenone are converted essentially quantitatively into the allylic alcohols (isolated yield 85%) by using 9-borabicyclo[3.3.1]nonane in tetrahydrofuran; (125, 485) the reagent leaves intact a great number of functional groups and is thus even more selective than diisobutylaluminum hydride. Reductions with $NaBH_3CN$ in acidic media show substantially lower differentiation between 1,2 and 1,4 addition. (107, 484)

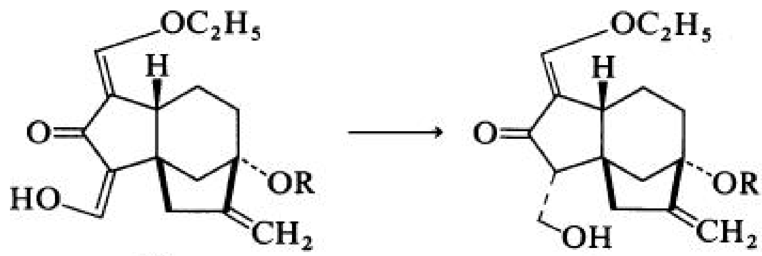
The 1,4 reduction of α , β -unsaturated ketones can be effected with high selectivity by using $AlH(OC_4H_9\text{-}t)_2$, $AlH(OC_3H_7\text{-}i)_2$, $AlH[N(C_3H_7\text{-}i)_2]_2$, or HBI_2 as reducing agents, forming saturated ketones in yields of 90–100%. However,

$AlH[N(C_3H_7\text{-}i)_2]_2$ does not accomplish 1,4 reduction of mesityl oxide or 3,5,5-trimethyl-2-cyclohexenone and shows only low selectivity in the reduction of 2-cyclohexenone or methyl vinyl ketone. The *trans* chalcone $C_6H_5CH=CHCOC_6H_5$ undergoes nearly quantitative 1,4 reduction on treatment with the above hydrides. (189) In the reduction of 9-anthryl styryl ketone and anthracene-9,10-diyl bis(styryl ketone), $LiAlH(OC_4H_9\text{-}t)_3$ affords the saturated ketones as the sole products. (516)

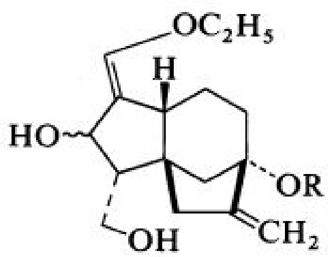
Hydrides such as $LiAlH(OC_4H_9\text{-}t)_3$ and $LiAlH(SC_4H_9\text{-}t)_3$ favor doublebond saturation in 2-cyclopentenones. (224, 225, 228, 231-233, 597) For instance, the $LiAlH(OC_4H_9\text{-}t)_3$ reduction of tricyclic *cis*-fused α -enone esters such as **231**, where steric factors allow only *exo* approach of the bulky hydride, proceeds selectively to give the saturated keto ester **232** with *trans* stereochemistry. (598, 599)



The sequential treatment of the α-enone **233** (R = β -methoxyethoxymethyl) with sodium hydride and $NaAlH_2(OCH_2CH_2OCH_3)_2$ produces the ketol **234** as the single stereoisomer. (600) The reaction of this ketol with the latter hydride in the presence of 1,4-diazabicyclo[2.2.2]octane leads essentially quantitatively to the diol **235**; this reduction is not achieved with $NaBH_4$, $LiBH_4$, lithium tri-*sec*-butylborohydride, or 9-borabicyclo[3.3.1]nonane.

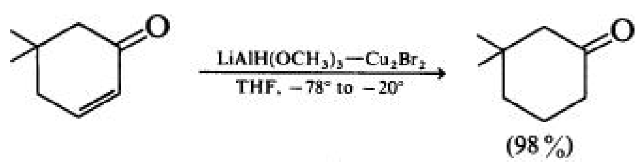


233 234



235

A convenient preparation of copper reagents that provide efficient 1,4 reduction of α -enones (Eqs. 56 and 57) is reported. (575, 601)

 (56)

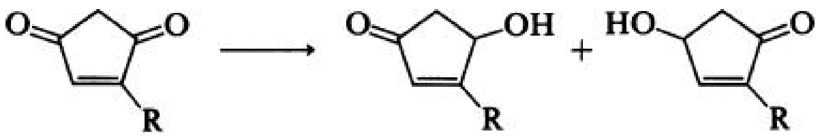
$$t\text{-}C_4H_9CH{=}CHCOC_4H_9\text{-}t \xrightarrow[\text{THF, 2-butanol, }-78\text{ to }-20^\circ]{NaAlH_2(OCH_2CH_2OCH_3)_2-Cu_2Br_2,} t\text{-}C_4H_9(CH_2)_2COC_4H_9\text{-}t \quad (98\%) \tag{57}$$

Steric effects, lower reactivity of a conjugated keto group, (602, 603) and the choice of the reducing agent affect the course of reductions of keto α -enones and di- α -enones. Treatment of the diketone **236** with $LiAlH(OC_4H_9\text{-}t)_3$ gives 78% of the 4-hydroxy- α -enone **237** accompanied by only 3% of the l-hydroxy isomer. On the other hand, reduction of the diketone **238** by the same hydride

236: R = n-C_5H_{11}
238: R = $CH_2{=}CHCH_2$

237: R = n-C_5H_{11}
239: R = $CH_2{=}CHCH_2$

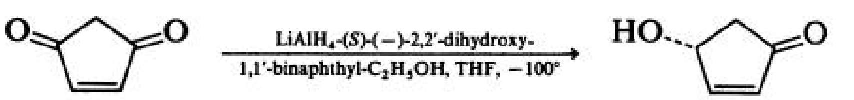
gives unsatisfactory results, and only reduction with using metallic zinc affords **239**. (604) While aluminum isopropoxide reacts with the unsaturated diketone **240** to give the conjugated ketols **241a** and **241b** in a 33 : 67 ratio, $LiAlH(OC_4H_9\text{-}t)_3$ yields **241a** and **241b** in a proportion of 90:10. 605a



R = $(CH_2)_6CO_2C_2H_5$

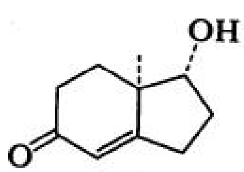
240 **241a** **241b**

Optically active l-hydroxycyclopentenones can be prepared by reducing 1,3-dioxo-4-cyclopentenes with a chiral lithium alkoxyaluminohydride complex. (Eq. 58). 605b,605c



(R)-(+) (67%) (94% e.e.) (58)

The less reactive α -enone grouping remains intact in the reduction of 1,5(6H)-7a α -methyl-7,7a-dihydroindane by $LiAlH(OC_4H_9\text{-}t)_3$ proceeding stereoselectively to form the 1 α -hydroxy- α -enone **242**; (606) the 1 β -hydroxy- α -enone **243** is



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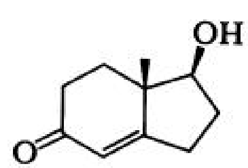
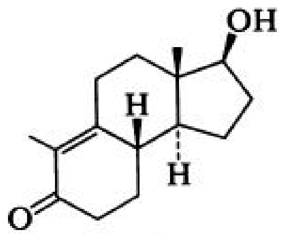


243

produced by reduction of the corresponding 7a β -methyl- α-enedione with $LiAlH(OC_4H_9\text{-}t)_3$. (607, 608) Similarly, selective reduction of the C-17 keto group in racemic 5,17-dioxo-des-A-androst-9-ene by the same hydride gives the 17 β -hydroxy-5-keto derivative **244** in 98% yield; (609) reduction of the (+)-dione leads to (–)-ketol **244**. The L-17 α -hydroxy-5-keto derivative **245** is



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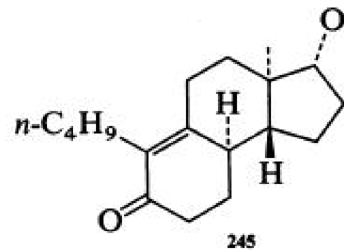
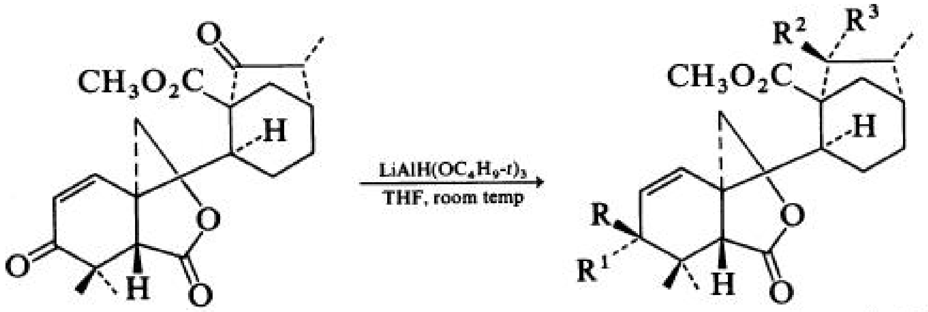


245

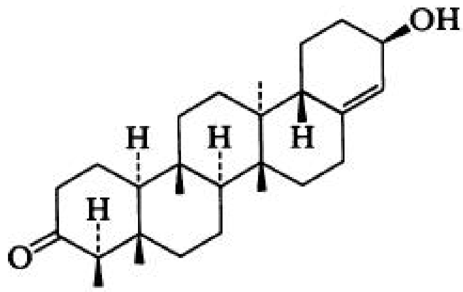
formed selectively by reduction of the corresponding L-5,17-dione with $LiAlH(OC_4H_9\text{-}t)_3$. (610) On the other hand, both the α -enone grouping and the unconjugated keto group in the compound **246** undergo reduction by this hydride to form the diols **247a** and **247b** in a 77:23 ratio, while $NaBH_4$ in absolute tetrahydrofuran gives the epimeric diol **247c** as the sole product. (554)



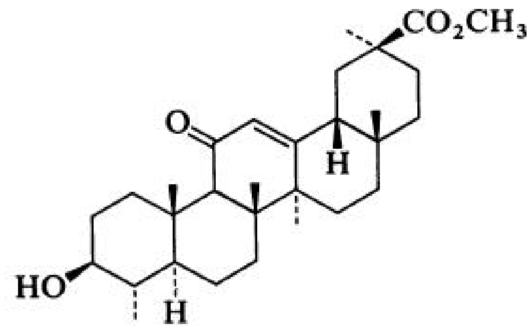
246

247a: R = OH, R^1 = H, R^2 = H, R^3 = OH
247b: R = H, R^1 = OH, R^2 = H, R^3 = OH
247c: R = H, R^1 = OH, R^2 = OH, R^3 = H

$LiAlH(OC_4H_9\text{-}t)_3$ reduces preferentially the α -enone keto group in a pentacyclic enedione to form the keto alcohol **248**. (611) However, reduction of methyl 3,11-dioxo-24-nor-18 β -olean-12-en-30-oate by the same hydride leaves intact the evidently less reactive 11-oxo group and gives the 3 β -hydroxy enone **249**. (612)

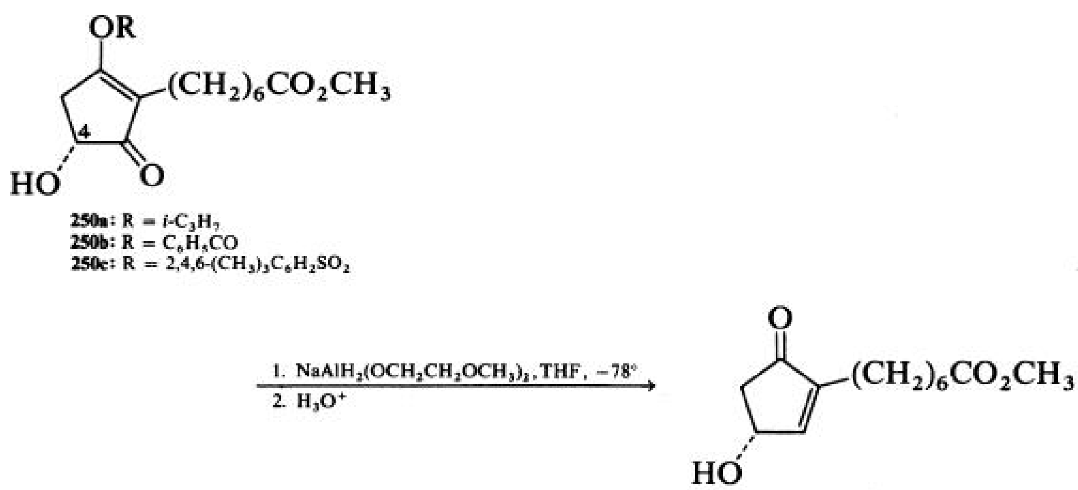


248



249
(74%)

Reduction of enol ethers and enol esters of 1,3-diketones by complex metal hydrides followed by an acid-catalyzed allylic rearrangement of the reduction product (see p. 85 in Ref. 134) is a useful route to α , β -unsaturated ketones. Aliphatic (613, 614) as well as alicyclic α -enones (615-621) have thus been prepared in good yields by low-temperature reduction with the use of $NaAlH_2(OCH_2CH_2OCH_3)_2$. Although a variety of metal hydrides can be used for the conversion of the isopropyl enol ether **250a**, enol benzoate **250b**, or the enol sulfonate **250c** into 2-(6-carbomethoxyhexyl)-(4*R*)-hydroxy-2-cyclo-pentenone (**251**), $NaAlH_2(OCH_2CH_2OCH_3)_2$ is the reagent of choice. The

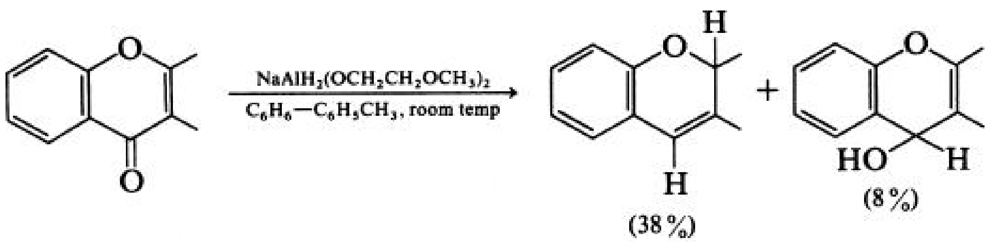


250a: R = $i\text{-}C_3H_7$
250b: R = C_6H_5CO
250c: R = $2,4,6\text{-}(CH_3)_3C_6H_2SO_2$

251
(60%)

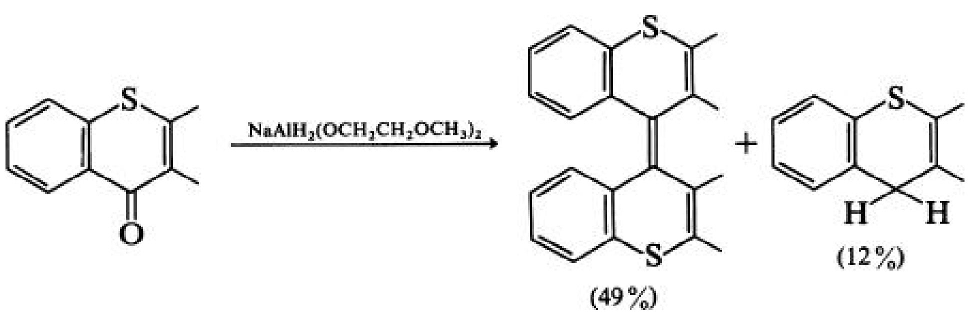
preparation of 2-(6-carbomethoxy-*cis*-2-hexenyl)-(4*R*)-hydroxy-2-cyclopentenone is based on a similar procedure. Compounds **250a–c**, in which the C-4 hydroxyl has been replaced by an ether or ester group, do not undergo reduction by $NaAlH_2(OCH_2CH_2OCH_3)_2$. (619, 620)

In contrast to $LiAlH_4$, $NaBH_4$– $CeCl_3$, or lithium in ammonia, which are either unreactive or give complex product mixtures, $NaAlH_2(OCH_2CH_2OCH_3)_2$ reduces 2,3-dimethylchromone to form 2,3-dimethyl-2*H*-chromene as the major product, along with 2,3-dimethyl-4*H*-chromen-4-ol (Eq. 59). Whereas



(59)

reduction of 2,3-dimethylthiochromone by the latter hydride produces a mixture of the dimer and 2,3-dimethyl-4*H*-thiochromene (Eq. 60), $NaBH_4$– $CeCl_3$



(60)

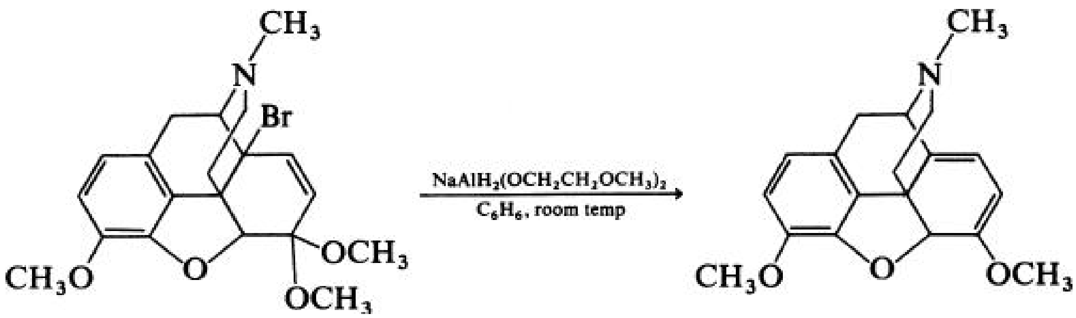
yields 2,3-dimethyl-2*H*-thiochromene along with 2,3-dimethyl-4*H*-thiochromene. (622)

3.13. Reduction of Quinones

Benzoquinone is reduced by $LiAlH(OCH_3)_3$ to hydroquinone. Reduction of anthraquinone by this hydride proceeds less cleanly, giving a mixture of 9,10-dihydroxyanthracene and 9,10-dihydroxy-9,10-dihydroanthracene. (30, 520) However, $LiAlH(OC_4H_9\text{-}t)_3$ reduces anthraquinone to 9,10-dihydroxyanthracene, isolated as the 9,10-diacetoxy derivative (75%). (623) This result contrasts with the course of reduction of 7-deoxydaunomycinone (**137**) by the same hydride, which attacks only the acetyl group in this 9,10-anthraquinone derivative. (492, 493) α-Quinones such as 9,10-dioxophenanthrene, 5,6-dioxochrysene, 4,5-dioxopyrene, and 7,12-dioxobenz[*a*]anthracene, all can be transformed by reduction with $LiAlH(OC_4H_9\text{-}t)_3$ into the corresponding diols, which after acetylation give the corresponding diacetoxy compounds in 78–92% yields. $NaBH_4$ in dimethylformamide or 1,2-dimethoxyethane affords the same products in 90–95% yields. 9,10-Dioxophenanthrene is reduced by $NaAlH_2(OCH_2CH_2OCH_3)_2$ in the same manner, forming, after subsequent acetylation, 9,10-diacetoxyphenanthrene as essentially the sole product. (623) Conversion of α -quinones of condensed aromatic hydrocarbons to *vic*-dihydrodiols can be effected with $LiAlH_4$. (624)

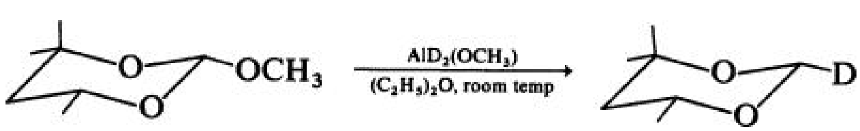
3.14. Reduction of Acetals and Ketals

Acetals and ketals are usually stable toward hydrogenolysis or elimination when treated with $LiAlH(OC_4H_9\text{-}t)_3$, $LiAlH[OC(CH_3)_2C_2H_5]_3$, $LiAlH[OC(C_2H_5)_3]_3$, or $NaAlH_2(OCH_2CH_2OCH_3)_2$ at 0–20°. Consequently, the ketal group is frequently used to protect a keto group in reductions of polyfunctional compounds by these and other hydrides. (470, 471, 473, 545, 546, 625, 626) However, presence of a conjugated carbon — carbon double bond and a bromo substituent in a cyclic ketone ketal such as in 14-bromocodeinone dimethyl ketal changes the picture; treatment of this bromo ketal with $NaAlH_2(OCH_2CH_2OCH_3)_2$ gives thebaine in 75% yield (Eq. 61). The bromo ketal resists the action of $LiAlH_4$ and $NaBH_4$ as well. (627, 628)



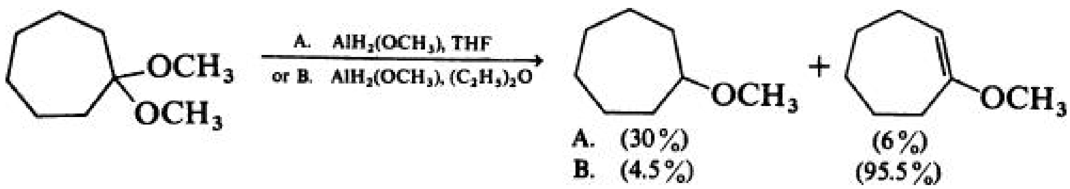
(61)

A detailed study aimed at determining best conditions for hydrogenolysis of acetals and ketals has shown that alkoxychloroaluminum hydrides are only moderately reactive, monoalkoxyaluminum hydrides even less reactive, and dialkoxyaluminum hydrides almost unreactive reagents in this reaction; for hydrogenolysis, diethyl ether and benzene are better solvents than tetrahydrofuran. In a reaction with $AlH_2(OCH_3)$ in refluxing diethyl ether, benzaldehyde dimethyl acetal exhibits higher reactivity than aliphatic ketals, which in turn are more reactive than an aliphatic acetal. (96) A rapid reaction of *cis*-4,4,6-trimethyl-2-methoxy-1,3-dioxane with $AlD_2(OCH_3)$ gives the corresponding deuteriated 1,3-dioxane in 73% yield (Eq. 62). (629) The reactivity of norcamphor ketals decreases in the following order: diethyl ketal > dimethyl ketal > ethylene ketal > isobutylene ketal. (96)



(62)

Ketals of strained cyclic ketones may undergo hydrogenolysis as well as alcohol elimination when treated with $AlH_2(OCH_3)$; thus cyclododecanone dimethyl ketal yields cyclododecyl methyl ether (72%) along with *trans*- and *cis*-1-cyclododecenyl methyl ethers (25%). The proportion of the hydrogenolytic and elimination reaction is strongly solvent dependent (Eq. 63). In a



(63)

reaction of 2,2,4,4-tetramethyl-1,3-dioxolane with alkoxychloroaluminum hydrides in refluxing diethyl ether, the extent of hydrogenolysis decreases from 80 to 11% as the alkoxyl group in the hydride changes from methoxyl to ethoxyl to isopropoxyl to *tert*-butoxyl; at the same time, the percentage of the primary alcohol in admixture with the tertiary alcohol thus produced increases from 3.5 to 24.4%. (96) The less hindered 2-methyl-1,3-dioxolane reacts more rapidly with $AlClH(OC_2H_5)$ to form 2-ethoxyethanol essentially quantitatively; (101) (for hydrogenolytic cleavage of acetals and ketals by “mixed hydrides,” see, e.g., pp. 46–52 in Ref. 27).

4. Experimental Considerations

4.1. The Hydrides

This section describes the preparation and handling of the most frequently used metal alkoxyaluminum hydrides. Solutions of $LiAlH(OCH_3)_3$ in tetrahydrofuran are only temporarily stable, (46, 188) and formation of the hydride *in situ* immediately prior to use is recommended. The procedure involves slow addition of the theoretical quantity of absolute methanol to a standardized solution of $LiAlH_4$ (see, e.g., Ref. 365) in tetrahydrofuran under dry nitrogen at 0°, stirring the mixture until complete dissolution of a little gel formed, and filtering the solution under nitrogen pressure through Celite; (43, 46, 173, 184, 188, 556) $LiAlD(OCH_3)_3$ can be obtained in a similar manner from $LiAlD_4$ and methanol. (173, 240, 575, 630) Concentrated solutions of $LiAlH(OCH_3)_3$ (2 *M*) in bis-(2-methoxyethyl) ether can be prepared in similar fashion; (43) the reaction of $LiAlH_4$ with methanol in diethyl ether proceeds less cleanly. (43, 175) The active hydrogen can be determined with a Toepler pump by measuring evolved hydrogen after decomposition (178) or by iodometric titration (241) according to Felkin. (631) Aluminum is determined by complexation with ethylenediamine-tetraacetic acid and back-titration with zinc acetate (178) or gravimetrically as the 8-hydroxyquinolate. (30, 43)

When $LiAlH(OC_4H_9\text{-}t)_3$ is not available from commercial sources,[*] it can be prepared as above by slowly adding absolute *tert*-butyl alcohol (3.15 equivalents) under nitrogen to a stirred standardized solution of $LiAlH_4$ in diethyl ether; most of the ether is removed by decantation, the last portion of ether and excess *tert*-butyl alcohol is evaporated *in vacuo*, and the white solid is dissolved in the desired solvent. (37, 40, 42, 185, 308, 441) In an atmosphere of nitrogen, the solid hydride is stable at temperatures below 400°; it can be sublimed at 280°/2 mm, and when heated at 165° for 5 hours it retains 92% of the active hydrogen. (40) Solubilities of the hydride (g/100 g solvent at 25°) in various solvents are as follows: (37, 40, 41)

Bis(2-methoxyethyl)ether	41	Diethyl ether	2
Tetrahydrofuran	36	Dibutyl ether	0.5
1,2-Dimethoxyethane	4	Acetonitrile	0.4

The hydride content in tetrahydrofuran solutions (1.5 *M*) (184) does not appear to change after several months' standing under nitrogen. (173, 414) According to another report, the hydride solutions in tetrahydrofuran lose only 2% of their activity when stored at 0° for 120 hours. (203) Iodometric titration is not suitable for analytical standardization of $LiAlH(OC_4H_9\text{-}t)_3$ solutions; the recommended method involves reduction of cyclohexanone and GLC and/or spectral analysis of the extent of reaction. (303, 632) The deuteride $LiAlD(OC_4H_9\text{-}t)_3$ can be prepared *in situ* from $LiAlD_4$ and *tert*-butyl alcohol. (633)

Solid amorphous $NaAlH_2(OCH_2CH_2OCH_3)_2$, which can be obtained by evaporating under nitrogen the benzene (70%)[*] or toluene (70%)[†] solutions of the hydride *in vacuo*, is soluble in benzene, 1,2-dimethoxyethane, or tetrahydrofuran and forms conjugated solutions with toluene (6 and 42%), xylenes (6 and 60%), and diethyl ether (5 and 60%). (72, 197-199) When $NaAlH_2(OCH_2CH_2OCH_3)_2$ is not available commercially, it can be prepared by reaction of $NaAlH_4$ with 2-methoxyethanol or of $NaAl(OCH_2CH_2OCH_3)_4$ or Na_3AlH_6 with $Al(OCH_2CH_2OCH_3)_3$. (72) The hydride is stable in an inert atmosphere for many hours at temperatures below 175°, (72, 204) however, in the presence of compounds that have an aryl-activated benzylic carbon atom, the hydride decomposes above 100° and functions as an alkylating agent. (204-206) Water reacts with $NaAlH_2(OCH_2CH_2OCH_3)_2$ in 1,2-dimethoxyethane to give hydrogen and $NaAlO(OCH_2CH_2OCH_3)_2$; in the presence of excess water, the latter hydrolyzes to $NaAlO_2$ and 2-methoxyethanol, which reacts with the hydride to form hydrogen and $NaAl(OCH_2CH_2OCH_3)_4$. (72, 634) Iodometric titration can be used for determining the active hydrogen in solutions of $NaAlH_2(OCH_2CH_2OCH_3)_2$. (72, 133)

Solutions of alkoxyaluminum hydrides such as $AlH_2(OCH_3)$, $AlH(OCH_3)_2$, or $AlH_2(OC_4H_9\text{-}t)$ are prepared by slowly adding the theoretical amount of the absolute alcohol under nitrogen to a stirred standardized solution of AlH_3 in tetrahydrofuran and by determining the hydride content as above. (30, 88, 89, 96, 100, 178, 189, 334) Solutions of alkoxyaluminum hydrides in benzene can be obtained by careful evaporation of tetrahydrofuran *in vacuo* and addition of anhydrous benzene. (334) Alkoxyaluminum deuterides result from reactions of AlD_3 with the corresponding alcohols (see, e.g., Ref. 629).

4.2. The Solvents and Chemicals

The most frequently used solvents for reductions with metal alkoxyaluminum hydrides are tetrahydrofuran and diethyl ether. Benzene, toluene, *n*-propyl-benzene, *n*-butylbenzene, mesitylene, or *p*-cymene are used for preparation of $NaAlH_2(OCH_2CH_2OCH_3)_2$ solutions. 1,2-Dimethoxyethane, bis(2-methoxyethyl) ether, or tetrahydropyran are used less often. Solvents should be freed of moisture, peroxides, and other impurities. Predried diethyl ether, tetrahydrofuran, 1,2-dimethoxyethane, benzene, and toluene are distilled in an atmosphere of dry nitrogen or argon from dark purple solutions of sodium–benzophenone ketyl under vacuum and stored over Linde 4A molecular sieves. Alternatively, the solvents can be purified by heating at reflux for 4 hours over $LiAlH_4$ and distilled from $LiAlH_4$ under nitrogen; $NaAlH_2(OCH_2CH_2OCH_3)_2$ can be used in place of $LiAlH_4$. (133) Bis(2-methoxyethyl) ether and aromatic hydrocarbons can be refluxed over CaH_2 and vacuum distilled. Anhydrous methanol, *tert*-butyl alcohol, and

2-methoxyethanol used for preparing the metal alkoxyaluminohydride reagents from the parent metal hydrides are purified by distillation from magnesium turnings under nitrogen. Dry methanol and *tert*-butyl alcohol can also be obtained by refluxing over and distilling from magnesium methoxide and sodium *tert*-butoxide, respectively.

4.3. The Apparatus

For most reductions it is convenient to use a three-necked, round-bottomed flask equipped with a drying-tube-capped reflux condenser, a mercury-sealed mechanical stirrer, a thermometer, a nitrogen inlet, and an additional funnel with a pressure-equalizing side arm. For small-scale reductions, magnetic stirrers can be used and the additional funnel replaced by a conventional hypodermic syringe. The glassware should be dried by flame and the apparatus flushed with nitrogen prior to beginning the experiment.

4.4. Selection of Reaction Conditions

Generally, alternative methods of introducing reactants (normal or inverse addition), quenching the reaction mixture (acidic, alkaline, or neutral decomposition), and isolating products are similar to those used in $LiAlH_4$ reductions (see, e.g., pp. 486–489 in Ref. 12 and pp. 12–14 in Ref. 27); the formation of alcohols by decomposition of metal alkoxyaluminum hydrides should be taken into account in the isolation procedure. The usual precautions for handling the hydride solutions (fire hazard), particularly in large-scale operations, and for conducting reactions under anhydrous conditions should be strictly observed. When excess hydride is used, quenching of reaction mixtures is accompanied by hydrogen evolution (fire hazard). The stereochemical course of reductions with metal alkoxyaluminum hydrides is often more dependent on reaction conditions than are reductions by the parent complex metal hydrides. A change in the initial reactant : hydride ratio may cause a reversal of the reduction stereochemistry (see, e.g., Refs. 182 and 569). Strong solvent effects have been observed to influence product distribution depending on the reactant structure and the hydride nature (see, e.g., Refs. 194 and 195). The effect of temperature on stereoselectivity is often more pronounced than in $LiAlH_4$ reductions. Importance of these and other factors should be evaluated in the light of the facts summarized in the preceding sections. A search for analogies in the tabular survey may facilitate the choice of the appropriate experimental conditions.

5. Experimental Procedures

5.1.1.1. (2S,3R)-1-(3,4-Dihydro-6-benzyloxy-2,5,7,8-tetramethyl-2H-1-benzopyran-2-yl)-trans-3-penten-2-ol [Partial Reduction of a 2-Alkyn-1-ol to a 2-Alken-1-ol by $NaAlH_2(OCH_2CH_2OCH_3)_2$] (635, 636)

(2*S*,3*R*)-1-(3,4-Dihydro-6-benzyloxy-2,5,7,8-tetramethyl-2H-1-benzopyran-2-yl)-3-pentyn-2-ol (5.0 g, 13.2 mmol) was dissolved in 50 mL of dry ether and treated dropwise with a solution of 4.1 mL (29 mg-atom of hydrogen) of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (70% solution in benzene) in 10 mL of ether. The resulting solution was refluxed for 17 hours under argon and then cooled in an ice bath. An aqueous solution of sulfuric acid (10%, v/v, 100 mL) was carefully added, the mixture was filtered, the organic phase was washed with ether and water, and the aqueous phase was extracted again with ether. The organic layer was washed with a saturated aqueous solution of sodium bicarbonate and with water and dried over $MgSO_4$. Evaporation to dryness *in vacuo* yielded 5.21 g of crude product that was crystallized from petroleum ether to give 4.23 g (84.6%) of white needles; mp 68–70°, $[\alpha]_D^{25}$ $-24.0°$ (*c* 5.0, $CHCl_3$); *m/e* 380 (M^+); Raman (5145 Å, neat) 1690 cm^{-1}; NMR ($CDCl_3$) δ 1.24 [s, 3, C(2)CH_3], 1.66 (d, C = CCH_3), 1.79–2.02 (m, 2CH_2), 2.06, 2.13, and 2.18 (3 s, 9, 3 ArCH_3), 2.63 (m, CH_2), 3.06 (s, OH), 4.42 (m, C*H*OH), 4.65 (s, ArCH_2O —), 5.58 (m, *trans*-CH = CH, *J* = 15.5 Hz), 7.4 (m, *Ar*CH_2 —).

5.1.1.2. trans-2,2,5-Trimethyl-1-(3-methyl-1,3-butadienyl)-4-cyclopentene-1,3-diol [Partial Reduction of a 4-Alken-2-yn-1-ol to a 2,4-Alkadien-1-ol by $NaAlH_2(OCH_2CH_2OCH_3)_2$] (637)

To a solution of 9.5 g (47.4 mmol) of 2,2,5-trimethyl-1-(3-methyl-3-buten-1-ynyl)-4-cyclopentene-1,3-diol in 350 mL of dry tetrahydrofuran was added under nitrogen and at room temperature 45 mL of a 70% solution of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (318 mg-atom of hydrogen) in benzene and the mixture was stirred for 1 hour. The excess hydride was destroyed with ethyl acetate (100 mL), the mixture was poured into a saturated aqueous solution of ammonium chloride, and the aqueous layer was extracted with ether. The combined organic phases were washed with water and dried. After evaporation of the solvents, the residue (9.3 g, 97%) was recrystallized from ether–hexane to give analytically pure product, mp 100–102°.

5.1.1.3. 1,3-Dihydro-1,3-dimethylbenzo[c]thiophene 2,2-dioxide [Reductive Dechlorination with $NaAlH_2(OCH_2CH_2OCH_3)_2$] (373)

To a solution of 1,3-dihydro-1,3-bis(chloromethyl)benzo[*c*] thiophene 2,2-dioxide (0.584 g, 2.2 mmol) in 50 mL of dry benzene was added 0.80 mL (2.8 mmol) of a 70% benzene solution of $NaAlH_2(OCH_2CH_2OCH_3)_2$ via syringe, and the solution was refluxed for 12 hours. The mixture was cooled to 0° and decomposed with 20% sulfuric acid. The benzene layer was separated, washed with 10 mL of water, dried over potassium carbonate, and concentrated to give the product as a yellow oil in 91% yield (0.480 g); IR (film) 770, 1140, and 1320 cm^{-1}; NMR ($CDCl_3$) δ4.22 (q, 2 H), 1.61 and 1.59 (2 d, 6 *H*, *J* = 7 Hz), 7.3 (s, 4 *H*); *m/e* (rel. intensity) 196 (M^+) (14), 132 (M-SO_2) (100); MS analysis 196.055796 (calc.), 196.057587 (obs.).

5.1.1.4. 1-Fluoro-1-octene [Partial Reductive Defluorination of a gem-Difluoroalkene with $NaAlH_2(OCH_2CH_2OCH_3)_2$] (401)

To a solution of 0.985 g (6.7 mmol) of 1,1-difluoro-1-octene in 3 mL of benzene was added 3.1 mL of a 70% benzene solution of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (11 mmol). The mixture was refluxed for 3 hours, poured into ice water, and acidified with concentrated hydrochloric acid. The organic layer was washed with aqueous sodium chloride solution, dried over $MgSO_4$, and distilled to give the product as a mixture of the *trans* and *cis* isomers (ratio 83:17) in a 78% overall yield (0.68 g), bp 131–134°; ^{19}F NMR (neat) δ 52.0 (d, d, t, *J* = 75.2, 16.9, and 1.9 Hz) and 52.4 (d, d, t, *J* = 75.2, 37.6, and 1.5 Hz) with a 83:17 ratio, respectively.

5.1.1.5. (R)-(+)-2-Cyclohexen-1-ol (Reductive Dehalogenation of a Halo α -Enone with the Masamune Hydride Reagent) (638)

A solution of $LiAlH(OCH_3)_3$ (70 mmol) in tetrahydrofuran (100 mL) was added dropwise under argon to a stirred and ice-cooled suspension of CuI (6.84 g, 36 mmol) in tetrahydrofuran (14 mL), and the mixture was stirred at 0° for 0.5 hour. A solution of (*R*)-(+)-3-iodo-2-cyclohexen-1-ol (0.67 g, 3.2 mmol) was added to the reducing agent in one portion. The mixture was stirred at 0–5° for 2.5 hours, and after standing at room temperature overnight and the addition of 200 mL of ether and 14 mL of methanol, it was filtered through Celite. The filtrate was washed with saturated ammonium chloride solution and the ammonium chloride layer was extracted with ether. The combined organic phase was washed with a saturated solution of sodium bicarbonate, water, and a saturated solution of sodium chloride, dried over K_2CO_3, and concentrated. The residue was distilled *in vacuo* to give the product in 86% yield (0.25 g), bp 81–83° (40 mm); $[\alpha]_D^{25} + 108 \pm 0.8°$ (*c* 1.003 $CHCl_3$); IR (film) 3360 (s), 3030 (m), 2940 (s), 2860 (m), 2840 (m), 1650 (m), 1455 (m), 1440 (m), 1395 (w), 1290 (w), 1170 (w), 1060 (s), 1000 (w), 960 (s), 900 (w), 810 (w), 730 (m) cm^{-1}. The IR spectrum was identical with that of authentic (±)-2-cyclohexen-1-ol.

5.1.1.6. 4-Methoxy-2,3,6-trimethylbenzyl Alcohol [Reduction of an Aldehyde Group to a Hydroxymethyl Group by $NaAlH_2(OCH_2CH_2OCH_3)_2$] (475)

A solution of 40 mL (0.14 mol) of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (70% in benzene) was mixed with stirring with 200 mL of ether and cooled to 0°, and a suspension of 35.6 g (0.2 mol) of 4-methoxy-2,3,6-trimethylbenzaldehyde was added dropwise at 0–10°. The mixture was stirred at 0° for 15 minutes and then allowed to warm to room temperature. Workup after addition of 200 mL of aqueous 20% sodium hydroxide gave the product as off-white crystals in 87% yield (31.4 g), mp 108–110°.

5.1.1.7. 2,4-Dihydroxytoluene [Hydrogenolysis of an Aromatic Aldehyde by $NaAlH_2(OCH_2CH_2OCH_3)_2$] (432)

To a stirred solution of 4.14 g (0.03 mol) of 2,4-dihydroxybenzaldehyde in 25 mL of dry xylene was added dropwise 25 mL of a 70% solution of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (0.09 mol) in benzene. The benzene was removed by distillation, and the mixture was heated to reflux (143°) for 2 hours. After cooling to 0°, 20 mL of ether was added and the excess hydride was destroyed with 20% sulfuric acid. The water layer was extracted with ether, the extracts and the organic layer were washed with water until neutral and dried over sodium sulfate, and the solvents were evaporated. The residue was distilled under reduced pressure to give the pure product in 81% yield (3.01 g), bp 152–153° (12 mm), mp 105–106°.

5.1.1.8. (R)-(+)-1-Phenylethanol (Asymmetric Reduction of an Aryl Alkyl Ketone) (160)

To a stirred 0.88 *M* solution of $LiAlH_4$ (69 mL, 0.06 mol) in dry ether was added dropwise during 1 hour 10.74 g of (–)-*N*-methylephedrine {mp 86–87°, $[\alpha]_D^{25}\ -30.6°$ (*c* 2.61, CH_3OH)} dissolved in 300 mL of ether. After 30 minutes of stirring at room temperature, a solution of 14.64 g (0.12 mol) of 3,5-dimethylphenol in 100 mL of ether was added dropwise within 30 minutes. The mixture was kept at room temperature for 2 hours and cooled to –15°, a solution of 6 g (0.05 mol) of acetophenone in 30 mL of ether was added dropwise during 2 hours, and stirring was continued at this temperature for 1 hour. The cooled reaction mixture was decomposed by successively adding dropwise 2.3 mL of water, 2.3 mL of a 15% sodium hydroxide solution, and 6.9 mL of water. After vigorous stirring for 20 minutes, the mixture was filtered with suction and the granular precipitate was washed thoroughly with ether. The combined ethereal solutions were washed twice with 100 mL of 2 *N* hydrochloric acid, twice with 100 mL of 2 *N* sodium hydroxide, and then with water until neutral, dried over sodium sulfate, and freed of solvents by evaporation. The residue was distilled *in vacuo* to give the pure product in 88.5% yield and 83.8% e.e., bp 100° (18 mm), $[\alpha]_D^{22} + 36.45°$ (neat).

Basification of the acidic extracts and ether extraction gave (–)-*N*-methylephedrine in a nearly quantitative yield and with unchanged optical purity.

5.1.1.9. (–)-2-Neoisocedranol [Reduction of a Polycyclic Ketone with $LiAlH(OCH_3)_3$] (556)

To a solution (30 mL) of $LiAlH_4$ in dry tetrahydrofuran (1.03 *M*) was slowly added anhydrous methanol dissolved in dry tetrahydrofuran until 2400 mL of hydrogen was evolved. A little gel appeared during the addition, and the mixture was stirred vigorously until the gel was dissolved. To this solution of $LiAlH(OCH_3)_3$ was added 3.61 g (16 mmol) of (–)-2-isocedranone in 5 mL of dry tetrahydrofuran with stirring at 0° within 15 minutes and the mixture was stirred at room temperature overnight. Water (1 mL) in 2 mL of tetrahydrofuran was added carefully to destroy the excess hydride. The amount of residual hydride indicated an almost quantitative reaction. To the mixture was added 30 mL of a saturated solution of potassium tartrate, and the aqueous phase was extracted with ether. The combined extracts were washed with brine, dried over magnesium sulfate, concentrated, and distilled to give 3.39 g (93%) of a product that contained 99% of (–)-2-neoisocedranol (**198**) and 1% of (–)-2-isocedranol. An analytical sample of (–)-2-neoisocedranol was obtained by preparative GLC (15% Carbowax 20 M on Chromosorb; 10 ft × 0.25 in.), bp 120° (2 mm), n_D^{25} 1.4511; $[\alpha]_D^{25}$ $-33.4°$ (*c* 37, CCl_4).

5.1.1.10. 2 β -Acetoxy-8-methoxy-4a β -methyl-7-isopropyl-1,2,3,4,4a,9,10,10a α -octahydrophenanthrene [Reduction of a Polycyclic Ketone with $LiAlH(OC_4H_9\text{-}t)_3$ Followed by Acetoxylation] (639)

To a solution of 47.62 g (0.182 mol) of $LiAlH(OC_4H_9\text{-}t)_3$ in 500 mL of dry tetrahydrofuran cooled to –15 to –20° (dry ice- CCl_4) was added via cannula a solution of 40.33 g (0.141 mol) of 8-methoxy-4a β -methyl-7-isopropyl-3,4,4a,9,10,10a α -hexahydro-2(1*H*)-phenanthrenone in 250 mL of dry tetrahydrofuran. After 20 minutes the cooling was removed and stirring was continued at room temperature for 4 hours. With ice-bath cooling 200 mL of aqueous 10% hydrochloric acid was added (with caution at first via syringe). The mixture was filtered and the salts were washed with tetrahydrofuran (100 mL) and ether (400 mL). The combined filtrate and washes were diluted with 250 mL of water and extracted with two 500-mL portions of ether. The ether solution was washed with two 500-mL portions of water and with saturated brine, dried over sodium sulfate, and concentrated to give a viscous oil that was stirred with 500 mL of acetic anhydride and 30 mL of pyridine at room temperature overnight. The volatiles were removed under high vacuum to give a wet solid, which was recrystallized from methanol (200 mL) to give 36.43 g (3 crops) (78%) of the product as colorless needles, mp 90–95°. An analytical sample was prepared by two crystallizations from methanol, giving colorless needles, mp 94.5–96°; IR (CCl_4) 2960, 2940, 2870, 1730, 1410, 1360, 1245, and 1035 cm^{-1}; NMR ($CDCl_3$, TMS, 90 MHz) δ 1.12 (s, 3 *H*), 1.23 (d, 6*H*, *J* = 7 Hz), 1.3–2.4 (m, 9 *H*), 2.03 (s, 3 *H*), 2.6–3.1 (m, 2 *H*), 3.28 (septet, 1 *H*, *J* = 7 Hz), 3.69 (s, 3 *H*), 4.75 (br m, l *H*), and 7.04 (s, 2 *H*); *m/e* (rel. intensity) 331 (12), 330 (M^+) (48), 256 (21), 255 (100), and 43 (63).

5.1.1.11. 2 β -Acetoxy-3 β -hydroxy-5 α -santanolide [Reduction of a Keto Ester Lactone to a Hydroxy Ester Lactone with $LiAlH(OC_4H_9\text{-}t)_3$] (640)

To a stirred solution of 308 mg (1 mmol) of 3-oxo-2 β -acetoxy-5 α-santanolide in 30 mL of dry tetrahydrofuran was added 305 mg (1.2 mmol) of $LiAlH(OC_4H_9\text{-}t)_3$, and stirring was continued at room temperature for 40 minutes to give, as shown by NMR analysis, the 3 β -hydroxy ester lactone in an essentially quantitative yield. The excess reagent was quenched by addition of a 10% ammonium chloride solution, and tetrahydrofuran was evaporated *in vacuo*. The residual mixture was cooled to 0°, decomposed by careful addition of aqueous 10% hydrochloric acid, and extracted with ethyl acetate. The combined extracts were washed successively with aqueous sodium bicarbonate and brine and dried. After evaporation of ethyl acetate *in vacuo*, the residue was recrystallized from ethyl acetate–hexane to give the product as colorless plates, mp 165–167°; $[\alpha]_D^{23} + 94.1°$(*c* 0.35, $CHCl_3$); IR (KBr) 3547, 1758, 1725, and 1242 cm^{-1}; *m/e* (rel. intensity) 310 (M^+) (6.9), 250 ($M^+\text{–}CH_3CO_2H$) (100), and 235 (76.3); NMR ($CDCl_3$, TMS) δ 1.08 (s, 3 *H*, 10-CH_3), 1.19 (d, 3 *H*, *J* = 7 Hz, 4-CH_3 or 11-CH_3), 1.23 (d, 3 *H*, *J* = 7 Hz, 4-CH_3 or 11-CH_3), 2.17 (s, 3 *H*, $OCOCH_3$), 2.30 (1 *H*, OH), 3.23 (dd, 1 *H*, *J* = 10.3 Hz, 3-H), 3.90 (t, 1 *H*, *J* = 10 Hz, 6-H), 5.13 (q, 1 *H*, *J* = 3 Hz, 2-H).

5.1.1.12. (5R, 6R)-6-Hydroxyspiro[4.4]nonan-1-one [Partial Reduction of a Cyclic Dione to a Ketol with $LiAlH(OC_4H_9\text{-}t)_3$] (566)

A solution of 1 g (6.57 mmol) of spiro[4.4]nonane-1,6-dione in 10 mL of dry tetrahydrofuran was added to a stirred solution of $LiAlH(OC_4H_9\text{-}t)_3$ (3 g, 11.8 mmol) in dry tetrahydrofuran (140 mL) under nitrogen at –30°. After 24 hours at this temperature the mixture was carefully acidified with 2 *M* hydrochloric acid and the aqueous layer was extracted with ether. The combined organic phase and extracts were washed with water and dried, and the solvent was evaporated. The recovered oil was largely (95%) one product (GLC), which on distillation *in vacuo* gave the pure ketol, bp 112° (0.05 mm) (air-bath temperature); IR (CCl_4) 3650 and 3520 cm^{-1}. *p*-Nitrobenzoate mp 83.5°; *p*-toluenesulfonate mp 99.5–100.5° [from toluene–petroleum (bp 60–80°)].

5.1.1.13. (–)-17 β -Hydroxy-des-A-androst-9-en-5-one [Reduction of a Polycyclic Keto α -Enone to a Hydroxy α -Enone by $LiAlH(OC_4H_9\text{-}t)_3$] (610)

To a stirred solution of chromatographically pure (+)-des-A-androst-9-ene-5,17-dione (32.3 g, 0.139 mol) in dry tetrahydrofuran (960 mL) was added $LiAlH(OC_4H_9\text{-}t)_3$ (63.6 g, 0.25 mol) at 0° within 10 minutes. The reaction mixture was stirred at 0° for 30 minutes and then carefully treated with 200 mL of 1 : 1 acetone–water. After addition of 650 mL of 3 *N* sulfuric acid, the mixture was extracted with chloroform. The combined extracts were washed with water, a saturated solution of sodium bicarbonate, and water and were then dried over sodium sulfate. The solvents were evaporated to give

32.0 g of crude crystalline product, which was chromatographed on silica gel (640 g). Elution with benzene–ether (4 : 1, 2 : 1, and 1 : 1) afforded 28.5 g of product, which was recrystallized from benzene (150 mL) at room temperature to give 14.4 g (44%) of pure product, mp 165–168°, $[\alpha]_D^{25}$ $-42.7°$(*c* 1.0, $CHCl_3$).

5.1.1.14. (S)-(+)-1-Iodo-trans-1-octen-3-ol (Asymmetric 1, 2 Reduction of an Acyclic Halo α -Enone) (169, 641)

A solution of $LiAlH_4$ (1.84 mL, 1.80 mmol) in dry tetrahydrofuran (0.97 *M*) was placed under argon via syringe in a long-arm single-necked flask capped with a rubber septum. To this solution 1.79 mL of dry ethanol in dry tetrahydrofuran (1.0 *M*) was slowly added and the whole was stirred for 10 minutes. There was then added 510 mg (1.80 mmol) of (S)-(–)-2,2¢-dihydroxy-1,1¢-binaphthyl {$[\alpha]_D^{24}$ $-37.8°$ (*c* 1.0, tetrahydrofuran)} dissolved in 6 mL of dry tetrahydrofuran, and the cloudy solution was stirred at room temperature for 30 minutes. A solution of 1-iodo-*trans*-1-octen-3-one (150 mg, 0.6 mmol) in dry tetrahydrofuran (1 mL) was added at –100° within 15 minutes. The mixture was stirred at this temperature for 2 hours and then at –78° for 1 hour. The excess reducing agent was destroyed by adding 0.5 mL of methanol at –78°, and the mixture was allowed to warm to room temperature. After addition of 1 mL of water and 40 mL of ether, the mixture was stirred for 30 minutes and magnesium sulfate (ca. 10 g) was added. In order to recover the binaphthol the filtrate was concentrated and mixed with 5 mL of hexane; three crystallizations from hexane–ether afforded the pure substance in 91% yield (465 mg). Column chromatography on silica gel (Merck Kieselgel 60, 70–230 mesh ASTM, 40 g) of the mother liquor from the crystallization of binaphthol and elution with petroleum ether–ether (4:1) afforded the product as a colorless oil in 95% chemical yield (143 mg). This product was further purified by bulb-to-bulb distillation at 135–140° (2 mm) to give an analytically pure sample in 97% e.e., $[\alpha]_D^{24} + 9.53°$(*c* 1.56, CH_3OH) {determined by comparison with an authentic sample showing $[\alpha]_D^{24} + 9.87°$(*c* 1.57, CH_3OH), which was obtained by optical resolution}. (642)

5.1.1.15. (–)-1-(5,8-Dimethoxy-3,4-dihydro-2-naphthyl)-(1S)-1-ethanol (Asymmetric 1,2 Reduction of an α -Enone) (162, 643)

To a stirred suspension of $LiAlH_4$ (500 mg, 13.2 mmol) in dry ether (25 mL) was added under argon a solution of (1*R*,2*S*)-(–)-*N*-methylephedrine * {mp 86.5–87.5°, $[\alpha]_D^{20}$ $-29.5°$(c 4.54, CH_3OH)} (2.43 g, 13.6 mmol) in dry ether (45 mL) over 5 minutes and the mixture was heated to reflux with stirring. After 1 hour, an ethereal solution (25 mL) of *N*-ethylaniline (3.30 g, 27.2 mmol) was added to the reaction mixture within 5 minutes and the stirring was continued under reflux for 1 hour. To the stirred ethereal suspension of the reducing agent cooled to –78° was added a solution of 2-acetyl-5,8-dimethoxy-3,4-dihydronaphthalene (mp 104–105°, 930 mg, 4.0 mmol) in dry ether (100 mL) over 5 minutes and the mixture was stirred at –78° for 6 hours. Aqueous 1 *N* hydrochloric acid (54 mL, 54 mmol) was added, the mixture was allowed to warm to room temperature, and the stirring was continued for 15 minutes. The ether layer was separated, and the acidic aqueous phase was extracted with 3 portions (100 mL) of ethyl acetate. The combined organic extracts were washed with 2 portions (100 mL) of aqueous 1% hydrochloric acid, 1 portion (100 mL) of aqueous 5% sodium bicarbonate, twice with 100 mL of water, and once with 100 mL of a saturated solution of sodium chloride and were then dried over magnesium sulfate. Filtration and evaporation of solvents *in vacuo* gave the alcohol in 92% e.e. as a pale yellow crystalline solid (980 mg, ~100%), which was homogeneous according to TLC and NMR spectral analyses, $[\alpha]_D^{20}\ -18.8°$ (*c* 2.48, C_2H_5OH). Recrystallization of this sample from 50 mL of hexane gave 817 mg (87%) of the analytically pure alcohol as colorless needles in essentially 100% optical purity. The optical purity of this sample was ascertained by its spectra recorded in the presence of the chiral shift reagent tris[3-(heptafluoropropylhydroxymethylene)-d-camphorate](III) [Eu(hfc)$_3$)]; mp 88–89°, $[\alpha]_D^{20}\ -20.4°$ (*c* 1.55, C_2H_5OH); IR ($CHCl_3$) 3600, 1260, and 1100 (OH) cm^{-1}; NMR ($CDCl_3$) δ 1.32 [d, 3*H*, *J* = 6 Hz, CH(OH)C*H*$_3$], 2.00–2.36 (m, 2*H*, CH$_2$C*H*$_2$C =), 2.12 (s, 1 *H*, OH), 2.64–2.88 (m, 2 *H*, C*H*$_2$CH$_2$C =), 3.74 (s, 6 *H*, OCH_3), 4.40 [q, 1 *H*, *J* = 6 Hz, C*H*(OH)], 6.60 (s, 2 *H*, Ar), 6.72 (br s, 1 *H*, C*H* =). The acidic aqueous phase resulting from the extractive isolation was made alkaline (pH > 12) with aqueous 10% sodium hydroxide and extracted with 3 portions (100 mL) of ethyl acetate. The combined extracts were washed with brine (200 mL) and dried over anhydrous potassium carbonate. Filtration and evaporation *in vacuo* afforded a 1:2 mixture of (1*R*,2*S*)-(–)-*N*-methylephedrine and *N*-ethylaniline as a mixture of oil and colorless crystals (5.62 g, 98% recovery). Fractional distillation of the mixture gave 2.00 g (83% recovery) of (1*R*, 2*S*)-(–)-*N*-methylephedrine in 99% optical purity {bp 120° (0.01 mm), mp 85–87.5°, $[\alpha]_D^{20}\ -29.1°$ (*c* 4.59, CH_3OH)} and 3.30 g (~100% recovery) of *N*-ethylaniline, bp 87–90° (15 mm).

5.1.1.16. 6 α -Carbetnoxy-1(9)-octal-2 β -ol [1,2 Reduction of a Cyclic α -Enone by LiAlH(OC_4H_9-t)$_3$] (593)

An opaque solution of 18.5 g (90 mmol) of LiAlH(OC_4H_9-*t*)$_3$ in 250 mL of dry tetrahydrofuran was cooled to 0°, and 5.02 g (22.5 mmol) of 6 α -carbethoxy-1(9)-octal-2-one dissolved in 150 mL of dry tetrahydrofuran was added dropwise with stirring within 15 minutes. Stirring was continued for 0.5

hour with cooling and then for 1 hour while warming to room temperature. The reaction mixture was poured into 500 mL of cold water containing 32 mL of concentrated hydrochloric acid. To the solution was added 70 mL of ether, the ether separated, and the aqueous phase extracted with three 150-mL portions of ether; the extracts combined with the organic layer were washed with water until neutral. The combined water washings were extracted with several smaller portions of ether; the extracts were combined, washed with water until neutral, mixed with the organic phase, and dried over magnesium sulfate. Evaporation of solvents *in vacuo* afforded 4.94 g (98%) of a yellow oil. Bulb-to-bulb distillation *in vacuo* (air bath) gave nearly colorless, analytically pure product in 91% yield (4.6 g), bp 105° (0.06 mm); IR (film) 3380, 1730, and 1665 cm^{-1}.

5.1.1.17. 2,2,6,6-Tetramethyl-3-heptanone (1,4 Reduction of an Acyclic α -Enone) (575)

A 70% solution of $NaAlH_2(OCH_2CH_2OCH_3)_2$ (1.34 mL, 4.8 mmol) in benzene was added dropwise to a suspension of 686 mg (4.8 mmol) of cuprous bromide in 12 mL of dry tetrahydrofuran at 0 to –5°. The brown–black suspension was stirred at 0° for 30 minutes and cooled to –78°, and 2.0 mL (1.6 g, 18 mmol) of dry 2-butanol was added at once. A solution of 2,2,6,6-tetramethyl-4-hepten-3-one (200 mg, 1.2 mmol) in 4 mL of dry tetrahydrofuran was added via syringe within 5 minutes, the mixture was stirred at –78° for 10 minutes and then at –20° for 1 hour, quenched by addition of 19.2 mL of water, and poured into 60 mL of saturated aqueous ammonium chloride solution. Ether was added, the blue aqueous phase was separated, the organic phase was washed with water and dried, and the solvents were evaporated. According to GLC analysis and NMR spectrum, the product 2,2,6,6-tetramethyl-3-heptanone obtained in 98% yield (198 mg) was free of 2,2,6,6-tetramethyl-4-hepten-3-ol and of the starting ketone.

5.1.1.18. (R)-(+)-6-Methyl-2-heptyn-4-ol (Asymmetric Reduction of an α , β -Alkynone) (329)

A solution of 1.16 g (4.1 mmol) of (2*S*,3*R*)-(+)-4-(dimethylamino)-3-methyl-1,2-diphenyl-2-butanol (Chirald®)* {$[\alpha]_D^{25} + 8.3°$ (*c* 6, C_2H_5OH)} in 7.5 mL of ether was added dropwise to a stirred mixture of 68.3 mg (1.8 mmol) of $LiAlH_4$ in 45 mL of dry ether at 0° within approximately 2 minutes. The mixture was then stirred for 2 minutes and cooled to –72°, and a solution of 186 mg (1.5 mmol) of 6-methyl-2-heptyn-4-one in 7.5 mL of dry ether was added dropwise within 10 minutes. The mixture was stirred at –72° for 7 hours, allowed to warm to room temperature during 14 hours, and finally decomposed by careful addition of water. The aqueous layer was extracted six times with ether, and the extracts were combined with the ether layer. The organic phase was washed several times with aqueous 1 *N* hydrochloric acid to remove the Chirald® reagent and then with saturated brine, dried over magnesium sulfate, filtered, and concentrated in a rotary evaporator under water–aspirator vacuum. The residue was chromatographed on EM silica gel 60 (0.063–0.2 mm), the acetylenic alcohol was eluted with hexane–ether and evaporatively distilled *in vacuo* at 98–101° (bath temperature)(16 mm) to give the pure product in 99% chemical yield and in 82% e.e., $[\alpha]_{D}^{25} + 12.16°$(*c* 5, $CHCl_3$). Basification of the aqueous acidic extracts with dilute sodium hydroxide followed by saturation with sodium chloride and extraction with ether gave the recovered Chirald® reagent. In a similar experiment, the recovery of Chirald® reagent {$[\alpha]_{D}^{22} + 7.93°$ (*c* 1.6, C_2H_5OH)} corresponded to 94%. (166)

6. Tabular Survey

The information summarized in the tables is an extension of that reviewed in the text and represents an attempt to cover all the literature published to the end of December 1981. Some important reductions by metal alkoxyaluminum hydrides that were published at the beginning of 1982 are also included. Arrangement of the tabular survey follows the division of the hydride reductions according to the type of the functional group, as given in the section entitled “Scope and Limitations.” The absence of tables on isomerization of aromatic hydrocarbons, reduction of peroxides and ozonides, and reduction of quinones was due to the lack of experimental details. Polyfunctional compounds, in which more than one group is attacked by a hydride, can be found in tables pertaining to reduction of each specific functional group. Exceptions are functionalized steroids, carbohydrates, and organometallic compounds, which are not treated in this chapter. Within each table the compounds are listed according to increasing carbon number and complexity of the molecular formula according to the *Chemical Abstracts* convention. The conditions stated refer in most cases only to the reduction itself. If a reference contains more than one set of conditions for the reduction of one reactant, only those providing the best product yield are presented. Yields and percent enantiomeric excess (if available) are given in parentheses, and numbers not in parentheses correspond to product ratios. A dash indicates that no yield is given in the reference(s). When there is more than one reference for a given reactant–hydride combination, the first reference is the one that gives the best recorded yield. A list of standard abbreviations used throughout the tables follows:

Ac	acetyl
9-BBN	9-borabicyclo[3.3.1]nonane
BCGF	3-*O*-benzyl-1,2-*O*-cyclohexylidene- α -D-glucofuranose
BME	bis(2-methoxyethyl) ether
(+)-CN	(+)-cinchonine
Cp	cyclopentadienyl
(–)-*threo*-DADE	(1*S*,2*S*)-(–)-*threo*-2-dimethylamino-1,2-diphenyl-ethanol
(+)-*erythro*-DADE	(1*S*,2*R*)-(+)-*erythro*-2-dimethylamino-1,2-diphenyl-ethanol
(–)-DAMP	(*R*)-(–)-3-dimethylamino-2-methyl-1-propanol
(+)-DBD	(2 *R*, 3*R*)-(+)-1,4-bis(dimethylamino)-2,3-butanediol
(–)-DBD	(2*S*,3*S*)-(–)-1,4-bis(dimethylamino)-2,3-butanediol
(–)-DBN	(*S*)-(–)-2,2¢-dihydroxy-1,1¢-binaphthyl
(+)-DBN	(*R*)-(+)-2,2¢-dihydroxy-1,1¢-binaphthyl

(+)-DMDB	(*S*,3*R*)-(+)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol (Chirald®)
(–)-DMDB	(2*R*,3*S*)-(–)-4-dimethylamino-3-methyl-1,2-diphenyl-2-butanol
DME	dimethoxyethane
DMP	3,5-dimethylphenol
DPB	(2*S*,3*S*)-1,4-dipyrrolidino-2,3-butanediol
EAN	*N*-ethylaniline
e.e.	enantiomeric excess
(–)-EPH	(–)-ephedrine
ether	diethyl ether
EtOH	ethanol
LAH	lithium aluminum hydride
LTBA	lithium tri-*tert*-butoxyaluminum hydride
LTMA	lithium trimethoxyaluminum hydride
MeOH	methanol
Ms	methanesulfonyl
NM	(+)-neomenthyl
(–)-NME	(–)-*N*-methylephedrine
o.p.	optical purity
(+)-PAB	(1*R*)-(+)-3-*endo*-phenylamino-2-*exo*-hydroxybornane
Py	pyridine
(–)-QN	(–)-quinine
(+)-QND	(+)-quinidine
r.t.	room temperature
SAH	sodium aluminum hydride
SMEAH	sodium bis(2-methoxyethoxy)aluminum hydride
THF	tetrahydrofuran
THP	tetrahydropyranyl
Ts	*p*-toluenesulfonyl

Table I. Reactions of Hydrocarbons

View PDF

Table II. Reduction of Halogen Compounds

View PDF

Table III. Reduction of Unsaturated Alcohols

View PDF

Table IV. Hydrogenolysis of Aromatic Alcohols

View PDF

Table V. Reductive Cleavage of Ethers

View PDF

Table VI. Reduction of 1,2-Oxides

View PDF

Table VII. Reduction of Aldehydes

View PDF

Table VIII. Reduction of α , β -Unsaturated Aldehydes

View PDF

Table IX. Reduction of Alkyl and Aryl Ketones

View PDF

Table X. Reduction of Monocyclic Ketones

View PDF

Table XI. Reduction of Bicyclic Ketones

View PDF

Table XII. Reduction of Polycyclic Ketones

View PDF

Table XIII. Reduction of Polyketones

View PDF

Table XIV. Reduction of α , β -Unsaturated Ketones

View PDF

Table XV. Reduction of Acetals and Ketals

View PDF

TABLE I. REACTIONS OF HYDROCARBONS

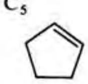
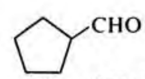
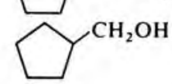
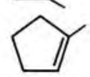
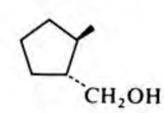
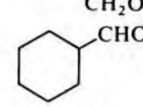
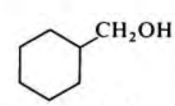
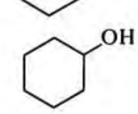
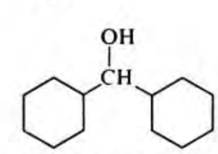
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_2			
$CH_2{=}CH_2$	1. BH_3, THF 2. LTMA, THF, CO 3. CH_3CO_2H 4. NaOH, H_2O_2	$(C_2H_5)_2CHOH$ (98)	644
C_4			
$NCCH_2CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$NC(CH_2)_3CHO$ (72)	645
$CH_3CH{=}CHCH_3$	1. BH_3, THF 2. LTMA, CO, H_2O_2	s-C_4H_9CHO (94)	646,647
	1. BH_3, THF 2. LTMA, THF, CO 3. HCl 4. NaOH, H_2O_2	$(s$-$C_4H_9)_2CHOH$ (82)	644
$(CH_3)_2CH{=}CH_2$	1. BH_3, THF 2. LTMA, CO, H_2O_2	i-C_4H_9CHO (91)	646,647
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	" (52)	647,648
	1. BH_3, THF 2. LTMA, THF, CO 3. HCl 4. NaOH, H_2O_2	$(i$-$C_4H_9)_2CHOH$ (84)	644
C_5			
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	 (79)	647,648
	1. 9-BBN, THF 2. LTMA, CO 3. KOH, EtOH	 (79)	648
$(CH_3)_2C{=}CHCH_3$	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	i-$C_3H_7CH(CH_3)CHO$ (60)	647,648
C_6			
$CH_2{=}CH(CH_2)_2CH{=}CH_2$	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	$OHC(CH_2)_6CHO$ (78)	647,648
	$LiAlH(OC_2H_5)_3$, THF, 40°, 2 hr	No reaction	649
	1. 9-BBN, THF 2. LTMA, CO 3. NaOH, EtOH	 (50)	650
	1. BH_3, THF 2. LTMA, CO, H_2O_2	 (93)	646,647
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	" (81)	648
	1. 9-BBN, THF 2. LTMA, CO 3. KOH, EtOH	 (~81)	648
	1. SMEAH, Cp_2ZrCl_2, toluene-THF, 40°, 24 hr 2. t-C_4H_9OOH, $C_2H_4Cl_2$, r.t., 1 hr	 (63)	651
	1. BH_3, THF 2. LTMA, THF, CO 3. HCl 4. NaOH, H_2O_2	 (80)	644
$CH_3CO_2(CH_2)_2CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$CH_3CO_2(CH_2)_4CHO$ (84)	645
$C_2H_5O_2CCH_2CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$C_2H_5O_2C(CH_2)_3CHO$ (70)	645

TABLE I. REACTIONS OF HYDROCARBONS (*Continued*)

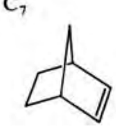
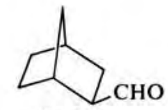
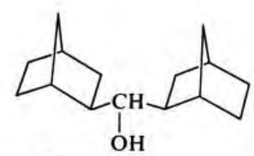
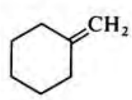
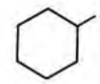
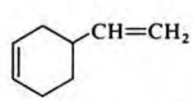
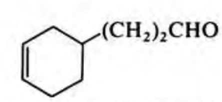
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
n-$C_4H_9CH{=}CH_2$	1. BH_3, THF 2. LTMA, CO, H_2O_2	n-$C_6H_{13}CHO$ (98)	647,646
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	" (93)	647,648
$(CH_3)_2C{=}C(CH_3)_2$	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	No reaction	648
C_7			
	1. BH_3, THF 2. LTMA, CO, H_2O_2	 (87)	646,647
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	" (59)	648,647
	1. BH_3, THF 2. LTMA, THF, CO 3. HCl 4. NaOH, H_2O_2	 (85)	644
	SMEAH, Cp_2TiCl_2, THF, r.t., 2 hr	 (70)	335
C_8			
$C_6H_5CH{=}CH_2$	1. SMEAH, Cp_2TiCl_2, THF, r.t., 2 hr 2. D_2O	$C_6H_5CHDCH_3$ (65)	335
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	$C_6H_5(CH_2)_2CHO$ (84)	648,647
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	 (83)	648,647
n-$C_3H_7C{\equiv}CC_3H_7$-n	SMEAH, Cp_2TiCl_2, THF, r.t., 2 hr	n-$C_3H_7CH{=}CHC_3H_7$-n (99)	335
n-$C_6H_{13}CH{=}CH_2$	1. SMEAH, Cp_2TiCl_2, THF, r.t., 2 hr 2. I_2, C_6H_6	n-$C_8H_{17}I$ (95)	335
	1. SMEAH, Cp_2ZrCl_2 THF–toluene, 23°, 4 hr 2. t-C_4H_9OOH, $C_2H_4Cl_2$, r.t., 1 hr	n-$C_8H_{17}OH$ (76)	651
	1. BH_3, THF 2. LTMA, THF, CO 3. HCl 4. NaOH, H_2O_2	$(n$-$C_8H_{17})_2CHOH$ (78)	644
n-$C_3H_7CH{=}CHC_3H_7$-n	1. SMEAH, Cp_2ZrCl_2, THF–toluene, 40°, 24 hr 2. t-C_4H_9OOH, $C_2H_4Cl_2$, r.t., 1 hr	n-$C_8H_{17}OH$ (73)	651
C_{10}			
$C_6H_5CO_2CH_2CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$C_6H_5CO_2(CH_2)_3CHO$ (74)	645
$C_6H_5C(C_2H_5){=}CH_2$	SMEAH, $(MCp)_2TiCl_2$, n-C_5H_{12}–THF–toluene, 20°[a]	$C_6H_5C_4H_9$-s (−)(15% e.e.) (S)-(+)	652a
	SMEAH, $(NMCp)_2TiCl_2$, n-C_5H_{12}–THF–toluene, 20°	$C_6H_5C_4H_9$-s (−)(10% e.e.) (R)-(−)	652a
C_{11}			
$NC(CH_2)_8CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$NC(CH_2)_{10}CHO$ (83)	645

TABLE I. REACTIONS OF HYDROCARBONS (*Continued*)

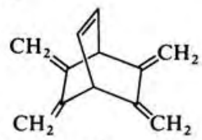
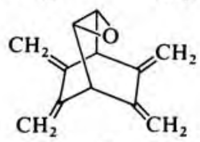
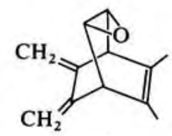
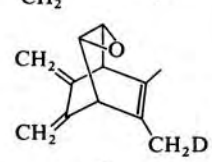
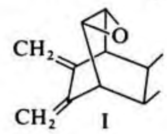
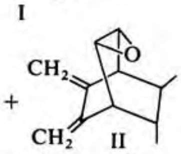
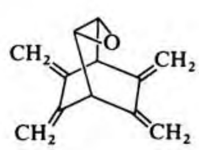
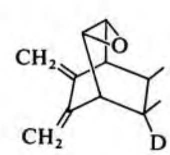
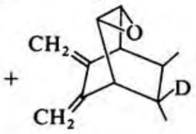
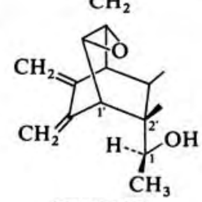
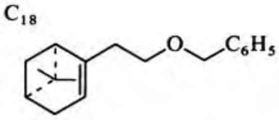
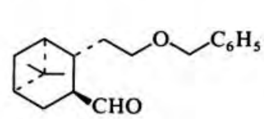
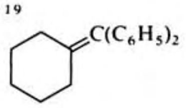
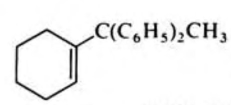
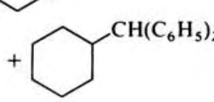
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{12}			
	SMEAH	No reaction	652b
	1. SMEAH, toluene, 20°, 1 hr 2. H_2O	 (85)	652b
"	1. SMEAH, toluene, 20°, 1 hr 2. D_2O	 (97)	652b
"	1. SMEAH, toluene, 20°, 1 hr 2. HCl, Ac_2O, 0°	 I +  II I : II = 60 : 40 (66)	652b
	1. SMEAH, toluene, 20°, 1 hr 2. DCl, D_2O, 0°	 +  (–)	652b
"	1. SMEAH, toluene, 20°, 30 min 2. CH_3CHO, 0° 3. 20°, 3 hr 4. H_2O	 (37) (1′S,2′R,1S)	652b
$CH_3O_2C(CH_2)_8CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$CH_3O_2C(CH_2)_{10}CHO$ (85)	645
C_{13}			
$CH_3CO_2(CH_2)_9CH{=}CH_2$	1. 9-BBN, THF 2. LTBA, CO, H_2O_2	$CH_3CO_2(CH_2)_{11}CHO$ (87)	645
C_{14}			
n-$C_6H_{13}CH{=}CHC_6H_{13}$-$n$	1. SMEAH, Cp_2ZrCl_2, THF–toluene, 40°, 72 hr 2. t-C_4H_9OOH, $C_2H_4Cl_2$ r.t., 1 hr	n-$C_{14}H_{29}OH$ (70) + n-$C_{14}H_{30}$ (10)	651
C_{18}			
	1. 9-BBN, THF 2. LTMA, CO, H_2O_2	 (81)	653

TABLE I. REACTIONS OF HYDROCARBONS (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{19}			
	SMEAH, *p*-cymene, reflux, 26 hr	 (42) +  (31)	208
C_{30}			
n-$C_{14}H_{29}CH{=}CHC_{14}H_{29}$-$n$	1. SMEAH, Cp_2ZrCl_2, THF–toluene, 40°, 96 hr 2. t-C_4H_9OOH, $C_2H_4Cl_2$, r.t., 1 hr	n-$C_{30}H_{61}OH$ (68) + n-$C_{30}H_{62}$ (10) + n-$C_{29}H_{59}OH$ (2)	651

[a]M = (−)-Menthyl

TABLE II. REDUCTION OF HALOGEN COMPOUNDS

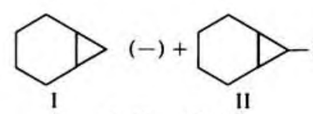
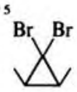
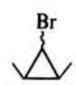
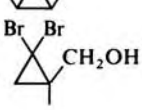
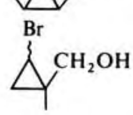
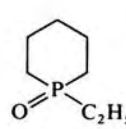
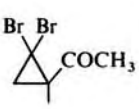
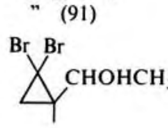
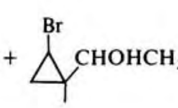
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_1			
$CHBr_3$	SMEAH, cyclohexene, C_6H_6	 I (−) + II (−); I : II = 60 : 40	390
C_2			
C_2H_5Br	SMEAH, $C_6H_5(CH_3)P(O)OCH_3$, toluene, 60°, 17 hr	$C_6H_5(CH_3)P(O)C_2H_5$ (41)	374,375
C_5			
	SMEAH, C_6H_6	 (19)	392
	SMEAH, C_6H_6, 88°, 2–5 hr	 (52) + $CH_2{=}C{=}C(CH_3)CH_2OH$ (28)	391
$Br(CH_2)_5Br$	SMEAH, $C_2H_5P(O)(OC_2H_5)_2$, C_6H_6, reflux, 27 hr	 (−)	377
C_6			
C_6H_5I	$NaAlH(OC_2H_5)_3$, THF, 30 min	C_6H_6 (96)	54
	$NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$, toluene, 80°, 2 hr	" (91)	371
	SMEAH, C_6H_6, 88°, 2–5 hr	 (82) +  (10)	391

TABLE II. REDUCTION OF HALOGEN COMPOUNDS (*Continued*)

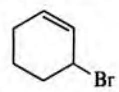
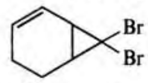
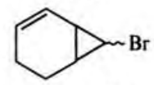
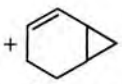
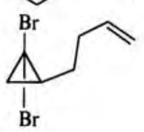
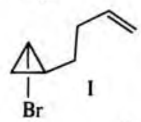
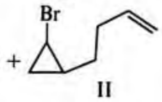
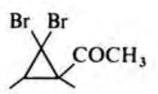
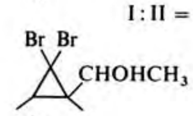
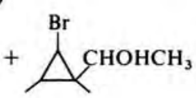
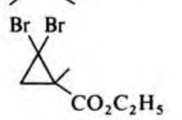
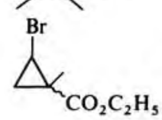
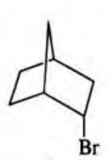
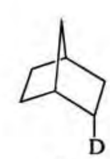
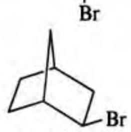
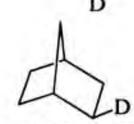
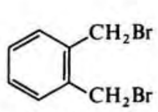
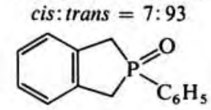
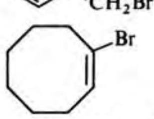
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTMA + CuI (2 : 1), THF, −30°, 30 min	 (99)	412
C_7			
$C_6H_5CCl_3$	SMEAH, C_6H_6, 80°, 1 hr	$C_6H_5CH_3$ (96)	370
$C_6H_5CHCl_2$	SMEAH, C_6H_6, 78°, 1 hr	" (63)	370
$C_6H_5CH_2Cl$	SMEAH + H_2O (1 : 1), xylene, reflux, 1 hr	" (99)	372
	SMEAH + CH_3OH (1 : 1), xylene, reflux, 1 hr	" (98)	372
p-$BrC_6H_4CH_3$	$NaAlH(OC_2H_5)_3$, THF, 65°, 2 hr	" (30)	54
	SMEAH, C_6H_6, 88°, 2–5 hr	 (80) +  (8)	391
	SMEAH, C_6H_6	 I (—) +  II (—) I : II = 74 : 26	654
	SMEAH, C_6H_6, 88°, 2–5 hr	 (70) +  (5)	391
	SMEAH, C_6H_6, 88°, 2–5 hr	 (63)	391
	$LiAlD(OCH_3)_3$ + CuI (2 : 1), THF, 25°, 1 hr	 (93)	412
	$LiAlD(OCH_3)_3$ + CuI (2 : 1), THF, 25°, 1 hr	 (92)	412
n-$C_7H_{15}Br$	$NaAlH[OCH_2CH_2N(CH_3)_2]_3$, THF, 60°, 1 hr	*n*-C_7H_{16} (99)	367
C_8			
$C_6H_5CH{=}CF_2$	SMEAH, C_6H_6, reflux, 3 hr	$C_6H_5CH{=}CH_2$ (86)	401
	SMEAH, C_6H_6, −5 to 0°, 30 min	$C_6H_5CH{=}CHF$ (91) *cis*:*trans* = 7:93	401
	SMEAH, $C_6H_5P(O)(OC_2H_5)_2$, C_6H_6, 70°, 48 hr	 (15)	379,376
	LTMA + CuI (2 : 1), THF, r.t., 2.5 hr	 (99)	412
n-$C_6H_{13}CH{=}CHBr$ *cis* or *trans*	LTMA + CuI (2 : 1), THF, 25°, 2.5 hr	*n*-$C_6H_{13}CH{=}CH_2$ (98)	412
n-$C_8H_{17}Cl$	LTMA + CuI (2 : 1), THF, r.t., 15 hr	*n*-C_8H_{18} (96)	412
n-$C_8H_{17}Br$	LTBA, THF, 25°, 4 hr	" (12)	365
	LTMA, THF, 25°, 6 hr	" (~100)	365
	LTMA + CuI (2 : 1), THF, 25°, 1 hr	" (98)	412
n-$C_8H_{17}I$	LTBA, THF, 25°, 4 hr	" (45)	365
n-$C_4H_9C(CH_3)_2CH_2Br$	LTMA + CuI (2 : 1), THF, r.t., 2 hr	*n*-$C_4H_9C_4H_9$-*t* (97)	412

TABLE II. REDUCTION OF HALOGEN COMPOUNDS (*Continued*)

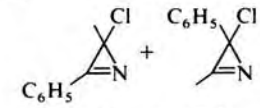
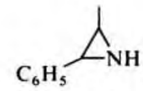
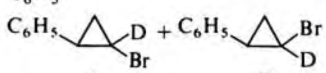
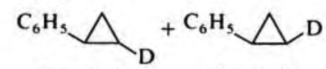
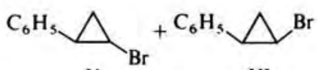
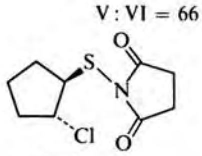
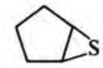
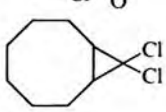
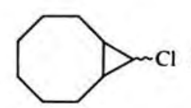
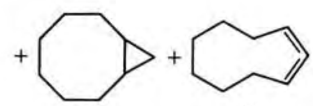
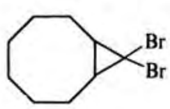
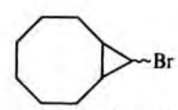
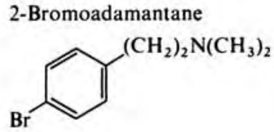
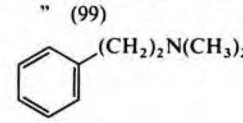
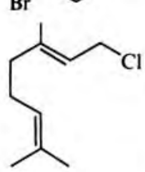
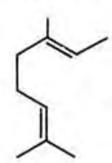
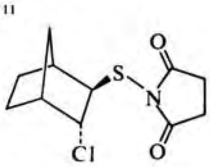
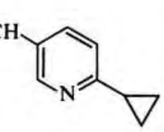
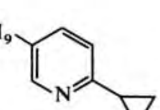
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_9			
	SMEAH, C_6H_6, 1 hr	 (~100)	655
 I II; I : II = 70 : 30	SMEAH, C_6H_6, 100°, 5.5 hr	 III (—) IV (—); III : IV = 80 : 20	654
I : II = 3 : 97	SMEAH, C_6H_6, 100°, 5.5 hr	III (—) + IV (—); III : IV = 4 : 96	654
 V VI; V : VI = 66 : 34	1. SMEAH, C_6H_6 2. D_2SO_4	IV (94)	654
	$LiAlH_3(OC_2H_5)$, THF, −78°	 (58)	656
	SMEAH, C_6H_6, 88°, 2–5 hr	 (20) +  I II (I + II = 3)	391
	SMEAH, C_6H_6, 88°, 2–5 hr	 (43) + I + II (I + II = 27)	391,392
	LTMA + CuI (2 : 1), THF, r.t., 1 hr	I (85)	412
$n\text{-}C_7H_{15}CHBrCH_3$	LTMA + CuI (2 : 1), THF, r.t., 1.25 hr	$n\text{-}C_9H_{20}$ (~100)	412
C_{10}			
1-Bromonaphthalene	LTMA + CuI (2 : 1), THF, r.t., 2 hr	Naphthalene (~100)	412
1-Bromoadamantane	LTMA + CuI (2 : 1), THF, r.t., 1.75 hr	Adamantane (~100)	412
2-Bromoadamantane	LTMA + CuI (2 : 1), THF, r.t., 1.5 hr	" (99)	412
	$LiAlH_2(OCH_3)_2$, THF, 4 hr	 (82)	657
	LTMA + CuI (2 : 1), THF, 0°, 0.5 hr	 (85)	412
C_{11}			
	$LiAlH_3(OC_2H_5)$, THF, −78°, 1.5 hr	 (58)	656
C_{12}			
$Br(CH_2)_2CH{=}CH$	SMEAH, C_6H_6, reflux, 6 hr	$n\text{-}C_4H_9$ (96)	658

TABLE II. REDUCTION OF HALOGEN COMPOUNDS (*Continued*)

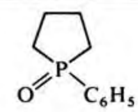
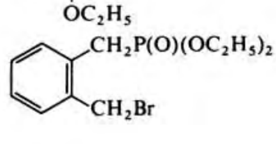
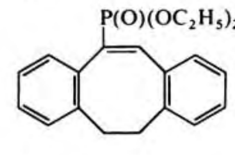
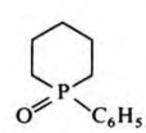
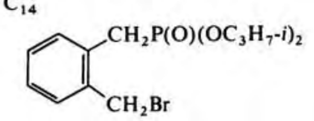
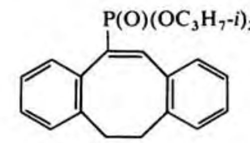
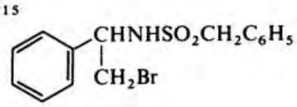
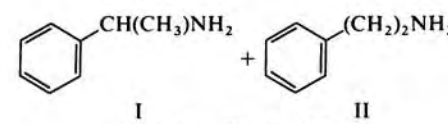
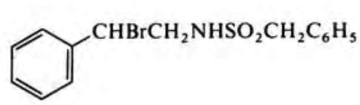
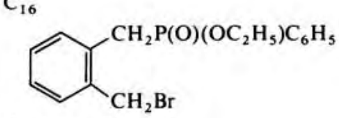
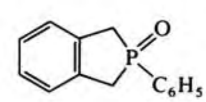
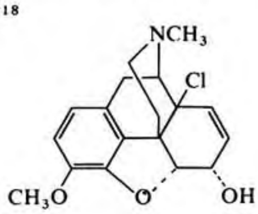
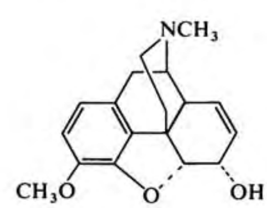
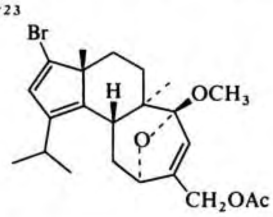
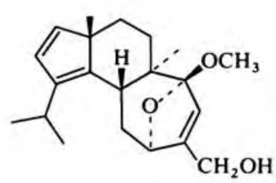
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
$C_6H_5P(O)(OC_2H_5)(CH_2)_4Br$	SMEAH, THF, 1. reflux, 2 hr 2. r.t., 6 hr	 (27)	374,375
	SMEAH, BME, 135°, 48 hr	 (—)	376
C_{13}			
$C_6H_5P(O)(OC_2H_5)(CH_2)_5Br$	SMEAH, THF, 1. reflux, 2 hr 2. r.t., 6 hr	 (28)	374,375
C_{14}			
	SMEAH, BME, 135°, 48 hr	 (31)	376
C_{15}			
	SMEAH, C_6H_6, reflux, 2 hr	 I + II; I : II = 90 : 10 (46)	394
	SMEAH, C_6H_6, reflux, 2 hr	I + II; I : II = 90 : 10 (22)	394
C_{16}			
	SMEAH	 (11)	376,379
C_{18}			
	SMEAH	 (~100)	659,660
C_{23}			
	LTMA + CuI (2 : 1), THF, 1. 0°, 5 min 2. r.t., 8 hr	 (76)	661

TABLE III. REDUCTION OF UNSATURATED ALCOHOLS

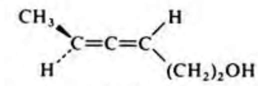
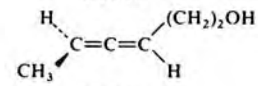
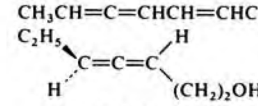
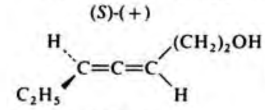
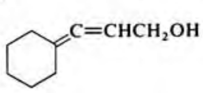
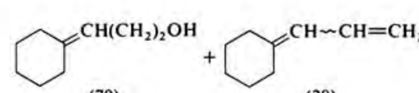
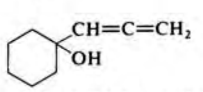
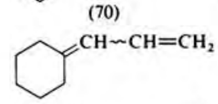
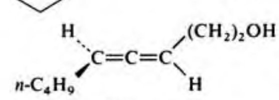
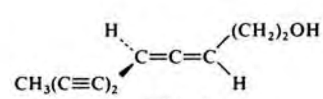
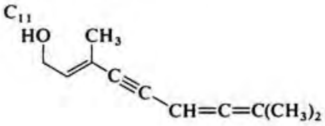
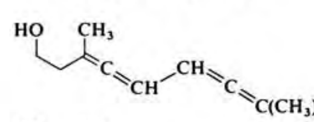
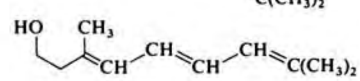
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6			
$CH_3C{\equiv}CCH{=}CHCH_2OH$	LAH + (−)-menthol (1 : 2), ether, reflux, 3 hr	 (31) (S)-(+)	421,422
	LAH + BCGF, ether, reflux, 4 hr	 (46) (R)-(−)	420
$CH_3CH{=}C{=}CHCHOHCH_3$	$LiAlH_3(OCH_3)$, THF, 80°	$CH_3CH{=}CHCH_2CHOHCH_3$ (58) *trans* + $CH_3CH{=}CHCH{=}CHCH_3$ (38)	214
C_7			
$CH_3CH{=}C{=}CHC{\equiv}CCH_2OH$	$LiAlH_3(OCH_3)$, THF, 70°, 1–3 hr	$CH_3CH{=}C{=}CHCH{=}CHCH_2OH$ (80)	662
$C_2H_5C{\equiv}CCH{=}CHCH_2OH$	LAH + (−)-menthol (1 : 2), ether, reflux, 3 hr	 (−) (S)-(+)	421,422
	LAH + BCGF, ether, reflux, 4 hr	 (76) (R)-(−)	420
C_8			
$(CH_3)_2C{=}C{=}CHCH{=}CHCH_2OH$	1. $LiAlH_3(OCH_3)$, THF, 90°, 9 hr 2. H_2O	$(CH_3)_2C{=}CH{\sim}CH{=}CH(CH_2)_2OH$ (64), + $(CH_3)_2C{=}CH{\sim}CH{=}CHCH{=}CH_2$ (34)	214
$(CH_3)_2C{=}C{=}CHCOH(CH_3)_2$	1. $LiAlH_3(OCH_3)$, THF, 80°, 21 hr 2. H_2O	$(CH_3)_2C{=}CHCH_2COH(CH_3)_2$ (39), + $(CH_3)_2C{=}CH{\sim}CH{=}C(CH_3)_2$ (36)	214
C_9			
	1. $LiAlH_3(OCH_3)$, THF, 80°, 3 hr 2. H_2O	 (70) (28)	214
	1. $LiAlH_3(OCH_3)$, THF, 80°, 4 hr 2. H_2O	 (80)	214
$n\text{-}C_4H_9C{\equiv}CCH{=}CHCH_2OH$	LAH + BCGF, ether, reflux, 4 hr	 (74) (R)-(−)	420
C_{10}			
$CH_3(C{\equiv}C)_3CH{=}CHCH_2OH$	LAH + BCGF, ether, r.t., 2 hr	 (10) (3.3% e.e.) (R)-(−)	420
$(CH_3)_2C{=}C{=}CHCH{=}CHCOH(CH_3)_2$	1. $LiAlH_3(OCH_3)$, THF, 90°, 12 hr 2. D_2O	$(CH_3)_2C{=}CD{\sim}CH{=}CHCH_2COH(CH_3)_2$ I + $(CH_3)_2C{=}CH{\sim}CH{=}CHCHDCOH(CH_3)_2$ II (I + II = 68) + $(CH_3)_2C{=}CH{\sim}CH{=}CHCD{=}C(CH_3)_2$ (30)	214
$n\text{-}C_6H_{13}C{\equiv}CCHOHCH_3$	LTMA, THF, 65°, 24 hr	$n\text{-}C_6H_{13}CH{=}C{=}CHCH_3$ (16) + $n\text{-}C_6H_{13}C{\equiv}CC_2H_5$ (5)	405
C_{11}			
	$LiAlH_3(OCH_3)$, THF, reflux, 3 hr	 (~60)	426–428
	$LiAlH_3(OCH_3)$, THF, reflux, 10 hr	 (75)	426–428

TABLE III. REDUCTION OF UNSATURATED ALCOHOLS (*Continued*)

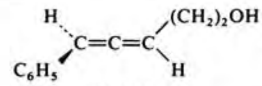
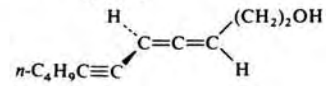
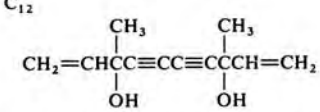
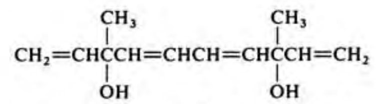
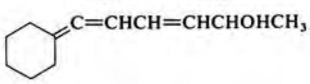
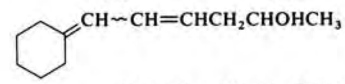
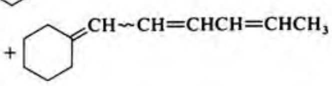
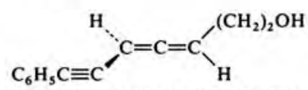
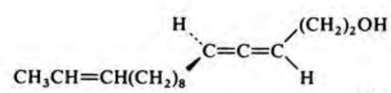
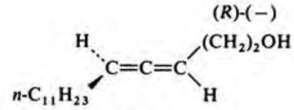
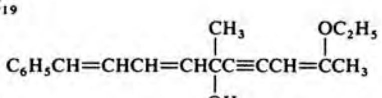
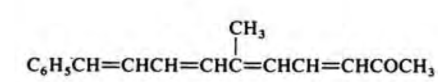
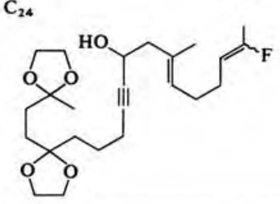
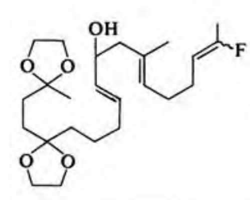
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
$C_6H_5C{\equiv}CCH{=}CHCH_2OH$	LAH + BCGF, ether, reflux, 4 hr	 (44) (*R*)-(−)	420
n-$C_4H_9(C{\equiv}C)_2CH{=}CHCH_2OH$	LAH + BCGF, ether, r.t., 2 hr	 (32) (*R*)-(−)	420
C_{12}			
	SMEAH, THF-C_6H_6, reflux	 (−)	663
	$LiAlH_3(OCH_3)$, THF, 90°, 9 hr	 (70) +  (29)	214
C_{13}			
$C_6H_5(C{\equiv}C)_2CH{=}CHCH_2OH$	LAH + BCGF, ether, r.t., 2 hr	 (14)	420
$(CH_3)_2C{=}CH(CH_2)_2CH(CH_3)CH_2CHOHC{\equiv}CCH_3$ (4*S*,6*R*)	SMEAH, C_6H_6-ether, reflux, 17 hr	$(CH_3)_2C{=}CH(CH_2)_2CH(CH_3)CH_2CHOHCH{=}CHCH_3$ (4*S*,6*R*, *trans*) (70)	664
i-$C_3H_7(CH_2)_3CH(CH_3)CH_2CHOHC{\equiv}CCH_3$ (4*S*,6*R*)	SMEAH, C_6H_6-ether, reflux, 20 hr	i-$C_3H_7(CH_2)_3CH(CH_3)CH_2CHOHCH{=}CHCH_3$ (4*S*,6*R*, *trans*) (84)	664
C_{14}			
$C_6H_5CHOHC{\equiv}CCH{=}C(CH_3)OC_2H_5$	1. LAH + C_2H_5OH (1 : 1) 2. H_3O^+	$C_6H_5CH{=}CHCH{=}CHCOCH_3$ (−)	665
C_{16}			
$CH_3CH{=}CH(CH_2)_8C{\equiv}CCH{=}CHCH_2OH$	LAH + BCGF, ether, reflux, 7 hr	 (75) (11.6% e.e.) (*R*)-(−)	419,420
n-$C_{11}H_{23}C{\equiv}CCH{=}CHCH_2OH$	LAH + BCGF, ether, r.t., 1 hr	 (44) (*R*)-(−)	420,418,419
C_{19}			
	1. LAH + EtOH (1 : 1), 0°, 3 hr 2. H_3O^+	 (59)	665
C_{24}			
	SMEAH, THF, reflux, 4 hr	 (91)	666

TABLE IV. HYDROGENOLYSIS OF AROMATIC ALCOHOLS

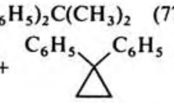
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_7			
o-$HOC_6H_4CH_2OH$	SMEAH, xylene, 141°, 7 hr	*o*-$HOC_6H_4CH_3$ (85)	430,432
p-$HOC_6H_4CH_2OH$	SMEAH, xylene, 141°, 7 hr	*p*-$HOC_6H_4CH_3$ (95)	430,432
C_9			
p-$(CH_3)_2NC_6H_4CH_2OH$	SMEAH, C_6H_6-xylene, 125°, 9 hr	*p*-$(CH_3)_2NC_6H_4CH_3$ (40)	431
C_{13}			
$(C_6H_5)_2CHOH$	SMEAH, *n*-propylbenzene, 162°, 4.5 hr	$(C_6H_5)_2C(CH_3)_2$ (77) +  (11)	206,207

TABLE V. Reductive Cleavage of Ethers

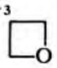
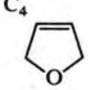
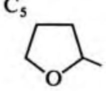
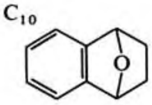
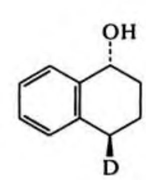
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_2			
$(CH_3)_2O$	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 3 hr	CH_3OH (94) + CH_4	442
C_3			
	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 1 hr	n-C_3H_7OH (98)	442
C_4			
	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 2 hr	*cis*-$CH_3CH{=}CHCH_2OH$ (95)	440,442
$CH_3OCH_2CH_2OCH_3$	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 24 hr	$CH_3OCH_2CH_2OH$ (65)	442
C_5			
	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 6 hr	n-$C_3H_7CHOHCH_3$ (95)	440,442
C_6			
$CH_3O(CH_2)_2O(CH_2)_2OCH_3$	LTBA, $(C_2H_5)_3B$, tetrahydropyran, 25°, 1 hr	$CH_3O(CH_2)_2O(CH_2)_2OH$ (60)	442
C_{10}			
	$LiAlD(OC_4H_9$-$t)_3$, $(C_2H_5)_3B$, tetrahydropyran, 12 hr	 (78)	667

TABLE V. REDUCTIVE CLEAVAGE OF ETHERS (*Continued*)

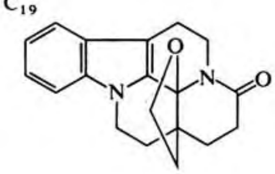
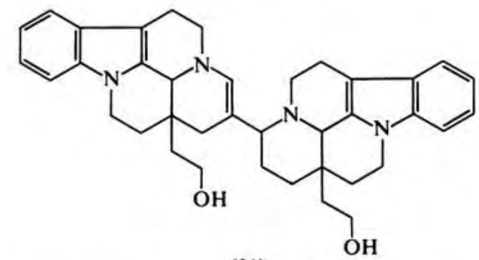
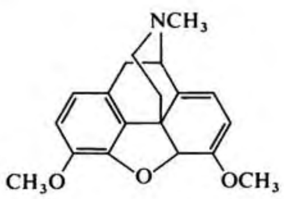
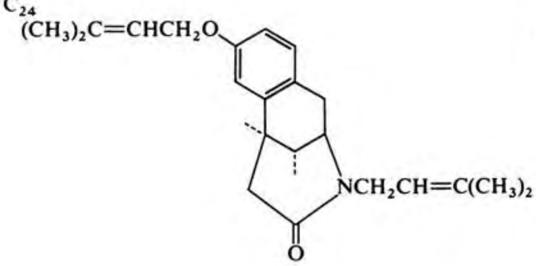
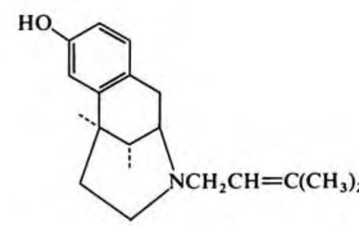
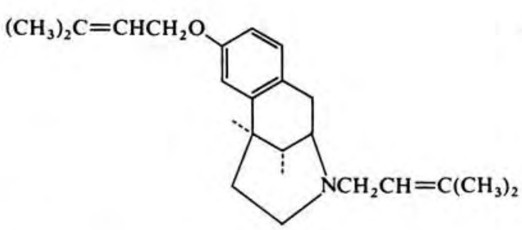
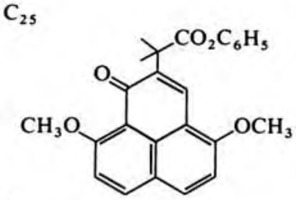
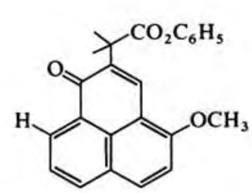
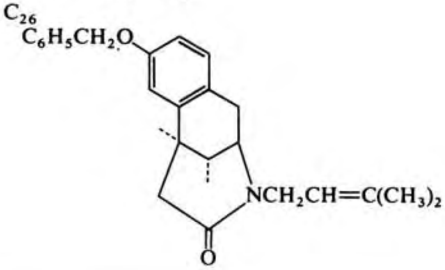
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{19} 	SMEAH, THF–C_6H_6, r.t., overnight	 (31)	668
	SMEAH	No reaction	628
C_{24} 	SMEAH, xylene, reflux, 42 hr	 I (62)	433
	SMEAH, xylene, reflux, 42 hr	I (74)	433
C_{25} 	LTBA, THF, r.t., 48 hr	 (16)	669
C_{26} 	SMEAH, xylene, reflux, 60 hr	I (55)	433

TABLE VI. REDUCTION OF 1,2-OXIDES

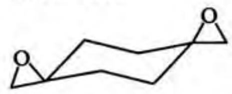
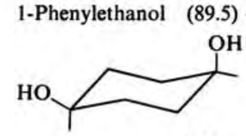
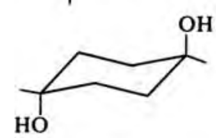
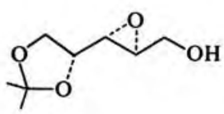
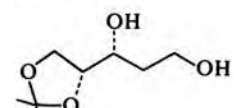
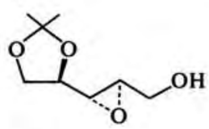
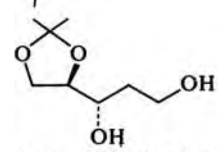
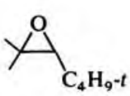
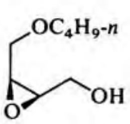
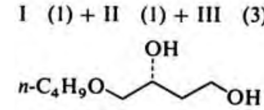
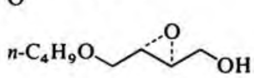
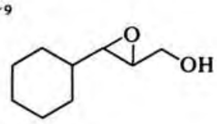
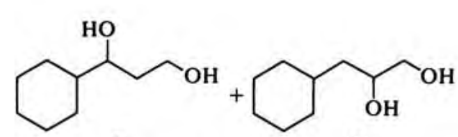
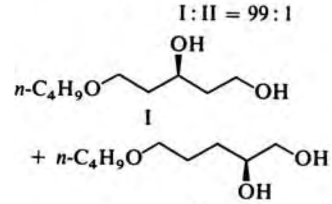
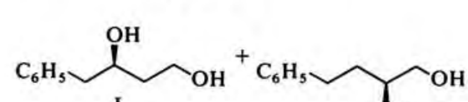
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6			
Cyclohexene oxide	LTBA, $(C_2H_5)_3B$, ether, 25°, 1 min	Cyclohexanol (~100)	440,442
C_8			
Styrene oxide	LTBA, $(C_2H_5)_3B$, THF, 25°, 10 min	1-Phenylethanol (89.5) + 2-Phenylethanol (10.5)	442
	SMEAH, THF, 1 hr	 (72)	670
	SMEAH, THF, 2 hr	 (33)	670
	SMEAH, CH_2Cl_2, 0°	 (82)	449a,449b
	SMEAH, THF, r.t.	 (89)	450a
	$AlH_2OC_3H_7$-*i*, THF, reflux, 6 hr	$(CH_3)_2COHCH_2C_4H_9$-*t* I (14), + *i*-$C_3H_7CHOHC_4H_9$-*t* II (34), + *t*-$C_4H_9C(CH_3)_2CH_2OH$ III (3), + $CH_2{=}C(CH_3)CHOHC_4H_9$-*t* IV (25)	100
	$AlH(OC_4H_9$-*t*$)_2$, THF, reflux, 6 hr	I (1) + II (1) + III (3) + IV (46)	100
	SMEAH, CH_2Cl_2, 0°	 (95)	449a,449b
	SMEAH, CH_2Cl_2, 0°	" (98)	449a,449b
C_9			
	SMEAH, THF, −15°	 (95) I II I : II = 99 : 1	449b
	SMEAH, THF, 0°	 (89) I : II = 98 : 2	449a,449b
C_{10}			
	SMEAH, THF, 0°	 (92) I II I : II = 99 : 1	449a,449b

TABLE VI. REDUCTION OF 1,2-OXIDES (*Continued*)

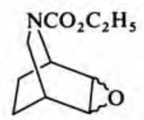
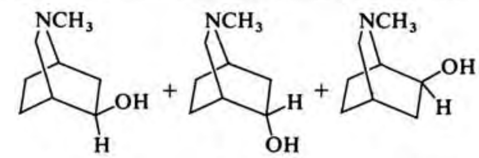
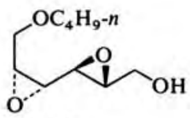
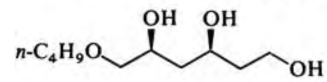
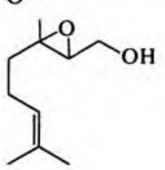
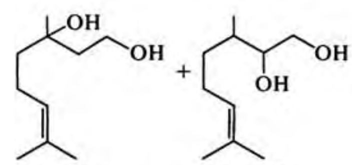
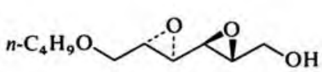
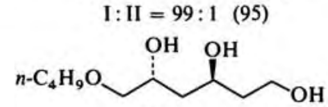
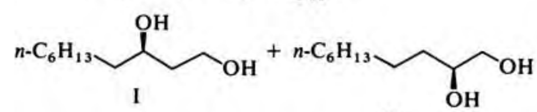
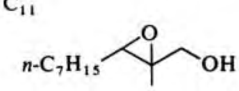
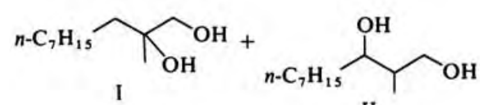
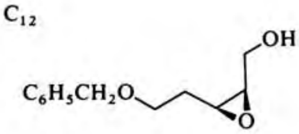
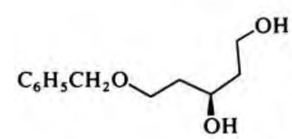
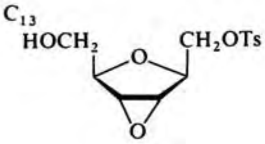
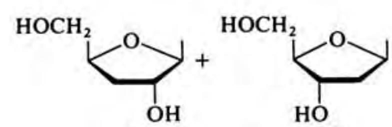
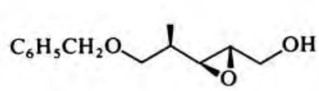
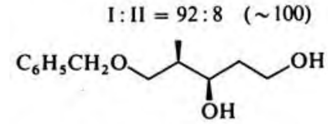
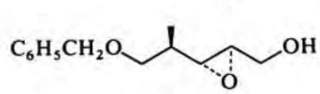
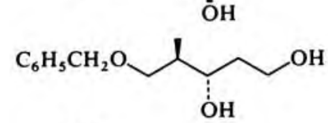
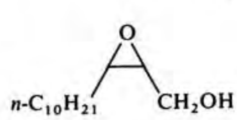
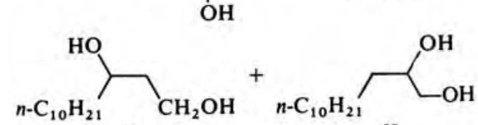
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6, reflux, 4 hr	 I (−) II (−) III (−) I : II : III = 45 : 45 : 10	671
	SMEAH, CH_2Cl_2, 22°, 3 hr	 (65)	449a,449b
	SMEAH, THF, −15°	 I II I : II = 99 : 1 (95)	449b
	SMEAH, CH_2Cl_2, 22°, 3 hr	 (70)	449a
	SMEAH, THF, −15°	 I II I : II = 99 : 1 (90)	449a,449b
C_{11}			
	SMEAH, THF, −15°	 I II I : II = 99 : 1 (70)	449b
C_{12}			
	SMEAH, THF, 0°	 (>95)	450b
C_{13}			
	SMEAH, toluene, reflux, 12 hr	 I II I : II = 92 : 8 (~100)	672,673
	SMEAH, THF, 0°	 (>95)	450b
	SMEAH, THF, 0°	 (>95)	450b
	SMEAH, THF, −15°	 I II I : II = 99 : 1 (95)	449b

TABLE VI. REDUCTION OF 1,2-OXIDES (*Continued*)

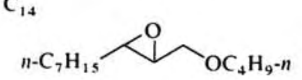
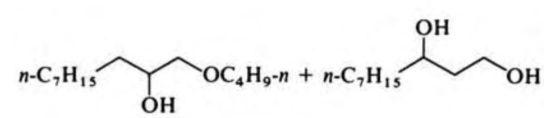
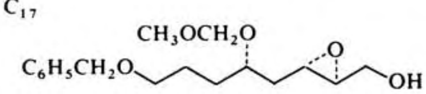
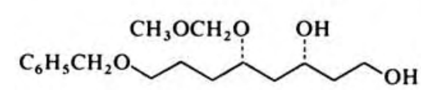
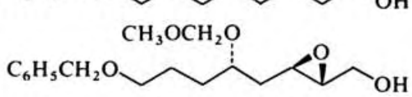
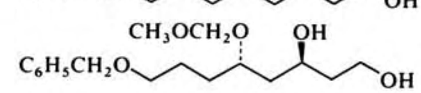
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{14} 	SMEAH, THF, reflux	 I II I : II = 60 : 40 (50)	449b
C_{17} 	SMEAH, THF, 0°	 (~100)	450b
	SMEAH, THF, 0°	 (~100)	450b

TABLE VII. Reduction of Aldehydes

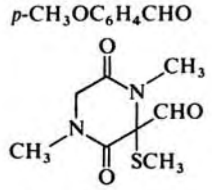
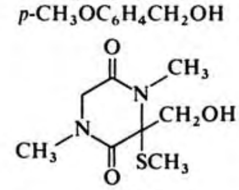
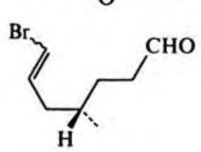
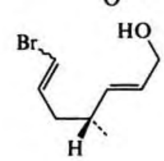
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6			
n-$C_5H_{11}CHO$	$AlH(OC_3H_7$-$i)_2$, C_6H_6, 50°, 2 hr	n-$C_6H_{13}OH$ (~100)	87
C_7			
C_6H_5CDO	LAH + (−)-QN, ether, reflux, 3 hr	C_6H_5CHDOH (52) (21% e.e.)	674
o-HOC_6H_4CHO	SMEAH, C_6H_6, 45°, 2 hr	o-$HOC_6H_4CH_2OH$ (94)	430,432
	SMEAH, xylene, 141°, 2 hr	o-$HOC_6H_4CH_3$ (52)	430,432
p-HOC_6H_4CHO	SMEAH, xylene, 141°, 2 hr	p-$HOC_6H_4CH_3$ (85)	432
C_8			
3,4-Methylenedioxybenzaldehyde	SMEAH, xylene, 70°, 10 min	3,4-Methylenedioxybenzyl alcohol (98)	432
$C_6H_5CH_2CHO$	SMEAH + CuBr, THF 1. −78° 2. −20°, 2 hr	$C_6H_5(CH_2)_2OH$ (~100)	575
o-$CH_3OC_6H_4CHO$	SMEAH, C_6H_6, 50°, 10 min	o-$CH_3OC_6H_4CH_2OH$ (89)	432
p-$CH_3OC_6H_4CHO$	SMEAH, C_6H_6, 50°, 10 min	p-$CH_3OC_6H_4CH_2OH$ (93)	432
	LTBA, THF 1. −78°, 1 hr 2. r.t., 3 hr	 (92)	675,676
	1. Piperidine 2. C_6H_5SeCl 3. LTBA, THF, −78°, 1 hr 4. m-Chloroperbenzoic acid	 (−)	677a

TABLE VII. REDUCTION OF ALDEHYDES (*Continued*)

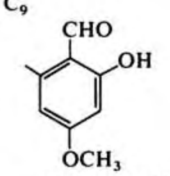
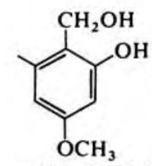
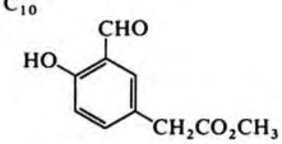
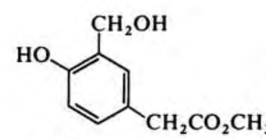
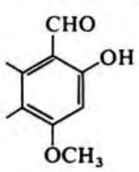
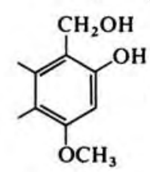
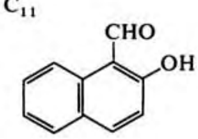
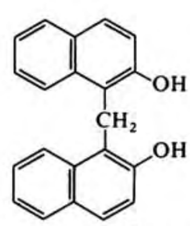
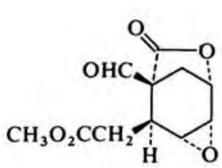
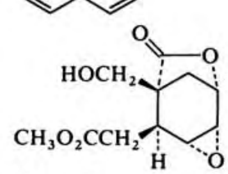
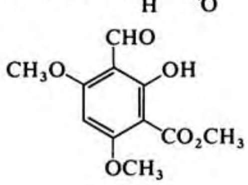
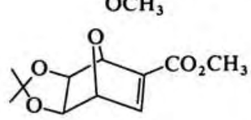
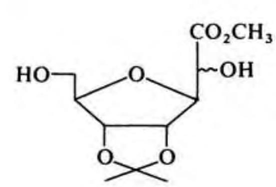
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_9			
	SMEAH, C_6H_6, 40°, 20 min	 (71)	677b
p-$(CH_3)_2NC_6H_4CHO$	SMEAH, C_6H_6-xylene, 143°, 7 hr	p-$(CH_3)_2NC_6H_4CH_3$ (95)	431
C_{10}			
	LTBA, THF, 0°, 2.25 hr	 (38)	678
	SMEAH, C_6H_6, 40°, 20 min	 (59)	677b
C_{11}			
	SMEAH, C_6H_6, 50°, 20 min	 (50)	435
	LTBA, THF, −10°, 30 min	 (—)	462
	LTBA, THF, r.t., 30 min	No reaction	679
	1. O_3 2. $(CH_3)_2S$ 3. LTBA, THF, 0°, 3 hr	 (65)	680

TABLE VII. REDUCTION OF ALDEHYDES (*Continued*)

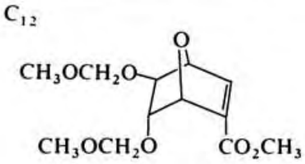
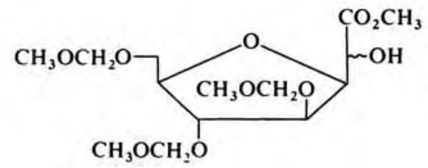
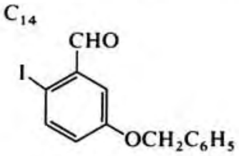
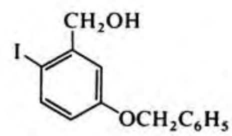
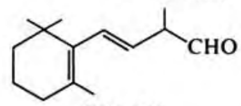
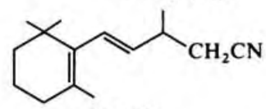
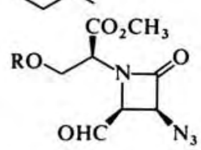
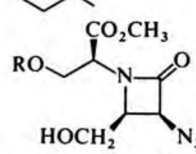
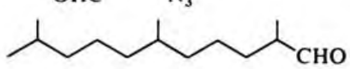
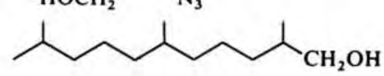
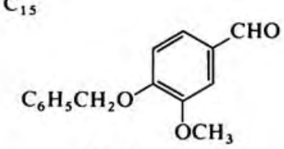
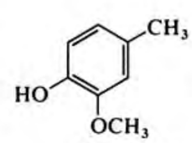
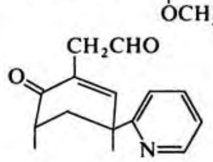
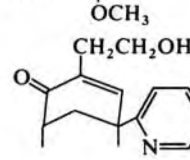
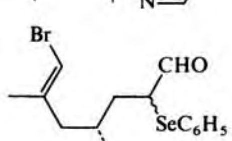
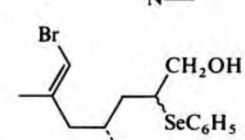
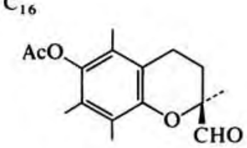
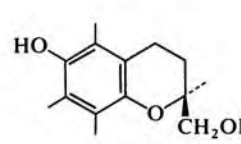
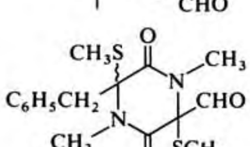
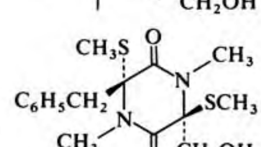
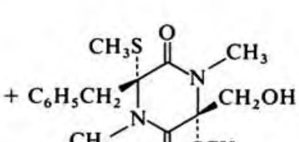
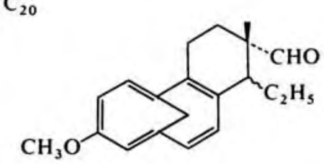
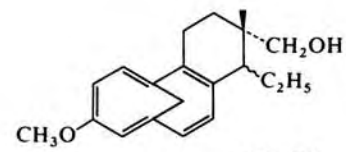
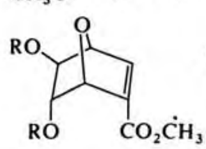
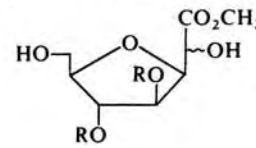
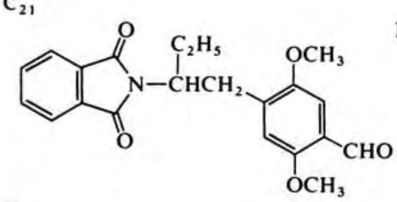
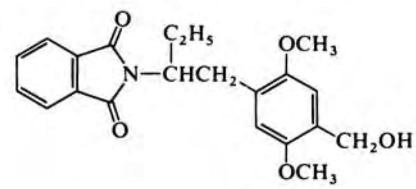
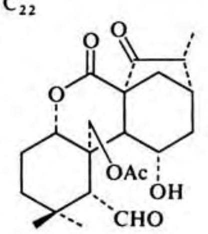
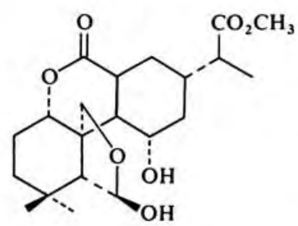
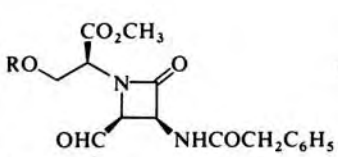
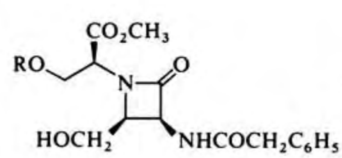
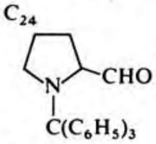
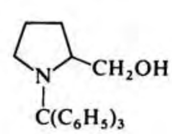
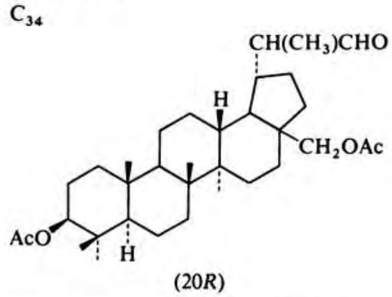
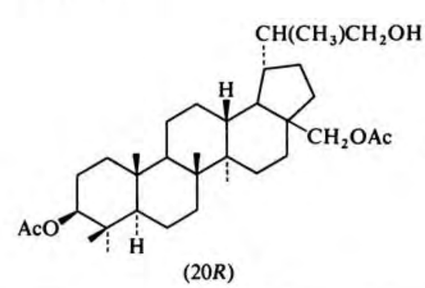
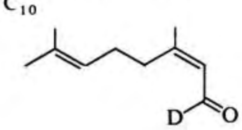
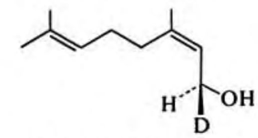
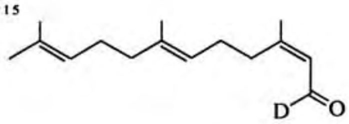
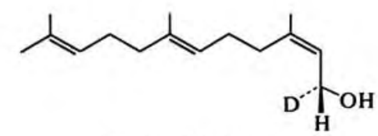
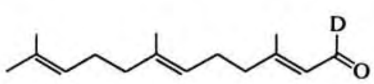
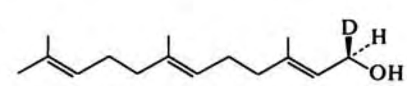
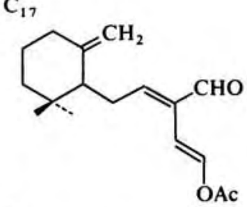
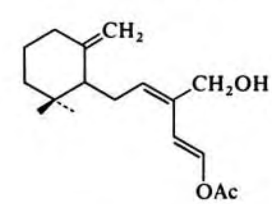
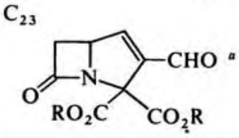
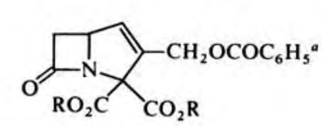
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{12}			
	1. O_3 2. $(CH_3)_2S$ 3. LTBA, THF, r.t., 12 hr	 (60)	680
C_{14}			
	LTBA, THF, 0°, 4 hr	 (75)	681
	1. SMEAH 2. TsCl 3. NaCN	 (56)	682
 *a*	LTBA, THF, 0°, 3 hr	 *a* (80)	683
	SMEAH, toluene–ether, 2 hr	 (—)	684
C_{15}			
	SMEAH, xylene, reflux, 10 hr	 (66)	433
	LTBA, THF	 (89)	685
	LTBA, THF, −78°, 1 hr	 (99)	686
C_{16}			
	SMEAH, C_6H_6–THF, r.t., 1 hr	 (92)	687
	LTBA, THF 1. −78°, 30 min 2. r.t., 1 hr	 (40) +  (16)	675,676

TABLE VII. REDUCTION OF ALDEHYDES (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{20} 	LTBA, THF 1. $-78°$, 1 hr 2. r.t., 0.5 hr	 (−)	689
 *a*	1. O_3 2. $(CH_3)_2S$ 3. LTBA, THF, 0°, 12 hr	 *a* (59)	680
C_{21} 	LTBA	 (−)	690
C_{22} 	1. LAH + CH_3OH, 0°, 4 hr 2. H_3O^+	 (28)	691
 *a*	LTBA, THF, 0°, 3 hr	 *a* (81)	683
C_{24} 	SMEAH, C_6H_6, reflux, 4 hr	 (68)	692a
C_{34}  (20*R*)	LTBA, THF, r.t., 2 hr	 (−) (20*R*)	692b

[a] R = t-$C_4H_9(CH_3)_2Si$—

TABLE VIII. REDUCTION OF α,β-UNSATURATED ALDEHYDES

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_9			
$C_6H_5CH{=}CHCHO$	$NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$, toluene, 25°, 1 hr	$C_6H_5(CH_2)_3OH$ (85)	371
C_{10}			
	LAH + (S)-(−)-DBN + EtOH (1 : 1 : 1), THF, −100°, 2 hr	 (S)-(+) (90) (72% e.e.)	483
C_{15}			
	LAH + (R)-(+)-DBN + EtOH (1 : 1 : 1), THF, −100°, 2 hr	 (R)-(−) (93) (82% e.e.)	483
	LAH + (R)-(+)-DBN + EtOH (1 : 1 : 1), THF, −100°, 2 hr	 (R)-(−) (91) (88% e.e.)	483
C_{17}			
	LTBA, ether, r.t., 1 hr	 (76)	693
C_{23}			
	1. LTBA, 0° 2. C_6H_5COCl, $(C_2H_5)_3N$	 (−)	694

[a] $R = p\text{-}O_2NC_6H_4CH_2$—.

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES

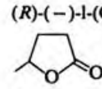
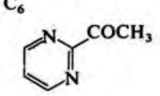
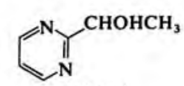
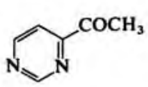
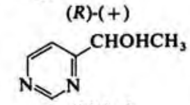
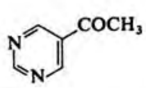
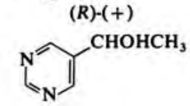
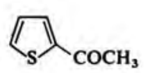
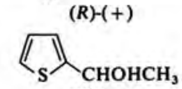
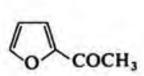
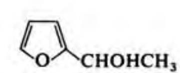
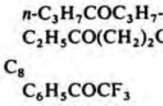
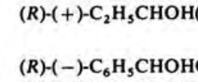
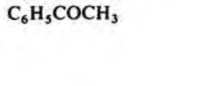
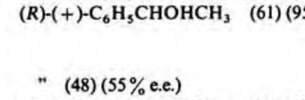
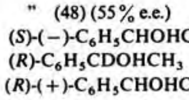
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_3			
CF_3COCF_3	$NaAlH_2(OC_2H_5)(C_2H_5)$, C_6H_6, 70°, 4.5 hr	$CF_3CHOHCF_3$ (90)	695
CF_3COCH_3	LAH + (−)-QN (1 : 1), ether, 25°, 15 hr	(+)-$CF_3CHOHCH_3$ (62) (30% e.e.)	696
C_4			
$CH_3COC_2H_5$	LAH + (+)-camphor, ether	$CH_3CHOHC_2H_5$ (−) (2% e.e.)	697–699
C_5			
Cyclopropyl methyl ketone	LAH + (−)-NME + DMP (1 : 1 : 2), ether, 0°	(*R*)-(−)-1-(Cyclopropyl)ethanol (−) (14.6% e.e.)	700
$CH_3CO(CH_2)_2CO_2H$	SMEAH, C_6H_6, −20°, 1.5 hr	 (57)	701
$CH_3COC_3H_7$-*i*	LAH + (+)-EPH, ether, reflux, 5 hr	(*S*)-(+)-$CH_3CHOHC_3H_7$-*i* (78) (13.7% e.e.)	313
$CH_3COCH_2N(CH_3)_2$	LAH + (−)-menthol, ether, −70°	(*S*)-(−)-$CH_3CHOHCH_2N(CH_3)_2$ (−) (87% e.e.)	702
C_6			
	LAH + (−)-QN, ether	 (−) (*R*)-(+)	703
	LAH + (−)-QN, ether	 (−) (*R*)-(+)	703
	LAH + (−)-QN, ether	 (−) (*R*)-(+)	703
	LAH + (−)-QN, ether	 (−) (*R*)-(+)	704
	LAH + (−)-QN, ether	 (−) (*R*)-(+)	704
$CH_3COC_4H_9$-*t*	LAH + (+)-CN, ether, reflux, 5 hr	(*R*)-(−)-$CH_3CHOHC_4H_9$-*t* (76) (6.7% e.e.)	313
C_7			
	LAH + (2*S*,3*S*)-DPB, ether, r.t., 4 hr	 (−) (13% e.e.) (*S*)-(−)	505
	1. LTBA, BME-ether, −30 to −35°, 1 hr 2. Cyclohexylamine	 (38)	705
	LAH + (−)-menthol, ether, −70°	 (−) (26% e.e.) (*R*)-(+)	702
n-$C_3H_7COC_3H_7$-*i*	LAH + (−)-DMDB, ether, 0°	(*S*)-(−)-*n*-$C_3H_7CHOHC_3H_7$-*i* (−) (20% e.e.)	503
$C_2H_5CO(CH_2)_2OC_2H_5$	LAH + (−)-DMDB, ether, 0°	(*R*)-(+)-$C_2H_5CHOH(CH_2)_2OC_2H_5$ (−) (17% e.e.)	503
C_8			
$C_6H_5COCF_3$	LAH + (+)-DMDB, ether, 0°	(*R*)-(−)-$C_6H_5CHOHCF_3$ (~100) (30% e.e.)	167
$C_6H_5COCH_3$	LAH + (+)-DBN + EtOH, THF, 1. −100°, 3 hr 2. −78°, 16 hr	(*R*)-(+)-$C_6H_5CHOHCH_3$ (61) (95% e.e.)	168
	NAH + (+)-DMDB, ether, r.t., 12 hr	" (48) (55% e.e.)	167
	LAH + (−)-DAMP, ether, −70°	(*S*)-(−)-$C_6H_5CHOHCH_3$ (83) (60% e.e.)	329
	$LiAlD_4$ + (+)-DMDB, ether, 0°	(*R*)-$C_6H_5CDOHCH_3$ (~100) (90% e.e.)	167
	LAH + (−)-*threo*-DADE (1 : 2.2), ether, −78°, 5 hr	(*R*)-(+)-$C_6H_5CHOHCH_3$ (55) (45% e.e.)	706
	LAH + (+)-*erythro*-DADE (1 : 2.2), ether, −78°, 5 hr	(*S*)-(−)-$C_6H_5CHOHCH_3$ (92) (67% e.e.)	706
	LAH + (+)-*erythro*-DADE + 2,4-xylenol (1 : 1.1 : 1)	(*S*)-(−)-$C_6H_5CHOHCH_3$ (83) (42% e.e.)	706
	LAH + (+)-*erythro*-DADE + EtOH (1 : 1.1 : 1), ether, −78°, 5 hr	(*S*)-(−)-$C_6H_5CHOHCH_3$ (82) (62% e.e.)	706

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

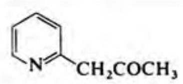
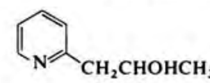
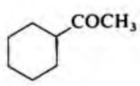
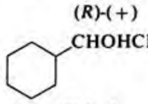
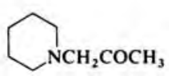
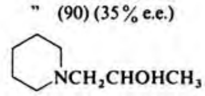
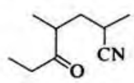
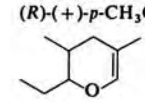
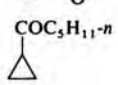
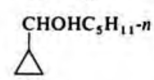
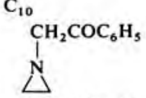
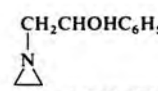
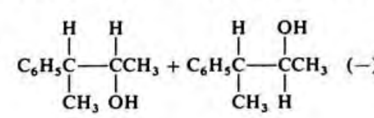
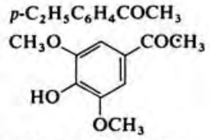
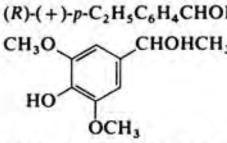
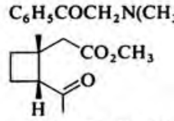
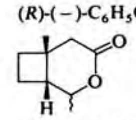
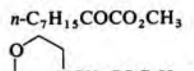
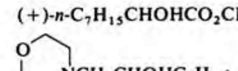
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LAH + (–)-menthol, ether, –70°	 (–) (44% e.e.) (R)-(+)	702
	LAH + (–)-QN, ether, reflux, 4 hr	 (–) (6.5% e.e.) (S)-(+)	313,325
	LAH + (–)-DBD, ether, r.t., 4 hr	" (–) (20% e.e.)	315
	LAH + (–)-NME + EAN, ether, –78°, 3 hr	" (90) (35% e.e.)	163,707
	LAH + (–)-menthol, ether, –70°	 (–) (8% e.e.) (R)-(+)	702
t-$C_4H_9COCH_2N(CH_3)_2$	LAH + (–)-menthol, ether, –70°	(–)-t-$C_4H_9CHOHCH_2N(CH_3)_2$ (–) (72% e.e.)	702
C_9			
$C_6H_5COC_2H_5$	LAH + (+)-DBN, THF, 30°, 5 hr	(R)-(+)-$C_6H_5CHOHC_2H_5$ (–) (81% e.e.)	708
	LAH + (+)-*erythro*-DADE (1 : 2.2), ether, –78°, 5 hr	(S)-(–)-$C_6H_5CHOHC_2H_5$ (83) (72% e.e.)	706
$C_6H_5CH_2COCH_3$	LAH + (–)-NME + EAN, ether, –78°, 3 hr	(S)-(+)-$C_6H_5CH_2CHOHCH_3$ (90) (41% e.e.)	163
o-$CH_3C_6H_4COCH_3$	LAH + (–)-QN, ether, reflux, 4 hr	(R)-(+)-o-$CH_3C_6H_4CHOHCH_3$ (–)	709a
m-$CH_3C_6H_4COCH_3$	LAH + (–)-QN, ether, reflux, 4 hr	(R)-(+)-m-$CH_3C_6H_4CHOHCH_3$ (–)	709a
p-$CH_3C_6H_4COCH_3$	LAH + (–)-NME + DMP, ether, 0°, 1 hr	(R)-(+)-p-$CH_3C_6H_4CHOHCH_3$ (>90) (67% e.e.)	159
	LAH + (–)-QN, ether, reflux, 4 hr	(R)-(+)-p-$CH_3C_6H_4CHOHCH_3$ (–)	709a
	$LiAlH_2(OC_2H_5)_2$	 (–)	709b
	LAH + (–)-NME + DMP, ether, 0°	 (–) (19% e.e.) (R)	700
C_{10}			
	SMEAH	 (–)	710
$C_6H_5COC_3H_7$-n	LAH + (+)-DBN, THF, 30°, 1.2 hr	(R)-(+)-$C_6H_5CHOHC_3H_7$-n (–) (87% e.e.)	708
	LAH + (–)-*erythro*-DADE (1 : 2.2), ether, –78°, 5 hr	(R)-(+)-$C_6H_5CHOHC_3H_7$-n (94) (69% e.e.)	706
$C_6H_5CH(CH_3)COCH_3$	SMEAH + MeOH (1 : 1), ether, 25°, 1 hr	 (–) I II I : II = 85 : 15	711
p-$C_2H_5C_6H_4COCH_3$	LAH + (–)-NME + DMP, ether, 0°, 1 hr	(R)-(+)-p-$C_2H_5C_6H_4CHOHCH_3$ (~90) (62% e.e.)	159,160
	SMEAH	 (–)	712
$C_6H_5COCH_2N(CH_3)_2$	LAH + (–)-menthol, ether, –70°	(R)-(–)-$C_6H_5CHOHCH_2N(CH_3)_2$ (–) (58% e.e.)	702,321
	1. LTBA 2. $CDCl_3$	 (–)	713
n-$C_7H_{15}COCO_2CH_3$	LAH + (+)-DMDB, ether	(+)-n-$C_7H_{15}CHOHCO_2CH_3$ (–) (62% e.e.)	714
	LAH + (–)-menthol, ether, –70°	 (–) (31% e.e.)	702
C_{11}			
$C_6H_5COC_4H_9$-n	LAH + (+)-DBN + EtOH, THF, 30°, 2 hr	(R)-(+)-$C_6H_5CHOHC_4H_9$-n (–)(74% e.e.)	708
(±)-$C_6H_5COC_4H_9$-s	LAH – (–)-QN, ether, 1. r.t., 1 hr 2. reflux, 2 hr	$C_6H_5CHOHC_4H_9$-s (99) *erythro*(25% o.p.) : *threo*(31% o.p.) = 56 : 44	715
(R)-(–)-$C_6H_5COC_4H_9$-s	LAH + (–)-QN, ether 1. r.t., 1 hr 2. reflux, 2 hr	$C_6H_5CHOHC_4H_9$-s (99) (+)-*erythro* : (–)-*threo* = 65 : 35	715

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

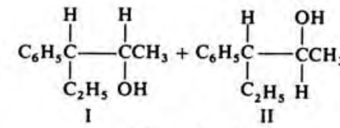
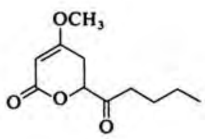
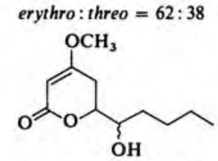
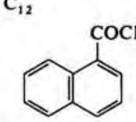
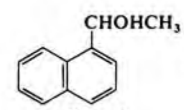
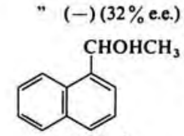
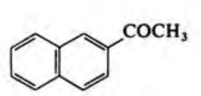
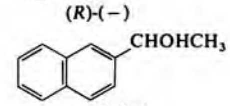
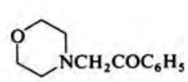
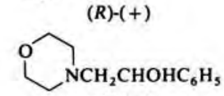
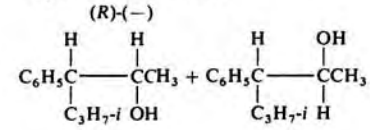
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
$C_6H_5CH(C_2H_5)COCH_3$	SMEAH + $CH_3O(CH_2)_2OH$ (1 : 1), ether, 25°, 1 hr	 (−) I:II = 84:16	711
$C_6H_5COC_4H_9$-*t*	LAH + (+)-DBN + EtOH, THF, 25°, 12 hr	(*R*)-(+)-$C_6H_5CHOHC_4H_9$-*t* (80) (44% e.e.)	168
	LAH + (−)-QN, ether, reflux, 10 min	(*R*)-(−)-$C_6H_5CHOHC_4H_9$-*t* (96)	716
2,4,6-$(CH_3)_3C_6H_2COCH_3$	LAH + (−)-DBD, ether, r.t., 4 hr	(*S*)-(−)-2,4,6-$(CH_3)_3C_6H_2CHOHCH_3$ (−) (75% e.e.)	315
$C_6H_5CO(CH_2)_2OC_2H_5$	LAH + (−)-DMDB, ether, 0°	(*S*)-(−)-$C_6H_5CHOH(CH_2)_2OC_2H_5$ (−) (54% e.e.)	503
(*R*)-(+)-*p*-$CH_3C_6H_4\overset{*}{S}OCH_2COC_2H_5$	LAH + (−)-borneol (1 : 1), THF–ether, −70°, 3–5 hr	(*R*)-(+)-*p*-$CH_3C_6H_4\overset{*}{S}OCH_2\overset{*}{C}HOHC_2H_5$ (80)	717
$C_6H_5CO(CH_2)_2N(CH_3)_2$	LAH + (−)-menthol, ether, 0°	(*R*)-(+)-$C_6H_5CHOH(CH_2)_2N(CH_3)_2$ (−) (77% e.e.)	718,321
(−)-$C_6H_5COCH(CH_3)N(CH_3)_2$	LAH + (+)-2-butanol, ether, reflux, 5 hr	$C_6H_5CHOHCH(CH_3)N(CH_3)_2$ *erythro* : *threo* = 53 : 47 (97)	719
	LAH + (−)-QN + EtOH, ether, reflux, 5 hr	*erythro* : *threo* = 90 : 10 (34)	719
	LAH + (−)-QN, ether, reflux, 5 hr	*erythro* : *threo* = 62 : 38 (86)	719
	LTBA, ether, 0°, 5 min	 *threo* : *erythro* = 59 : 41 (92)	720
	LAH + (+)-DBD, ether, −40°	" : " = 52.5 : 47.5 (80)	721,720
	LAH + (+)-PAB, ether, −78°	" : " = 55 : 45 (79)	720
C_{12}			
	LAH + (2*S*,3*S*)-DPB, ether, r.t., 4 hr	 (−) (45% e.e.) (*S*)-(−)	505
	LAH + (−)-DBD, ether, r.t., 4 hr	" (−) (32% e.e.)	315
	LAH + (−)-QN, ether, reflux, 4 hr	 (−) (*R*)-(−)	709a,501
	LAH + BCGF + EtOH, ether, reflux, 2 hr	 (−) (40% e.e.) (*R*)-(+)	319
	LAH + (−)-menthol, ether, −70°	 (−) (95% e.e.) (*R*)-(−)	702
$C_6H_5CH(C_3H_7$-*i*$)COCH_3$	SMEAH + $CH_3O(CH_2)_2OH$, C_6H_6, 25°, 1 hr	 I:II = 86:14 (−)	711
(*R*)-(+)-*p*-$CH_3C_6H_4\overset{*}{S}OCH_2COC_3H_7$-*i*	LAH + (−)-menthol (1 : 1), THF–ether, −70°, 3–5 hr	(*R*)-(+)-*p*-$CH_3C_6H_4\overset{*}{S}OCH_2\overset{*}{C}HOHC_3H_7$-*i* (73)	717
C_{13}			
o-$ClC_6H_4COC_6H_5$	LAH + (+)-QND, ether, reflux, 5 hr	(*R*)-(+)-*o*-$ClC_6H_4CHOHC_6H_5$ (88)	716
	LAH + (−)-QN, ether, reflux, 5 hr	(*S*)-(−)-*o*-$ClC_6H_4CHOHC_6H_5$ (87)	716

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

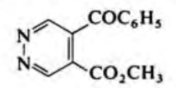
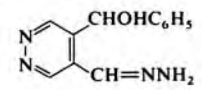
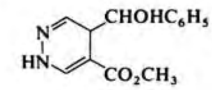
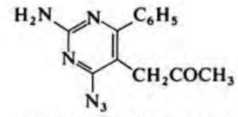
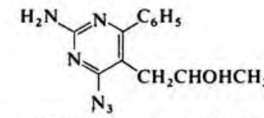
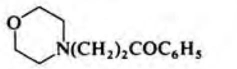
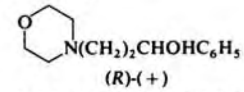
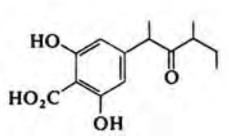
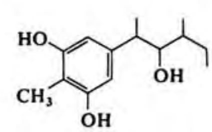
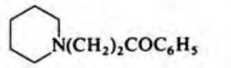
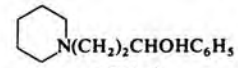
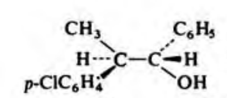
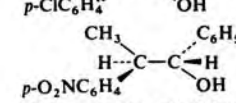
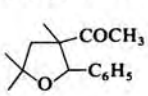
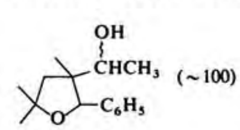
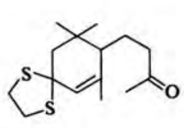
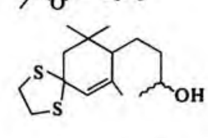
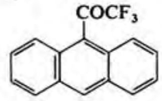
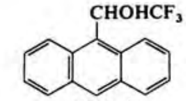
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	1. SMEAH, THF, −70°, 4 hr 2. N_2H_4	 (15) +  (19)	722
	LTBA	 (—)	488
p-ClC$_6$H$_4$COC(CH$_3$)$_2$(CH$_2$)$_2$CN	LTBA, THF, r.t., 2 days	p-ClC$_6$H$_4$CHOHC(CH$_3$)$_2$(CH$_2$)$_2$CN (71)	460
C$_6$H$_5$COC$_6$H$_{11}$	LAH + (+)-QND, ether, reflux, 4 hr	C$_6$H$_5$CHOHC$_6$H$_{11}$ (—) (10% e.e.) (S)-(−)	325
	LAH + (−)-menthol, ether, 0°	 (—) (59% e.e.) (R)-(+)	718
C$_6$H$_5$CH$_2$SC(CH$_3$)$_2$CH$_2$COCH$_3$	LAH + (+)-DMDB, ether	(−)-C$_6$H$_5$CH$_2$SC(CH$_3$)$_2$CH$_2$CHOHCH$_3$ (98) (53% e.e.)	723
(R)-(+)-p-CH$_3$C$_6$H$_4$$\overset{*}{S}OCH_2COC_4H_9$-$t$	LAH + NME + DMP (1 : 1 : 2), THF–ether, −70°, 3–5 hr	(R)-(+)-p-CH$_3$C$_6$H$_4$$\overset{*}{S}OCH_2$$\overset{*}{C}$HOHC$_4H_9$-$t$ (—)	717
C$_{14}$			
o-CH$_3$C$_6$H$_4$COC$_6$H$_5$	LAH + (−)-QN, ether, reflux, 5 hr	(S)-(+)-o-CH$_3$C$_6$H$_4$CHOHC$_6$H$_5$ (85)	724
	LAH + (+)-QND, ether, reflux, 5 hr	(R)-(−)-o-CH$_3$C$_6$H$_4$CHOHC$_6$H$_5$ (87)	724
o-CH$_3$C$_6$H$_4$COC$_6$H$_{11}$	LAH + (−)-QN, ether, reflux, 4 hr	(R)-(+)-o-CH$_3$C$_6$H$_4$CHOHC$_6$H$_{11}$ (—)	325
	LAH + (+)-QND, ether, reflux, 4 hr	(S)-(−)-o-CH$_3$C$_6$H$_4$CHOHC$_6$H$_{11}$ (—)	325
p-CH$_3$OC$_6$H$_4$CO(CH$_2$)$_3$CO$_2$C$_2$H$_5$	LTBA, THF, r.t., 22 hr	p-CH$_3$OC$_6$H$_4$CHOH(CH$_2$)$_3$CO$_2$C$_2$H$_5$ (—)	725
	SMEAH, toluene–xylene, 140°, 6 hr	 (55)	726
	LAH + (−)-menthol, ether, 0°	 (—) (66% e.e.) (R)-(+)	718
C$_{15}$			
p-ClC$_6$H$_4$CH(CH$_3$)COC$_6$H$_5$	LTBA, THF, reflux, 4 hr	 (—)	727
p-O$_2$NC$_6$H$_4$CH(CH$_3$)COC$_6$H$_5$	LTBA, THF, reflux, 4 hr	 (—)	727
(C$_6$H$_5$)$_2$CHCOCH$_3$	LAH + cis-2,3-pinanediol (1 : 1), ether, reflux, 1–2 hr	(S)-(−)-(C$_6$H$_5$)$_2$CHCHOHCH$_3$ (~100) (7% e.e.)	510
	LAH + (−)-QN, ether, r.t.	 (~100)	728
	SMEAH, THF–C$_6$H$_6$, 0°, 1 hr	 (98)	589
C$_{16}$			
	LAH + (−)-DBD, ether, r.t., 4 hr	 (—) (R)-(−)	315

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

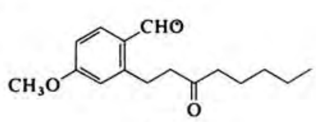
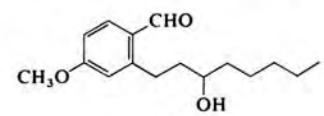
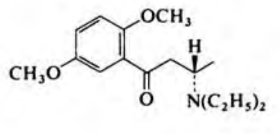
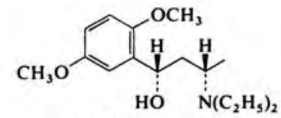
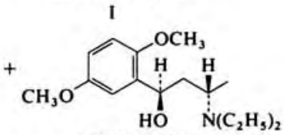
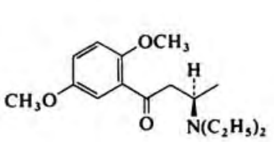
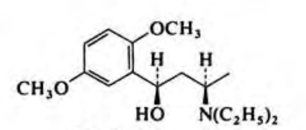
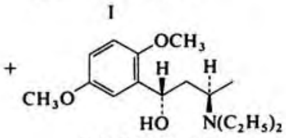
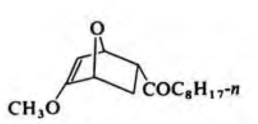
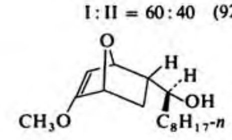
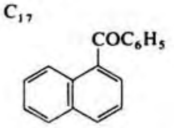
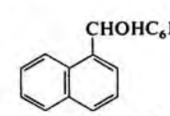
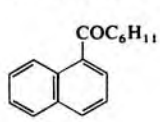
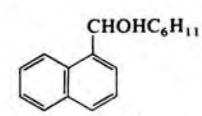
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
2,4,6-$(CH_3)_3C_6H_2COC_6H_5$	LAH + (−)-QN, ether, reflux, 4 hr	(*S*)-(−)-2,4,6-$(CH_3)_3C_6H_2CHOHC_6H_5$ (85) (39% e.e.)	316
	LAH + (+)-pseudoephedrine, ether, reflux, 4 hr	(*R*)-(+)-2,4,6-$(CH_3)_3C_6H_2CHOHC_6H_5$ (—) (27% e.e.)	316
	LAH + (+)-QND, ether, reflux, 5 hr	" (84)	724
$(C_6H_5)_2CHCOC_2H_5$	LAH + *cis*-2,3-pinanediol + $C_6H_5CH_2OH$ (1 : 1 : 1), ether, reflux, 1–2 hr	(*S*)-(−)-$(C_6H_5)_2CHCHOHC_2H_5$ (~100) (19% e.e.)	510
	LTBA, THF 1. −70°, 2 hr 2. −70° to r.t., 8 hr	 (−)	688
	SMEAH, C_6H_6-ether, −10°, 1 hr	 (1*S*,3*S*)-(−)-*erythro* I +  (1*R*,3*S*)-(+)-*threo* II I : II = 65 : 35 (58–75)	729–731
	SMEAH, C_6H_6-ether, −10°, 1 hr	 (1*R*,3*R*)-(+)-*erythro* I +  (1*S*,3*R*)-(−)-*threo* II I : II = 60 : 40 (92)	731
	LTBA, THF, 0°, 1 hr	 (90)	732
C_{17}			
	LAH + (−)-QN, ether, reflux, 5 hr	 (*S*)-(−) (89)	724
	LAH + (+)-QND, ether, reflux, 5 hr	" (*R*)-(+) (87)	724
$(C_6H_5)_2CHCOC_3H_7$-*n*	LAH + *cis*-2,3-pinanediol + $C_6H_5CH_2OH$ (1 : 1 : 1), ether, reflux, 1–2 hr	(*S*)-(−)-$(C_6H_5)_2CHCHOHC_3H_7$-*n* (~75) (25% e.e.)	510
$(C_6H_5)_2CHCOC_3H_7$-*i*	LAH + *cis*-2,3-pinanediol (1 : 1), ether, reflux, 1–2 hr	(*R*)-(+)-$(C_6H_5)_2CHCHOHC_3H_7$-*i* (90) (9% e.e.)	510
	LAH + (+)-QND, ether, reflux, 4 hr	 (−) (*R*)-(+)	325,733

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

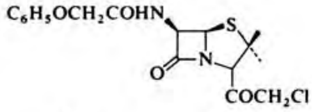
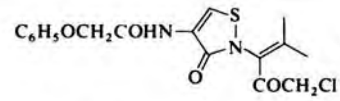
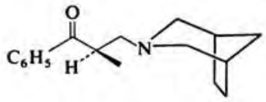
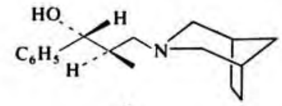
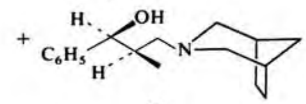
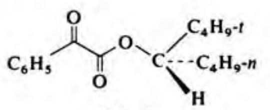
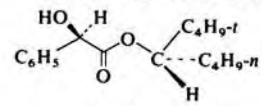
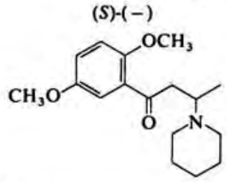
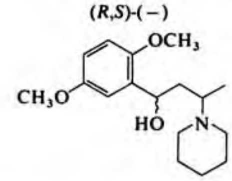
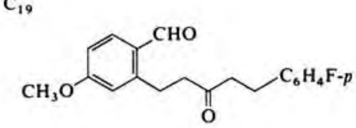
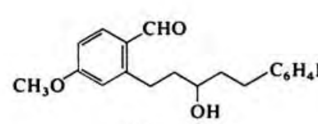
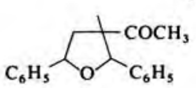
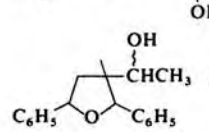
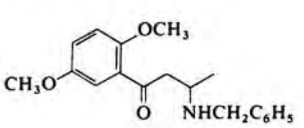
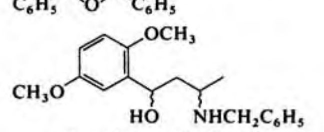
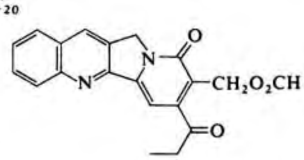
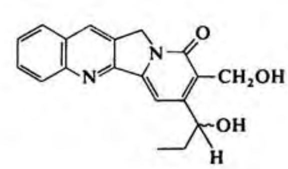
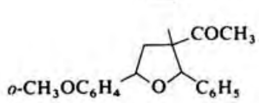
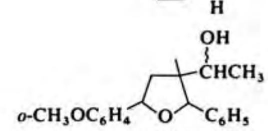
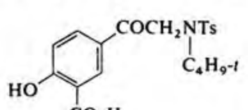
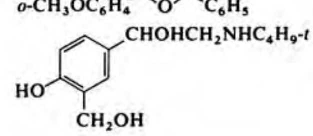
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA	 (−)	734
	LTBA, THF, reflux, 3 hr	 I +  II; I : II = 56 : 44 (~100)	735
 (*S*)-(−)	LTBA, THF, 0°, 2 hr	 (99) (13% e.e.) (*R*,*S*)-(−)	736
	SMEAH, C_6H_6–ether, −10°, 2 hr	 (93)	730
C_{18}			
$(C_6H_5)_2CHCOC_4H_9$-*n*	LAH + *cis*-2,3-pinanediol + $C_6H_5CH_2OH$ (1 : 1 : 1), ether, reflux, 1–2 hr	(*S*)-(−)-$(C_6H_5)_2CHCHOHC_4H_9$-*n* (~40) (20% e.e.)	510
$C_6H_5COCO_2M$ [a]	LAH + (−)-menthol (1 : 3), ether, reflux, 30 min	(*R*)-(−)-$C_6H_5CHOHCO_2M$ [a] (74) (40% e.e.)	737
C_{19}			
	LTBA, THF 1. −70°, 2 hr 2. −70° to r.t., 8 hr	 (−)	688
	LAH + (−)-QN, ether, r.t.	 (~100)	728
	SMEAH, C_6H_6–ether, −5°, 1 hr	 *erythro* : *threo* = 70 : 30 (91)	730
C_{20}			
	LAH + BCGF, ether, reflux, 2 hr	 (−)	738
	LAH + (−)-QN, ether, r.t.	 (~100)	728
	SMEAH, C_6H_6, 12 hr	 (−)	739

TABLE IX. Reduction of Alkyl and Aryl Ketones (*Continued*)

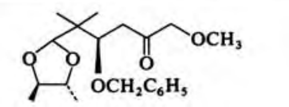
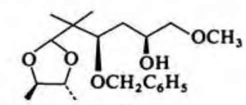
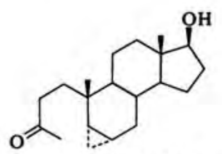
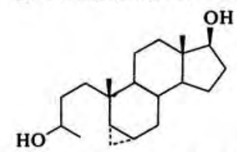
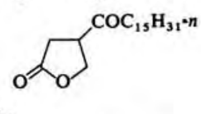
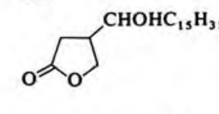
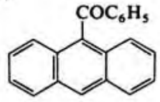
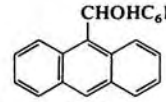
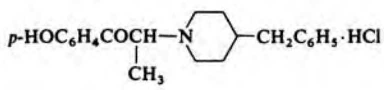
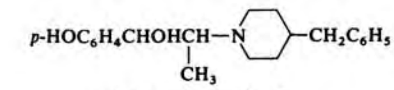
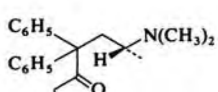
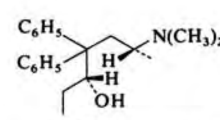
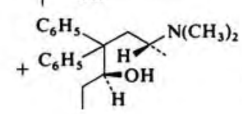
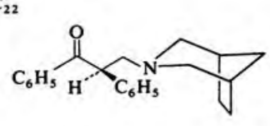
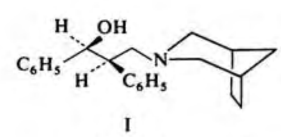
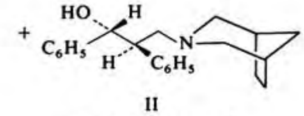
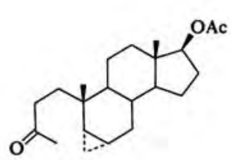
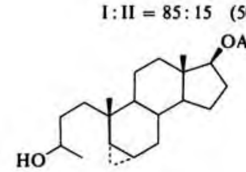
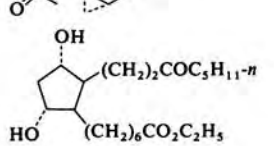
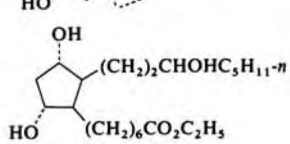
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, ether, −78°, 30 min	 (95) (15*R*,17*S*)-(−) [(15*R*,17*S*):(15*R*,17*R*) = 91:9]	740a
	LTBA, THF	 (−)	740b
	LTBA, THF, r.t., 2 hr	 (66)	741
C_{21}			
	LAH + (−)-QN, ether, reflux, 5 hr	 (99) (*S*)-(−)	724
	LAH + (+)-QND, ether, reflux, 5 hr	" (*R*)-(+) (89)	724
	SMEAH, C_6H_6, r.t.	 (−) *threo*:*erythro* = 57:43	742
 (2*R*)-(−)	SMEAH, C_6H_6	 (59) +  (30)	743
C_{22}			
	LTBA, THF, reflux, 24 hr	 I +  II I:II = 85:15 (50)	735
	LTBA, THF, r.t., 40 min	 (−)	740b
	LTBA, THF, r.t., 3 hr	 (−)	744

TABLE IX. REDUCTION OF ALKYL AND ARYL KETONES (*Continued*)

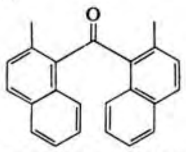
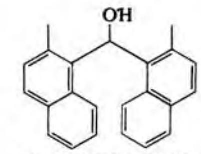
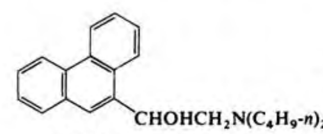
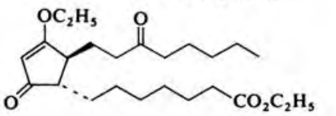
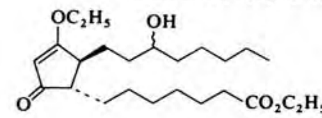
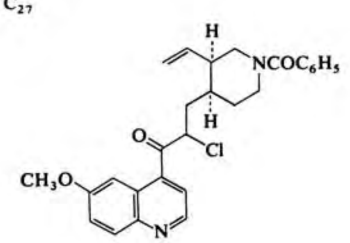
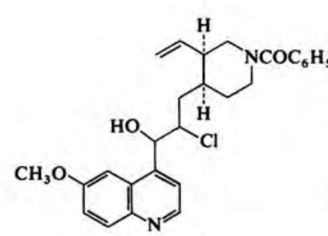
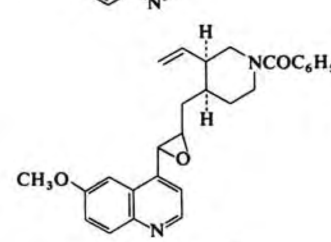
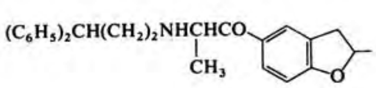
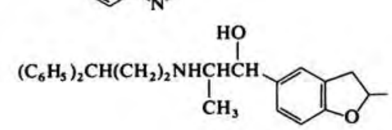
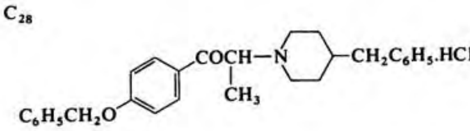
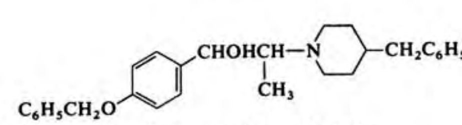
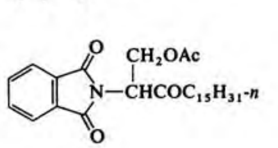
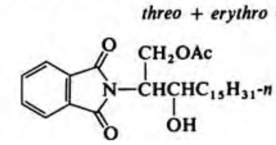
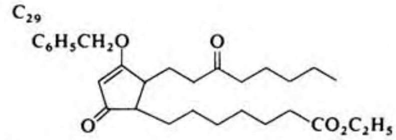
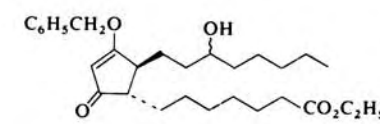
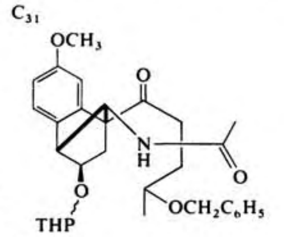
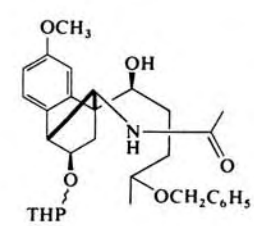
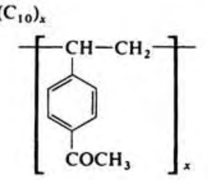
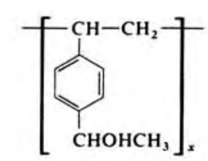
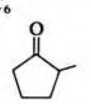
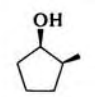
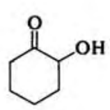
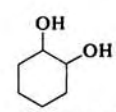
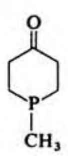
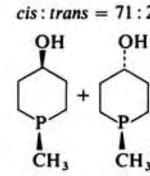
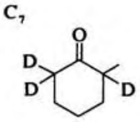
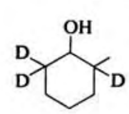
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{23}			
	LAH + (−)-QN, ether, reflux, 10 hr	 (7)	745
$C_6H_5COCH(CH_3)N(CH_2C_6H_5)_2$	SMEAH	$C_6H_5CHOHCH(CH_3)N(CH_2C_6H_5)_2$ (+)-*threo* + (−)-*threo* (77)	746
C_{24}			
	SMEAH, C_6H_6, ether	 (69)	747,748a
	LTBA, THF, 20°, 2 hr	 (50)	748b,748c
C_{26}			
2,4,6-Tricyclohexylphenyl methyl ketone	LAH + (−)-QN, ether, reflux, 5 hr	(*R*)-(+)-1-(2,4,6-Tricyclohexylphenyl)ethanol (82) (16% e.e.)	313
C_{27}			
	LTBA, THF, 1. −78°, 2 hr 2. r.t., 2 hr	 (91)	749
	1. LTBA 2. aq. KOH 3. DIBAL, toluene, −100°	 (−)	750
	LAH + MeOH (1 : 1), THF	 (−)	751
C_{28}			
	SMEAH, C_6H_6, r.t.	 *threo* + *erythro* = (55 + 24)	742
	LTBA, THF, 0°, 35 min	 (96)	752

TABLE IX. Reduction of Alkyl and Aryl Ketones (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{29} 	LTBA	 (85)	748c
C_{31} 	LTBA		753
$(C_{10})_x$ 	LAH + (−)-QN, (1:1) THF, reflux, 6 hr	 (~100) (+)-(9.8% e.e.)	754

[a] M = (−)-menthyl.

TABLE X. REDUCTION OF MONOCYCLIC KETONES

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6			
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, −78°, 1 hr	 (99)	522
Cyclohexanone	SMEAH, C_6H_6, r.t., 1 hr	Cyclohexanol (82)	459
	$Al_2H_3(OCH_2CH_2OCH_3)_3$, C_6H_6, 25°, 2 hr	" (94)	368
	$NaAl_2H_4[OCH_2CH_2N(CH_3)_2]_3$, C_6H_6, 25°, 2 hr	" (99)	371
	$AlH_2(OC_4H_9\text{-}t)$, THF, 0°	 (—) *cis* : *trans* = 71 : 29	755
	LTBA, THF 1. reflux, 2 hr 2. r.t., 8 hr	 (64) I II I : II = 55 : 45	756
C_7			
	LTBA, THF	 *cis* : *trans* = 40 : 60	757

153

TABLE X. REDUCTION OF MONOCYCLIC KETONES (*Continued*)

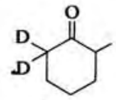
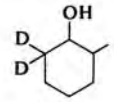
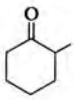
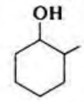
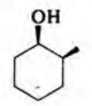
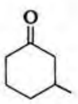
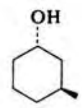
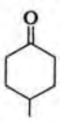
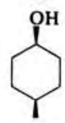
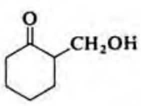
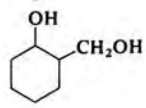
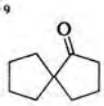
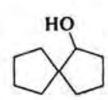
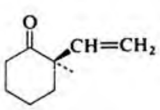
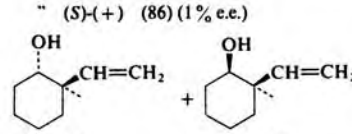
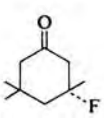
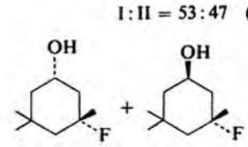
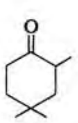
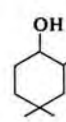
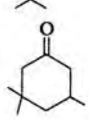
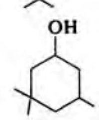
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF	 *cis* : *trans* = 40 : 60	757
	LTMA, THF, 0°	 *cis* : *trans* = 68 : 32 (—)	51,173
	$LiAlH(OC_2H_5)_3$, THF, 0°, 1 hr	" *cis* : *trans* = 27 : 73 (95)	173
	LTBA, THF, 0°, 1 hr	" *cis* : *trans* = 30 : 70 (93)	173, 51
	$NaAlH(OC_4H_9\text{-}t)_3$, THF, 20°	" *cis* : *trans* = 33 : 67 (—)	758
	SMEAH, C_6H_6, 30°	" *cis* : *trans* = 28 : 72 (—)	459
	$NaAlH[OCH_2CH_2N(CH_3)_2]_3$, C_6H_6, 25°, 2 hr	" (98)	367
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, 0°, 30 min	 (99)	522
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, −78°, 2 hr	 (94.5)	522
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, −78°, 1 hr	 (90)	522
	$AlH_2(OC_4H_9\text{-}t)$, THF, 0°	 *cis* : *trans* = 51 : 49 (—)	755
C_9 	LAH + (−)-QN, ether	 (*R*)-(−) (97) (5% e.e.)	759
	LAH + (+)-CN, ether	" (*S*)-(+) (86) (1% e.e.)	759
	LTBA, THF, r.t., 22 hr	 I + II; I : II = 53 : 47 (75)	760
	LTBA, THF, 25°, 1 hr	 I + II (—); I : II = 88 : 12	200
	LTBA, THF	 *cis* : *trans* = 9 : 91 (—)	521
	$LiAlH(OC_2H_5)_3$, ether	 *cis* : *trans* = 17 : 83 (—)	153,275
	$LiAlH[OCH(CH_3)C_4H_9\text{-}t]_3$, ether	" *cis* : *trans* = 20 : 80 (68)	155
	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°, 2 hr	" *cis* : *trans* = 20 : 80 (—)	178
	$LiAlH(OC_6H_5)_3$, THF, 0°	" *cis* : *trans* = 37 : 63 (92)	51
	$LiAlH(OC_6H_4CH_3\text{-}p)_3$, ether, reflux	" *cis* : *trans* = 33 : 67 (—)	170
	$LiAlH(OC_6H_4Cl\text{-}p)_3$, THF, 0°	" *cis* : *trans* = 35 : 65 (92)	51
	$LiAlH[OC_6H_4(C_4H_9\text{-}t)\text{-}p]_3$, THF, 0°	" *cis* : *trans* = 39 : 61 (94)	51

TABLE X. REDUCTION OF MONOCYCLIC KETONES (*Continued*)

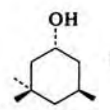
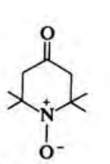
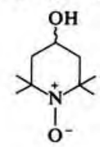
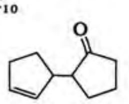
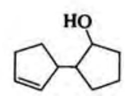
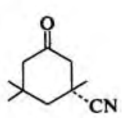
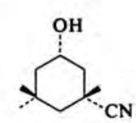
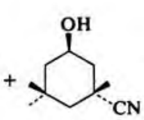
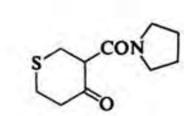
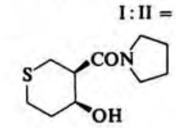
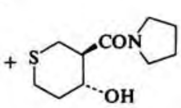
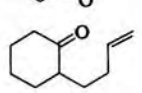
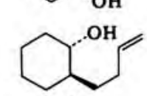
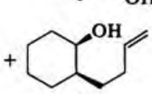
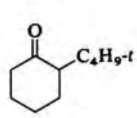
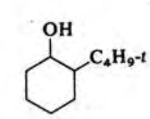
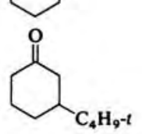
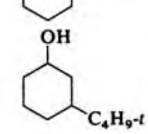
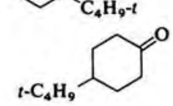
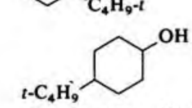
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	$LiAlH[OC_6H_2(C_4H_9\text{-}t)_3\text{-}2,4,6]_3$, ether, reflux, 1.75 hr	" *cis* : *trans* = 64 : 36 (84)	170
	$LiAlH_2[OC_6H_2(C_4H_9\text{-}t)_3\text{-}2,4,6]_2$, ether	" *cis* : *trans* = 30 : 70 (96)	170
	LAH + 2-methyl-2,4-pentanediol (1 : 1), ether, 25°	" *cis* : *trans* = 37 : 63 (—)	183
	LAH + 2,2-dimethyl-1,3-propanediol (1 : 1.5), ether, 25°	" *cis* : *trans* = 25 : 75 (—)	183
	$NaAlH(OCH_3)(OCH_2CH_2OCH_3)_2$, C_6H_6, 25°	" *cis* : *trans* = 23 : 77 (—)	191
	$NaAlH(OC_4H_9\text{-}t)(OCH_2CH_2OCH_3)_2$, THF, 25°	" *cis* : *trans* = 19 : 81 (—)	192
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, 0°, 3 hr	 (99.8)	522
	$LiAlH(OC_2H_5)_3$	 (—)	761
C_{10} 	LTBA, THF, 25°	 *cis* : *trans* = 34 : 66 (—)	762
	LTBA, THF, 25°, 1 hr	 (90) +  (—) I:II = 94 : 6	200
	LTBA, THF, 0°, 45 min	 (39) +  (38)	763
	LTBA, THF, −78°	 (—) +  (—) I:II = 67 : 33	764
	LTBA, THF, 0°, 1 hr	 *cis* : *trans* = 54 : 46 (63)	173
	LTBA, THF	 *cis* : *trans* = 19 : 81 (—)	521
	SMEAH, C_6H_6, 30°, 6 min	 *cis* : *trans* = 8 : 92 (95)	459
	LTBA, THF, 0°	" *cis* : *trans* = 10 : 90 (—)	51,154,200,261,263,303,521
	LTMA, THF, 0°	" *cis* : *trans* = 44 : 56 (—)	51,154
	$LiAlH(OC_6H_5)_3$, THF, 0°	" *cis* : *trans* = 7 : 93 (92)	51
	$LiAlH(OC_6H_4Cl\text{-}p)_3$, THF, 0°	" *cis* : *trans* = 8 : 92 (~100)	51
	$LiAlH[OC_6H_4(C_4H_9\text{-}t)\text{-}o]_3$, THF–ether, 25°	" *cis* (9) + *trans* (82)	193
	$LiAlH[OC_6H_4(C_4H_9\text{-}t)\text{-}p]_3$, THF, 0°	" *cis* : *trans* = 7 : 93 (82)	51

TABLE X. Reduction of Monocyclic Ketones (*Continued*)

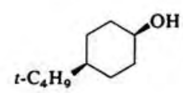
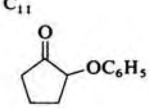
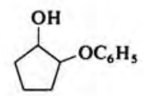
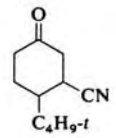
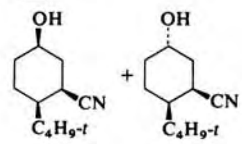
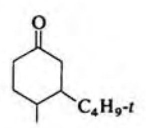
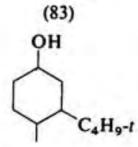
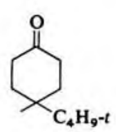
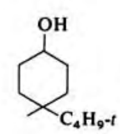
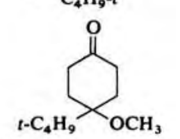
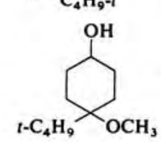
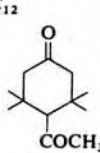
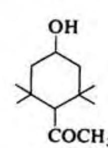
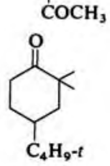
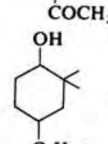
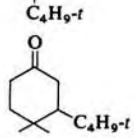
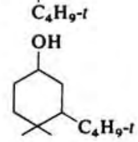
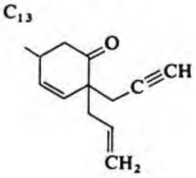
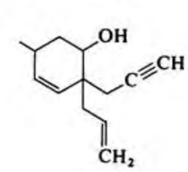
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	$LiAlH[OC_6H_3(C_3H_7\text{-}i)_2\text{-}2,6]_3$, THF–ether, 25°	" *cis* (70) + *trans* (28)	193
	$LiAlH(OC_3H_7\text{-}i)[OC_6H_3(C_4H_9\text{-}t)_2\text{-}2,6]_2$, THF–ether, 25°	" *cis* (70) + *trans* (18)	193
	$LiAlH(OCH_2CH_2OCH_2CH_2OC_2H_5)_3$	" *cis*: *trans* = 56 : 44 (80)	531
	LAH + (*R*)-(+)-DBN + CH_3OH, THF, −90° to r.t., overnight	" *cis* : *trans* = 85 : 15 (—)	708
	LTMA + $(s\text{-}C_4H_9)_3B$, THF, −78°, 3 hr	 (96.5)	522
C_{11}			
	LTBA, BME, 2 hr	 *cis* : *trans* = 90 : 10 (~100)	765
	LTBA, THF, r.t., 30 min	 (83) (14)	530
	LTBA, THF	 *cis* : *trans* = 21 : 79 (—)	521
	LTBA, THF	 *cis* : *trans* = 11 : 89 (—)	521
	LTBA, THF	 *cis* : *trans* = 7 : 93 (—)	521
C_{12}			
	LTBA, THF	 *cis* : *trans* = 95 : 5 (—)	303,309
	LTBA, THF, 0°	 *cis*:*trans* = 9:91 (—)	154
	LTBA, THF	 *cis* : *trans* = 19 : 81 (—)	521
C_{13}			
	LTBA, THF, 0°, 5 hr	 (81)	766

TABLE X. Reduction of Monocyclic Ketones (*Continued*)

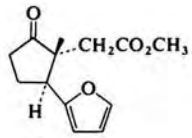
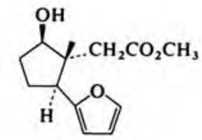
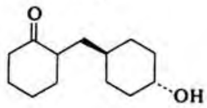
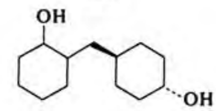
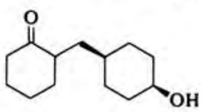
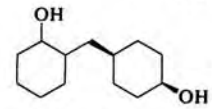
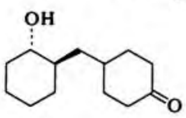
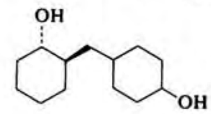
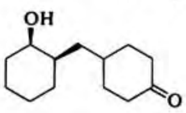
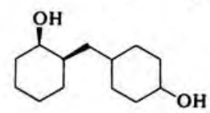
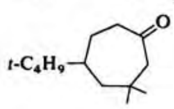
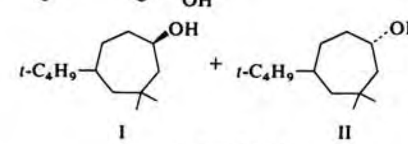
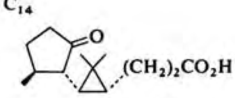
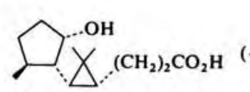
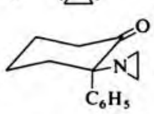
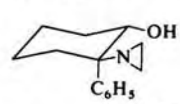
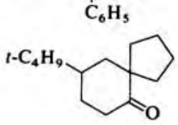
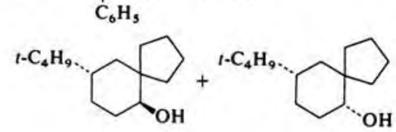
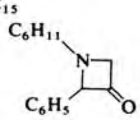
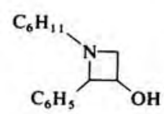
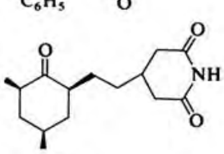
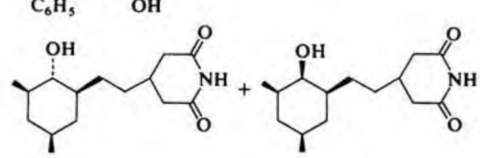
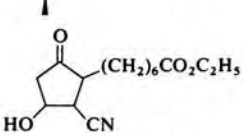
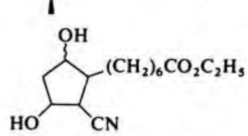
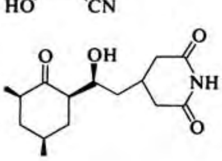
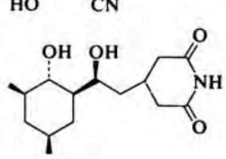
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF	 (81)	767
	LTMA, THF	 *trans,trans* : *cis,trans* = 30 : 70 (—)	158,172
	LTMA, THF	 *trans,cis* : *cis,cis* = 32 : 68 (—)	158
	LTMA, THF	 *trans,trans* : *trans,cis* = 55 : 45 (—)	158,172
	LTMA, THF	 *cis,trans* : *cis,cis* = 80 : 20 (—)	158
	LTBA, THF	 I + II (—) I : II = 70 : 30	768
C_{14}			
	LTBA, ether, 0°, 15 min	 (—)	769,770
	LTBA, THF, 0°, overnight	 (~100)	215,216
	LTBA, THF	 I + II (—) I : II = 93 : 7	771
C_{15}			
	SMEAH, C_6H_6, r.t., 2 hr	 *trans* : *cis* = 80 : 20 (87)	772
	LTBA, THF, 0°, 2 hr	 (88)	773
	LTBA	 (—)	774
	LTBA, THF, 0 to 5°, 2 hr	 (~32)	775

TABLE X. Reduction of Monocyclic Ketones (*Continued*)

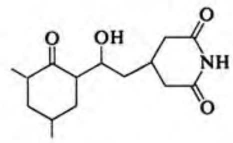
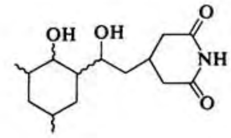
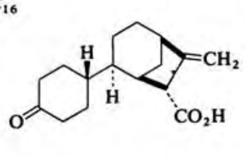
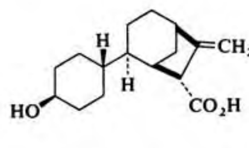
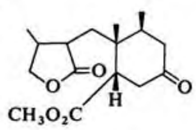
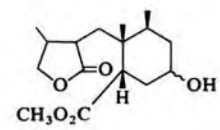
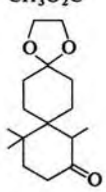
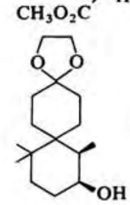
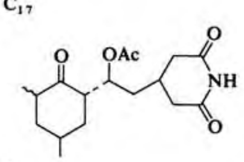
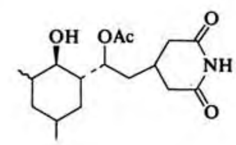
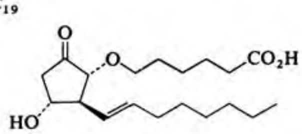
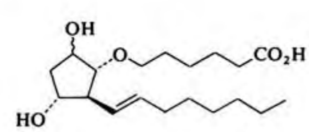
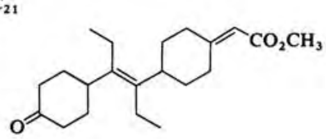
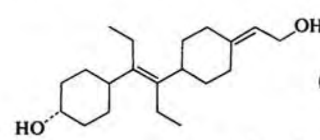
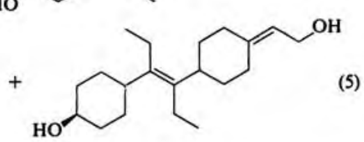
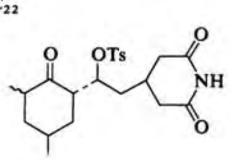
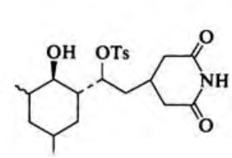
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, −5 to 5°, 1 hr	 (63)	776
C_{16}			
	LTBA, THF, 1. 0°, 3 hr 2. 24°, 16 hr	 (83)	777
	LTBA, THF, 5–10°, 30 min	 (50)	778
	LTBA, THF, r.t., 30 min	 (~100)	779
	LTBA, THF, 0°, 2 hr	 (33)	626,625
C_{17}			
	LTBA, THF, 3–5°, 1.5 hr	 (86)	780,781
C_{19}			
	LTBA	 (—)	782
C_{21}			
	SMEAH, C_6H_6–ether, r.t., 48 hr	 (78) +  (5)	783
C_{22}			
	LTBA, THF, 3–5°, 1.5 hr	 (79)	780,781

TABLE X. REDUCTION OF MONOCYCLIC KETONES (*Continued*)

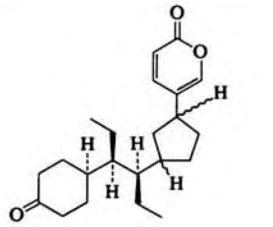
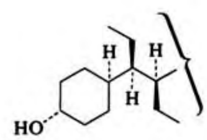
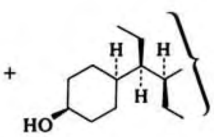
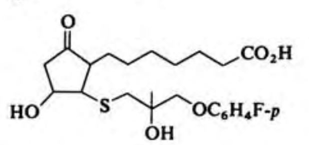
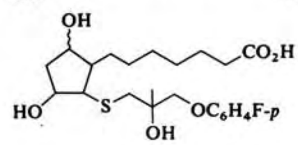
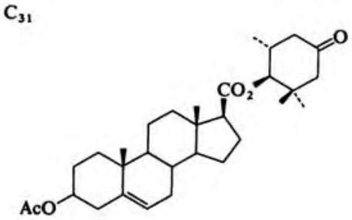
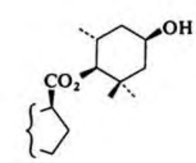
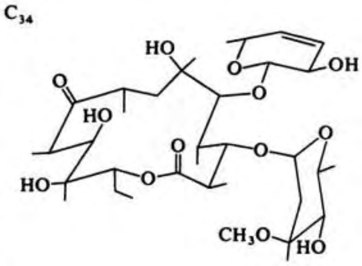
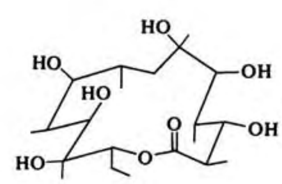
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, BME, r.t., 12 hr	 (82) +  (11)	784
	LTBA	 (—)	785,786
C_{31}			
	LTBA, THF, 0–5°, 12 hr	 (57)	788,787
C_{34}			
	1. SMEAH, THF–toluene, −78 to 30° 2. HCl, CH_3OH, 25°	 (52)	789

TABLE XI. REDUCTION OF BICYCLIC KETONES

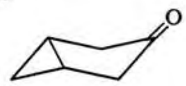
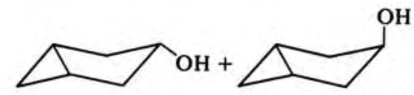
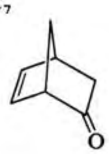
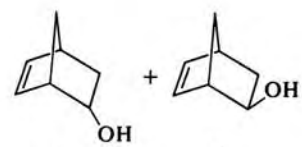
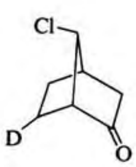
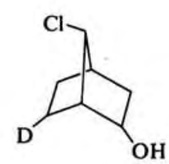
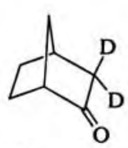
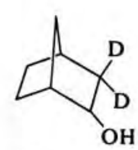
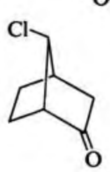
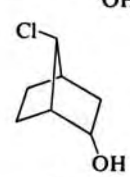
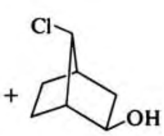
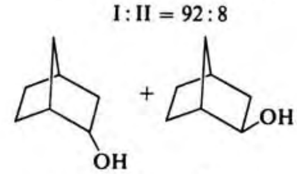
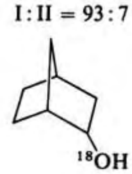
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6 	LTBA, THF, 25°	 (−) I II I : II = 88 : 12	536
C_7 	SMEAH, ether, reflux, 2 hr	 (−) I II I : II = 90 : 10	790
	LTBA, THF 1. 0°, 30 min 2. r.t., 1 hr	" (77)	791
	LTBA, THF, reflux, 7.5 hr	 (−)	792
	LTMA, THF	 (94)	793
	LTBA, THF, reflux, 7.5 hr	 (84) +  (7) I II I : II = 92 : 8	792
	LTMA, THF, 0°, 1 hr	 (I : 72) I II I : II = 98 : 2	173,30,794–796
	LTBA, THF, 0°, 1 hr	I : II = 95 : 5 (−)	178,173,30,791
	$LiAlH(OC_2H_5)_3$, THF, 0°, 1 hr	I : II = 85 : 15 (−)	173
	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°, 1 hr	I : II = 93 : 7 (−)	178
	LTMA, THF, 1 hr	 (−)	795

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

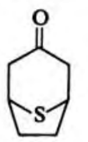
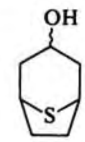
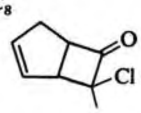
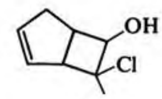
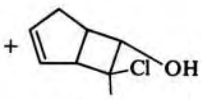
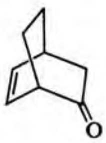
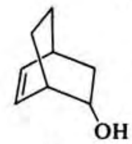
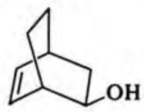
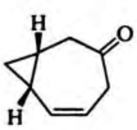
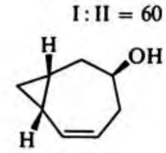
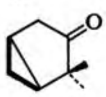
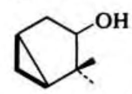
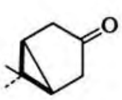
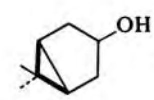
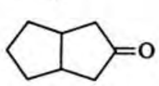
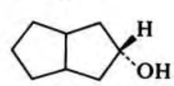
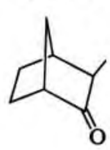
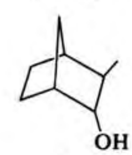
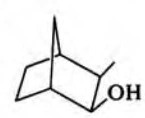
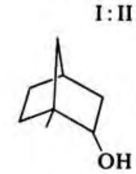
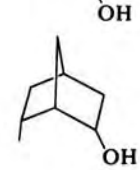
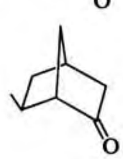
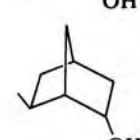
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., 48 hr	 (−)	797
C_8 	LTBA, ether	 +  (78) I II I : II = 60 : 40	798
	LTBA	 +  (−) I II I : II = 60 : 40	799
	LTBA	 (−)	800
	LTBA, THF	 *cis* : *trans* = 53 : 47 (−)	801
	LTBA, THF	 *cis* : *trans* = 99.5 : 0.5 (−)	537
	LTBA, THF, r.t., 1 hr	 (−)	802
	LTBA, BME	 +  (−) I II I : II = 93 : 7	803
	LTMA, THF, 0°, 2 hr	 (−)	804
	LTMA, THF, 0°, 2 hr	 (−)	804
	LTMA, THF, 0°, 2 hr	 (−)	804

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

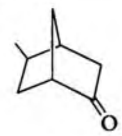
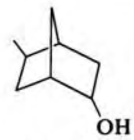
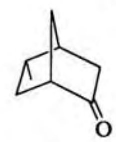
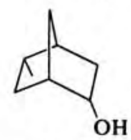
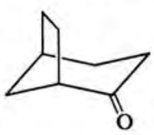
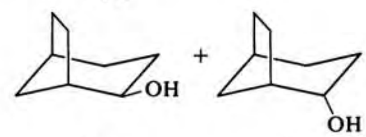
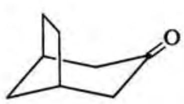
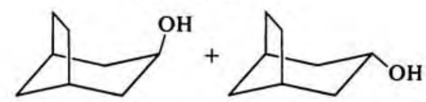
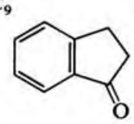
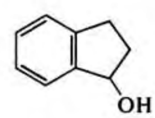
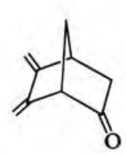
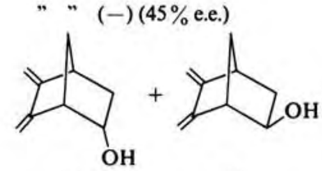
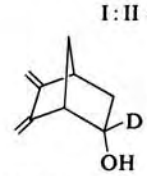
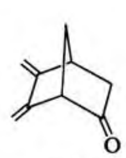
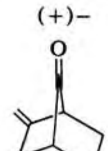
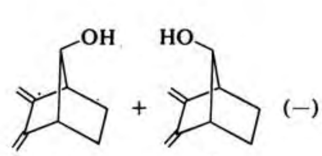
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTMA, THF, 0°, 2 hr	 (−)	804
	LTMA, THF, 0°, 2 hr	 (−)	804
	LTBA, THF, 1. r.t., 24 hr, 2. reflux, 16 hr	 (93) I II I : II = 92 : 8	805
	LTMA, THF, 0°, 2 hr	 (−) I II I : II = 83 : 17	806
C_9 	LAH + (−)-QN, ether, reflux, 4 hr	 (*R*)-(−) (−) (21% e.e.)	314
	LAH + (−)-DBD, ether, r.t., 4 hr	" (*S*)-(+) (−) (15% e.e.)	315
	LAH + DPB, ether, r.t., 4 hr	" (*S*)-(+) (−) (5% e.e.)	505
	LAH + (−)-NME + NEA (1 : 1 : 2), ether, −78°, 3 hr	" ". (88) (71% e.e.)	163,707
	LAH + (−)-DMDB, ether, 0°	" " (−) (45% e.e.)	503
	LTMA	 (−) I II I : II = 98 : 2	807
	$LiAlD(OCH_3)_3$, THF, r.t., 1 hr	 (90)	630
 (+)−	LTMA, THF, r.t., 1 hr	(1*R*,2*R*)-(+)-I (90)	808
	LTBA, THF	 (−) I II I : II = 89 : 11	809

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

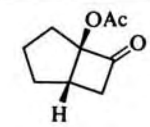
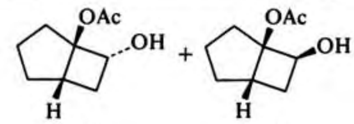
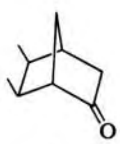
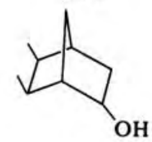
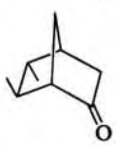
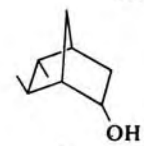
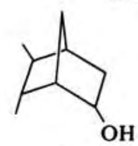
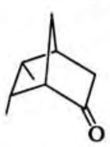
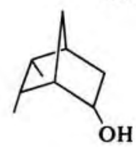
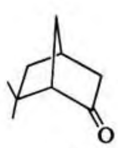
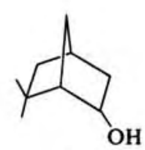
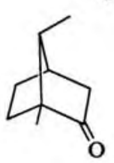
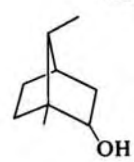
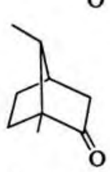
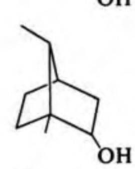
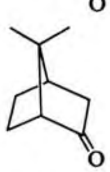
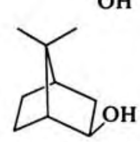
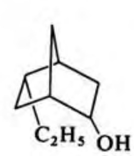
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, reflux, 2 hr	 (40) (8)	810
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 2 hr	 (—)	804
	LTMA, THF, 0°, 1 hr	 (89)	811

TABLE XI. Reduction of Bicyclic Ketones (*Continued*)

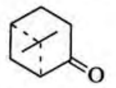
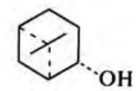
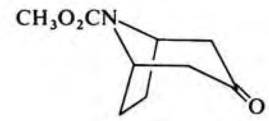
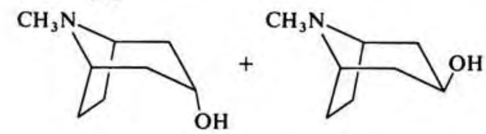
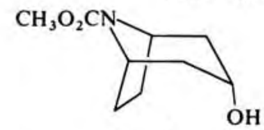
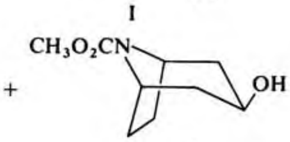
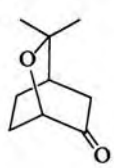
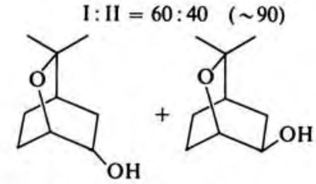
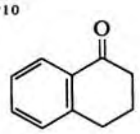
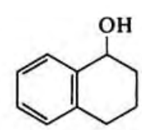
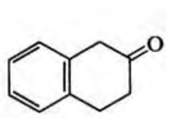
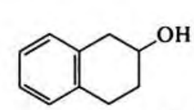
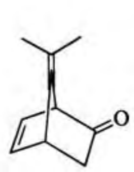
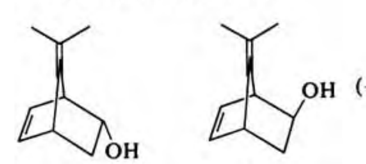
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6, reflux, 3 hr	 (88)	812
	SMEAH, C_6H_6, 25°, 22 hr	 I + II; I : II = 60 : 40 (90)	815
	LTBA, THF, 25°, 18 hr	 I +  II; I : II = 60 : 40 (~90)	815
	LTMA, THF, 0°, 1 hr	 I + II; I : II = 57 : 43 (97)	825
C_{10} 	LAH + (4*S*,5*S*)-(−)-4-hydroxymethyl-2-ethyl-5-phenyl-2-oxazoline (1:2.3), THF, −78°	 (*S*)-(+) (89) (3.7% e.e.)	502
	LAH + (−)-QN, ether, reflux, 4 hr	" (*R*)-(−) (−) (44.5% e.e.)	314
	LAH + NME + NEA (1 : 1 : 2), ether, −78°, 3 hr	" (*S*)-(+) (96) (51% e.e.)	163
	LAH + (−)-DMDB, ether, 0°	" " (−) (40% e.e.)	503
	LAH + (*S*)-4-anilino-3-methylamino-1-butanol, THF, −100°, 3–4 hr	" " (89) (88% e.e.)	813
	LAH + (+)-DBN + EtOH, THF 1. −50°, 6 hr 2. 20°, 16 hr	" (*R*)-(−) (91) (62% e.e.)	168
	LAH + (−)-DMDB, ether, 0°	 (*R*)-(+) (−) (38% e.e.)	503
	LAH + (−)-NME + NEA (1 : 1 : 2), ether, −78°, 3 hr	" (*R*)-(+) (98) (67% e.e.)	163
	LTBA, THF 1. 0°, 30 min 2. r.t., 1 hr	 I + II (−); I : II = 93 : 7	791

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

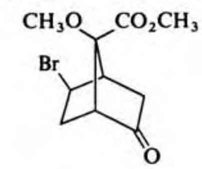
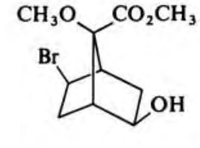
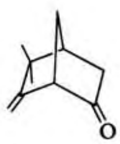
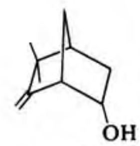
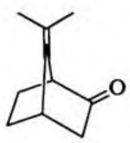
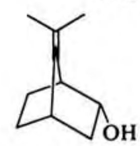
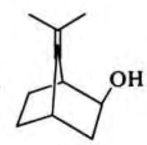
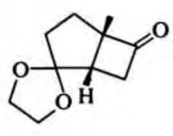
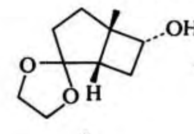
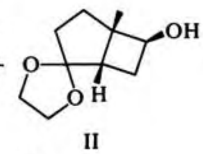
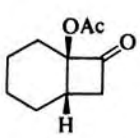
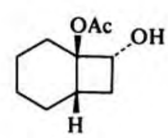
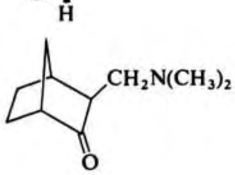
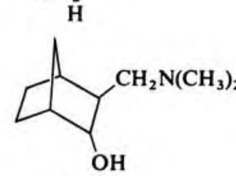
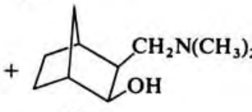
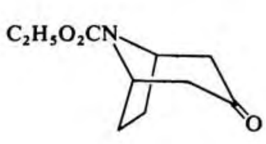
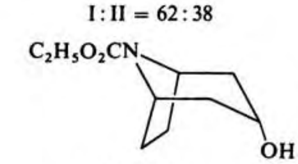
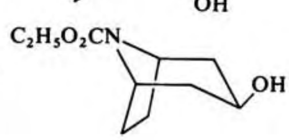
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 0°	 (85)	814
	LTBA	 (–)	816
	LTBA, THF 1. 0°, 30 min 2. r.t., 1 hr	 +  (–) I II I : II = 98 : 2	791
	LTBA	 +  (–) I II I : II = 52 : 48	817
	LTBA, THF, reflux, 12 hr	 (69)	810
	LTBA, BME	 I +  (–) II I : II = 62 : 38	803
	LTBA, THF, r.t., 3 hr	 (68) +  (23)	818

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

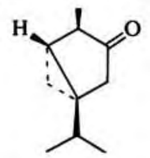
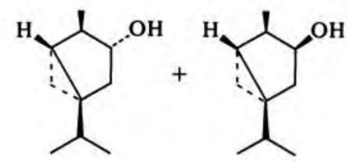
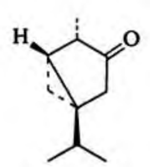
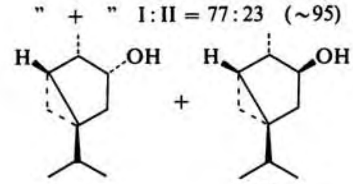
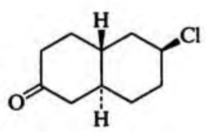
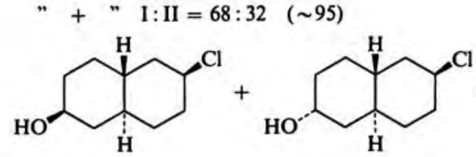
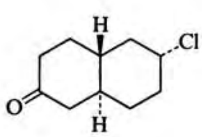
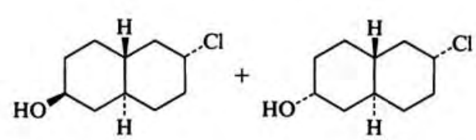
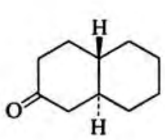
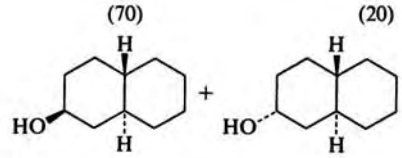
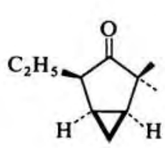
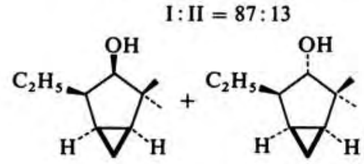
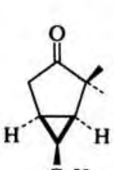
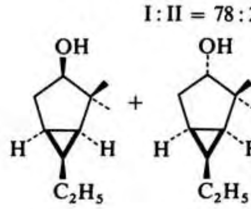
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTMA, THF, 20°, 15 hr	 I + II; I : II = 47 : 54 (~95)	181
	LTBA, THF, 20°, 15 hr	" + " I : II = 41 : 59 (~95)	181
	$LiAlH_3(OC_4H_9\text{-}t)$, THF, 20°, 15 hr	" + " I : II = 77 : 23 (~95)	181
	LTMA, THF, 96°, 2 hr	 I + II; I : II = 54 : 46 (~95)	181
	LTBA, THF, 20°, 15 hr	" + " I : II = 61 : 39 (~95)	181
	$LiAlH_3(OC_4H_9\text{-}t)$, THF, 20°, 15 hr	" + " I : II = 68 : 32 (~95)	181
	LTBA, THF, 0–10°, 5 hr	 I + II (–); I : II = 91.5 : 8.5	819a
	LTBA, THF, 0–10°, 5 hr	 (70) + (20)	819a
	LTBA, THF	 I + II (–); I : II = 87 : 13	521
	LTBA, THF	 I + II (–); I : II = 78 : 22	537
	LTBA, THF	 I + II; I : II = 98 : 2 (–)	537

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

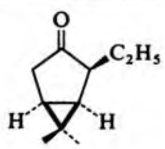
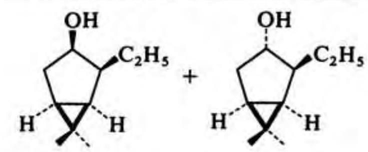
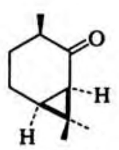
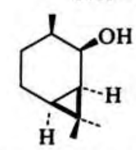
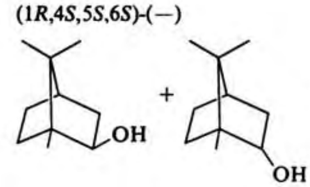
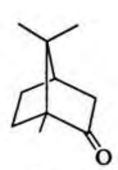
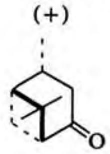
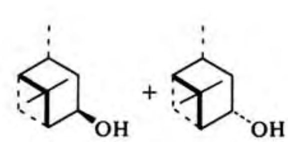
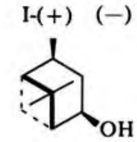
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF	 I II (−) I : II = 99.5 : 0.5	537
 (1*R*,4*S*,6*S*)-(−)	LTBA	 (−) (1*R*,4*S*,5*S*,6*S*)-(−)	820
 (±)	LTBA, THF, 20°	 I II I:II = 96:4 (−)	180,173,178, 259,261,519 821,822
	LTMA, THF, 25°	" + " I : II = 99 : 1 (−)	173,180
	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°, 2 hr	" + " I : II = 80 : 20 (−)	178
	SMEAH, C_6H_6, 25°	" + " I : II = 89 : 11 (−)	191
	$NaAlH(OC_4H_9\text{-}t)(OCH_2CH_2OCH_3)_2$, C_6H_6, 25°	" + " I : II = 91 : 9 (−)	191
	LAH + (−)-QN, ether, 1. r.t., 1 hr 2. reflux, 2 hr	" + " I : II = 90 : 10 (98) I (o.p. 2.5%) II (o.p. 21%)	715
 (−)	LAH + (−)-QN, ether, 1. r.t., 1 hr 2. reflux, 2 hr	I-(+) + II-(−) I-(+):II-(−) = 92:8 (−)	715
 (+)	LAH + (−)-QN, ether, 1. r.t., 1 hr 2. reflux, 2 hr	I-(−) + II-(+) I-(−):II-(+) = 92:8 (−)	715
	SMEAH, C_6H_6, reflux, 1 hr	 I II I : II = 94 : 6 (−)	823
	LTMA	I-(+) (−)	824
	LTMA	 (−)	824

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

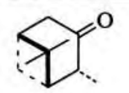
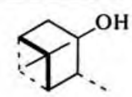
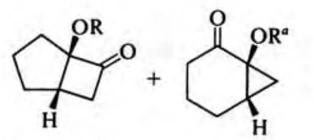
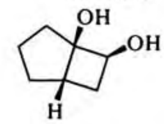
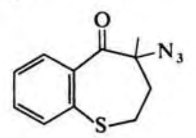
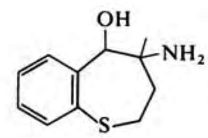
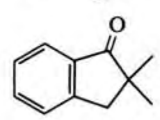
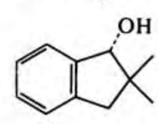
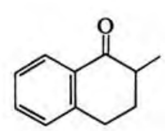
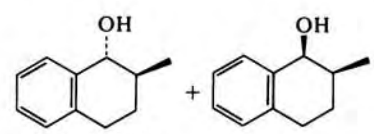
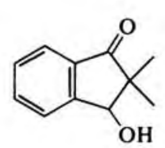
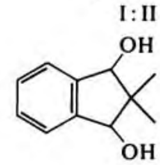
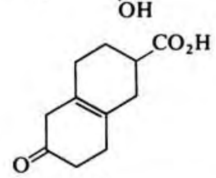
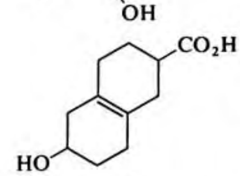
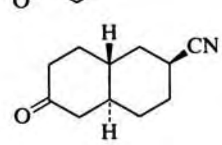
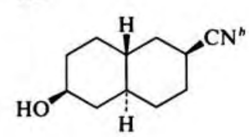
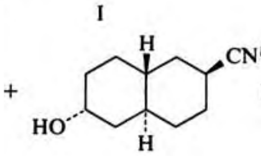
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, C_6H_6, reflux	 *cis* : *trans* = 70 : 30 (—)	196
	LTBA, THF, reflux	" *cis* : *trans* = 60 : 40 (—)	196,520
	LTMA, THF	" *cis* : *trans* = 30 : 70 (—)	196,520
	LTBA, THF 1. −78°, 1 hr 2. r.t., 18 hr 3. H_3O^+	 (56)	810
C_{11}			
	SMEAH, C_6H_6, 16 hr	 (65)	826
	LAH + (−)-QN, ether, reflux, 4 hr	 (*R*)-(−) (−) (31.5% e.e.)	314,544
	LAH + (−)-QN, ether, reflux, 5 hr	 (1*R*,2*S*)-(+) I + II (—) I : II = 67 : 33	827
	LTBA, ether, −78°	 *trans* : *cis* = 96 : 4 (—)	182
	LTBA, THF, 0–20°, 2 hr	 (90)	828,829
	LTBA, THF, 0–10°, 5 hr	 I +  II I : II = 92 : 8 (—)	819a,819b

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

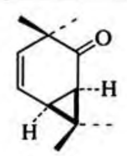
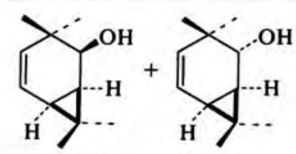
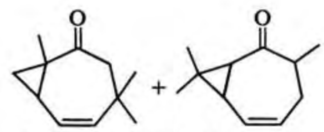
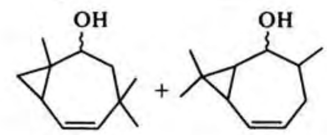
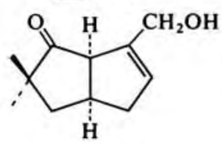
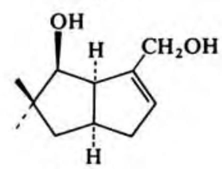
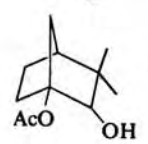
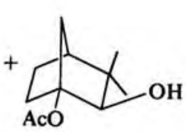
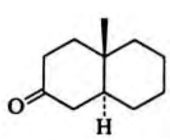
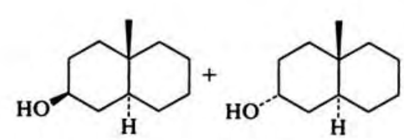
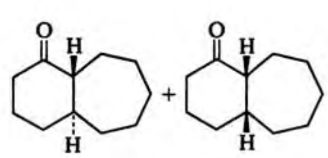
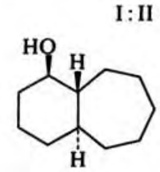
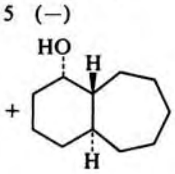
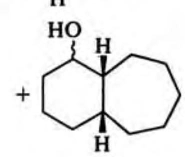
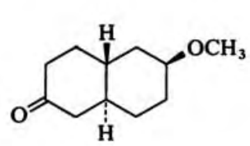
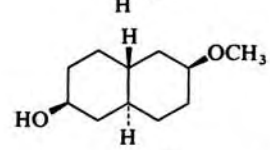
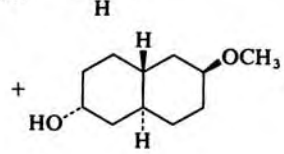
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF	 I II I:II = 94:6 (—)	830
	LTBA, THF, 20°, 20 hr	 (—)	831
	LTBA	 (85)	832
	LTBA, THF, reflux, 1 hr	 (67) +  (13)	833
	LTBA, THF, 20°	 I II I:II = 95:5 (—)	297,521,298
 I II I:II = 86:14	LTBA, THF, 50°, overnight	 (45) +  (40) +  (—)	834
	LTBA, THF, 0–10°, 5 hr	 (87) +  (5)	819a

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

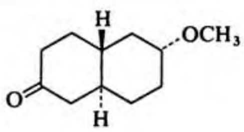
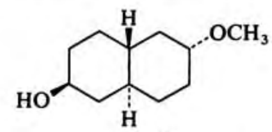
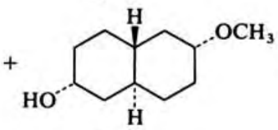
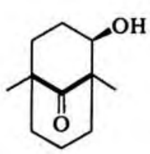
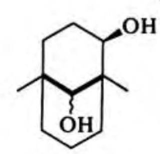
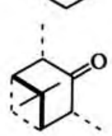
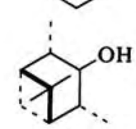
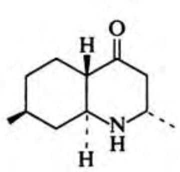
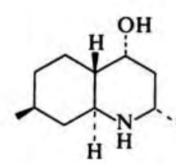
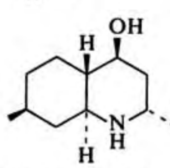
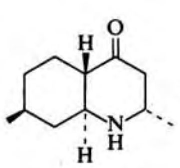
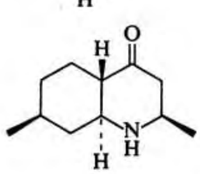
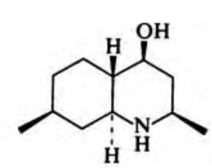
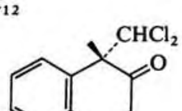
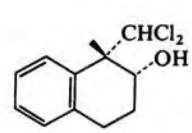
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 0–10°, 5 hr	 (68) +  (6)	819a
	LTBA, THF, reflux, 15 min	 (98)	835
	LTBA, THF, reflux, 4 days	 *trans*:*cis* = 95:5 (−)	196
	SMEAH, C_6H_6, reflux, 12 hr	" *trans*:*cis* = 25:75 (−)	196
	SMEAH, C_6H_6–THF, reflux, 12 hr	" *trans*:*cis* = 70:30 (−)	196
	LTBA, THF, 60°, 20 hr	 (56) +  (24)	836
 HCl	LTBA, EtOH, 78°, 18 hr	" (12) + " (70)	836
	LTBA, THF, 60°, 12 hr	 (85)	836
C_{12}			
	LTBA, BME, 2 hr	 (93)	837

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

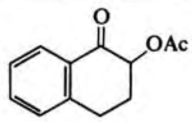
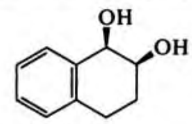
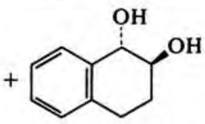
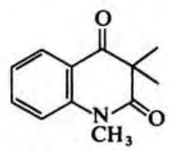
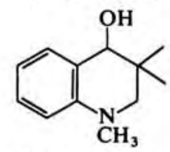
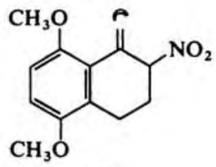
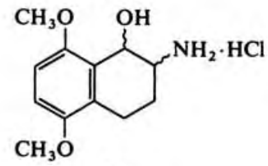
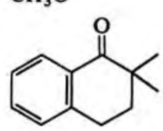
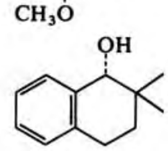
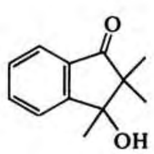
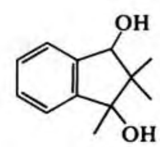
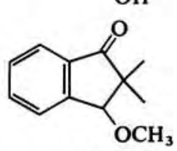
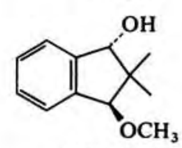
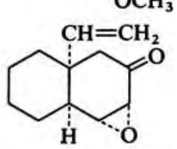
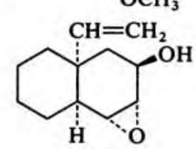
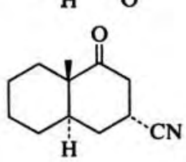
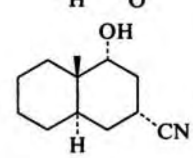
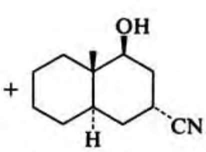
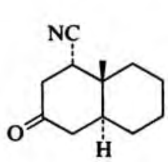
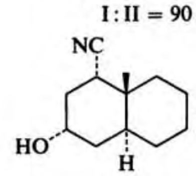
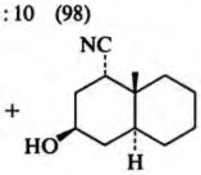
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LAH + (+)-DMDB (1 : 2), ether, 0°, 16 hr	 (1*R*,2*S*)-(−) (30) (20% e.e.) +  (1*R*,2*R*)-(+) (5) (62% e.e.)	533
	SMEAH, C_6H_6, reflux, 1.5 hr	 (68)	838
	1. SMEAH, C_6H_6, reflux, 6 hr 2. C_6H_6, HCl	 (39)	839
	LAH + (−)-QN, ether, reflux, 4 hr	 (−) (20% e.e.) (*R*)-(−)	314,544
	LTBA, ether, 0°	 *cis* : *trans* = 60 : 40 (−)	182
	LTBA, ether, 34°	 (~100)	182
	LTBA, ether	 (85)	840
	LTBA, THF, r.t., 15 min	 I +  II I : II = 90 : 10 (98)	549
	LTBA, THF, 30°	 I +  II I : II = 85 : 15 (−)	297,298

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

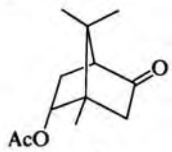
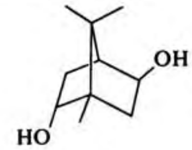
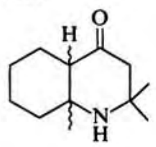
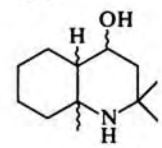
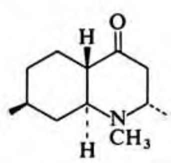
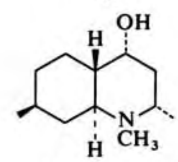
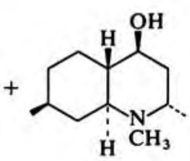
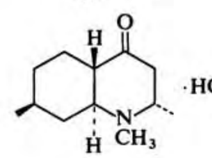
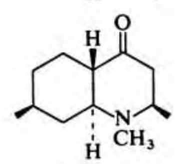
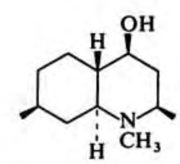
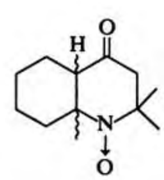
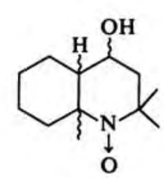
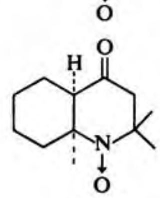
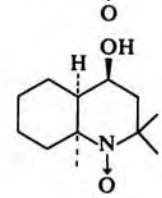
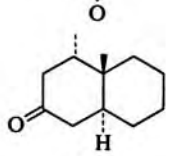
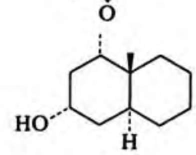
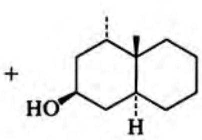
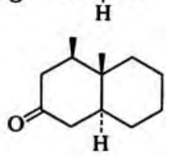
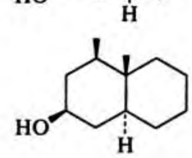
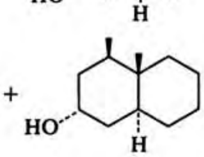
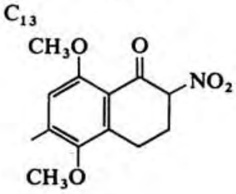
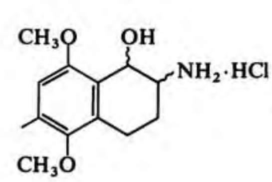
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTMA, THF 1. 0°, 30 min 2. r.t., 17 hr	 (84)	841
	LTBA, THF, 4 hr	 (82)	842
	LTBA, THF, 60°, 26 hr	 (52) +  (30)	836
	LTBA, EtOH, 78°, 22 hr	" (10) + " (78)	836
	LTBA, THF, 60°, 14 hr	 (95)	836
	LTBA, THF, 0°	 (99)	842
	LTBA, THF, r.t., 16 hr	 (—)	842
	LTBA, THF, 30°, 3 hr	 (68) +  (29)	298
	LTBA, THF, 230°, 2 hr	 (80) +  (14)	298
C_{13}			
	1. SMEAH, C_6H_6, reflux, 8 hr 2. Ether–$CHCl_3$, HCl	 (62)	843

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

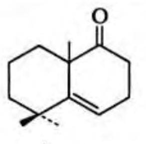
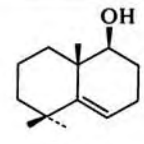
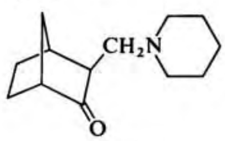
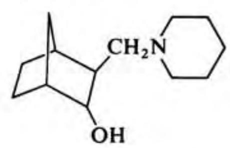
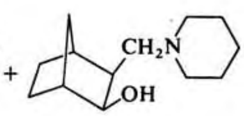
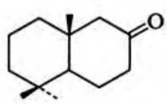
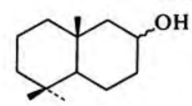
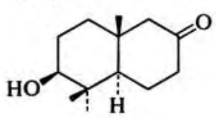
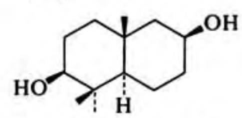
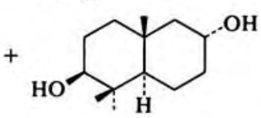
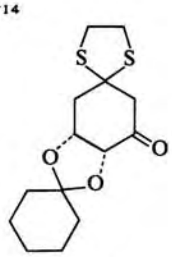
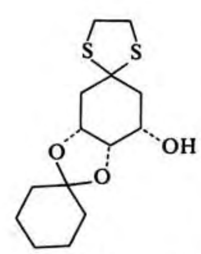
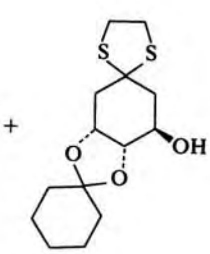
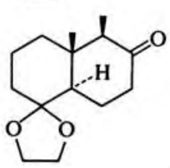
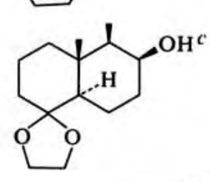
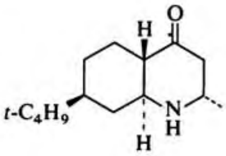
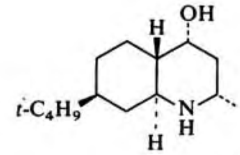
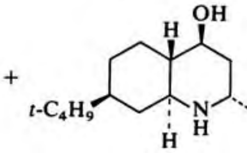
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., overnight	 (71)	844
	LTBA, BME	 +  I II I : II = 82 : 18 (—)	803
	LTBA, BME	 (~100)	845
	LTBA, ether, reflux, 3 hr	 (75) +  (~25)	846
C_{14}			
	LTBA	 (70) +  (6)	847
	LTBA, THF, r.t., 12 hr	 [c] (98)	848a,848b
	LTBA, THF, 60°, 18 hr	 (53) +  (29)	849

TABLE XI. Reduction of Bicyclic Ketones (*Continued*)

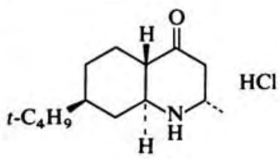
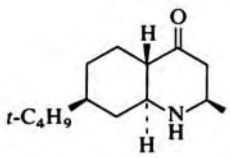
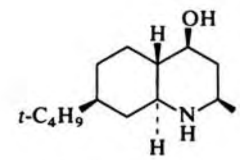
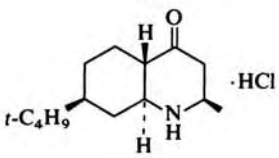
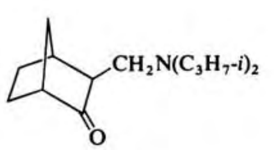
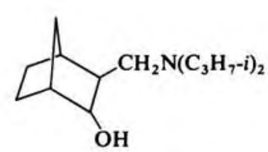
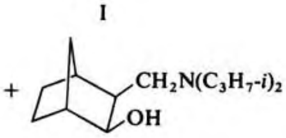
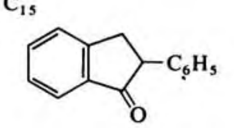
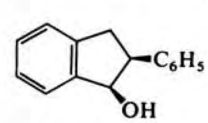
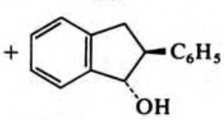
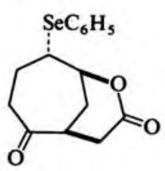
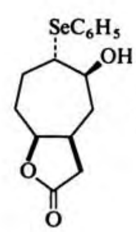
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, EtOH, 78°, 16 hr	" (12) + " (76)	849
	LTBA, THF, 60°, 12 hr	 (83)	849
	LTBA, EtOH, 78°, 10 hr	" (88)	849
	LTBA, BME	 I +  II I:II = 85:16 (−)	803
C_{15}			
	LTBA	 (55) +  (~45)	850
	LTBA, THF, −10°, 1 hr	 (83)	851

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

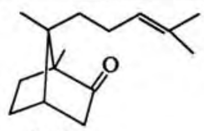
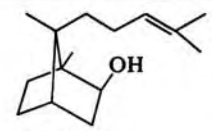
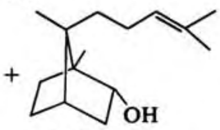
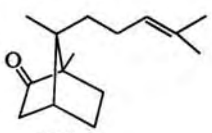
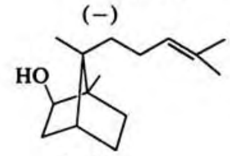
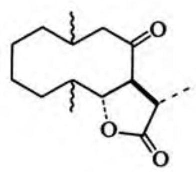
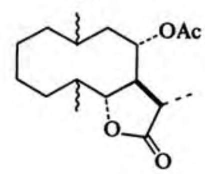
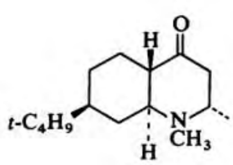
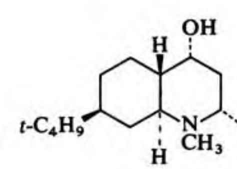
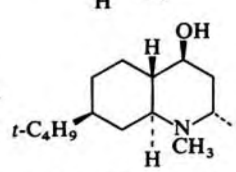
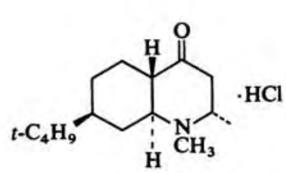
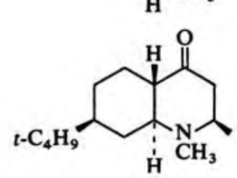
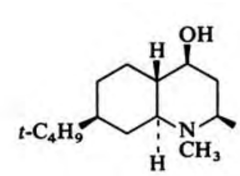
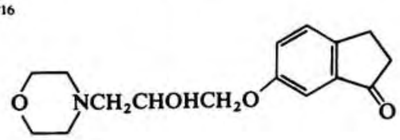
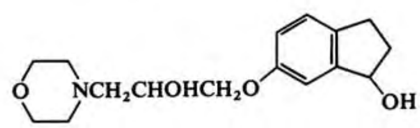
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
 (−)	LTMA, THF, 16 hr	 (95) (+) +  (−) (−)	852–854
 (+)	LTMA, THF, 16 hr	 (−) (+)	852–854
	1. LTBA, THF, r.t., 15 min 2. Ac_2O, Py	 (−)	855
	LTBA, THF, 60°, 24 hr	 (55) +  (25)	849
	LTBA, EtOH, 78°, 22 hr	" (8) + " (78)	849
	LTBA, THF, 60°, 18 hr	 (94)	849
C_{16}			
	SMEAH, C_6H_6	 (−)	856

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

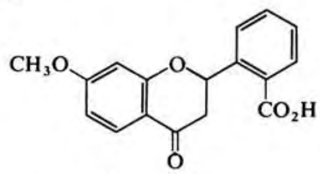
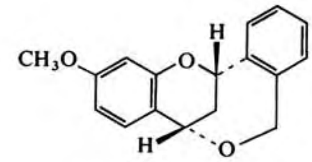
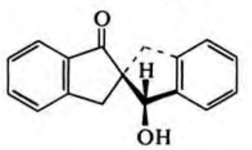
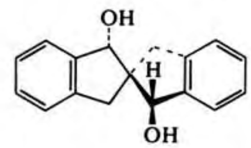
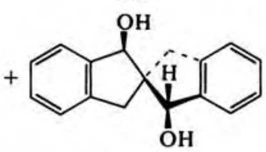
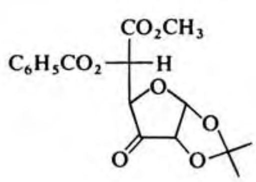
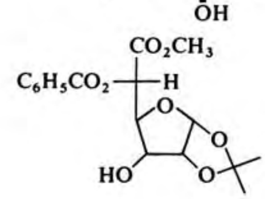
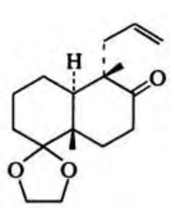
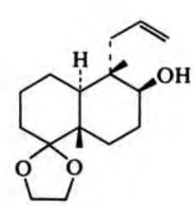
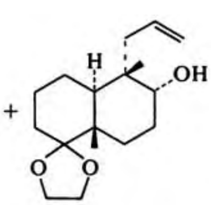
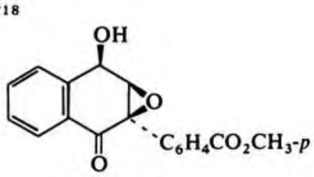
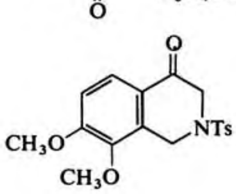
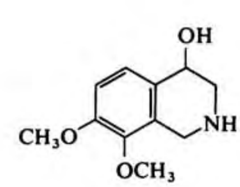
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{17}			
	1. SMEAH, C_6H_6, reflux, 3 hr 2. Silica gel	 (54)	857
	LTBA, THF, reflux, 3 hr	 (70) +  (—)	858
	LTBA, THF, r.t., 30 min	 (71)	859
	LTBA, THF, reflux, 48 hr	 (47) +  (25)	860
C_{18}			
	LTBA	No reaction	861
	SMEAH, C_6H_6, reflux	 (62)	862,863

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

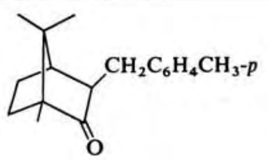
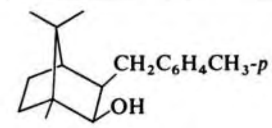
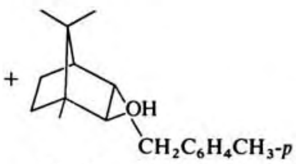
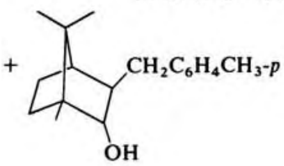
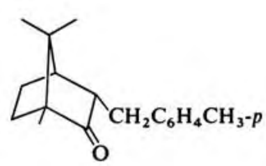
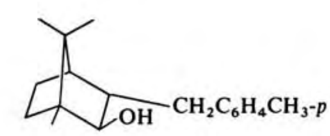
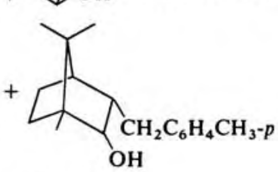
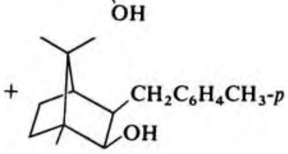
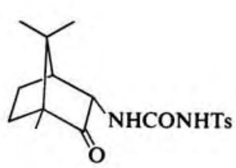
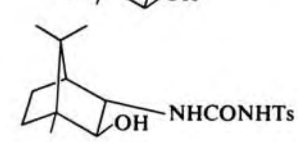
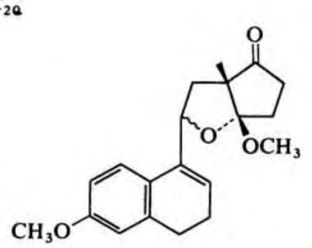
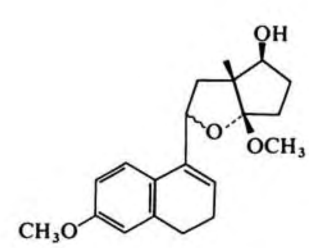
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 70°, 6 hr	 (96) +  (3) +  (1)	864
	LTBA, THF, 70°, 6 hr	 (63) +  (33) +  (4)	864
	SMEAH, C_6H_6–BME 1. 0°, 1 hr 2. r.t., 3 hr	 (46)	865
C_{20}			
	LTBA, THF, r.t., 15 min	 (–)	866

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

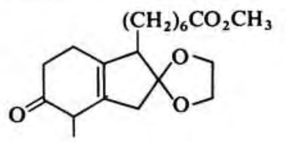
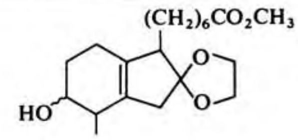
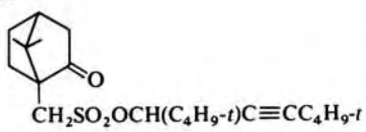
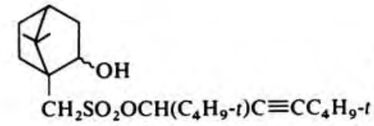
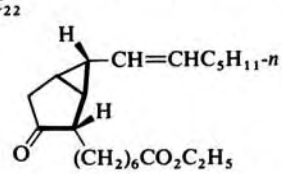
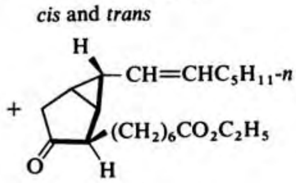
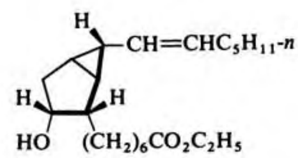
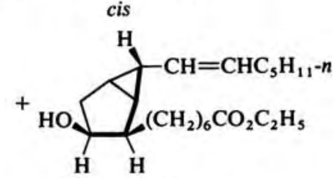
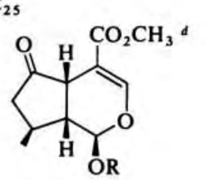
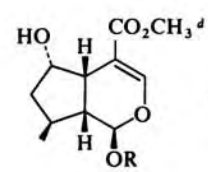
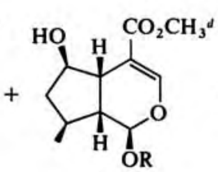
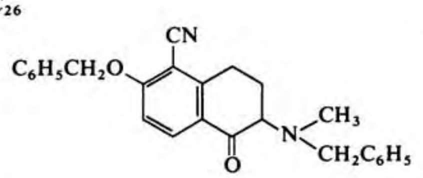
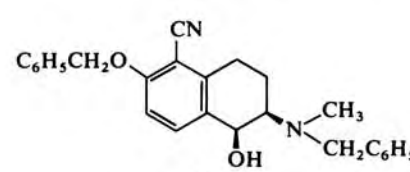
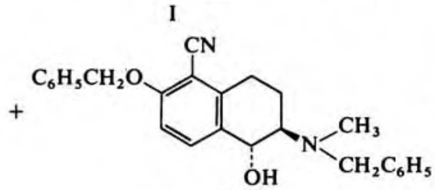
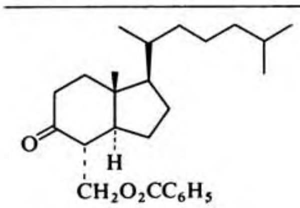
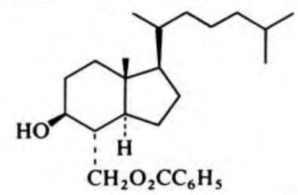
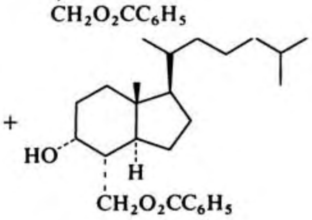
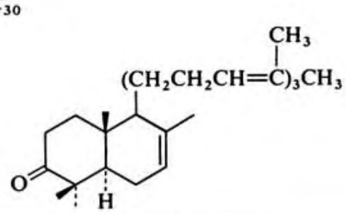
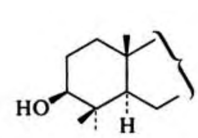
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 0°, 4 hr	 (~100)	867,868
C_{21} 	LTBA, THF, reflux, 18 hr	 (—)	869
C_{22}  *cis* and *trans* +  *cis* and *trans*	LTBA	 *cis* +  *cis* (—)	870
C_{25} 	LTBA, THF, 30 min	 I +  II (—) I : II = 67 : 33	871
C_{26} 	LTBA, THF, r.t., 6 hr	 I +  II (—) I : II = 67 : 33	872

TABLE XI. REDUCTION OF BICYCLIC KETONES (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, ether, r.t., 3 hr	 (95) +  (~5)	873
C_{30} 	LTBA, ether, r.t., 19 hr	 (—)	874

[a] R = $(CH_3)_3Si$—.
[b] The original paper gives both products erroneously in a reverse ratio.[819b]
[c] In the original paper the alcohol structure is given erroneously as *trans*-5,5-ethylenedioxy-1β,8aβ-dimethyldecalin-2α-ol.[848b]
[d] R = $(AcO)_4OC_6H_7$—.

TABLE XII. REDUCTION OF POLYCYCLIC KETONES

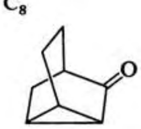
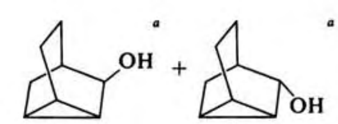
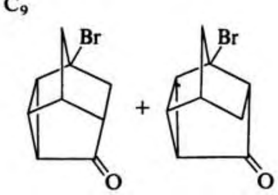
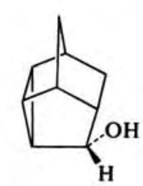
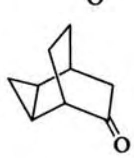
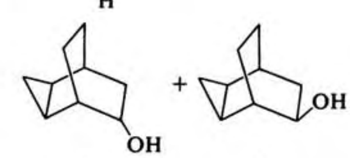
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_8			
	LTMA, THF, 0°, 1 hr	 [a] [a] (~100) I II I : II = 98 : 2	173,520
C_9			
	1. LTBA, THF, r.t., 5 hr 2. Li, t-C_4H_9OH, THF	 (72)	875
	LTBA, ether, r.t., 67 hr	 I II I : II = 35 : 65 (75)	876

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

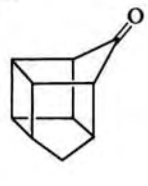
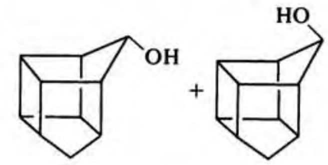
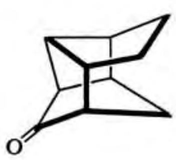
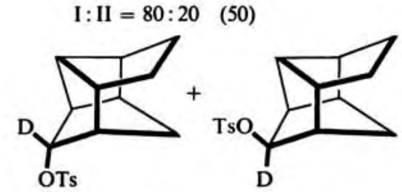
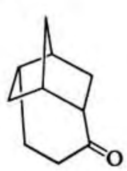
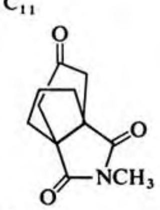
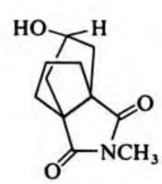
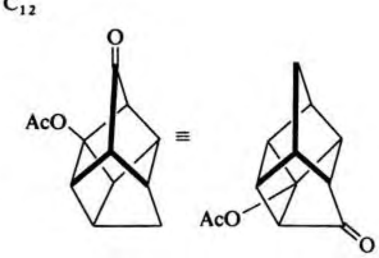
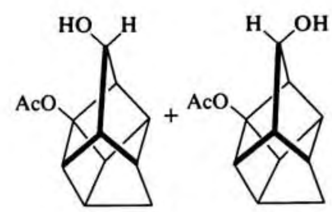
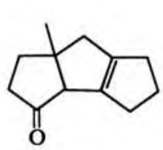
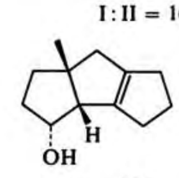
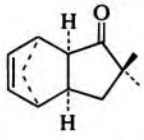
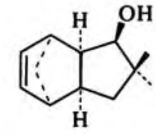
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{10}			
	LTBA, ether, r.t., 1 hr	 I II I : II = 80 : 20 (50)	877
	1. $LiAlD(OC_4H_9\text{-}t)_3$ 2. TsCl, Py	 (–)	878
	LTBA, THF, reflux, 19 hr	No reaction	879
C_{11}			
	LTBA	 (–)	880
C_{12}			
	LTBA, ether	 I II I : II = 16 : 84 (80)	881
	LTBA, ether, 25°, 20 hr	 (86)	882
	LTMA, THF, 0°, 1 hr	 (98)	832

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

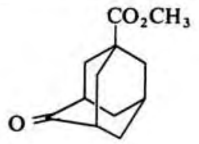
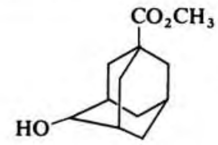
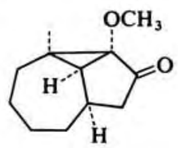
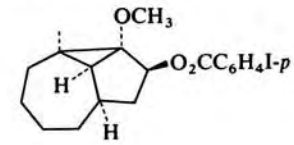
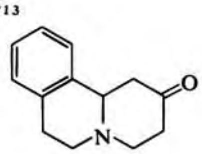
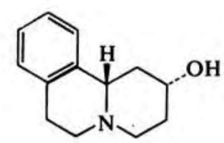
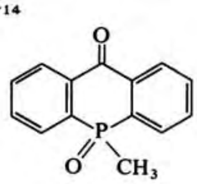
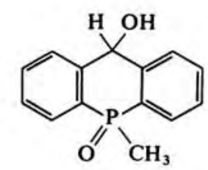
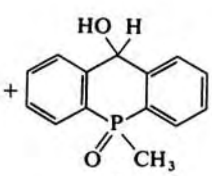
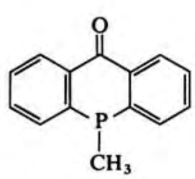
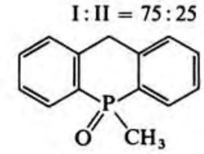
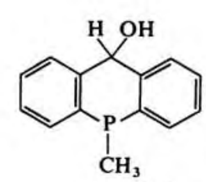
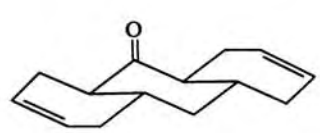
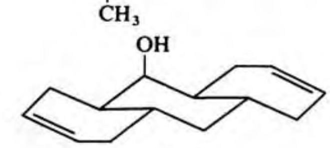
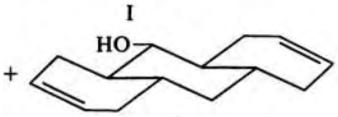
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, reflux, 3 hr	 *trans* : *cis* = 83 : 17 (72)	883
	1. LTBA, THF, r.t., 1 hr 2. *p*-IC_6H_4COCl, Py	 (52)	884
C_{13} 	LTBA, THF, 22 hr	 (70)	885
C_{14} 	LTBA, THF, r.t., 30 min	 (90) I	886,887
	SMEAH	I +  (—) II I : II = 75 : 25	886
	1. LTBA, THF, r.t., 20 min 2. H_3O^+	 (90)	886
	SMEAH, r.t., 20 min	 (83)	886
	LTMA, THF, 0°, 1 hr	 I +  (—) II I : II = 56 : 44	888

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

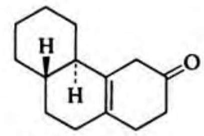
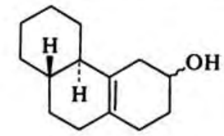
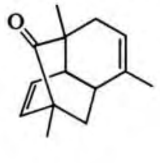
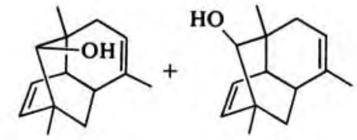
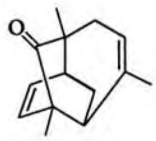
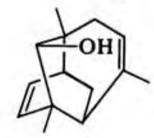
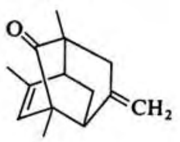
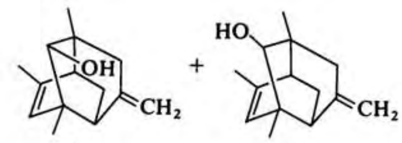
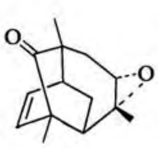
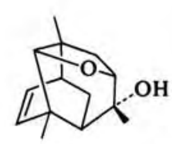
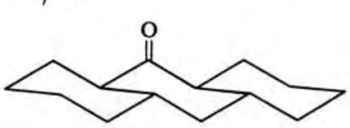
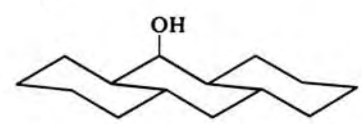
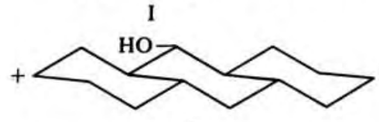
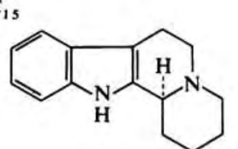
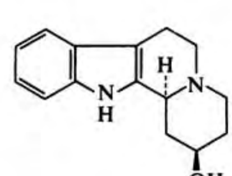
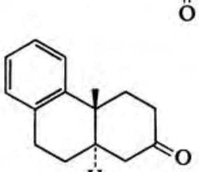
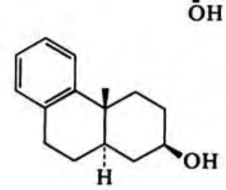
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 3 hr	 (98)	889
	SMEAH, C_6H_6 1. 30°, 4 hr 2. 60°, 17 hr	 I II I : II = 60 : 40 (77)	890,891
	SMEAH, C_6H_6, reflux, 1.5 hr	 (93)	892,891
	SMEAH, C_6H_6, r.t., 2 days	 I II I : II = 79 : 21 (92)	893
	SMEAH, C_6H_6, 30–40°, 2 hr	 (93)	890
	LTMA, THF, r.t., 6 hr	 (–) I +  (–) II I : II = 67 : 33	888
C_{15}			
	$LiAlH_2(OC_2H_5)_2$	 (~100)	894
	LTBA, THF 1. 0°, 1 hr 2. 25°, 12 hr	 (–)	895

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

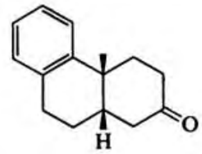
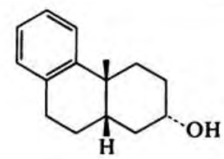
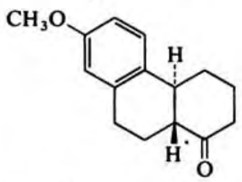
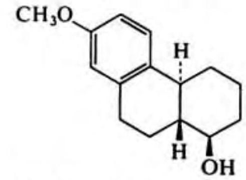
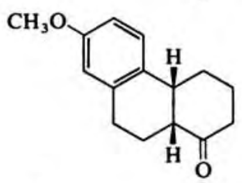
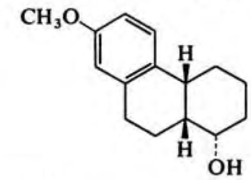
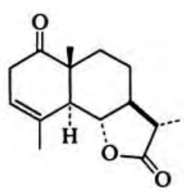
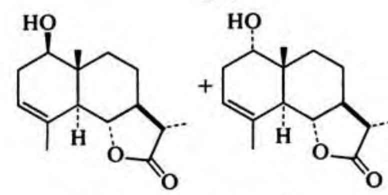
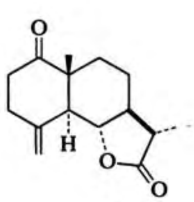
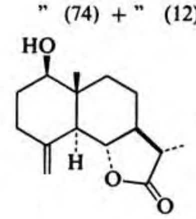
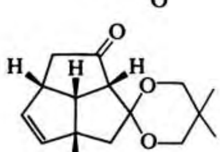
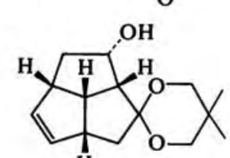
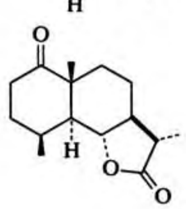
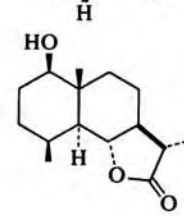
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6, reflux, 2 hr	 (−)	895
	LTBA, THF 1. 0°, 30 min 2. r.t., 1 hr	 (60)	896
	LTBA, THF 1. 0°, 30 min 2. r.t., 1 hr	 (−)	896
	LTBA, THF, 0°, 2 hr	 I II I : II = 83 : 17 (99)	897,898
	LTMA	" (74) + " (12)	899
	LTBA, THF, 0°, 2 hr	 (−)	898
	LTBA, THF, reflux, 40 hr	 (80)	900
	LTBA, THF, 0°, 1 hr	 (−)	901

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

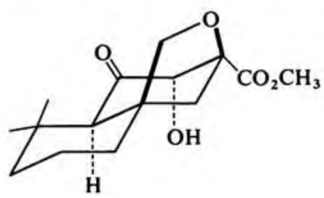
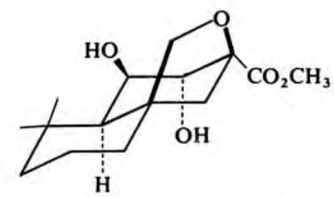
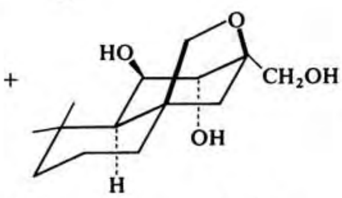
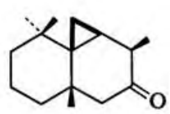
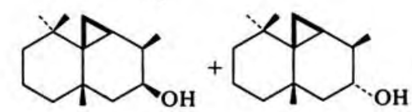
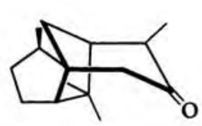
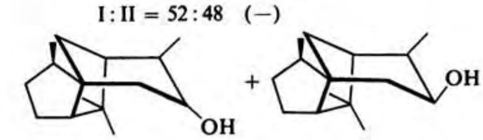
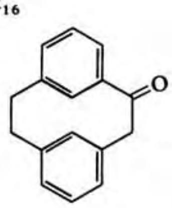
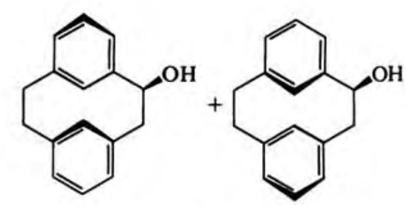
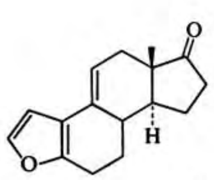
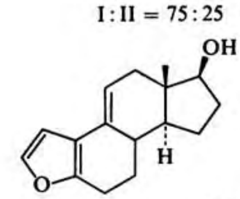
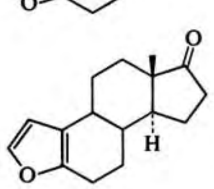
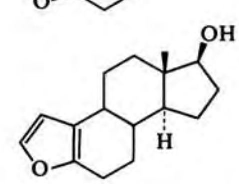
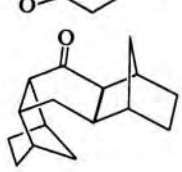
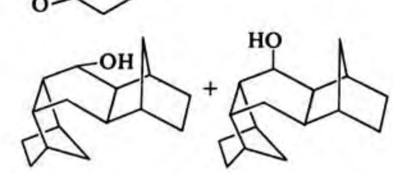
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, r.t., 2 hr	 +  (—)	902
	LTMA, THF, r.t., 12 hr	 I + II; I : II = 52 : 48 (—)	555
	LTMA, THF, r.t., 12 hr	 I + II; I : II = 83 : 17 (~100)	556
C_{16} 	LTBA, THF, 22 hr	 I + II; I : II = 75 : 25 (—)	903
	LTBA, THF, 5 hr	 (84)	904,905
	LTBA, THF, 5 hr	 (—)	905
	LTBA	 (—)	562

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

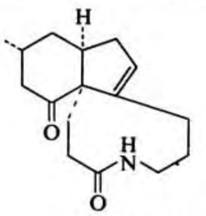
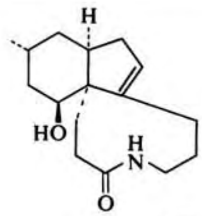
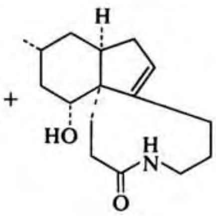
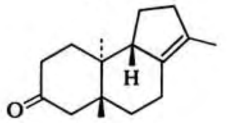
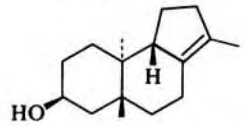
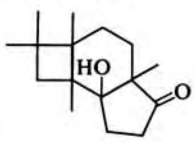
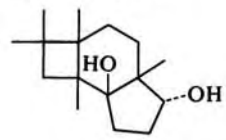
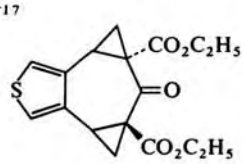
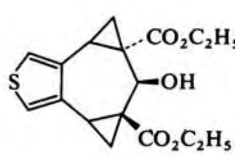
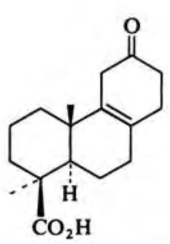
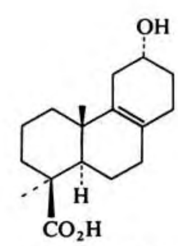
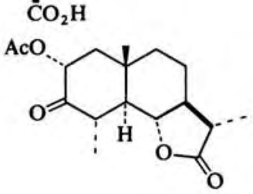
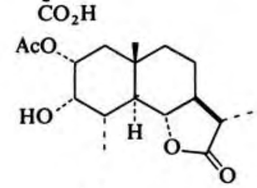
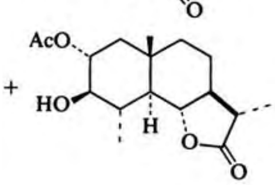
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., 20 hr	 (76) +  (~24)	906
	LTBA, THF, r.t., 2 hr	 (82)	907
	LTBA	 (—)	908
C_{17}			
	LAH + (−)-QN (1 : 1), ether, −20 to −30°, 2 hr	 (—)	909
	LTBA, THF, 14 hr	 (70)	910
	LTBA, THF, r.t., 2 hr	 (39) +  (34)	640

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

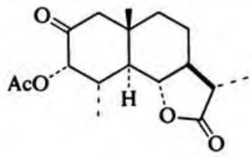
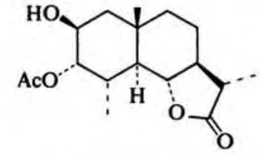
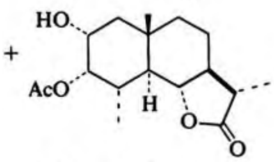
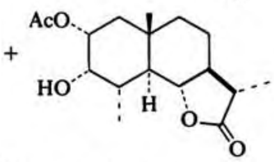
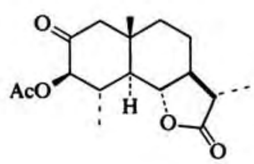
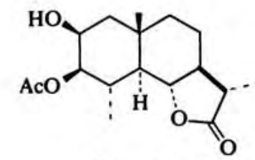
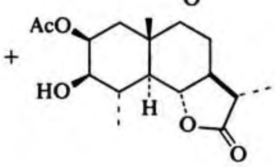
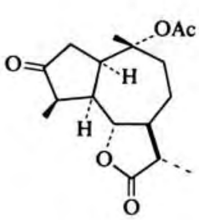
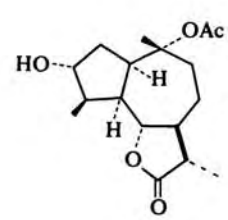
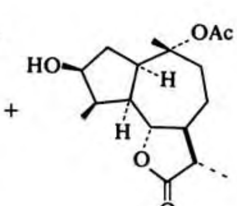
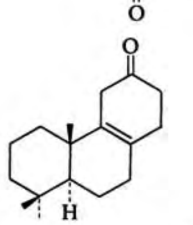
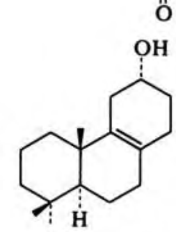
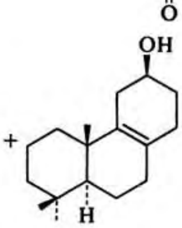
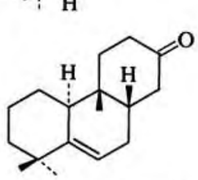
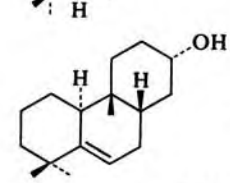
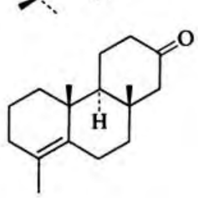
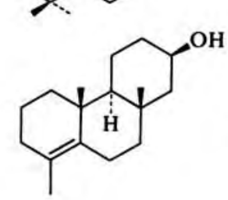
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., 45 min	 (55) +  (15) +  (24)	640
	LTBA, THF, r.t., 3 hr	 (80) +  (10)	640
	LTBA, DME, 0°, 2 hr	 +  (—)	911
	LTBA, THF, r.t.	 (68) +  (23)	912
	LTBA, THF, 0°, 8 hr	 (58)	913
	LTBA, THF, r.t., 24 hr	 (61)	914

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

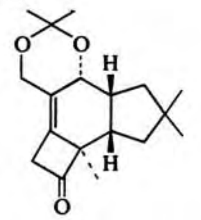
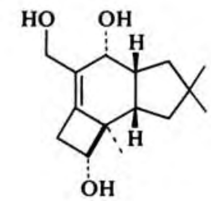
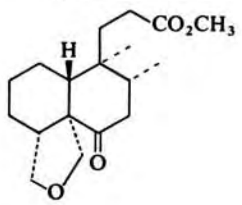
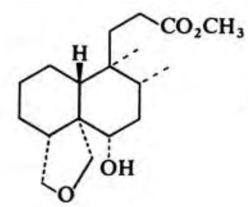
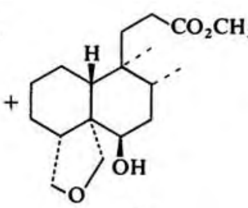
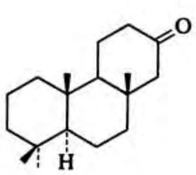
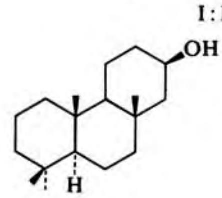
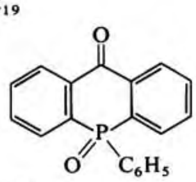
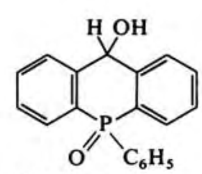
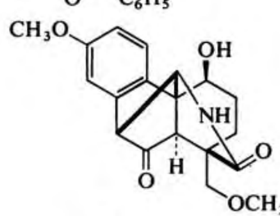
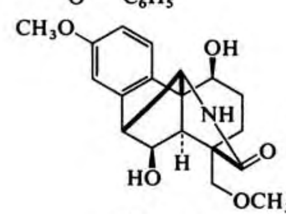
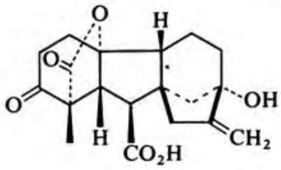
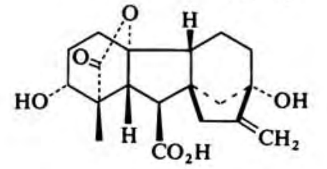
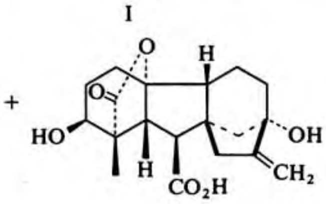
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{18} 	1. SMEAH, C_6H_6, 25°, 24 hr 2. H_3O^+	 (—)	915,916
	LTBA	 I +  II (—) I : II = 80 : 20	917
	LTBA	 (83)	918
C_{19} 	LTBA, THF, 6 hr	 (90)	919,887
	LTBA, THF, r.t., 2 days	 (~100)	920
	LTBA	 I +  II (—) I : II = 67 : 33	921

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

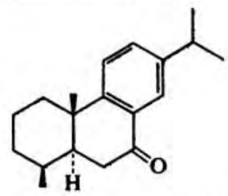
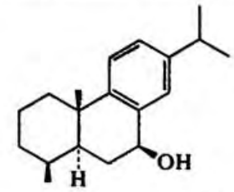
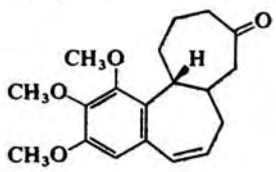
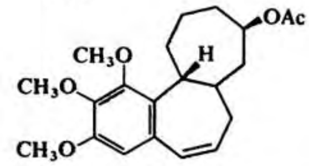
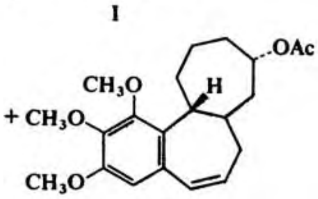
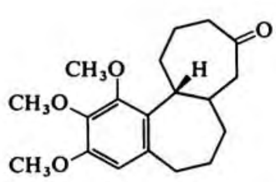
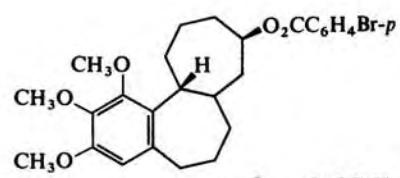
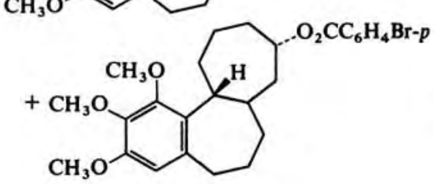
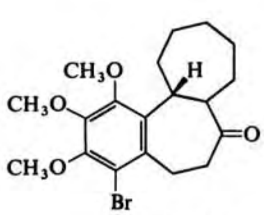
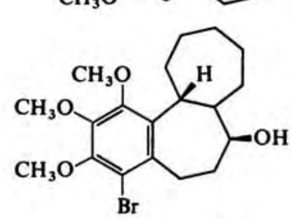
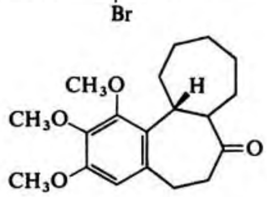
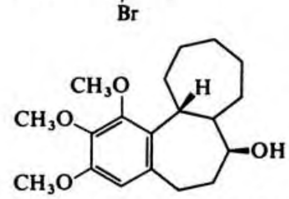
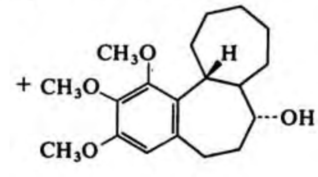
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6–ether, 25°, 4 hr	 (76)	922
	1. LTBA, THF, r.t., overnight 2. Ac_2O, Py	 I +  (–) II I : II = 80 : 20	923
	1. LTBA, THF, r.t., overnight 2. p-BrC_6H_4COCl, Py	 +  (–)	923
	LTBA, THF, r.t., overnight	 (82)	924
	LTBA, THF, r.t., overnight	 (90) +  (2)	924

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

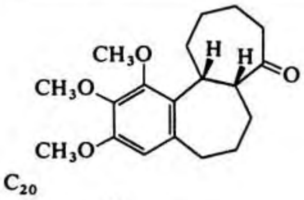
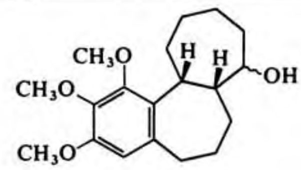
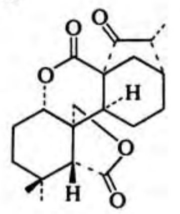
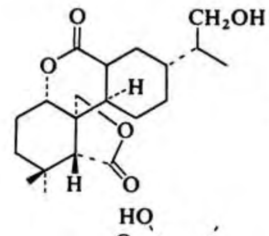
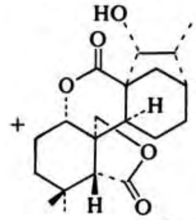
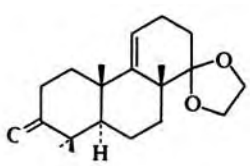
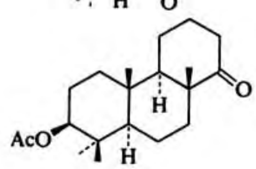
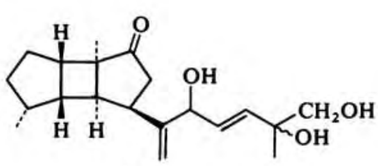
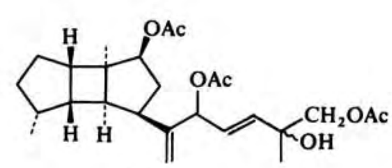
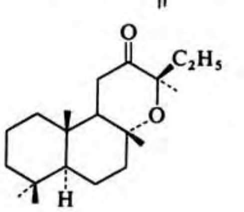
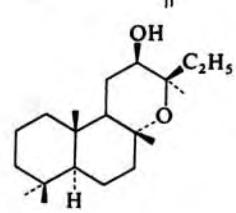
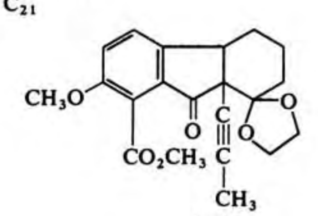
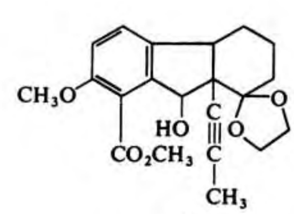
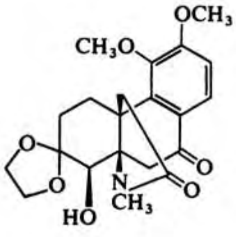
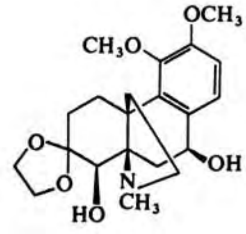
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., overnight	 (90)	924
C_{20}			
	LTBA, THF, r.t., 3 days	 (29) +  (8)	925
	1. LTBA 2. H_3O^+ 3. Ac_2O, Py 4. H_2, Pd—C	 (81)	926
	1. LTBA, EtOH, 0°, 1.5 hr 2. Ac_2O, Py, 18 hr	 (59)	927
	LTBA, ether, reflux, 2 hr	 (85)	928
C_{21}			
	LTBA, THF	 (80)	929
	SMEAH, C_6H_6, reflux, 2 hr	 (36)	930,931

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

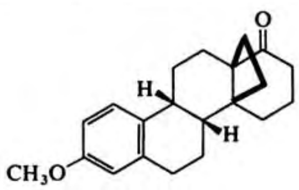
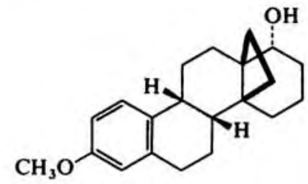
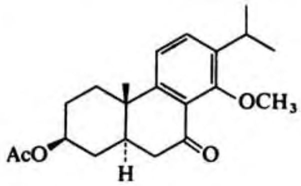
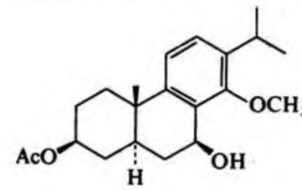
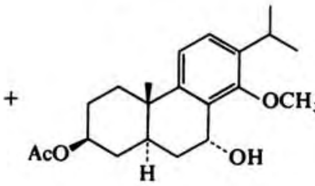
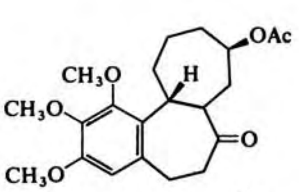
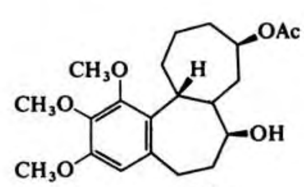
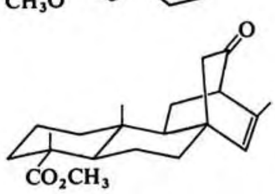
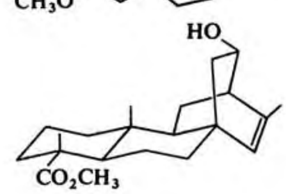
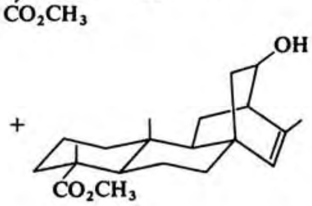
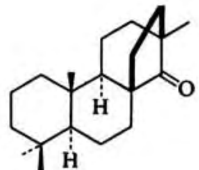
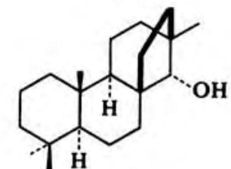
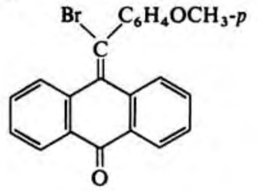
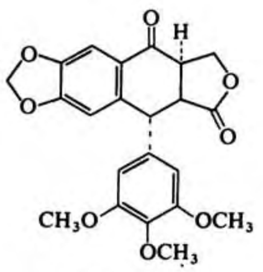
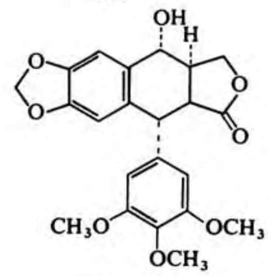
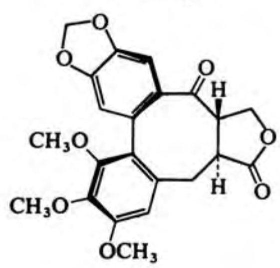
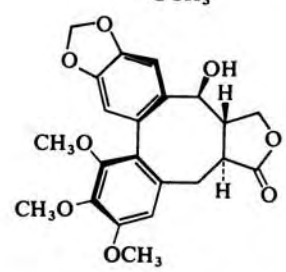
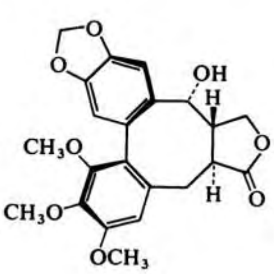
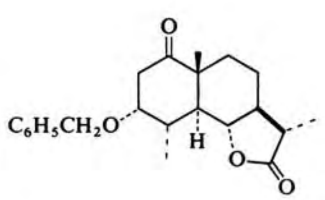
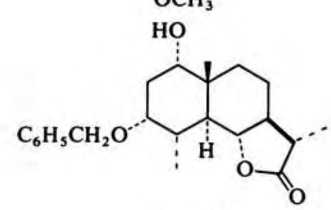
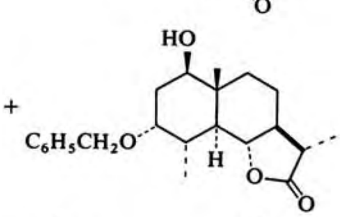
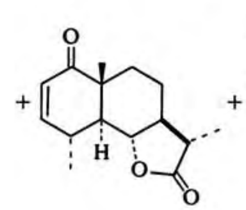
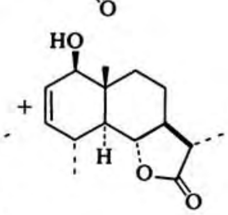
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 0°, 75 min	 (95)	932
	LTBA, THF	 I +  (—) II I : II = 94 : 6	639
	LTBA, THF, r.t., overnight	 (86)	923
	LTBA, ether, 6 hr	 (82) +  (16)	933
	LTBA	 (~100)	934

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{22}			
	LAH + (−)-QN (1 : 1), ether	 (+) (−)	935
	LTBA, THF, r.t., 3 hr	 (62)	936
	LTBA, THF, 0°, 15 min	 (65) +  (27)	937a
	LTBA	 +  +  +  (−)	937b

228

229

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

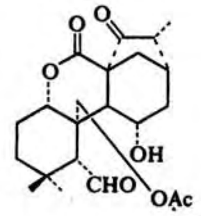
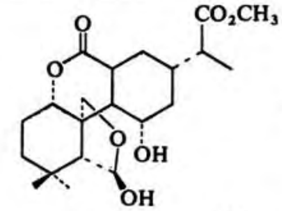
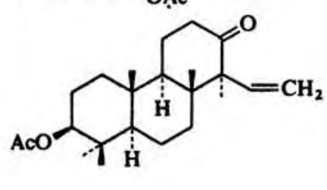
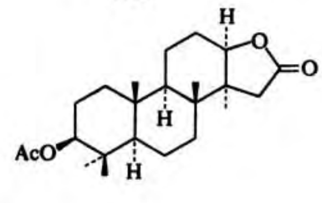
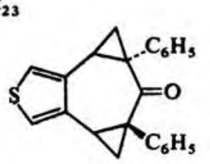
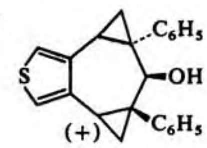
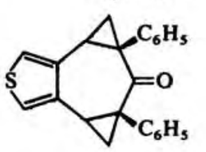
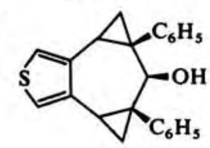
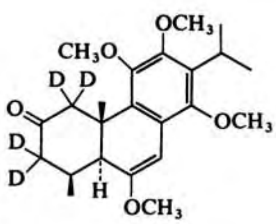
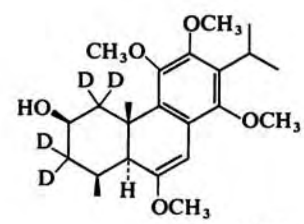
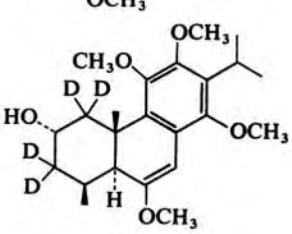
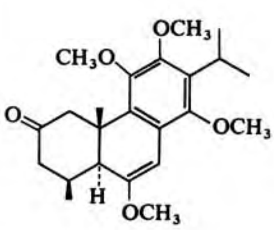
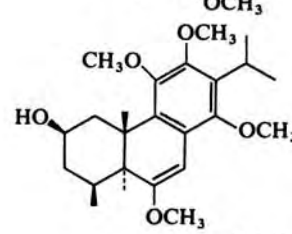
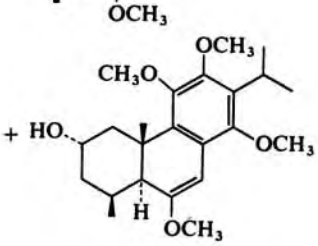
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	1. LAH + MeOH, 0°, 4 hr 2. H_3O^+	 (28)	691
	1. LTBA 2. $(CH_3)_2BH$, H_2O_2, OH^- 3. $CrO_3 \cdot 2Py$	 (34)	926
C_{23}			
	LAH + (−)-QN (1 : 1), ether, r.t., 4 hr	 (66)	909
	LAH + (−)-QN (1 : 1), ether, r.t., 4 hr	 (48)	909
	LTBA, ether 1. r.t., 1 hr 2. reflux, 30 min	 (88) +  (9)	938
	LTBA, ether, 20–26°, 2.5 hr	 (90) +  (~10)	938

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

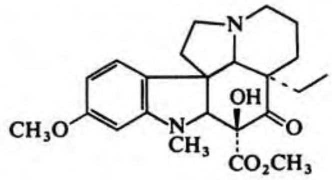
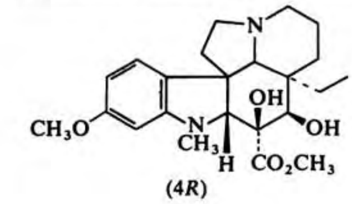
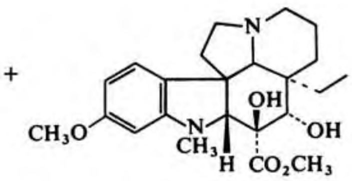
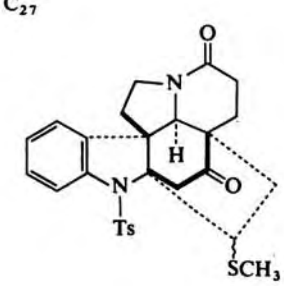
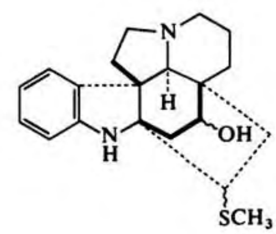
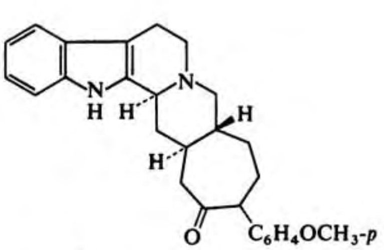
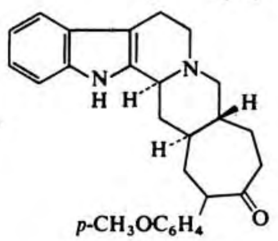
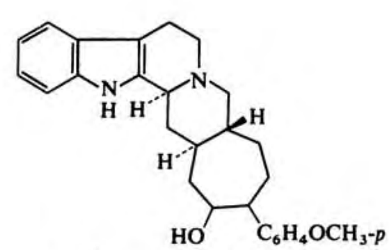
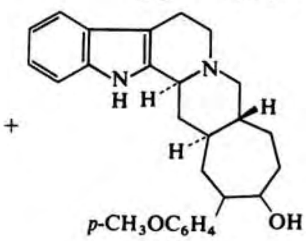
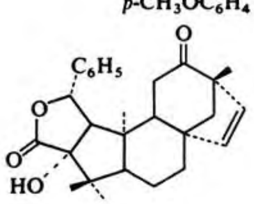
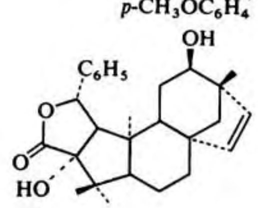
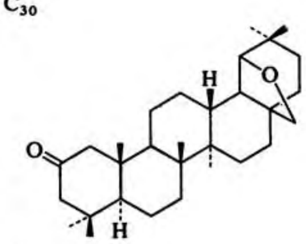
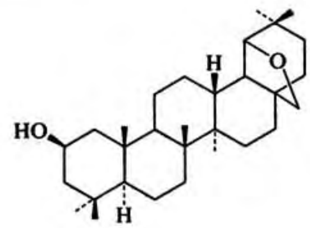
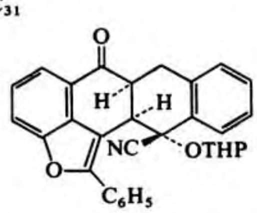
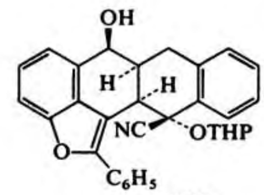
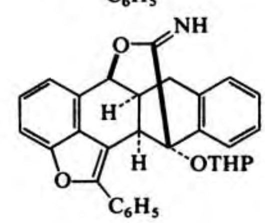
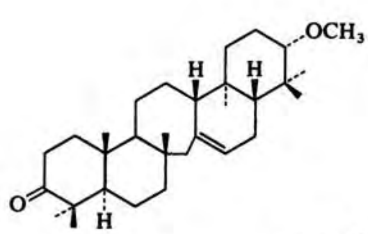
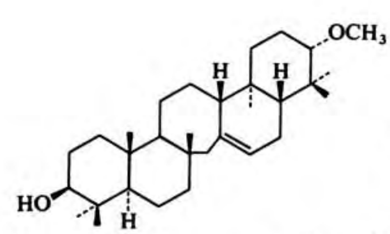
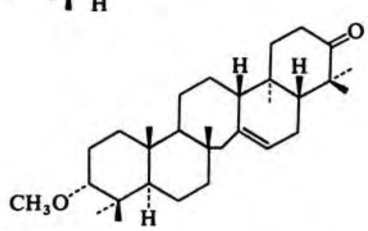
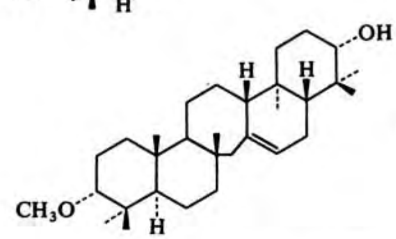
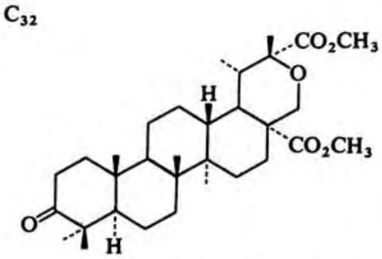
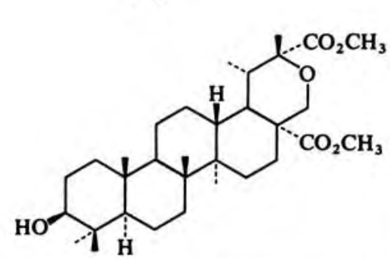
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, reflux, 5.5 hr	 (4) (4*R*)	560
	1. $AlCl_3$, THF, −25° 2. SMEAH, −20°	" (5) +  (13)	560,561
C_{27} 	SMEAH, dioxane, reflux, 2.5 hr	 (—)	939
 + 	LTBA, THF, 5 hr	 +  (74)	940
	LTBA	 (70)	941

TABLE XII. REDUCTION OF POLYCYCLIC KETONES (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{30} 	LTBA, $CH_3CO_2C_2H_5$, r.t., 24 hr	 (64)	942
C_{31} 	LTBA, THF, r.t.	 (59)	943
	LTBA, THF, r.t., 24 hr	 (—)	943
	LTBA	 (—)	944
	LTBA, dioxane	 (—)	945
C_{32} 	LTBA, THF, r.t., 2 hr	 (90)	946

[a] The structures of products given erroneously in the original paper[173] are corrected according to personal communication of Professor H. C. Brown, Purdue University, Lafayette, Indiana, USA.

TABLE XIII. REDUCTION OF POLYKETONES

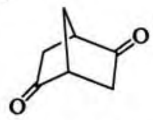
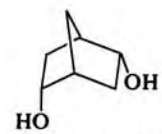
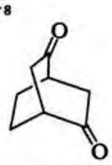
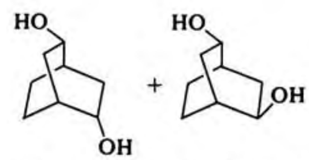
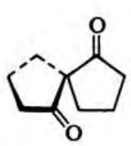
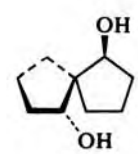
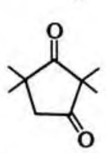
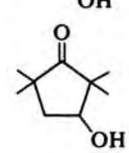
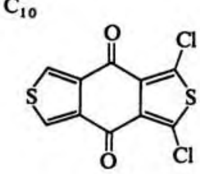
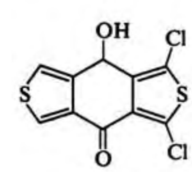
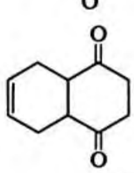
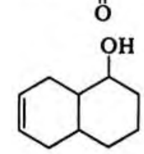
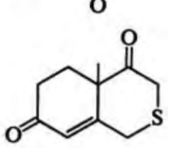
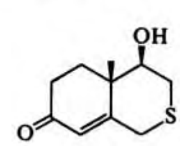
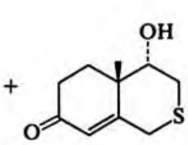
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_6			
i-$C_3H_7COCOCH_3$	LTMA, THF 1. −78°, 4 hr 2. r.t., 18–20 hr	i-$C_3H_7CHOHCHOHCH_3$ (−) *erythro*:*threo* = 53:47	240
C_7			
	LTBA, THF, 20°, 16 hr	 (60)	947
t-$C_4H_9COCOCH_3$	LTMA, THF 1. −78°, 4 hr 2. r.t., 18–20 hr	t-$C_4H_9CHOHCHOHCH_3$ (−) *erythro*:*threo* = 71:29	240
C_8			
	LTBA	 (−)	948
n-$C_5H_{11}COCOCH_3$	LTMA, THF 1. −78°, 4 hr 2. r.t., 18–20 hr	n-$C_5H_{11}CHOHCHOHCH_3$ (−) *erythro*:*threo* = 54:46	240
C_9			
$C_6H_5COCOCH_3$	LTMA, THF 1. −78°, 4 hr 2. r.t., 18–20 hr	$C_6H_5CHOHCHOHCH_3$ (−) *erythro*:*threo* = 78:22	240
	SMEAH	 (1*S*,5*S*,6*R*) (−)	949
	LTBA	 (78)	950
C_{10}			
	LTBA, THF, r.t., 4.5 hr	 (74)	951
	1. LTBA, THF, 3 hr 2. H_2NNH_2, KOH	 (64)	952
	LTBA, THF–ether, 0°, 10 min	 (62) +  (25)	953

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

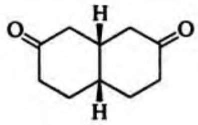
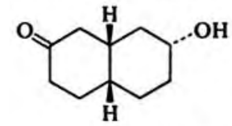
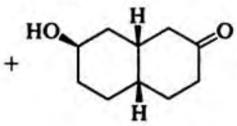
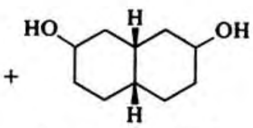
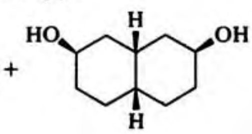
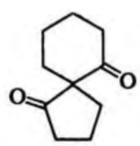
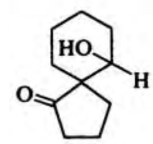
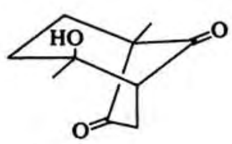
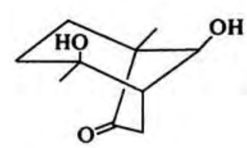
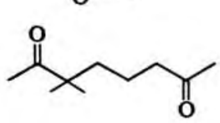
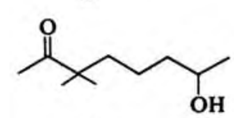
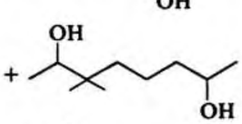
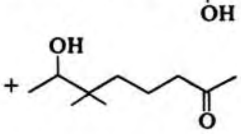
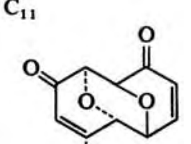
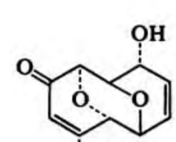
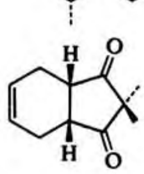
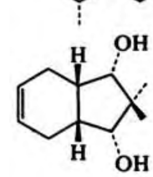
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 30 min	 (56)	954
		+  (8)	
		+  2-*trans*,7-*trans* I (5) 2-*trans*,7-*cis* II (1)	
	LTBA (excess), THF, 2 hr	I (82) + II (16) +  (~2)	954
	LTBA, THF, −30°, 24 hr	 (90) (5*R*,6*R*)	566
	LTBA, THF, r.t., 16 hr	 (78)	955
	LTBA, THF, 0°, 10 min	 (35)	956
		+  (33)	
		+  (5)	
C_{11}			
	SMEAH, THF 1. −78° 2. 15°, 3 hr	 (26)	957
	LTMA, THF, 0°	 (~80)	958

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

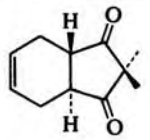
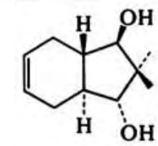
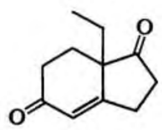
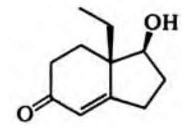
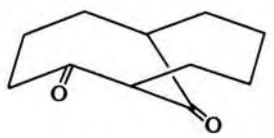
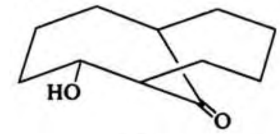
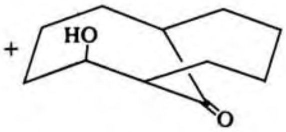
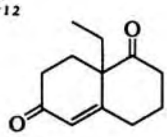
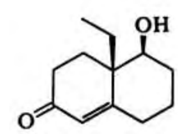
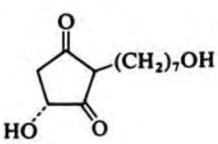
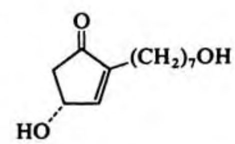
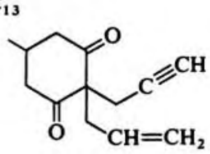
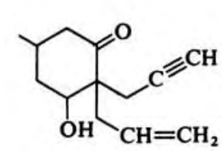
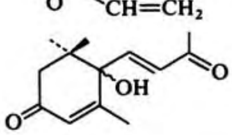
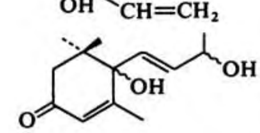
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTMA, THF, 0°	 (−)	958
	LTBA, THF, r.t.	 (91)	959a
	LTBA, THF, −78°	 (25) +  (25)	959b
C_{12} 	LTBA, THF, 20–25°	 (95)	959a
	1. Mesitylenesulfonyl chloride, Et_3N, THF, 0° 2. SMEAH, THF, −78° 3. $(CO_2H)_2$, $(CO_2Na)_2$, $CHCl_3$	 (50)	960
C_{13} 	LTBA, THF, 0°, 5 hr	 (94)	766
	LTBA, THF	 (−)	961

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

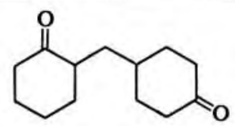
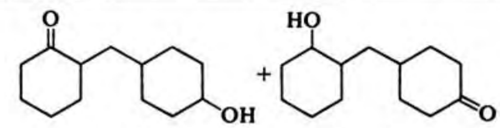
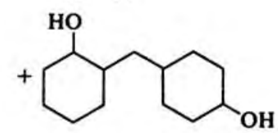
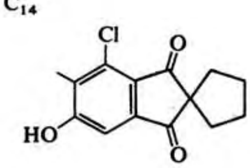
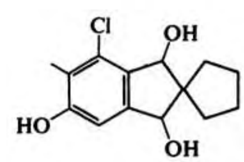
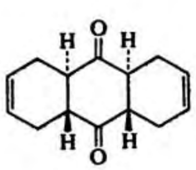
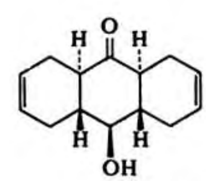
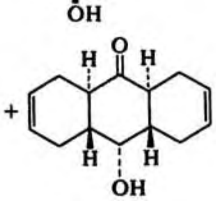
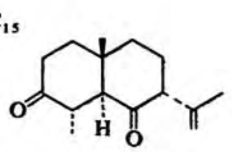
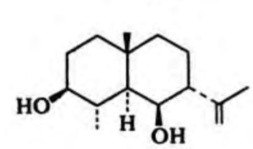
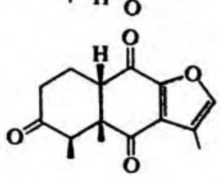
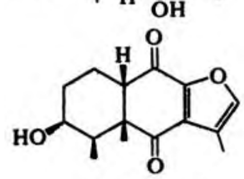
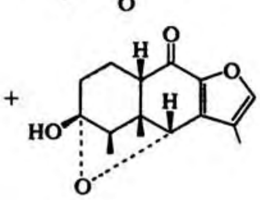
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, ether, 0°, 1 hr	 *trans* I, *cis* II; *trans* III, *cis* IV +  *trans,trans* V, *trans,cis* VI, *cis,trans* VII, *cis,cis* VIII I : II : (III + IV) : (V + VI + VII + VIII) = 59 : 13 : 20 : 8 (28)	158
	LTBA (excess), ether, 0°, 1 hr	V : VI : VII : VIII = 51 : 19 : 24 : 6 (~100)	158
	LTMA, THF, 0°, 1 hr	I : II : III : IV : (V + VI + VII + VIII) = 33 : 20 : 9 : 4 : 34 (39)	158,172
C_{14} 	SMEAH, THF	 (—)	962
	LTBA, THF, r.t., 3.5 hr	 (61) +  (30)	963
C_{15} 	LTBA, THF, 20°, 2 hr	 (—)	548
	LTBA, THF, 0°, 25 min	 (57) +  (31)	964,965

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

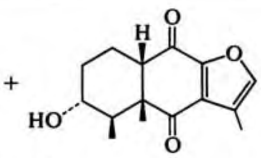
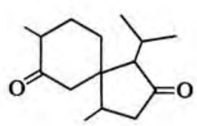
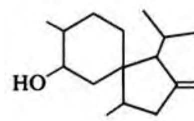
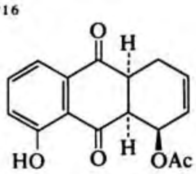
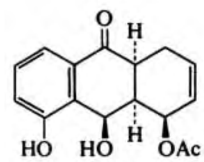
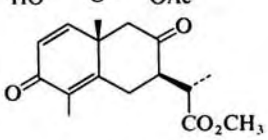
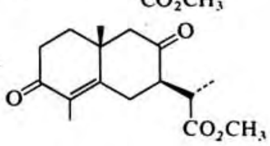
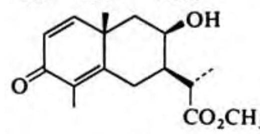
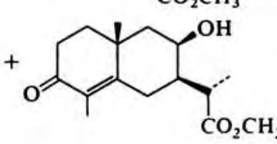
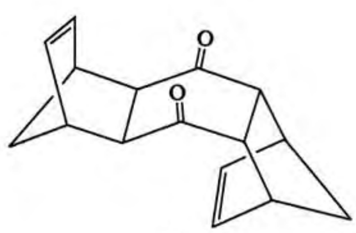
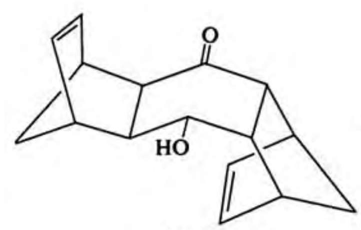
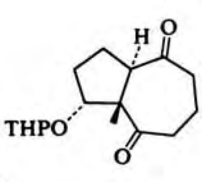
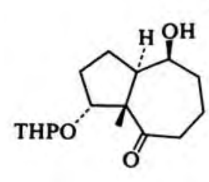
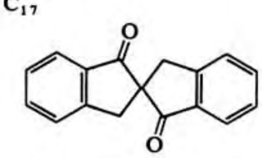
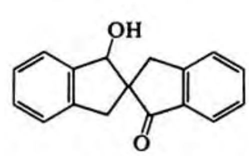
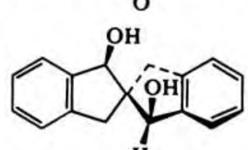
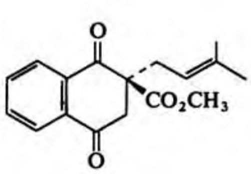
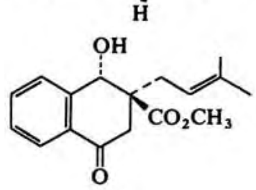
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6–CH_2Cl_2, r.t.	" (34) +  (17)	965
	LTBA, THF, r.t., 2 hr	 (84)	966
C_{16}			
	LTBA	 (64)	967a
 + 	LTBA	 +  (—)	967b
	LTBA	 (—)	562
	LTBA, THF, 0°, 30 min	 (93)	968
C_{17}			
	LTBA, THF, reflux, 2 hr	 (72)	969
	LTBA (excess), THF, reflux, 3 hr	 (65)	858
	LTBA	 (—)	970

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

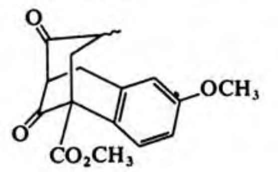
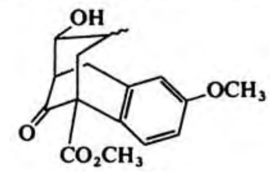
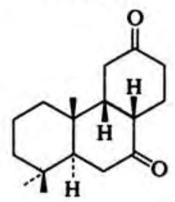
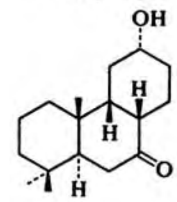
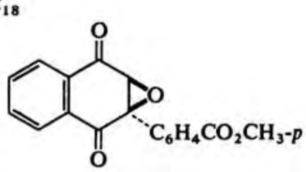
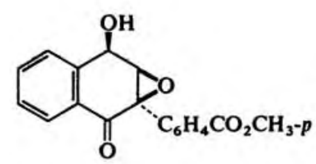
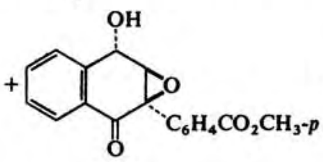
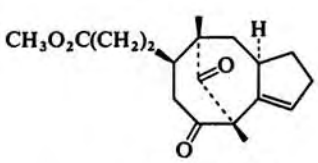
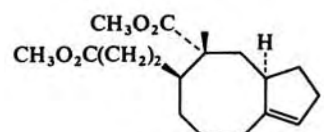
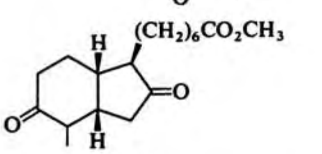
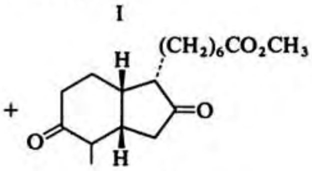
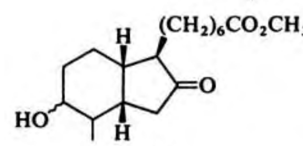
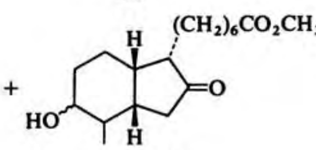
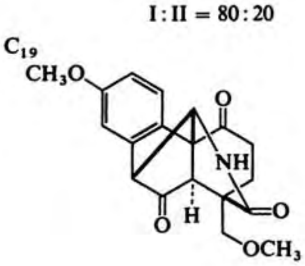
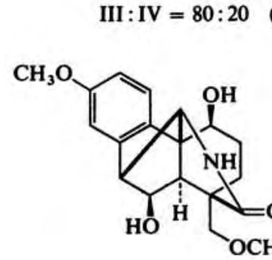
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, reflux, 2 hr	 (54)	971
	LTBA, THF, 0°, 10 min	 (57)	972
C_{18} 	LTBA, THF, −30°, 16 hr	 (81) +  (16)	861
	1. LTBA 2. TsCl 3. $NaOCH_3$	 (~33)	973
 I +  II I : II = 80 : 20	LTBA, THF, 0°, 1.5 hr	 III +  IV III : IV = 80 : 20 (98)	867
C_{19} 	LTBA, THF, r.t., 2 days	 (~100)	920

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

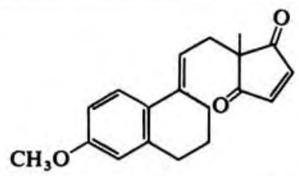
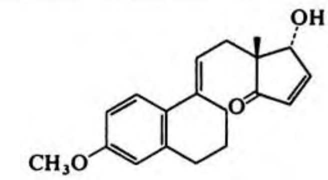
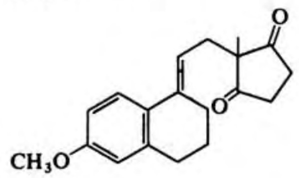
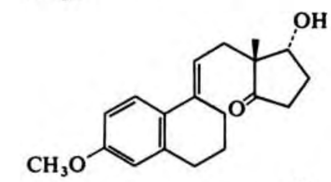
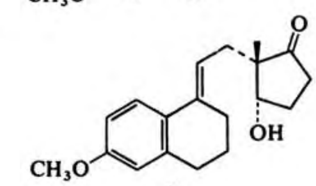
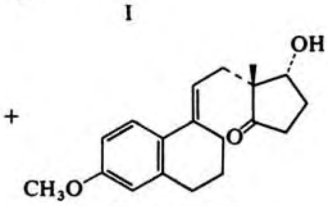
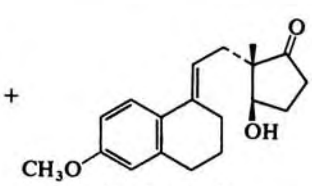
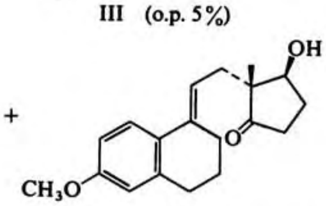
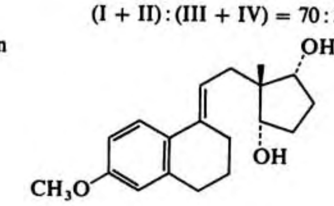
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF	 (−)	974
	LTBA, THF, 20–25°, 16 hr	 (85)	975–978,974
	LAH + (−)-EPH + $C_6H_5CH_2OH$ (1 : 1 : 1), THF, −30°	 I +  (13*R*,17*R*) II (o.p. 23%) +  (13*S*,14*R*) III (o.p. 5%) +  IV (I + II) : (III + IV) = 70 : 30 (60)	979
	1. LTBA, THF, −68 to −72°, 30 min 2. LAH, THF, −68 to −72°, 1 hr	 (59)	978

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

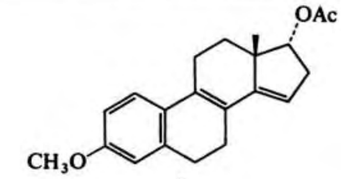
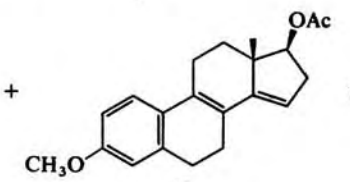
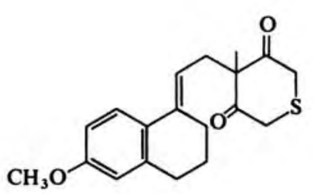
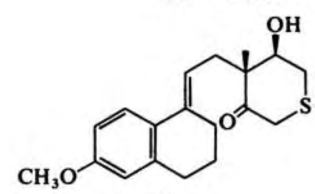
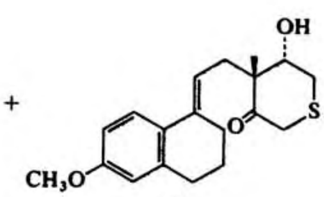
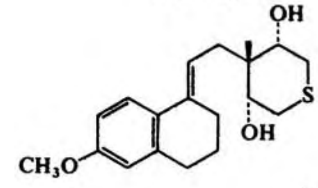
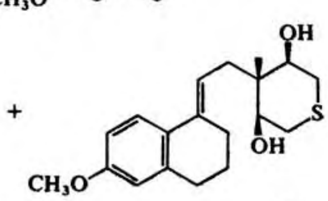
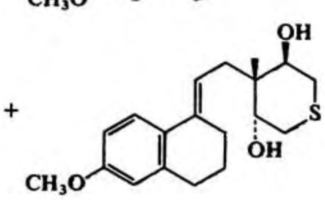
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	1. LTBA, THF, 25°, 23 hr 2. Ac_2O, Py 3. TsOH, C_6H_6, reflux	 I +  (−) II I : II = 85 : 15	980
	LTBA, THF, r.t., 5 hr	 I +  (−) II I : II = 58 : 42	981
	SMEAH, C_6H_6, r.t., 7 hr	 (42) +  (39) +  (9)	982

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

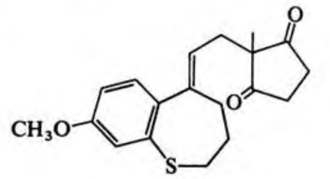
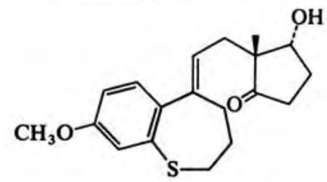
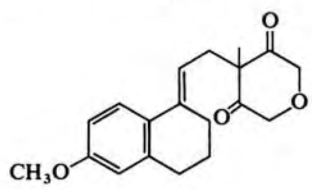
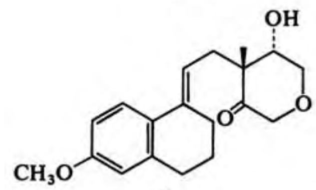
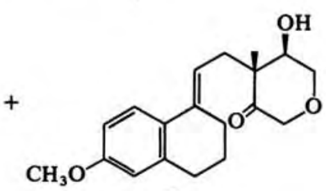
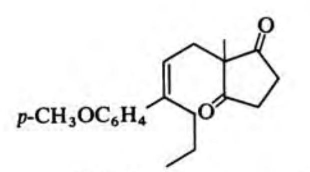
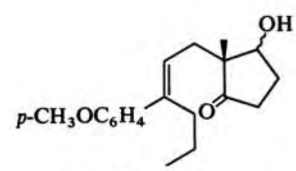
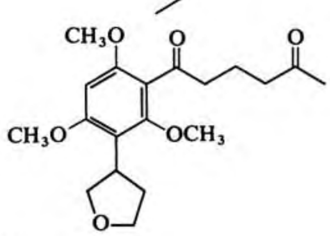
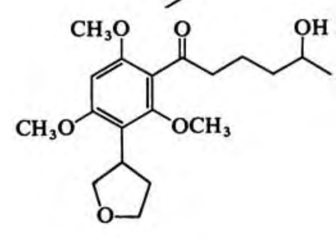
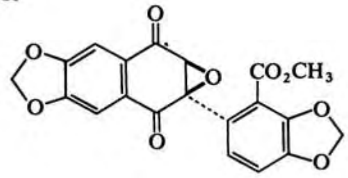
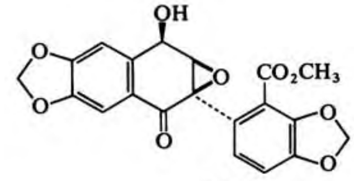
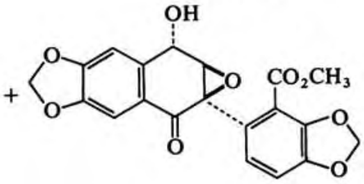
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, r.t., overnight	 (68)	983
	LTBA, THF, r.t., 5 hr	 I +  (—) II I : II = 84 : 16	981
	LTBA, THF, r.t., overnight	 (97)	983
	LTBA, ether, −5°, 35 min	 (—)	568
C_{20} 	LTBA, THF, −35°, 3 hr	 (84) +  (15)	984

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

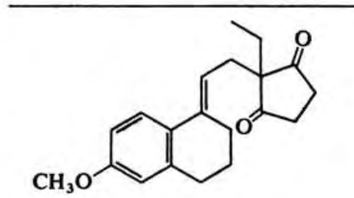
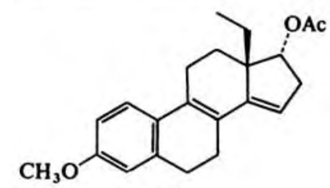
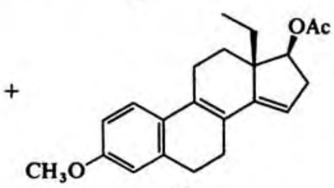
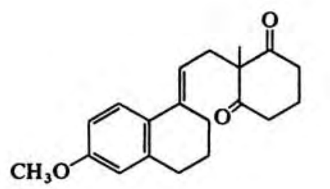
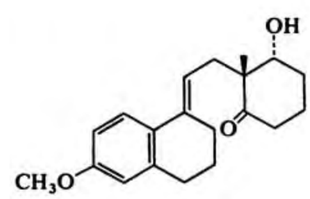
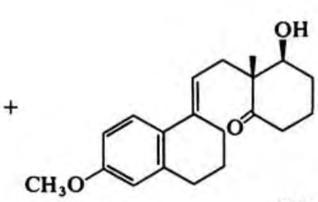
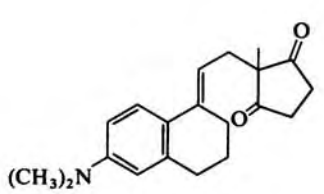
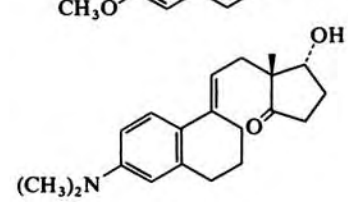
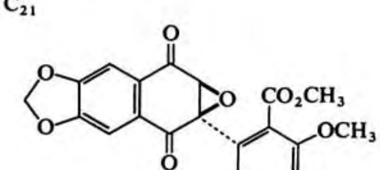
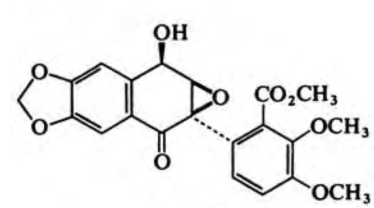
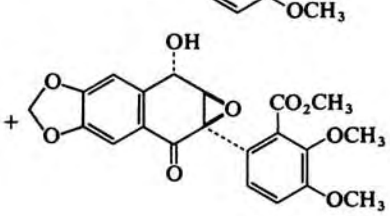
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	1. LTBA, THF, 25°, 23 hr 2. Ac_2O, Py 3. TsOH, C_6H_6, reflux	 I +  (−) II I : II = 60 : 40	980
	1. TsOH, C_6H_6, reflux 2. LTBA, THF, 25°, 3 hr 3. Ac_2O, Py	II (96)	980
	LTBA, THF, −35°, 3 hr	 +  (95)	985
	LTBA, Py, 0–5°, 3 hr	 (−)	986,987
C_{21} 	LTBA, THF, −70°, 2 hr	 (45) +  (38)	984

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

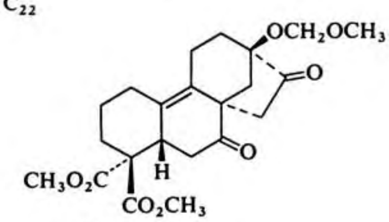
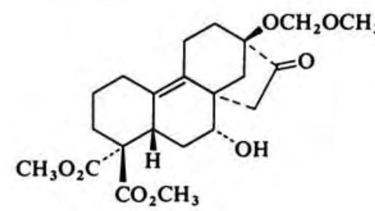
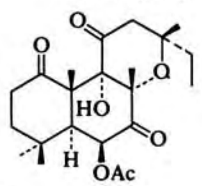
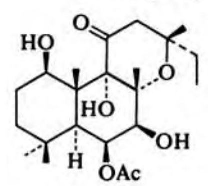
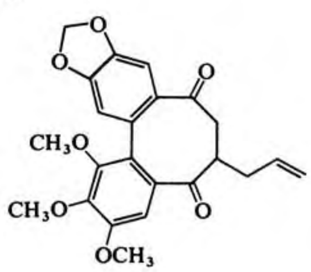
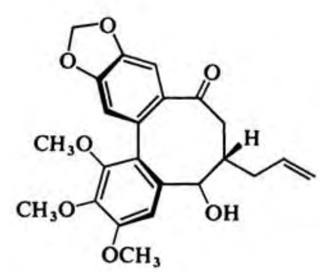
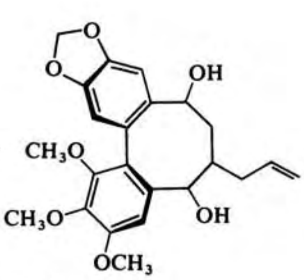
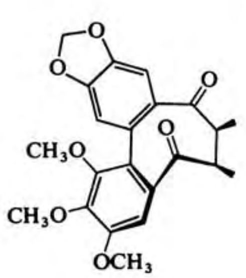
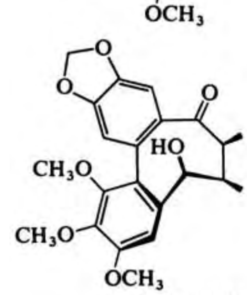
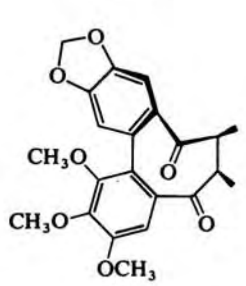
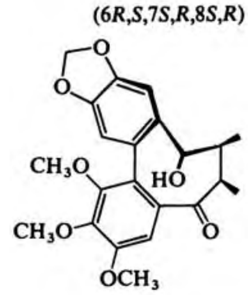
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{22}			
	LTBA, THF, 5°, overnight	 (−)	988
	LTBA, ether, 0–5°, 1 hr	 (38)	989
C_{23}			
	LTBA, THF, −10°, 2 hr	 (61) +  (21)	990
	LTBA, THF, 0°, 2 hr	 (86) (6*R*,*S*,7*S*,*R*,8*S*,*R*)	991
	LTBA, THF, 0°, 2 hr	 (85)	991

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

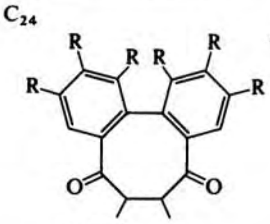
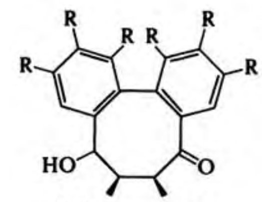
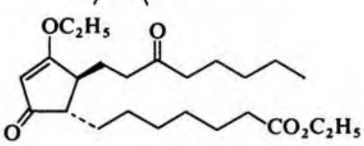
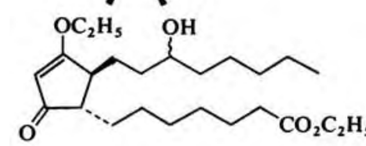
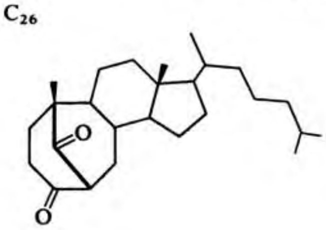
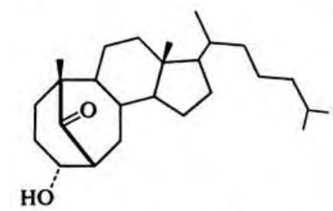
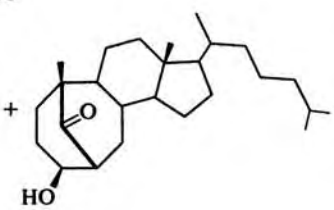
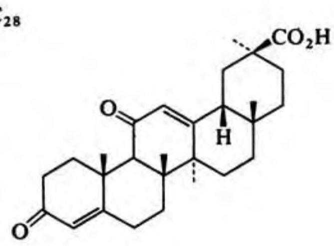
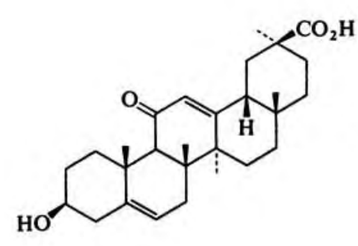
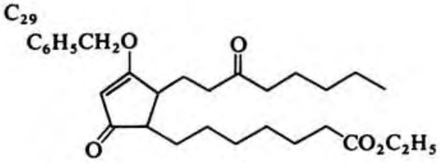
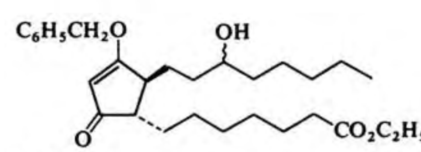
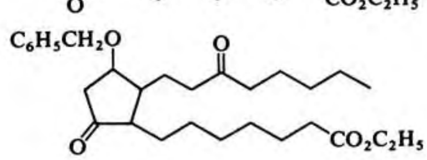
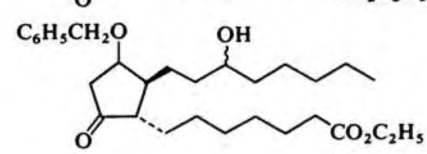
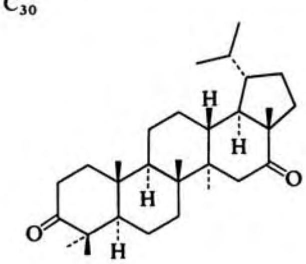
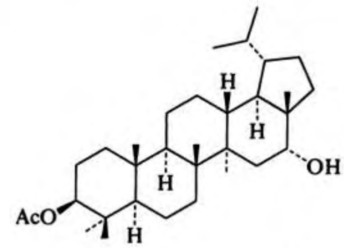
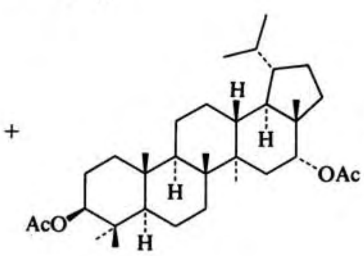
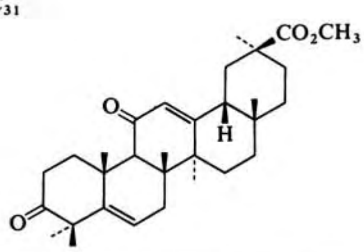
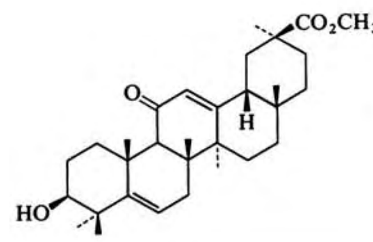
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{24}			
 [a]	LTBA, THF	 [a] (—)	992
	LTBA, THF, 20°, 2 hr	 (50)	748b
C_{26}			
	LTBA, THF, reflux, 2 hr	 (76) +  (11)	835
C_{28}			
	1. t-C_4H_9OK, t-C_4H_9OH 2. LTBA, THF, 22°, 18 hr	 (38)	993
C_{29}			
	LTBA	 (85)	748c
	LTBA, THF, 20°, 2 hr	 (—)	748b

TABLE XIII. REDUCTION OF POLYKETONES (*Continued*)

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{30} 	1. LTBA, BME, 20°, 36 hr 2. Ac_2O, Py	 (72) +  (22)	994
C_{31} 	LTBA, THF, 22°, 2 hr	 (79)	993

[a] R = OCH_3.

TABLE XIV. Reduction of α,β-Unsaturated Ketones

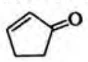
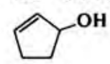
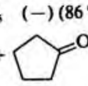
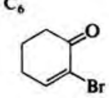
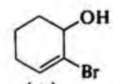
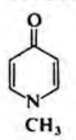
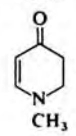
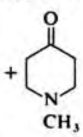
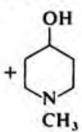
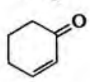
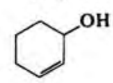
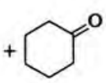
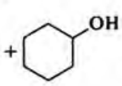
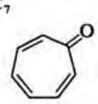
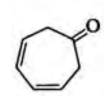
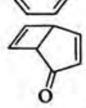
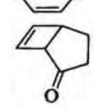
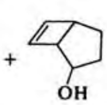
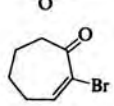
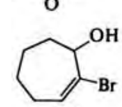
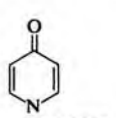
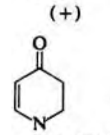
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_4			
$HC\equiv CCOCH_3$	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHCH_3$ (−) (79% e.e.)	161,327
C_5			
$HC\equiv CCOC_2H_5$	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHC_2H_5$ (−) (86% e.e.)	161,327,585
	$LiAlH(OCH_2CH_2OCH_2CH_2OC_2H_5)_3$	 (56) +  (12)	531
$CH_3CH{=}CHCOCH_3$	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°, 12 hr	$n\text{-}C_3H_7COCH_3$ (94) + $CH_3CH{=}CHCHOHCH_3$ (5)	189
	$AlH(OC_3H_7\text{-}i)_2$, THF, 0°, 3 hr	" (95) + " (2)	189
C_6			
	LAH + (−)-QN, ether, 0°, 1 hr	 (80) (+)	995
$(CH_3)_2C{=}CHCOCCl_3$	LAH + (+)-EPH·HCl, ether, −78°, 1–3 hr	(2R)-(−)-$(CH_3)_2C{=}CHCHOHCCl_3$ (86) (72% e.e.)	996
	$LiAlH(OC_2H_5)_3$, THF, 15°, 3 hr	 (87) +  (5) +  (1)	997
	SMEAH, C_6H_6, 30–45°, 6 min	 (80)	459
	$AlH(OC_4H_9\text{-}t)_2$	" (87) +  (13)	998
	$LiAlH(OCH_2CH_2OCH_2CH_2OC_2H_5)_3$	" (64) + " (3) +  (5)	531
	LTMA + Cu_2Br_2, THF, −20°, 1 hr	" (3) + " (84)	575,601
	LAH + (−)-QN, ether, 0°, 1 hr	" (R)-(+) (58) (~13% e.e.)	999
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	" (S)-(−) (58) (32% e.e.)	328,707
$HC\equiv CCOC_3H_7\text{-}i$	LAH + (S)-(−)-DBN + MeOH, THF, 1. −100°, 1 hr 2. −78°, 2 hr	$HC\equiv CCC_3H_7\text{-}i$ (H, OH) (84) (57% e.e.) (S)-(−)	326
	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHC_3H_7\text{-}i$ (−) (86% e.e.)	161
$(CH_3)_2C{=}CHCOCH_3$	LAH + BCGF + EtOH, ether, reflux, 2 hr	$(CH_3)_2C{=}CHCHOHCH_3$ (R)-(−) (82) (31% e.e.)	319
	LAH + BCGF, ether	" (S) (−) (30% e.e.)	318
$CH_3CH{=}C(CH_3)COCH_3$	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°	$s\text{-}C_4H_9COCH_3$ (90) + $CH_3CH{=}C(CH_3)CHOHCH_3$ (6)	189
	$AlH(OC_3H_7\text{-}i)_2$, THF, 0°	" (96) + " (~4)	189
C_7			
	SMEAH, C_6H_6-ether, r.t., 2 hr	 (16)	1000, 1001
	LTBA	 (61) +  (9)	597
	LAH + (−)-QN, ether, 0°, 1 hr	 (81) (+)	995
	$LiAlH(OC_2H_5)_3$, THF, 15°, 3 hr	 (78)	997
$HC\equiv CCOC_4H_9\text{-}n$	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHC_4H_9\text{-}n$ (−) (85% e.e.)	161
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	HO, H $HC\equiv CCC_4H_9\text{-}n$ (88) (76% e.e.) (S)-(−)	328
$HC\equiv CCOC_4H_9\text{-}i$	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHC_4H_9\text{-}i$ (−) (88% e.e.)	161
$HC\equiv CCOC_4H_9\text{-}t$	LAH + (−)-NME + DMP, ether	$HC\equiv CCHOHC_4H_9\text{-}t$ (−) (90% e.e.)	161

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

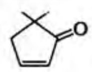
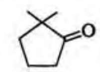
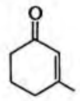
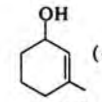
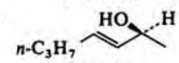
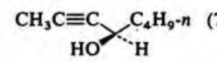
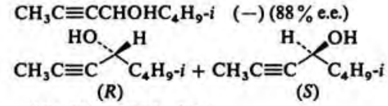
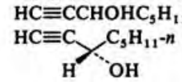
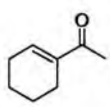
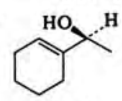
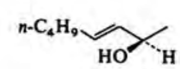
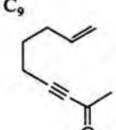
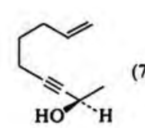
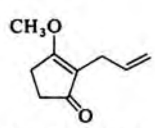
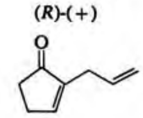
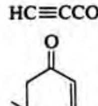
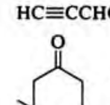
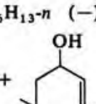
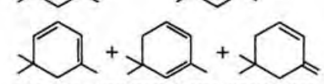
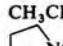
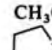
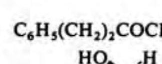
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF 1. −78°, 3 hr 2. r.t., 16 hr	 (66)	1002
	LAH + (−)-QN, ether, reflux, 4 hr	 (+) (−)	1003
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	" (88) (24% e.e.)	328
n-$C_3H_7CH{=}CHCOCH_3$	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (92) (88% e.e.) (*S*)-(−)	328
C_8			
$CH_3C{\equiv}CCOC_4H_9$-n	LAH + (*R*)-(+)-DBN + CH_3OH, THF, 1. −100°, 1 hr 2. −78°, 2 hr	 (79) (84% e.e.) (*R*)-(+)	326
$CH_3C{\equiv}CCOC_4H_9$-i	LAH + (−)-NME + DMP, ether	$CH_3C{\equiv}CCHOHC_4H_9$-i (−) (88% e.e.)	161
	LAH + (+)-DMDB ("fresh"), ether, 1. −72°, 7 hr 2. −72° to r.t., 14 hr	 (*R*):(*S*) = 91:9 (99)	329
$HC{\equiv}CCOC_5H_{11}$-n	LAH + (−)-NME + DMP, ether	$HC{\equiv}CCHOHC_5H_{11}$-n (−) (84% e.e.)	161,327
	LAH + (*S*)-(−)-DBN + CH_3OH, THF 1. −100°, 1 hr 2. −78°, 2 hr	 (87) (84% e.e.) (*S*)-(−)	326
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (92) (78% e.e.) (*S*)-(−)	328
n-$C_4H_9CH{=}CHCOCH_3$	LAH + (*R*)-(+)-DBN + EtOH, THF 1. −100°, 1-2 hr 2. −78°, 2-4 hr	 (73) (79% e.e.) (*R*)	168
C_9 	LAH + (+)-DMDB, ether, −72°, 5-7 hr	 (77) (72% e.e.) (*R*)-(+)	1004
	1. SMEAH, THF, −20°, 30 min 2. H_3O^+	 (50)	1005
$HC{\equiv}CCOC_6H_{13}$-n	LAH+(−)-NME + DMP, ether	$HC{\equiv}CCHOHC_6H_{13}$-n (−) (83% e.e.)	161
	LTMA + Cu_2Br_2, THF, −20°, 1 hr	 (98) +  (1)	575,601
	1. SMEAH, ether 2. Al_2O_3, 300°	 (80)	1006
$CH_3CH{=}CHCOCH_2CHOHCH{=}CHCH_3$	SMEAH	$CH_3CH{=}CHCHOHCH_2CHOHCH{=}CHCH_3$ (−)	613
 $NCH{=}C(CH_3)COCH_3$	SMEAH, ether, −5 to 0°, 30 min	 $NCH_2CH(CH_3)COCH_3$ (55)	1007
C_{10}			
$C_6H_5CH{=}CHCOCH_3$	$AlH(OC_4H_9$-$t)_2$, THF	$C_6H_5(CH_2)_2COCH_3$ (92) + $C_6H_5CH{=}CHCHOHCH_3$ (8)	998
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (98) (98% e.e.) (*S*)-(−)	328

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

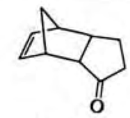
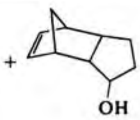
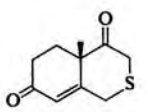
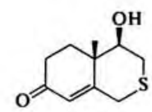
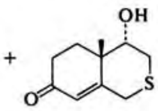
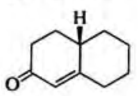
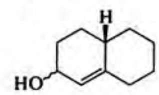
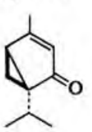
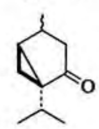
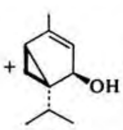
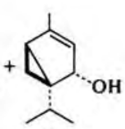
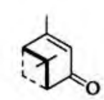
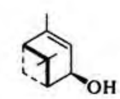
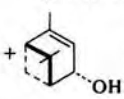
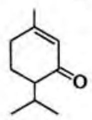
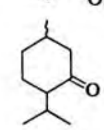
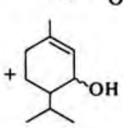
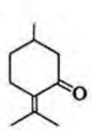
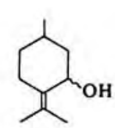
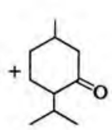
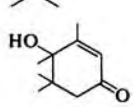
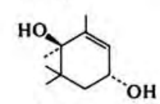
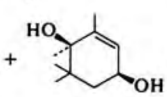
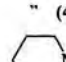
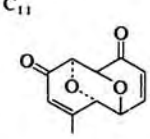
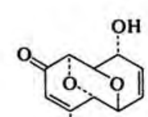
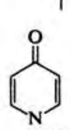
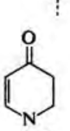
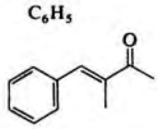
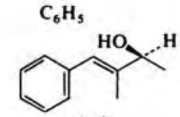
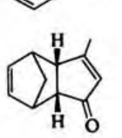
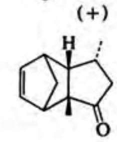
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, ether, r.t., 16 hr	 (71) +  (13)	1008
	1. LTBA, ether, 2. CrO_3, Py	" (60)	1009
	LTBA, THF–ether, 0°, 10 min	 (62) +  (25)	953
	LTBA, THF	 (91)	1010
	LTBA, ether, r.t., 40 min	 (80) +  I +  II (I + II = 4)	1011
	SMEAH, C_6H_6, reflux, 1 hr	 (82) +  (~18)	823
	LTBA, ether, r.t., 40 min	 (47) +  (24)	1011
	LTBA, ether, r.t., 40 min	 (43) +  (18)	1011
	LTBA	 (54) +  (44)	1012
	$LiAlH(OC_2H_5)_3$	" (49) + " (39)	1012
NCH=C(CH_3)$COCH_3$	SMEAH, ether, −5 to 5°	$NCH_2CH(CH_3)COCH_3$ (35)	1007
C_{11}			
	SMEAH, THF 1. −78° 2. 15°, 3 hr	 (26)	957
 C_6H_5	$LiAlH(OC_2H_5)_3$, THF, 15°, 3 hr	 (88) C_6H_5	997
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (~100) (~90% e.e.) (+)	328
	LTBA, ether, r.t., 16 hr	 (80)	233

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

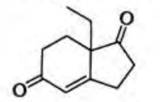
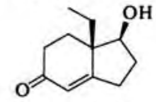
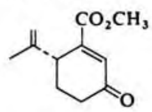
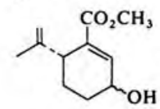
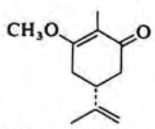
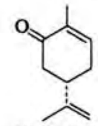
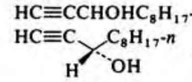
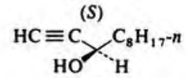
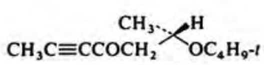
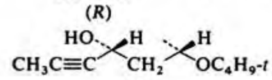
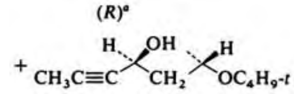
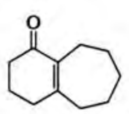
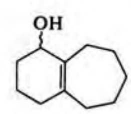
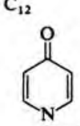
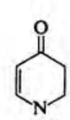
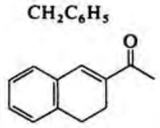
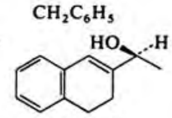
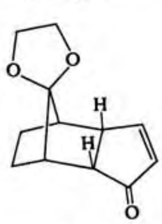
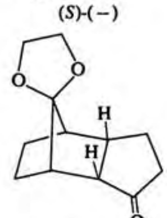
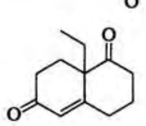
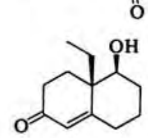
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
$C_6H_5NHCH{=}C(CH_3)COCH_3$	SMEAH, ether, −5 to 5°	$C_6H_5NHCH_2CH(CH_3)COCH_3$ (30)	1007
	LTBA	 (91)	959a
	LTBA, THF, 0°, 3 hr	 (45)	592
	1. SMEAH 2. H_3O^+	 (−)	1013
$HC{\equiv}CCOC_8H_{17}$-*n*	LAH + (−)-NME + DMP, ether	$HC{\equiv}CCHOHC_8H_{17}$-*n* (−) (89% e.e.)	327,585
	LAH + (*S*)-(−)-DBN + MeOH, THF 1. −100°, 1 hr 2. −78°, 2 hr	 (*S*) (80) (96% e.e.)	326
	LAH + (*R*)-(+)-DBN + MeOH, THF, 1. −100°, 1 hr 2. −78°, 2 hr	 (*R*) (69) (94% e.c.)	326
 (*R*)-(−)	LAH + (+)-DMDB ("fresh"), ether, 1. −72°, 7 hr 2. −72° to r.t., 14 hr	 (*R*)[a] +  (*S*)[a] (*R*):(*S*) = 93:7[a] (94)	329
	LTBA, THF, reflux, 2 hr	 (38)	834
t-$C_4H_9CH{=}CHCOC_4H_9$-*t*	$AlH(OC_4H_9\text{-}t)_2$, THF, 0°, 12 hr	*t*-$C_4H_9(CH_2)_2COC_4H_9$-*t* (98)	189
	$AlH(OC_3H_7\text{-}i)_2$, THF, 0°, 3 hr	" (~100)	189
	$LiAlD(OCH_3)_3 + Cu_2Br_2$, THF, −20°, 1 hr	*t*-$C_4H_9CHDCH_2COC_4H_9$-*t* (87) + *t*-$C_4H_9CH{=}CHCDOHC_4H_9$-*t* (12)	575
C_{12}			
 $CH_2C_6H_5$	$LiAlH(OC_2H_5)_3$, THF, 15°, 3 hr	 $CH_2C_6H_5$ (80)	997
	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (*S*)-(−) (~100) (~90% e.e.)	328
	LTMA + Cu_2Br_2, THF, −78°, 10 min	 (84)	1014
	LTBA, THF, 20–25°	 (95)	959a

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

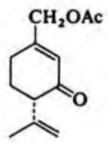
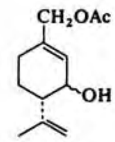
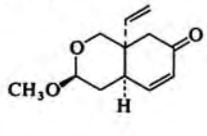
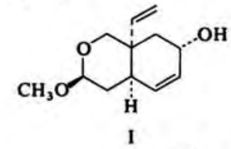
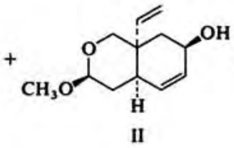
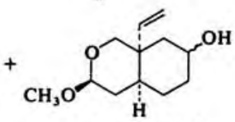
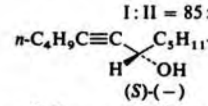
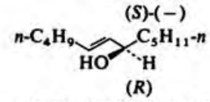
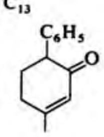
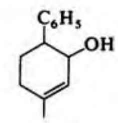
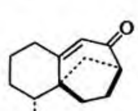
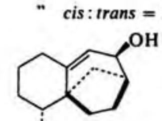
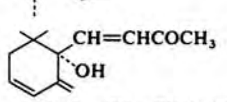
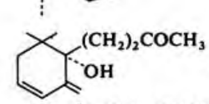
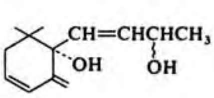
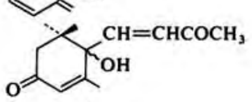
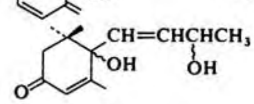
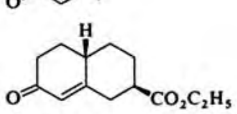
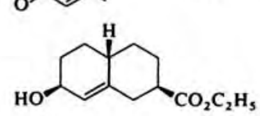
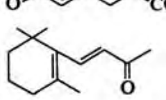
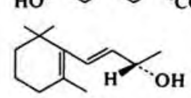
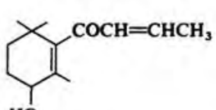
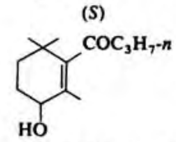
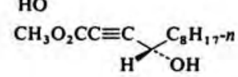
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 0° to r.t., 4 hr	 (89)	1015
	SMEAH	 I (−) +  II (−) +  (20) I : II = 85 : 15	1016
n-$C_4H_9C{\equiv}CCOC_5H_{11}$-$n$	LAH + (*S*)-(−)-DBN + MeOH, THF, 1. −100°, 1 hr 2. −78°, 2 hr	 (85) (90% e.e) (*S*)-(−)	326
n-$C_4H_9CH{=}CHCOC_5H_{11}$-n	LAH + (*R*)-(+)-DBN + EtOH, THF, 1. −100°, 1–2 hr 2. −78°, 2–4 hr	 (85) (91% e.e.) (*R*)	168
n-$C_5H_{11}CHOHCH_2COCH{=}C(CH_3)OCH_3$	1. SMEAH, C_6H_6, 15°, 2 hr 2. H_3O^+	n-$C_5H_{11}CHOHCH_2CH{=}CHCOCH_3$ (−)	614
C_{13}			
	LTMA, THF, r.t., 1.5 hr	 *cis* : *trans* = 74 : 26 (−)	195
	SMEAH, C_6H_6, r.t., 1 hr	" *cis* : *trans* = 35 : 65 (−)	195
	LTBA, THF, 20–25°, 22 hr	 (−)	1017,1018
	LTMA + Cu_2Br_2, −20°, THF	 (48) +  (49)	1019,1020
	LTBA, THF	 (−)	961
	LTBA, THF 1. 0°, 70 min 2. r.t., 1 hr	 (−)	1021
	LAH + (*S*)-(−)-DBN + EtOH, THF 1. −100°, 1–2 hr 2. −78°, 2–4 hr	 (87) (~100% e.e.) (*S*)	168
	LTBA, THF	 (53)	1022
$CH_3O_2CC{\equiv}CCOC_8H_{17}$-$n$	LAH + (*S*)-(−)-DBN + MeOH, THF 1. −100°, 1 hr 2. −78°, 2 hr	 (80) (87% e.e.) (*S*)-(−)	326

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

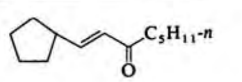
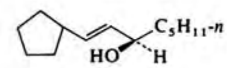
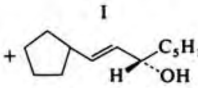
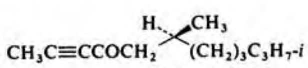
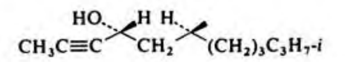
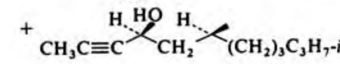
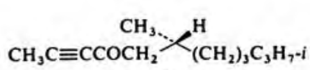
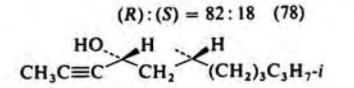
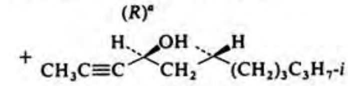
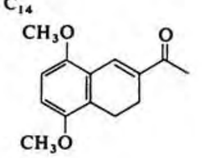
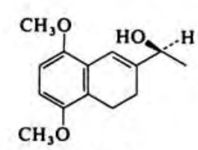
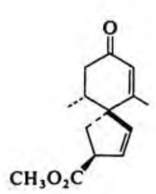
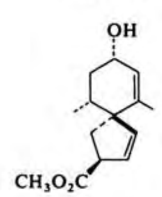
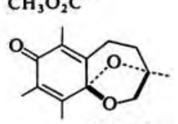
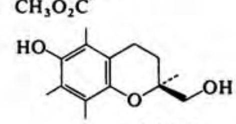
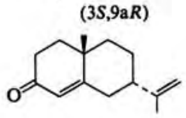
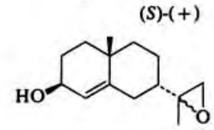
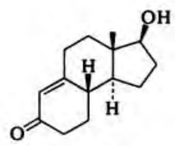
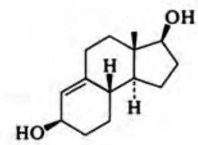
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LAH + (R)-(+)-DBN + EtOH, THF 1. −100°, 1–2 hr 2. −78°, 2–4 hr	 (91) (92% e.e.) (*R*) I	168
	LAH + (*S*)-(−)-DBN + EtOH, THF 1. −100°, 1–2 hr 2. −78°, 2–4 hr	I +  (−) (*S*) II I : II = 4 : 96	168
 (*R*)-(+)	LAH + (+)-DMDB ("fresh"), ether 1. −72°, 7 hr 2. −72° to r.t., 14 hr	 (*R*)[a] +  (*S*)[a] (*R*) : (*S*) = 82 : 18 (78)	329
 (*S*)-(−)	LAH + (+)-DMDB ("fresh"), ether 1. −72°, 7 hr 2. −72° to r.t., 14 hr	 (*R*)[a] +  (*S*)[a] (*R*) : (*S*) = 84 : 16 (62)	329
C_{14} 	LAH + (−)-NME + EAN, ether, −78°, 3 hr	 (~100) (~90% e.e.) (*S*)-(−)	707,328
	LAH + (−)-NME + $C_6H_5NHCH_3$, ether, −78°, 3 hr	" (97) (86% e.e.)	162
	LAH + (−)-NME + $C_6H_5NHC_4H_9$-*n*, ether, −78°, 3 hr	" (96) (86% e.e.)	162
	LTBA, ether, r.t., 4 hr	 (62)	1023
 (3*S*,9a*R*)	SMEAH, THF–C_6H_6, 0°, 1 hr	 (82) (*S*)-(+)	687
	1. *m*-$ClC_6H_4CO_3H$, CH_2Cl_2, 0° 2. LTBA, THF	 (50)	1024
	LTBA, THF, 5 hr	 (91)	904,905

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

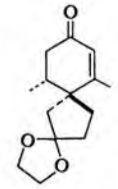
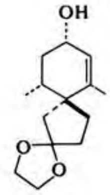
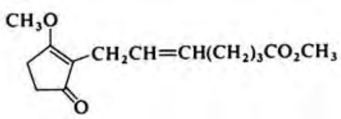
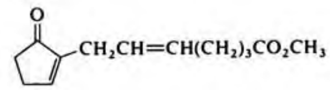
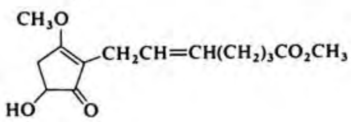
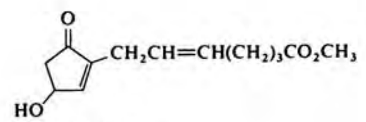
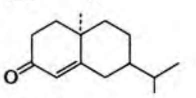
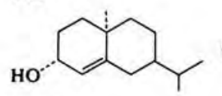
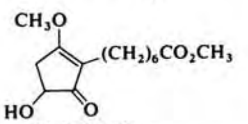
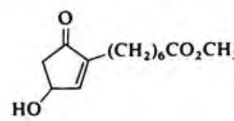
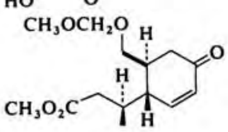
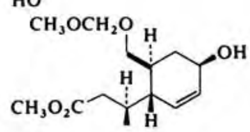
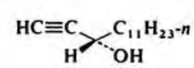
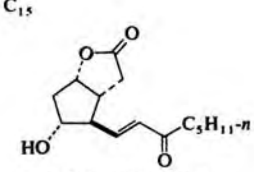
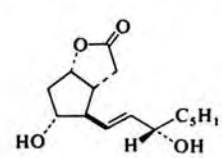
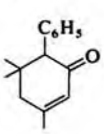
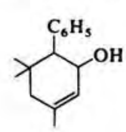
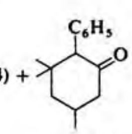
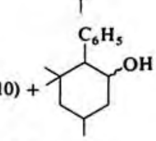
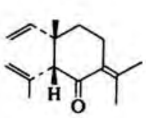
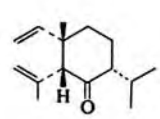
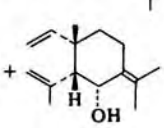
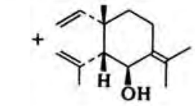
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, ether, r.t., 18 hr	 (83)	1023
	1. SMEAH, THF, $-60°$, 6 hr 2. H_3O^+	 (38)	1005
	1. SMEAH, toluene, $-70°$, 4 hr 2. H_3O^+	 (61)	1025
	LTBA	 (86)	1026
	1. SMEAH, toluene, $-70°$, 4 hr 2. H_3O^+	 (78)	1025
	LTBA, THF, 22°, 8 hr	 (92)	1027
$(CH_3)_2C{=}CH(CH_2)_2C(CH_3)OHCH_2COCH{=}C(CH_3)OCH_3$	1. SMEAH, C_6H_6, 15°, 2 hr 2. H_3O^+	$(CH_3)_2C{=}CH(CH_2)_2C(CH_3)OHCH_2CH{=}CHCOCH_3$ (—)	614
$HC{\equiv}CCOC_{11}H_{23}$-*n*	LAH + (*S*)-(−)-DBN + MeOH, THF 1. $-100°$, 1 hr 2. $-78°$, 2 hr	 (90) (92% e.e.) (*S*)-(−)	326
	LAH + (−)-NME + DMP, ether	$HC{\equiv}CCHOHC_{11}H_{23}$-*n* (−) (75% e.e.)	161
C_{15}			
	LAH + (*S*)-(−)-DBN + EtOH, THF 1. $-100°$, 2 hr 2. $-78°$, 1 hr	 (41) (~100% e.e.) (15*S*)	169,168,479
$C_6H_5CH{=}CHCOC_6H_5$	SMEAH + Cu_2Br_2, THF, 2-butanol, -78 to $-20°$, 1 hr	$C_6H_5(CH_2)_2COC_6H_5$ (65)	601,575
	SMEAH, C_6H_6, r.t., 1 hr	 *cis*(80) + *trans*(14) +  (5)	195
	LTBA, THF, 2 hr	" *cis*(33) + *trans*(10) + " (10) +  (15)	195
	LTMA, THF, r.t., 45 min	 (34) +  (30) +  (17)	1028

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

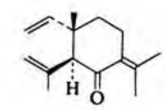
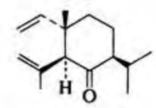
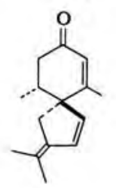
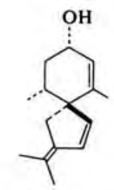
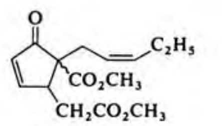
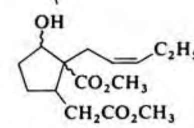
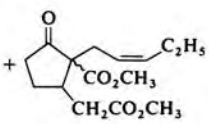
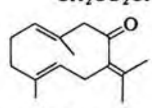
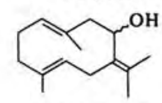
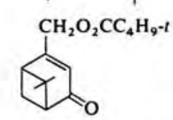
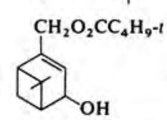
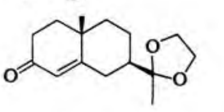
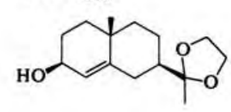
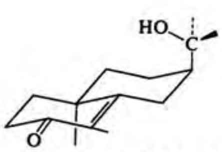
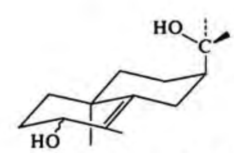
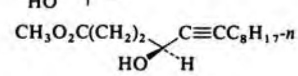
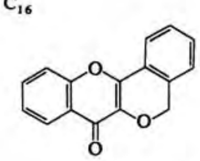
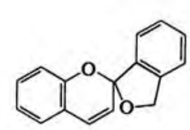
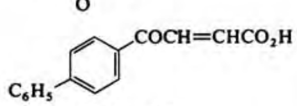
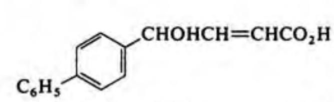
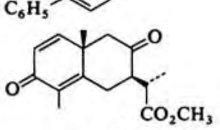
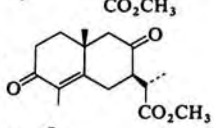
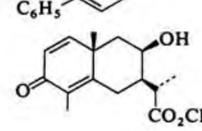
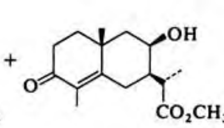
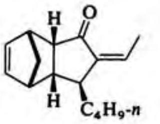
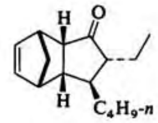
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, 50°, 2 hr	" (44)	1028
	LTBA, THF, 50°, 2 hr	 (~25)	1028
	LTBA, ether, reflux, 7 hr	 (67)	1023
	LTBA, THF, 5°, 18 hr	 (51) +  (26)	1029
	LAH + (−)-QN, ether	 (−)	1030
	LTBA	 (−)	1031
	LTBA, THF	 (89)	1024
	LTBA, ether, r.t., 4 hr	 (~100)	1032
$CH_3O_2C(CH_2)_2COC\equiv CC_8H_{17}$-*n*	LAH + (*R*)-(+)-DBN + MeOH, THF 1. −100°, 1 hr 2. −78°, 2 hr	 (82) (84% e.e.) (*R*)-(+)	326
C_{16}			
	SMEAH, C_6H_6–ether, r.t., 1 hr	 (74)	1033
	SMEAH, C_6H_6–THF, 10–20°, 1.5 hr	 (−)	1034
 + 	LTBA	 +  (−)	967b
	LTBA, ether, r.t., 5 hr	 (~100)	598,599

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

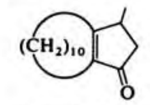
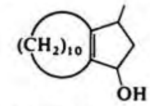
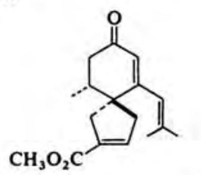
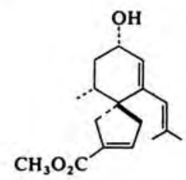
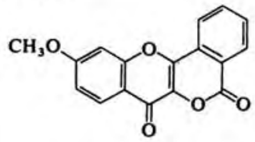
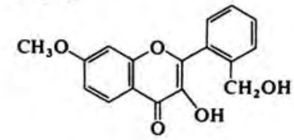
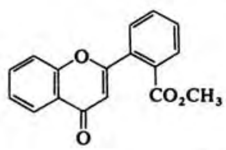
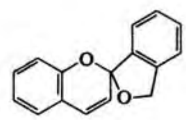
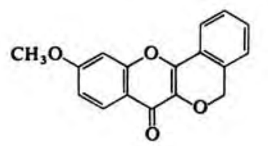
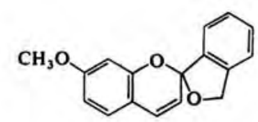
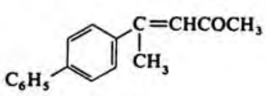
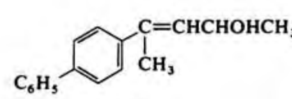
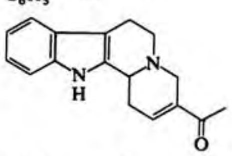
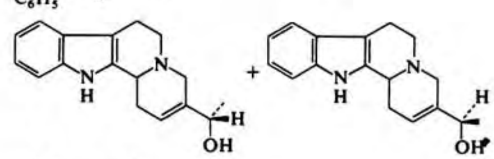
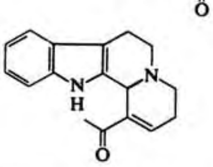
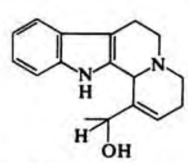
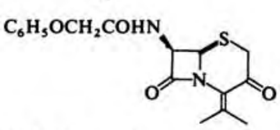
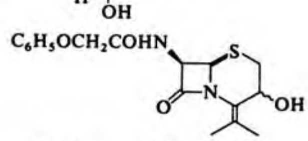
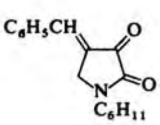
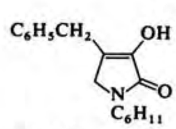
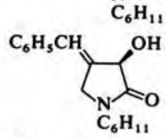
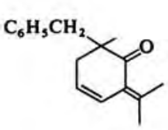
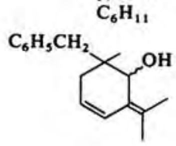
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH	 (−)	1035
HC≡CCOC$_{13}$H$_{27}$-*n*	LAH + (−)-NME + DMP, ether	HC≡CCHOHC$_{13}$H$_{27}$-*n* (−) (86% e.e.)	585
C$_{17}$			
	LTBA, ether, r.t., 4 hr	 (88)	1023
	LTBA, THF, reflux, 6 hr	 (51)	1036
	SMEAH, C$_6$H$_6$–ether, r.t., 1 hr	 (86)	1033
	SMEAH, C$_6$H$_6$–ether, r.t., 1 hr	 (68)	1033
	LTBA	 (−)	1037
	LTBA, THF, overnight	 (90)	1038
	LTBA, THF, r.t., overnight	 (84)	1039
	LTBA, THF, 4 hr	 (97)	1040
	LTBA, THF, r.t., 1 hr	 (74)	577
	LTBA, THF, 0°, 2 hr	 (87)	577
	LTBA	 (−)	831

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

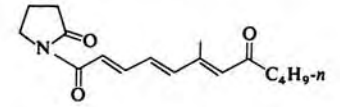
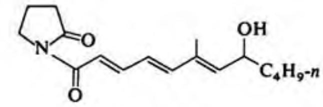
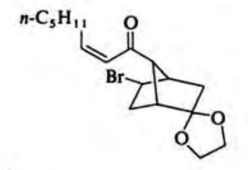
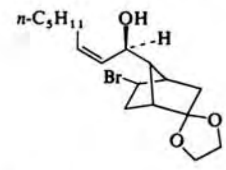
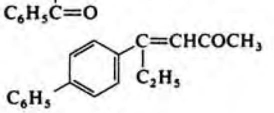
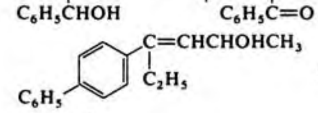
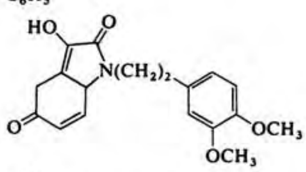
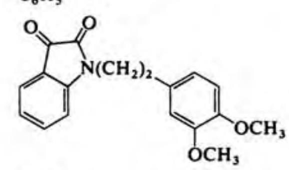
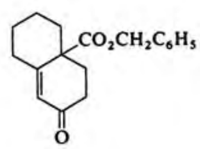
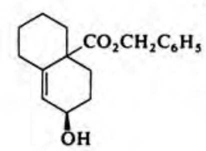
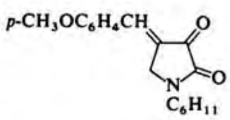
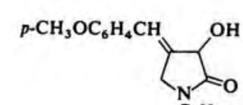
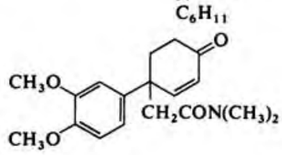
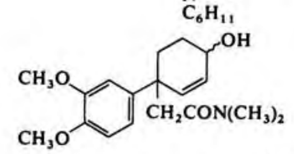
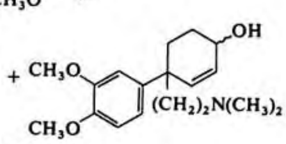
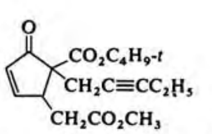
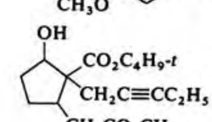
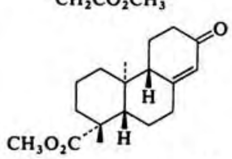
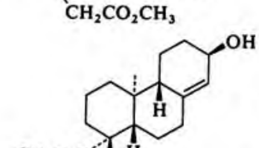
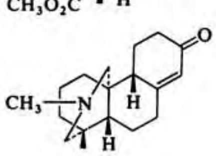
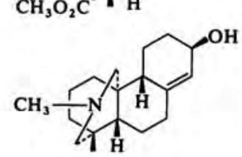
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	LTBA, THF, −10°	 (29)	1041
	LTMA, THF, −100°	 (84)	1042
C_{18}			
$C_6H_5C{=}CHCO_2C_2H_5$ / $C_6H_5C{=}O$	$LiAlH_3(OC_2H_5)$	$C_6H_5C{=}CHCH_2OH$ / C_6H_5CHOH + $C_6H_5CHCH_2CH_2OH$ / $C_6H_5C{=}O$ (~100)	1044
	LTBA	 (−)	1037
	1. LTBA, THF, r.t., 12 hr 2. H_3PO_4	 (−)	1045
	LTBA	 (96)	1046
	LTBA, THF, 0°, 45 min	 (93)	577
	$LiAlH(OC_2H_5)_3$	 +  (−)	1047
	LAH + MeOH, reflux, 1 hr	 (93)	1048
	LTBA, THF, 0°, 30 min	 (−)	1049
	LTBA, THF, −10°, overnight	 (~80)	1050

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

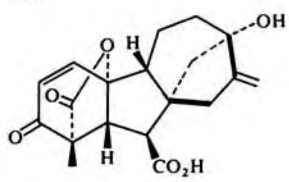
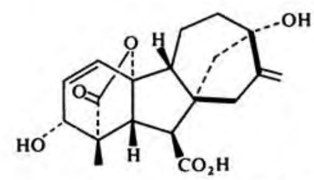
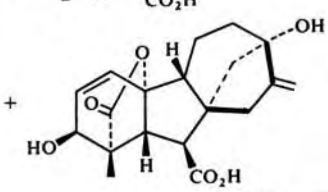
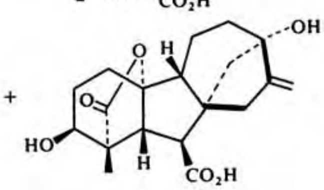
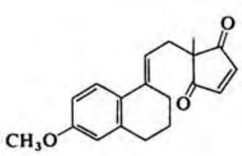
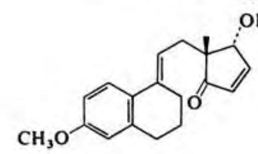
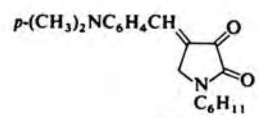
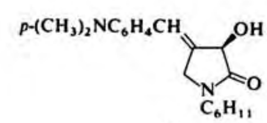
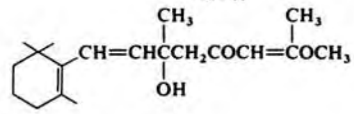
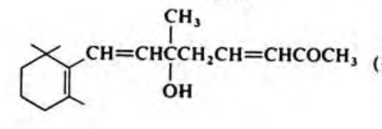
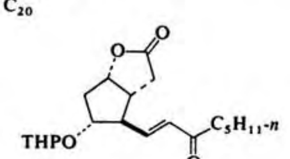
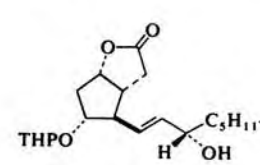
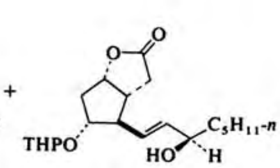
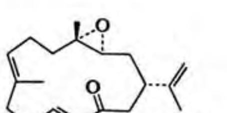
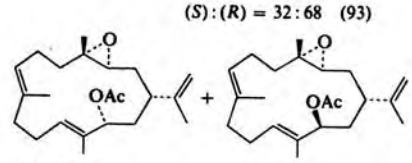
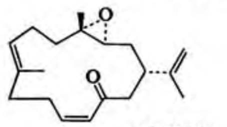
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{19}			
	LTMA, THF-t-C_4H_9OH, 0°, 1.5 hr	 (19) +  (18)	1052
	LTBA, THF, 0°, 100 min	" +  (−)	1053
	LTBA, THF	 (−)	974
	LTBA, THF, 0°, 2 hr	 (56)	577
	1. SHEAH, C_6H_6, 15°, 2 hr 2. H_3O^+	 (−)	614
C_{20}			
	LAH + (R)-(+)-DBN-EtOH, THF, 1. −100°, 1–2 hr 2. −78°, 1–2 hr	 (S) +  (R) (S):(R) = 32:68 (93)	168,169
 (1S,3S,4S)	1. LTBA, THF–ether, r.t., 100 min 2. Ac_2O, Py	 (−)	1054
 (1S,3S,4S)	LTBA	No reaction	1054

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

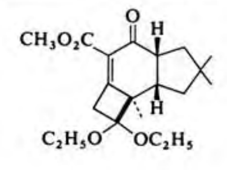
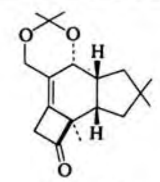
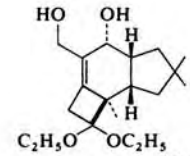
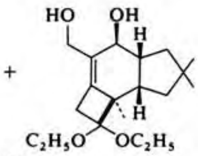
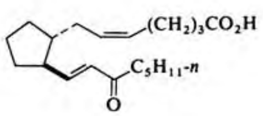
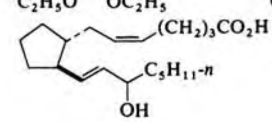
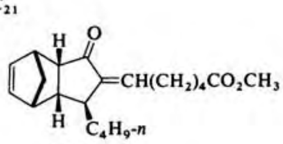
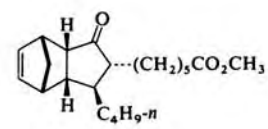
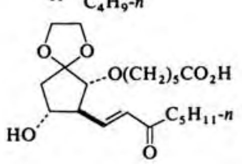
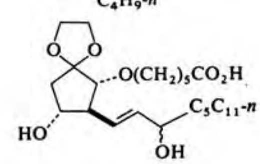
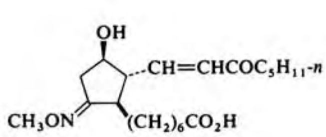
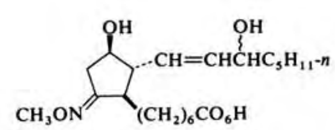
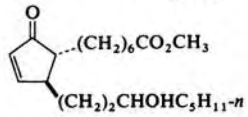
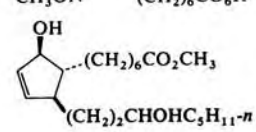
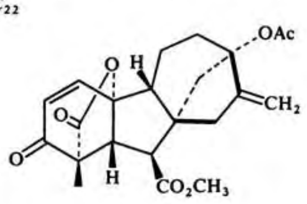
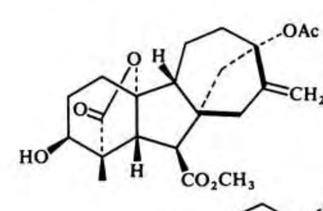
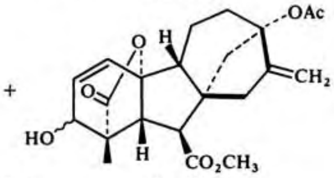
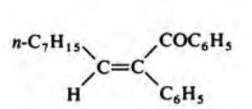
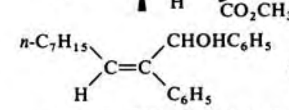
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	1. SMEAH, C_6H_6, 25°, 14 hr 2. TsOH, 25°, acetone	 (–)	916
	SMEAH, C_6H_6, 25°, 20 hr	 (47) +  (17)	915
	LTBA	 (–)	1055
C_{21}			
	LTBA, ether, r.t., 5 hr	 (82)	599,598
	LTBA	 (–)	782
	LTBA, DME, r.t., 4 hr	 (–)	487
	LTBA	 (–)	1056
C_{22}			
	LTBA	 (25) +  (65)	1057
	SMEAH, C_6H_6	 (75) + n-$C_8H_{17}CH(C_6H_5)COC_6H_5$ (8) I	1058

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

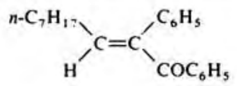
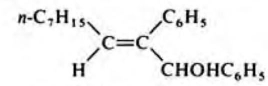
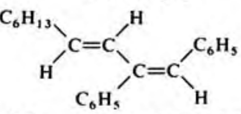
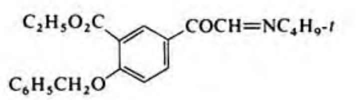
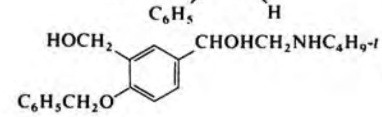
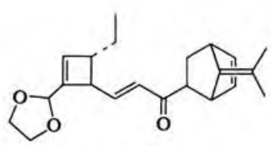
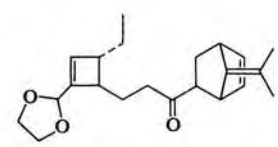
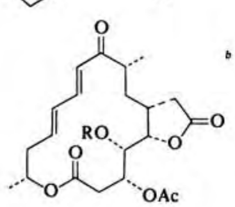
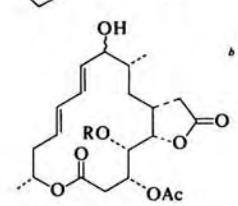
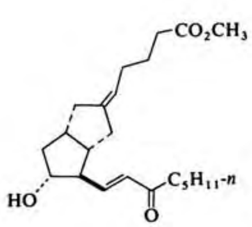
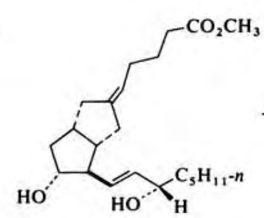
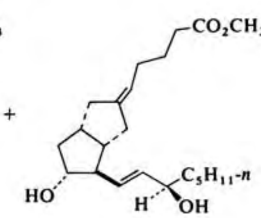
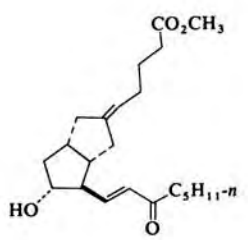
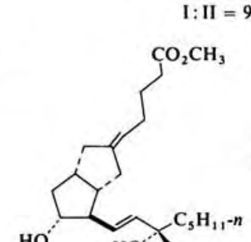
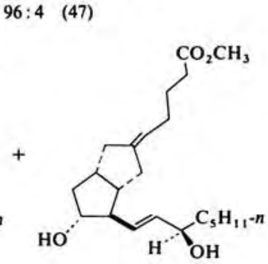
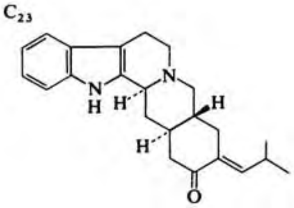
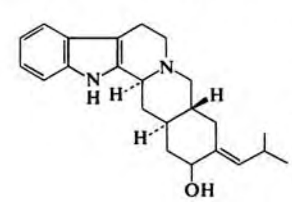
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
	SMEAH, C_6H_6	 (50) +  (6) + I (4)	1058
	SMEAH, C_6H_6, reflux, 1 hr	 (−)	1059
	SMEAH + CuI, THF, −45 to −10°, 2 hr	 (34)	1060
 [b]	LTBA, THF, 25°	 [b] (50)	461
	LAH + (*S*)-(−)-DBN + EtOH, THF, −78°, 1.5 hr	 I +  II; I : II = 96 : 4 (47)	1061
	LAH + (*S*)-(−)-DBN + EtOH, THF, −78°, 1.5 hr	 I +  II; I : II = 94 : 6 (47)	1061
C_{23} 	LTBA, THF, 0°, 1 hr	 (42)	1062

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

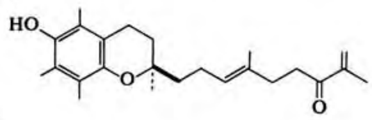
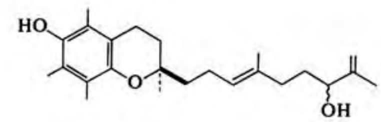
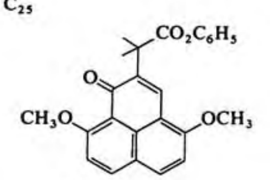
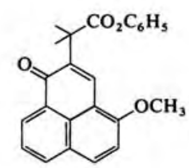
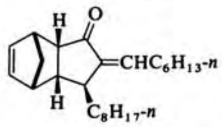
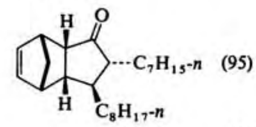
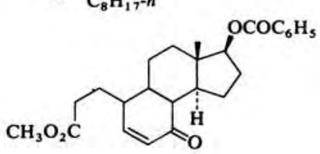
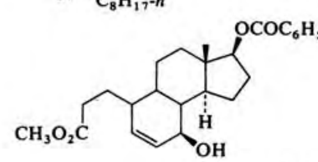
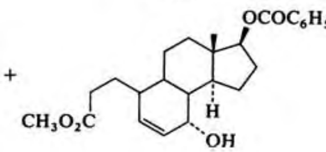
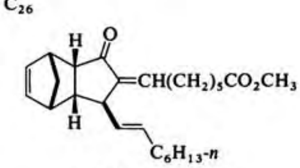
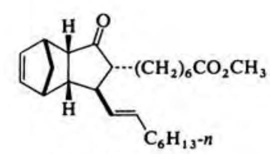
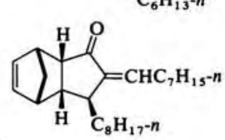
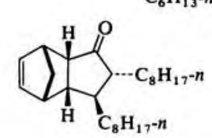
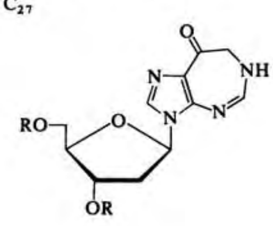
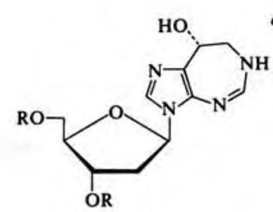
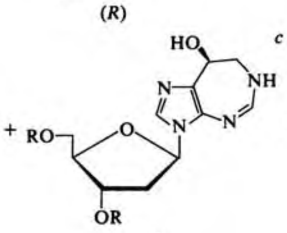
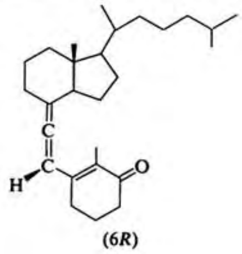
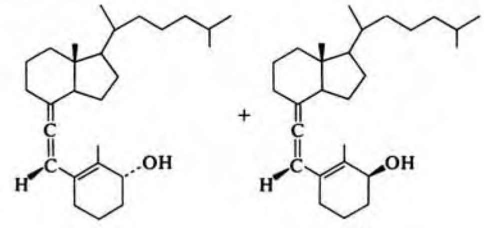
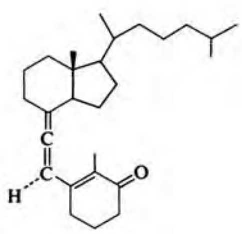
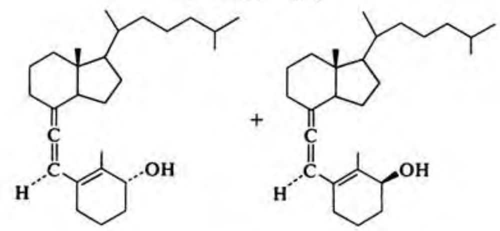
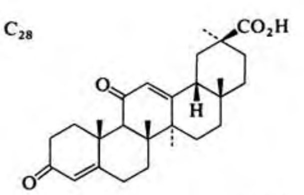
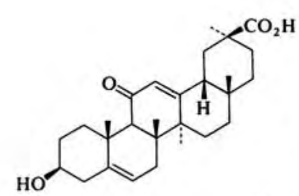
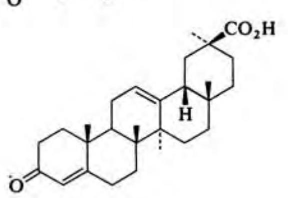
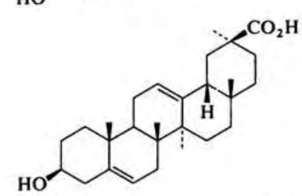
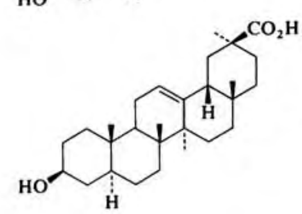
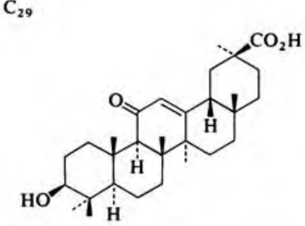
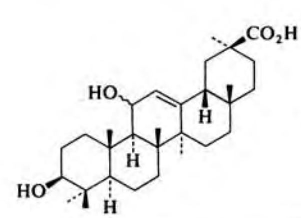
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_{24}			
	SMEAH, THF, 0°, 1.5 hr	 (90)	363
C_{25}			
	LTBA, THF, r.t., 48 hr	 (16)	669
	LTBA, ether	 (95)	599
	LTBA, THF, 0°, 45 min	 (66) +  (30)	740b
C_{26}			
	LTBA, ether, r.t., 5 hr	 (92)	599
	LTBA, ether, r.t., 5 hr	 (~100)	598
C_{27}			
	LTBA	 (*R*) [c] +  (*S*) [c] (—)	1063

TABLE XIV. REDUCTION OF α,β-UNSATURATED KETONES (*Continued*)

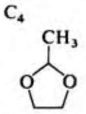
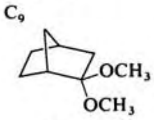
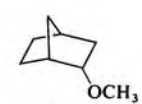
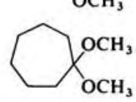
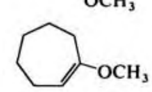
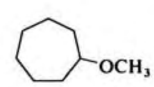
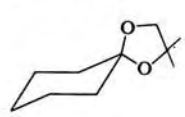
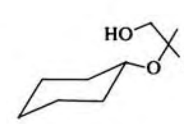
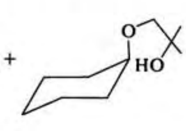
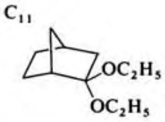
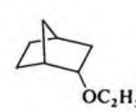
Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
 (6*R*)	LTBA, THF	 I (1*R*,6*R*); II (1*S*,6*R*); I : II = 46 : 54 (71)	1064
 (6*S*)	LTBA, THF	 I (1*R*, 6*S*); II (1*S*, 6*S*); I : II = 52 : 48 (75)	1064
C_{28} 	1. t-C_4H_9OK, t-C_4H_9OH 2. LTBA, THF, 22°, 18 hr	 (38)	993
	1. t-C_4H_9OK, t-C_4H_9OH 2. LTBA, THF, 22°, 18 hr	 (32)	993
	1. Li, NH_3 2. LTBA, THF, r.t., overnight	 (58)	993
C_{29} 	SMEAH, THF	 (—)	1065,1066

[a] The stereochemistry is in relation to the carbinol center.

[b] R = CH_3.

[c] R = p-$CH_3C_6H_4CO$—.

TABLE XV. REDUCTION OF ACETALS AND KETALS

Reactant	Conditions	Product(s) and Yield(s)(%)	Refs.
C_4			
	$AlH(OCH_2CH_2SCH_3)Cl$, ether, r.t., 1 hr	$C_2H_5O(CH_2)_2OH$ (50)	101
C_9			
	$AlH_2(OCH_3)$, ether, reflux, 48 hr	 (96)	96
	$AlH_2(OCH_3)$, ether, r.t., 22 hr	 (96)  (~4)	96
$n\text{-}C_6H_{13}CH(OCH_3)_2$	$AlH_2(OCH_3)$, ether, reflux, 168 hr	$n\text{-}C_6H_{13}CHOCH_3$ (53)	96
C_{10}			
$C_6H_5C(OCH_3)_3$	$AlH_2(OCH_3)$, ether, reflux, 48 hr	$C_6H_5CH_2OCH_3$ (61) + $C_6H_5CH(OCH_3)_2$ (~39)	96
	$AlH_2(OCH_3)$, ether, reflux, 168 hr	 (12) +  (11)	96
C_{11}			
	$AlH_2(OCH_3)$, ether, reflux, 168 hr	 (75)	96

7. Acknowledgment

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End U.S. Suppliers: Aldrich Chemical Company; Metal Hydrides, Inc.; Alfa Inorganics, Inc.; Ventron Corporation. In Europe: Fluka A. G.

Notes

*

* Aldrich Chemical Company (RED-AL); Eastman Kodak Company (VITRIDE); Synthesia (SYNHYDRID) (Kolín, Czechoslovakia).

† Matheson, Coleman, and Bell, Division of the Matheson Company, Inc. (VITRIDE); Paesel Company (VITRIDE) (Frankfurt/Main, FRG).

* Prepared according to K. Nakajima, *Nippon Kagaku Zasshi*, **81**, 1476 (1960).

* Aldrich Chemical Company, Milwaukee, Wisconsin, USA.

References

1. H. C. Brown, H. I. Schlesinger, and A. B. Burg, J. Am. Chem. Soc., **61**, 673 (1939).
2. H. I. Schlesinger and H. C. Brown, U.S. Pat. 2,461,661 (1949) [C. A., **43**, 4684e (1949)].
3. H. I. Schlesinger and H. C. Brown, U.S. Pat. 2,683,721 (1954) [C. A., **49**, 6991a (1955)].
4. H. I. Schlesinger, H. C. Brown, H. R. Hoekstra, and L. R. Rapp, J. Am. Chem. Soc., **75**, 199 (1953).
5. H. I. Schlesinger, H. C. Brown, and A. E. Finholt, J. Am. Chem. Soc., **75**, 205 (1953).
6. A. E. Finholt, A. C. Bond, Jr., and H. I. Schlesinger, J. Am. Chem. Soc., **69**, 1199 (1947).
7. G. Zweifel and H. C. Brown, Org. React., **13**, 1 (1963).
8. H. C. Brown and S. Krishnamurthy, Tetrahedron, **35**, 567 (1979).
9. S. W. Chaikin and W. G. Brown, J. Am. Chem. Soc., **71**, 122 (1949).
10. H. I. Schlesinger, H. C. Brown, B. Abraham, A. C. Bond, N. Davidson, A. E. Finholt, J. R. Gilbreath, H. Hoekstra, L. Horvitz, E. K. Hyde, J. J. Katz, J. Knight, R. A. Lad, D. L. Mayfield, L. Rapp, D. M. Ritter, A. M. Schwartz, I. Sheft, L. D. Tuck, and A. O. Walker, J. Am. Chem. Soc., **75**, 186 (1953).
11. R. F. Nystrom and W. G. Brown, J. Am. Chem. Soc., **69**, 1197 (1947).
12. W. G. Brown, Org. React., **6**, 469 (1951).
13. J. Rudinger, M. Ferles, and M. Protiva, Chem. Listy, **45**, 309 (1951) [C. A., **46**, 4463 (1952)].
14. M. Ferles and J. Rudinger, Chem. Listy, **47**, 91 (1953) [C. A., **48**, 3239c (1954)].
15. V. M. Mi / ovi / and M. L. Mihailovi / , *Lithium Aluminum Hydride in Organic Chemistry*, Nau / na Knjiga, Belgrade, 1955.
16. N. G. Gaylord, *Reductions with Complex Metal Hydrides*, Wiley-Interscience, New York, 1956.
17. J. Rudinger and M. Ferles, *Lithium Aluminium Hydrid a P | ibuzná1 inidla v Organické Chemii*, Nakladatelství *1* SAV, Prague, 1956.
18. E. Schenker, Angew. Chem., **73**, 81 (1961).
19. E. Schenker, *Neuere Methoden der Organischen Chemie*, Vol. **V**., Verlag Chemie, Weinheim, 1963, pp. 173–293.
20. E. Schenker, in *Newer Methods of Preparative Organic Chemistry*, Vol. **IV**., W. Foerst, Ed., Academic Press, New York, 1968, pp. 163–335.
21. (a) A. Hajós, *Komplexe Hydride*, VEB Deutscher Verlag der

Wissenschaften, East Berlin, 1966; (b) *Complex Hydrides and Related Reducing Agents in Organic Synthesis*, Elsevier Scientific Publishing Company, Amsterdam, 1979.

22. H. C. Brown, *Hydroboration*, W. A. Benjamin, New York, 1962.
23. E. Wiberg and M. Schmidt, Z. Naturforsch., **6b**, 460 (1951).
24. E. C. Ashby and J. Prather, J. Am. Chem. Soc., **88**, 729 (1966).
25. M. N. Rerick, *The Mixed Hydrides*, Metal Hydrides, Beverly, Mass., 1959.
26. E. L. Eliel, Rec. Chem. Progr., **22**, 129 (1961).
27. M. N. Rerick, in *Reduction*, R. L. Augustine, Ed., Marcel Dekker, New York, 1968, pp. 1–94.
28. E. L. Eliel and M. N. Rerick, J. Am. Chem. Soc., **82**, 1367 (1960).
29. E. Wiberg, H. Graf, M. Schmidt, and R. Usó Lacal, Z. Naturforsch., **7b**, 578 (1952).
30. H. C. Brown and N. M. Yoon, J. Am. Chem. Soc., **88**, 1464 (1966).
31. K. N. Semenko, B. M. Bulychev, and E. A. Sheblyagina, Usp. Khim., **35**, 1529 (1966) [C. A., **66**, 51729g (1967)].
32. H. Noeth and E. Wiberg, Fortschr. Chem. Forsch., **8**, 321 (1967).
33. H. C. Brown, H. I. Schlesinger, I. Sheft, and D. M. Ritter, J. Am. Chem. Soc., **75**, 192 (1953).
34. H. C. Brown and E. J. Mead, J. Am. Chem. Soc., **75**, 6263 (1953).
35. I. Goodman, J. Chem. Soc., **1951**, 2209.
36. O. Schmitz-DuMont and V. Habernickel, Naturwissenschaften, **39**, 20 (1952).
37. H. C. Brown and R. F. McFarlin, J. Am. Chem. Soc., **78**, 252 (1956).
38. O. Schmitz-DuMont and V. Habernickel, Chem. Ber., **90**, 1054 (1957).
39. C. J. Shoaf, Ph. D. Dissertation, Purdue University, Lafayette, Ind., 1957.
40. H. C. Brown and R. F. McFarlin, J. Am. Chem. Soc., **80**, 5372 (1958).
41. H. C. Brown, R. F. McFarlin, and B. C. Subba Rao, U.S. Pat. 3,147,272 (1964) [C. A., **62**, 11689c (1965)].
42. H. C. Brown and B. C. Subba Rao, J. Am. Chem. Soc., **80**, 5377 (1958).
43. H. C. Brown and C. J. Shoaf, J. Am. Chem. Soc., **86**, 1079 (1964).
44. H. C. Brown and C. P. Garg, J. Am. Chem. Soc., **86**, 1085 (1964).
45. H. C. Brown and A. Tsukamoto, J. Am. Chem. Soc., **86**, 1089 (1964).
46. H. C. Brown and P. M. Weissman, J. Am. Chem. Soc., **87**, 5614 (1965).
47. H. C. Brown, *U.S. Clearinghouse Fed. Sci. Tech. Inform.*, AD 645581 (1966) [C. A., **67**, 99306x (1967)].

48. J. S. Meek and C. Bouboulis, J. Org. Chem., **26**, 1302 (1961).
49. Z. Tuba, S. Bor, and S. Görög, Hung. Pat. 154,609 (1968) [C. A., **69**, 87351m (1968)].
50. Z. Tuba, M. Bor, and S. Görög, Ger. Pat. 1,668,604 (1971) [C. A., **76**, 46396f (1972)].
51. E. C. Ashby and J. R. Boone, J. Org. Chem., **41**, 2890 (1976).
52. H. C. Brown and S. K. Gupta, J. Am. Chem. Soc., **93**, 4062 (1971).
53. G. Hesse and R. Schrödel, Angew. Chem., **68**, 438 (1956).
54. G. Hesse and R. Schrödel, Justus Liebigs Ann. Chem., **607**, 24 (1957).
55. G. Hesse and R. Schrödel, Trans. Bose Research Inst. (Calcutta), **22**, 127 (1958) [C. A., **54**, 22311f (1960)].
56. G. Hamprecht, M. Schwarzmann, and M. Tittel, Ger. Pat. 1,085,515 (1960) [C. A., **55**, 15350d (1961)].
57. C. D. Nenitzesku and F. Badea, Bull. Inst. Politeh. Bucuresti, **20**, 93 (1958) [C. A., **55**, 2325i (1961)].
58. L. I. Zakharkin, D. N. Maslin, and V. V. Gavrilenko, Zh. Obshch. Khim., **36**, 200 (1966) [C. A., **64**, 15724f (1966)].
59. M. Cole. U.S. Pat. 3,184,492 (1965) [C. A., **63**, 7933h (1965)].
60. P. Chini, A. Baradel, C. Vacca, and M. Malde, Neth. Pat. Appl. 6,411,538 (1965) [C. A., **63**, 14418a (1965)].
61. P. Chini, A. Baradel, and C. Vacca, Chim. Ind. (Milan), **48**, 596 (1966).
62. *1* eskoslovenská Akademie V \ d, Fr. Pat. 1,546,482 (1968) [C. A., **72**, 21304d (1970)].
63. M. *1* erný, J. Málek, and J. Vít, Czech. Pat. 177,202 (1979) [C. A., **91**, 55639z (1979)].
64. Anon., Chem. Eng. News, **1969** (October 13), 80.
65. H. J. Sanders, Chem. Eng. News, **1972** (June 19), 29.
66. M. Born and C. Lassau, Ger. Offen. 2,122,432 (1971) [C. A., **76**, 59430n (1972)].
67. M. Born and C. Lassau, Fr. Pat. 2,087,530 (1972) [C. A., **77**, 101370r (1972)].
68. O. Schmitz-DuMont and G. Bungard, Chem. Ber., **92**, 2399 (1959).
69. B. *1* ásenský, J. Machá / ek, and J. Vít, Czech. Pat. 133,379 (1969) [C. A., **73**, 87417v (1970)].
70. B. *1* ásenský, J. Machá / ek, and J. Vít, Czech. Pat. 132,462 (1969) [C. A., **73**, 34788k (1970)].
71. B. *1* ásenský, J. Machá / ek, and J. Vít, Czech. Pat. 132,463 (1969) [C. A., **73**, 35047e (1970)].

72. B. *1* ásenský, J. Machá / ek, and K. Abrham, Collect. Czech. Chem. Commun., **36**, 2648 (1971).
73. *1* eskoslovenská Akademie V \ d, Br. Pat. 1,189,512 (1970) [C. A., **73**, 47138y (1970)].
74. B. *1* ásenský, J. Machá / ek, and J. Vít, Czech. Pat. 132,638 (1969) [C. A., **73**, 44884c (1970)].
75. J. Vít, B. *1* ásensky, and J. Machá / ek, Fr. Pat. 1,515,582 (1968) [C. A., **70**, 115009x (1969)].
76. B. *1* ásenský, J. Machá / ek, and J. Vít, Czech. Pat. 134,720 (1970) [C. A., **74**, 89240b (1971)].
77. *1* eskoslovenská Akademie V \ d, Br. Pat. 1,241,218 (1971) [C. A., **75**, 109840y (1971)].
78. J. Vít, B. *1* ásenský, and J. Machá / ek, Czech. Pat. 140,864 (1971) [C. A., **77**, 19173v (1972)].
79. B. *1* ásenský, J. Machá / ek, and K. Abrham, Collect. Czech. Chem. Commun., **37**, 1178 (1972).
80. B. *1* ásenský, J. Machá / ek, and K. Abrham, Collect. Czech. Chem. Commun., **37**, 2537 (1972).
81. J. Machá / ek, B. *1* ásenský, and K. Abrham, Collect. Czech. Chem. Commun., **38**, 343 (1973).
82. J. Machá / ek and B. *1* ásenský, Z. Chem., **16**, 236 (1976).
83. J. Vít, B. *1* ásenský, and J. Machá / ek, Fr. Pat. 1,515,581 (1968) [C.A., **70**, 98383v (1969)].
84. B. *1* ásenský, and J. Machá / ek, and J. Vít, Czech. Pat. 138,484 (1970) [C.A., **76**, 24684w (1972)].
85. J. Machá / ek and B. *1* ásenský, Czech. Pat. 158,862 (1975) [C.A., **84**, 89607h (1976)].
86. Continental Oil Co., Br. Pat. 938,043 (1963) [C.A., **60**, 2764d (1964)].
87. Continental Oil Co., Br. Pat. 938,044 (1963) [C.A., **60**, 2764e (1964)].
88. K. Suchy, Dissertation, University of Munich, 1966.
89. H. Noeth and K. Suchy, Z. Anorg. Allg. Chem., **358**, 44 (1968).
90. A. Mazzei, F. Bonati, W. Marconi, G. Manara, and G. Castelfranchi, Ital. Pat. 684,730 (1965) [C.A., **66**, 28671f (1967)].
91. E. E. Flagg and D. L. Schmidt, J. Inorg. Nucl. Chem., **31**, 2329 (1969).
92. N. E. Matzek and W. H. Crawford, U.S. Pat. 3,524,870 (1970) [C.A., **73**, 98379k (1970)].
93. B. *1* ásenský, K. Abrham, and J. Machá / ek, Czech. Pat. 155,026 (1974) [C.A., **82**, 127083c (1975)].
94. B. *1* ásenský, O. K | í E , and H. Kadlecová, Z. Chem., **13**, 436 (1973).
95. O. K | í E , P. Trška, and B. *1* ásenský, Collect. Czech. Chem.

Commun., **39**, 2559 (1974).

96. W. W. Zajac, Jr., and K. J. Byrne, J. Org. Chem., **38**, 384 (1973).
97. D. L. Schmidt and A. L. Daniels, U.S. Pat. 3,435,059 (1969) [C.A., **71**, 3130u (1969)].
98. Continental Oil Co., Belg. Pat. 615,566 (1962) [C.A., **57**, 16400a (1962)].
99. E. C. Ashby and R. A. Kovar, Inorg. Chem., **10**, 893 (1972).
100. B. Cooke, E. C. Ashby, and J. Lott, J. Org. Chem., **33**, 1132 (1968).
101. H. A. Davis and R. K. Brown, Can. J. Chem., **49**, 2166 (1971).
102. Thiokol, Ventron Alembic, **15**, 3 (1979) [C.A., **91**, 122953n (1979)].
103. A. L. Gemal and J. L. Luche, J. Am. Chem. Soc., **103**, 5454 (1981).
104. S. K. Chung, J. Org. Chem., **44**, 1014 (1979).
105. T. L. Ho, Synthesis, **1979**, 1.
106. R. F. Borch, M. D. Bernstein, and H. D. Durst, J. Am. Chem. Soc., **93**, 2897 (1971).
107. C. F. Lane, Synthesis, **1975**, 135.
108. R. O. Hutchins, Ventron Alembic, **8**, 2 (1977) [C.A., **91**, 4688g (1979)].
109. R. O. Hutchins and N. R. Natale, Org. Prep. Proced. Int., **11**, 201 (1979).
110. R. F. Borch and H. D. Durst, J. Am. Chem. Soc., **91**, 3996 (1969).
111. J. M. Lalancette, A. Freche, J. R. Brindle, and M. Laliberté, Synthesis, **1972**, 526.
112. W. J. Gensler, F. Johnson, and A. D. B. Sloan, J. Am. Chem. Soc., **82**, 6074 (1960).
113. N. M. Yoon, H. J. Lee, and H. K. Kim, Teahan Hwahak Hoechi, **20**, 59 (1976) [C.A., **85**, 4641n (1976)].
114. L. I. Zakharkin and I. M. Khorlina, Dokl. Akad. Nauk SSSR, **116**, 422 (1957) [C.A., **52**, 8040f (1958)].
115. L. I. Zakharkin and I. M. Khorlina, Izv. Akad. Nauk SSSR, Ser. Khim., **1959**, 2146 [C.A., **54**, 10932b (1960)].
116. L. I. Zakharkin and I. M. Khorlina, Tetrahedron Lett., **1962**, 619.
117. E. Winterfeldt, Synthesis, **1975**, 617.
118. K. Ziegler, Angew. Chem., **76**, 545 (1964).
119. G. J. M. van der Kerk, J. G. Noltes, and J. G. A. Luitjen, J. Appl. Chem., **7**, 366 (1957).
120. H. G. Kuivila and O. F. Beumel, J. Am. Chem. Soc., **83**, 1246 (1961).
121. H. C. Brown, *Boranes in Organic Chemistry*, Cornell University Press, Ithaca, New York, 1972, Chaps. "12–13".
122. G. M. L. Cragg, *Organoboranes in Organic Synthesis*, Marcel Dekker, New York, 1973, p. 319.
123. S. Krishnamurthy, Aldrichimica Acta, **7**, 55 (1974).

124. H. C. Brown, G. W. Kramer, A. B. Levy, and M. M. Midland, *Organic Syntheses via Boranes*, Wiley-Interscience, New York, 1975.

125. H. C. Brown, *U.S. NTIS, AD Rep.* AD-A026132 (1976) [C.A., **85**, 176353m (1976)].

126. H. C. Brown, Chem. Eng. News, **57** (10), 24 (1979).

127. H. C. Brown and S. Krishnamurthy, Aldrichimica Acta, **12**, 3 (1979).

128. (a) J. A. Gladycz, Aldrichimica Acta, **12**, 13 (1979); (b) H. C. Brown, J. L. Hubbard, and B. Singaram, Tetrahedron, **37**, 2359 (1981).

129. (a) H. C. Brown, S. C. Kim, and S. Krishnamurthy, J. Org. Chem., **45**, 1 (1980); (b) H. C. Brown, P. K. Jadhav, and A. K. Mandal, Tetrahedron, **37**, 3547 (1981).

130. M. Fieser and L. F. Fieser, *Reagents for Organic Synthesis*, Vols. **I–VIII**, Wiley-Interscience, New York, 1967–1980.

131. S. I. Yamada and K. Koga, in *Selective Organic Transformations*, Vol. **I**., B. S. Thyagarajan, Ed., Wiley-Interscience, New York, 1970.

132. B. D. James, Rec. Chem. Progr., **31**, 199 (1970).

133. J. Vít, Eastman Org. Chem. Bull., **42**, 1 (1970) [C.A., **74**, 99073p (1971)].

134. H. O. House, *Modern Synthetic Reactions*, 2nd ed., W. A. Benjamin, Menlo Park, Calif., 1972.

135. D. M. S. Wheeler and M. M. Wheeler, in *Organic Reactions in Steroid Chemistry*, J. Fried and J. A. Edwards, Eds., Vol. **I**., Van Nostrand Reinhold, New York, 1972, Chap. "2".

136. J. Málek and M. *1* erný, Synthesis, **1972**, 217.

137. A. S. Kushner and T. Vaccariello, J. Chem. Educ., **50**, 154, 157 (1973).

138. H. Mishima, Yuki Gosei Kagaku Kyokai Shi, **32**, 1014 (1974) [C.A., **82**, 138613b (1975)].

139. E. R. H. Walker, Chem. Soc. Revs., **5**, 23 (1976).

140. C. F. Lane, Chem. Rev., **76**, 773 (1976).

141. C. F. Lane, in *Aspects of Mechanistic Organometallic Chemistry (Proceedings of Symposium)*, J. H. Brewster; Ed., Plenum Press, New York, 1978, pp. 181–198.

142. J. R. Boone and E. C. Ashby, Top. Stereochem., **11**, 53 (1979).

143. P. A. Bartlett, Tetrahedron, **36**, 2 (1980).

144. S. O. Kim, Hwahak Kwa Kongop Ui Chinbo, **20**, 293 (1980) [C.A., **94**, 102222g (1981)].

145. D. R. Boyd and M. A. McKervey, Quart. Rev: (London), **22**, 95 (1968).

146. J. Mathieu and J. Weill-Raynal, Bull. Soc. Chim. Fr., **1968**, 1211.

147. T. D. Inch, Synthesis, **1970**, 466.

148. J. D. Morrison and H. S. Mosher, *Asymmetric Organic Reactions*,

Prentice Hall, Englewood Cliffs, N. J., 1971, pp. 116–132, 202–215, 386–389; Reprint Ed., American Chemical Society, Washington, D.C., 1976.

149. H. J. Schneider and R. Haller, Pharmazie, **28**, 417 (1973).
150. J. W. Scott and D. Valentine, Jr., Science, **184**, 943 (1974).
151. D. Valentine, Jr. and J. W. Scott, Synthesis, **1978**, 329.
152. J. W. ApSimon and R. P. Seguin, Tetrahedron, **35**, 2797 (1979).
153. H. Haubenstock and E. L. Eliel, J. Am. Chem. Soc., **84**, 2363 (1962).
154. E. L. Eliel and Y. Senda, Tetrahedron, **26**, 2411 (1970).
155. H. Haubenstock, J. Org. Chem., **38**, 1765 (1973).
156. J. C. Richer and C. Gilardeau, Can. J. Chem., **43**, 3419 (1965).
157. D. C. Ayres and R. Sawdaye, J. Chem. Soc., Chem. Commun., **1966**, 527.
158. J. M. Bec and J. Huet, Bull. Soc. Chim. Fr., **1972**, 1636.
159. I. Jacquet and J. P. Vigneron, Tetrahedron Lett., **1974**, 2065.
160. J. P. Vigneron and I. Jacquet, Tetrahedron, **32**, 939 (1976).
161. J. P. Vigneron and V. Bloy, Tetrahedron Lett., **1979**, 2683.
162. S. Terashima, N. Tanno, and K. Koga, Tetrahedron Lett., **21**, 2753 (1980).
163. S. Terashima, N. Tanno, and K. Koga, Chem. Lett., **1980**, 981.
164. T. H. Johnson and K. C. Klein, J. Org. Chem., **44**, 461 (1979).
165. T. H. Johnson and G. Rangarajan, J. Org. Chem., **44**, 3966 (1979).
166. S. Yamaguchi, H. S. Mosher, and A. Pohland, J. Am. Chem. Soc., **94**, 9254 (1972).
167. S. Yamaguchi and H. S. Mosher, J. Org. Chem., **38**, 1870 (1973).
168. R. Noyori, I. Tomino, and Y. Tanimoto, J. Am. Chem. Soc., **101**, 3129 (1979); R. Noyori, Kankyo Kagaku Tokubetsu Kenkyu Kenkyu Hokokushu, **1980**, B43-R-32-6, Kagakuteki Kankyo Kaizen Gijutsu, 33 (1980) [C.A., **93**, 166992v (1980)]; R. Noyori, Pure Appl. Chem., **53**, 2315 (1981).
169. R. Noyori, I. Tomino, and M. Nishizawa, J. Am. Chem. Soc., **101**, 5843 (1979).
170. H. Haubenstock, T. A. Mester, Jr., and H. Zieger, J. Org. Chem., **45**, 3443 (1980).
171. H. Haubenstock and N. L. Yang, J. Org. Chem., **43**, 1463 (1978).
172. J. M. Bec and J. Huet, C. R. Acad. Sci., Ser. C, **270**, 1131 (1970).
173. H. C. Brown and H. R. Deck, J. Am. Chem. Soc., **87**, 5620 (1965).
174. M. Barthélémy and Y. Bessière-Chrétien, Tetrahedron Lett., **1970**, 4265.
175. J. Fusek, F. Hanousek, and F. Haruda, Collect. Czech. Chem.

Commun., **41**, 187 (1976).

176. V. V. Gavrilenko, M. I. Vinnikova, V. A. Antonovich, and L. I. Zakharkin, Izv. Akad. Nauk SSSR, Ser. Khim., **1979**, 1273 [C.A., **91**, 123027a (1979)].
177. P. Stilbs and S. Forsen, Org. Magn. Reson., **8**, 382 (1976).
178. E. C. Ashby, J. P. Sevenair, and F. R. Dobbs, J. Org. Chem., **36**, 197 (1971).
179. K. E. Wiegers and S. G. Smith, J. Am. Chem. Soc., **99**, 1480 (1977).
180. K. E. Wiegers and S. G. Smith, J. Org. Chem., **43**, 1126 (1978).
181. D. V. Banthorpe and H. S. Davies, J. Chem. Soc. (B), **1968**, 1356.
182. J. J. Cawley and D. V. Petrocine, J. Org. Chem., **41**, 2608 (1976).
183. R. J. McMahon, K. E. Wiegers, and S. G. Smith, J. Org. Chem., **46**, 99 (1981).
184. M. Hilal Abdel Kader, Chem. Ber., **103**, 1225 (1970).
185. N. Ya. Turova, M. I. Karpovskaya, and A. V. Novoselova, Zh. Obshch. Khim., **47**, 1338 (1977) [C.A., **87**, 84444e (1977)].
186. H. C. Brown and A. Tsukamoto, J. Am. Chem. Soc., **81**, 502 (1959).
187. C. P. Garg, Ph. D. Dissertation, Purdue University, Lafayette, Ind. [Diss. Abstr., **23**, 830 (1962)].
188. E. C. Ashby, F. R. Dobbs, and H. P. Hopkins, Jr., J. Am. Chem. Soc., **97**, 3158 (1975).
189. E. C. Ashby and J. J. Lin, Tetrahedron Lett., **1976**, 3865.
190. J. Fusek and F. Hanousek, Collect. Czech. Chem. Commun., **42**, 967 (1977).
191. O. Štrouf, Collect. Czech. Chem. Commun., **36**, 2707 (1971).
192. O. Štrouf, Collect. Czech. Chem. Commun., **37**, 2693 (1972).
193. H. Haubenstock, J. Org. Chem., **40**, 926 (1975).
194. H. Haubenstock and S. J. Hong, Tetrahedron, **34**, 2445 (1978).
195. N. C. Danh, C. Arnaud, and J. Huet, Bull. Soc. Chim. Fr., **1974**, 1071.
196. Y. Bessière-Chrétien, G. Boussac, and M. Barthélémy, Bull. Soc. Chim. Fr., **1972**, 1419.
197. I. Véle, J. Fusek, and O. Štrouf, Collect. Czech. Chem. Commun., **37**, 3063 (1972).
198. H. Kadlecová, V. Kadlec, and O. Štrouf, Collect. Czech. Chem. Commun., **38**, 2379 (1973).
199. J. Duben, B. *1* ásenský, and O. Štrouf, Collect. Czech. Chem. Commun., **39**, 546 (1974).
200. C. Agami, A. Kazakos, J. Levisalles, and A. Sevin, Tetrahedron, **36**, 2977 (1980).

201. M. Hilal Abdel Kader, Tetrahedron Lett., **1969**, 2301.
202. D. A. Horne, J. Am. Chem. Soc., **102**, 6011 (1980).
203. D. C. Ayres and R. Sawdaye, J. Chem. Soc. (C), **1971**, 44.
204. M. *1* erný and J. Málek, Collect. Czech. Chem. Commun., **41**, 119 (1976).
205. J. Málek, M. *1* erný, and R. ￥ e ｜ icha, Collect. Czech. Chem. Commun., **39**, 2656 (1974).
206. M.*1* erný and J. Málek, Tetrahedron Lett., **1972**, 691.
207. M. *1* erný and J. Málek, Collect. Czech. Chem. Commun., **39**, 842 (1974).
208. J. Málek and M. *1* erný, J. Organomet. Chem., **84**, 139 (1975).
209. E. C. Ashby, A. B. Goel, and R. N. DePriest, J. Am. Chem. Soc., **102**, 7779 (1980).
210. E. C. Ashby and A. B. Goel, J. Org. Chem., **46**, 3934 (1981).
211. E. C. Ashby, A. B. Goel, R. N. DePriest, and H. S. Prasad, J. Am. Chem. Soc., **103**, 973 (1981).
212. E. C. Ashby and A. B. Goel, Tetrahedron Lett., **22**, 4783 (1981).
213. J. R. M. Giles and B. P. Roberts, J. Chem. Soc., Chem. Commun., **1981**, 1167.
214. R. Baudouy and J. Gore, Tetrahedron, **31**, 383 (1975).
215. K. J. TerBeek, Ph. D. Dissertation, Wayne State University, Detroit, Mich., 1974 [C.A., **82**, 156615h (1975)].
216. C. L. Stevens, K. J. TerBeek, and P. M. Pillai, J. Org. Chem., **39**, 3943 (1974).
217. C. Bénard, M. T. Maurette, and A. Lattes, C. R. Acad. Sci., Ser. C, **273**, 426 (1971).
218. C. Bénard, M. T. Maurette, and A. Lattes, Tetrahedron Lett., **1973**, 2763.
219. M. J. Jorgenson and A. F. Thacher, J. Chem. Soc., Chem. Commun., **1969**, 1290.
220. M. J. Jorgenson and A. F. Thacher, Org. Synth., **48**, 75 (1968).
221. J. Málek, unpublished results.
222. M. J. Jorgenson and A. W. Friend, J. Am. Chem. Soc., **87**, 1815 (1965).
223. O. Eisenstein, J. M. Lefour, C. Minot, N. T. Anh, and G. Soussan, C. R. Acad. Sci., Ser. C, **274**, 1310 (1972).
224. J. Durand, N. T. Anh, and J. Huet, Tetrahedron Lett., **1974**, 2397.
225. J. Bottin, O. Eisenstein, C. Minot, and N. T. Anh, Tetrahedron Lett., **1972**, 3015.
226. R. G. Pearson, J. Chem. Educ., **45**, 581 (1968).
227. J. Seyden-Penne, Bull. Soc. Chim. Fr., **1968**, 3871.

228. H. C. Brown and H. M. Hess, J. Org. Chem., **34**, 2206 (1969).
229. J. C. Richer and A. Rossi, Can. J. Chem., **50**, 438 (1972).
230. J. A. Marshall and J. A. Ruth, J. Org. Chem., **39**, 1971 (1974).
231. W. L. Dilling and R. A. Plepys, J. Chem. Soc. Chem. Commun., **1969**, 417.
232. W. L. Dilling and R. A. Plepys, J. Org. Chem., **35**, 2971 (1970).
233. J. P. Bugel, P. Ducos, O. Gringore, and F. Rouessac, Bull. Soc. Chim. Fr., **1972**, 4371.
234. D. J. Cram and F. A. Abd Elhafez, J. Am. Chem. Soc., **74**, 5828 (1952).
235. D. J. Cram and K. R. Kopecky, J. Am. Chem. Soc., **81**, 2748 (1959).
236. J. W. Cornforth, R. H. Cornforth, and K. K. Mathew, J. Chem. Soc., **1959**, 112.
237. J. H. Stocker, P. Sidisunthorn, B. M. Benjamin, and C. J. Collins, J. Am. Chem. Soc., **82**, 3913 (1960).
238. D. J. Cram and D. R. Wilson, J. Am. Chem. Soc., **85**, 1245 (1963).
239. J. A. Katzenellenbogen and S. B. Bowlus, J. Org. Chem., **38**, 627 (1973).
240. S. B. Bowlus and J. A. Katzenellenbogen, J. Org. Chem., **39**, 3309 (1974).
241. L. Angiolini and M. Tramontini, J. Org. Chem., **39**, 2056 (1974).
242. T. J. Leitereg and D. J. Cram, J. Am. Chem. Soc., **90**, 4011 (1968).
243. T. J. Leitereg and D. J. Cram, J. Am. Chem. Soc., **90**, 4019 (1968).
244. M. J. Brienne, C. Ouannés and J. Jacques, Bull. Soc. Chim. Fr., **1968**, 1036.
245. M. J. Brienne, C. Foguey, and J. Jacques, Bull. Soc. Chim. Fr., **1969**, 2395.
246. R. A. Auerbach and C. A. Kingsbury, Tetrahedron, **29**, 1457 (1973).
247. M. Chérest, H. Felkin, and N. Prudent, Tetrahedron Lett., **1968**, 2199.
248. M. Chérest and N. Prudent, Tetrahedron, **36**, 1599 (1980).
249. E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, *Conformational Analysis*, Wiley-Interscience, New York, 1965, pp. 5–12.
250. G. J. Karabatsos, J. Am. Chem. Soc., **89**, 1367 (1967).
251. T. Fukuyama, B. Vranesic, D. P. Negri, and Y. Kishi, Tetrahedron Lett., **1978**, 2741.
252. E. Ruch and I. Ugi, Top. Stereochem., **4**, 99 (1969).
253. E. Ruch, Acc. Chem. Res., **5**, 49 (1972).
254. L. Salem, J. Am. Chem. Soc., **95**, 94 (1973).
255. N. T. Anh, O. Eisenstein, J. M. Lefour, and M. E. Trân Huu Dâu, J. Am. Chem. Soc., **95**, 6146 (1973).

256. N. T. Anh and O. Eisenstein, Tetrahedron Lett., **1976**, 155.
257. D. H. R. Barton, J. Chem. Soc., **1953**, 1027.
258. W. G. Dauben, G. J. Fonken, and D. S. Noyce, J. Am. Chem. Soc., **78**, 2579 (1956).
259. W. G. Dauben, R. E. Bozak, R. E. Ellis, and F. Willey, Rev. Chim. Acad. Rep. Pop. Roumaine, **7**, 803 (1962) [C.A., **61**, 4424a (1964)].
260. E. L. Eliel and R. S. Ro, J. Am. Chem. Soc., **79**, 5992 (1957).
261. J. C. Richer, J. Org. Chem., **30**, 324 (1965).
262. G. Perrault, *Mémoire de Maîtrise*, Faculté des Sciences, Université de Montréal, 1962.
263. J. Klein, E. Dunkelblum, E. L. Eliel, and Y. Senda, Tetrahedron Lett., **1968**, 6127.
264. E. C. Ashby and S. A. Noding, J. Org. Chem., **42**, 264 (1977).
265. E. C. Ashby and S. A. Noding, J. Am. Chem. Soc., **98**, 2010 (1976).
266. J. M. Cense, Tetrahedron Lett., **1972**, 2153.
267. A. Calvet and J. Levisalles, Tetrahedron Lett., **1972**, 2157.
268. M. H. Rei, J. Org. Chem., **44**, 2760 (1979).
269. D. C. Wigfield, Tetrahedron, **35**, 449 (1979).
270. D. C. Wigfield and F. W. Gowland, Tetrahedron Lett., **1979**, 2209.
271. O. R. Vail and D. M. S. Wheeler, J. Org. Chem., **27**, 3803 (1962).
272. A. V. Kamernitskii and A. A. Akhrem, Tetrahedron, **18**, 705 (1962).
273. A. M. Prokhoda, A. V. Kamernitskii, and A. A. Akhrem, Izvest. Akad. Nauk SSSR, Ser. Khim., **1964**, 1060 [C.A., **61**, 6929b (1964)].
274. J. A. Marshall and R. D. Carroll, J. Org. Chem., **30**, 2748 (1965).
275. S. R. Landor and J. P. Regan, J. Chem. Soc. (C), **1967**, 1159.
276. J. Klein, Tetrahedron Lett., **1973**, 4307.
277. J. Klein and D. Lichtenberg, J. Org. Chem., **35**, 2654 (1970).
278. J. Klein, Tetrahedron, **30**, 3349 (1974).
279. C. Liotta, Tetrahedron Lett., **1975** 519.
280. W. T. Wipke and P. Gund, J. Am. Chem. Soc., **98**, 8107 (1976).
281. D. C. Wigfield and F. W. Gowland, J. Org. Chem., **42**, 1108 (1977).
282. J. Royer, Tetrahedron Lett., **1978**, 1343.
283. M. Chérest and H. Felkin, Tetrahedron Lett., **1968**, 2205.
284. M. Chérest and H. Felkin, Tetrahedron Lett., **1971**, 383.
285. M. Chérest, H. Felkin, and C. Frajerman, Tetrahedron Lett., **1971**, 379.
286. M. Chérest, Tetrahedron, **36**, 1593 (1980).
287. J. Huet, Y. Maroni-Barnaud, N. T. Anh, and J. Seyden-Penne, Tetrahedron Lett., **1976**, 159.

288. N. T. Anh and O. Eisenstein, Nouv. J. Chim., **1**, 61 (1977).
289. N. T. Anh, Top. Curr. Chem., **88**, 145 (1980).
290. D. V. Banthorpe, A. J. Curtis, and W. D. Fordham, Tetrahedron Lett., **1972**, 3865.
291. D. Varech and J. Jacques, Tetrahedron Lett., **1973**, 4443.
292. M. J. Brienne, D. Varech, and J. Jacques, Tetrahedron Lett., **1974**, 1233.
293. M. Chérest, H. Felkin, P. Tacheau, J. Jacques, and D. Varech, J. Chem. Soc., Chem. Commun., **1977**, 372.
294. D. Varech, M. J. Brienne, and J. Jacques, J. Chem. Res., Synop., **1979**, 319; J. Chem. Res. (M), **1979**, 3622.
295. M. R. Giddings and J. Hudec, Can. J. Chem., **59**, 459 (1981).
296. A. S. Cieplak, J. Am. Chem. Soc., **103**, 4540 (1981).
297. C. Agami, A. Kazakos, and J. Levisalles, Tetrahedron Lett., **1977**, 4073.
298. C. Agami, M. Fadlallah, A. Kazakos, and J. Levisalles, Tetrahedron, **35**, 969 (1979).
299. T. Terasawa and T. Okada, J. Chem. Soc., Perkin Trans. 1, **1978**, 1252.
300. H. Haubenstock and E. L. Eliel, J. Am. Chem. Soc., **84**, 2368 (1962).
301. D. C. Wigfield and D. J. Phelps, J. Org. Chem., **41**, 2396 (1976).
302. K. D. Hardy and R. J. Wicker, J. Am. Chem. Soc., **80**, 640 (1958).
303. D. C. Wigfield and F. W. Gowland, J. Org. Chem., **45**, 653 (1980).
304. D. C. Wigfield and F. W. Gowland, Tetrahedron Lett., **1979**, 2205.
305. K. Bowden and M. Hardy, Tetrahedron, **22**, 1169 (1966).
306. D. C. Wigfield and D. J. Phelps, J. Chem. Soc., Chem. Commun., **1970**, 1152.
307. D. C. Wigfield and D. J. Phelps, Can. J. Chem., **50**, 388 (1972).
308. D. C. Ayres, D. N. Kirk, and R. Sawdaye, J. Chem. Soc. (B), **1970**, 1133.
309. D. C. Wigfield, D. J. Phelps, R. F. Pottie, and R. Sander, J. Am. Chem. Soc., **97**, 897 (1975).
310. F. W. Gowland, Ph.D. Thesis, Carleton University, Ottawa (1978) [C.A. **91**, 174874g (1979)].
311. E. C. Ashby and J. R. Boone, J. Am. Chem. Soc., **98**, 5524 (1976).
312. O. K | í E, F. Haruda, J. Stuchlík, F. Hanousek, and O. Štrouf, Chem. Ind. (London), **1975**, 86.
313. O. *1* ervinka, Collect. Czech. Chem. Commun., **30**, 1684 (1965).
314. P. Briaucourt, J. P. Guetté, and A. Horeau, C. R. Acad. Sci., Ser. C, **268**, 2342 (1969).
315. D. Seebach and H. Daum, Chem. Ber., **107**, 1748 (1974).
316. O. *1* ervinka and O. B \lovský, Collect. Czech. Chem. Commun., **32**,

3897 (1967).
317. S. R. Landor, B. J. Miller, and A. R. Tatchell, J. Chem. Soc. (C), **1966**, 1822.
318. S. R. Landor, B. J. Miller, and A. R. Tatchell, J. Chem. Soc. (C), **1966**, 2280.
319. S. R. Landor, B. J. Miller, and A. R. Tatchell, J. Chem. Soc. (C), **1967**, 197.
320. O. *1* ervinka and A. Fábryová, Z. Chem., **9**, 426 (1969).
321. S. Yamaguchi and K. Kabuto, Bull. Chem. Soc. Jpn., **50**, 3033 (1977).
322. J. L. Pierre and H. Handel, Tetrahedron Lett., **1974**, 2317.
323. H. Handel and J. L. Pierre, Tetrahedron, **31**, 997 (1975).
324. O. *1* ervinka, Chimia (Aarau), **13**, 332 (1959).
325. O. *1* ervinka and O. B \ lovský, Collect. Czech. Chem. Commun., **30**, 2487 (1965).
326. M. Nishizawa, M. Yamada, and R. Noyori, Tetrahedron Lett., **22**, 247 (1981).
327. J. P. Vigneron and V. Bloy, Tetrahedron Lett., **21**, 1735 (1980).
328. S. Terashima, N. Tanno, and K. Koga, J. Chem. Soc., Chem. Commun., **1980**, 1026.
329. N. Cohen, R. J. Lopresti, C. Neukom, and G. Saucy, J. Org. Chem., **45**, 582 (1980).
330. J. D. Morrison, E. R. Grandbois, S. I. Howard, and G. R. Weisman, Tetrahedron Lett., **22**, 2619 (1981).
331. J. M. Wilson and D. J. Cram, J. Am. Chem. Soc., **104**, 881 (1982).
332. A. I. Meyers and K. A. Lutomski, J. Am. Chem. Soc., **104**, 879 (1982).
333. P. T. Lansbury and R. E. MacLeay, J. Org. Chem., **28**, 1940 (1963).
334. E. C. Ashby and S. A. Noding, J. Org. Chem., **44**, 4364 (1979).
335. E. C. Ashby and S. A. Noding, J. Org. Chem., **45**, 1035 (1980).
336. D. W. Hart and J. Schwartz, J. Am. Chem. Soc., **96**, 8115 (1974).
337. J. Schwartz and J. A. Labinger, Angew. Chem., Int. Ed. Engl., **15**, 333 (1976).
338. T. Gibson and L. Tulich, J. Org. Chem., **46**, 1821 (1981).
339. T. W. Gibson, Eur. Pat. Appl. 21,496 (1981) [C.A., **94**, 191662r (1981)].
340. P. C. Wailes, H. Weigold, and A. P. Bell, J. Organomet. Chem., **43**, C32 (1972).
341. C. A. Bertelo and J. Schwartz, J. Am. Chem. Soc., **97**, 228 (1975).
342. D. W. Hart, T. F. Blackburn, and J. Schwartz, J. Am. Chem. Soc., **97**, 679 (1975).
343. J. C. Leblanc and C. Moise, J. Organomet. Chem., **120**, 65 (1976).

344. W. F. Little and R. C. Koestler, J. Org. Chem., **26**, 3247 (1961).

345. K. Conrow, J. Am. Chem. Soc., **83**, 2343 (1961).

346. S. L. Grundy and P. M. Maitlis, J. Chem. Soc., Chem. Commun., **1982**, 379.

347. D. F. Lindow, C. N. Cortez, and R. G. Harvey, J. Am. Chem. Soc., **94**, 5406 (1972).

348. H. E. Zaugg and R. J. Michaels, J. Org. Chem., **39**, 851 (1974).

349. I. Granoth, R. Alkabets, Y. Segall, E. Rachaman, and H. Leader, J. Chem. Soc., Chem. Commun., **1975**, 348.

350. I. Granoth, Y. Segall, H. Leader, and R. Alkabets, J. Org. Chem., **41**, 3682 (1976).

351. R. Alkabets and I. Granoth, J. Chem. Soc., Perkin Trans. 1, **1976**, 2380.

352. E. H. Gold and E. Babad, J. Org. Chem., **37**, 2208 (1972).

353. K. Suzuki and M. Minabe, Tetrahedron Lett., **1974**, 1541.

354. H. Minabe and K. Suzuki, Bull. Chem. Soc. Jpn., **48**, 1480 (1975).

355. J. C. Hilscher, Chem. Ber., **108**, 727 (1975).

356. J. C. Hilscher, Ger. Offen. 2,438,424 (1976) [C.A., **84**, 165114n (1976)].

357. J. C. Hilscher, Ger. Offen. 2,518,612 (1976) [C.A., **86**, 72994a (1977)].

358. H. D. Holtz, P. W. Solomon, and J. E. Mahan, J. Org. Chem., **38**, 3175 (1973).

359. M. Matic and D. A. Sutton, J. Chem. Soc., **1952**, 2679.

360. E. H. Jensen, *A Study on Sodium Borohydride*, Nyt Nordisk Forlag, Arnold Busck, Copenhagen, 1954.

361. R. Kanazawa, H. Kotsuki, and T. Tokoroyama, Tetrahedron Lett., **1975**, 3651.

362. T. Tokoroyama, K. Matsuo, H. Kotsuki, and R. Kanazawa, Tetrahedron, **36**, 3377 (1980).

363. J. W. Scott, F. T. Bizzarro, D. R. Parrish, and G. Saucy, Helv. Chim. Acta, **59**, 290 (1976).

364. S. W. Pelletier, S. Lajši / , Y. Ohtsuka, and Z. Djarmati, J. Org. Chem., **40**, 1607 (1975).

365. S. Krishnamurthy and H. C. Brown, J. Org. Chem., **45**, 849 (1980).

366. B. N. Blackett, J. M. Coxon, M. P. Hartshorn, and K. E. Richards, Aust. J. Chem., **23**, 2077 (1970).

367. O. K | ĭE and J. Machá / ek, Collect. Czech. Chem. Commun., **37**, 2175 (1972).

368. O. K | ĭE , B. *1* ásenský, and O. Štrouf, Collect. Czech. Chem. Commun., **38**, 842 (1973).

369. V. Ba E ant, M. *1* apka, M. *1* erny, V. Chvalovský, K. Kochloefl, M.

Kraus, and J. Málek, Tetrahedron Lett., **1968**, 3303.

370. M. *1* apka and V. Chvalovský, Collect. Czech. Chem. Commun., **34**, 2782 (1969).
371. O. K | ĭE , J. Machá /ek, and O. Štrouf, Collect. Czech. Chem. Commun., **38**, 2072 (1973).
372. M. *1* apka and V. Chvalovský, Collect. Czech. Chem. Commun., **34**, 3110 (1969).
373. T. J. Barton and R. C. Kippenhan, Jr., J. Org. Chem., **37**, 4194 (1972).
374. R. B. Wetzel and G. L. Kenyon, J. Am. Chem. Soc., **94**, 1774 (1972).
375. R. B. Wetzel and G. L. Kenyon, J. Org. Chem., **39**, 1531 (1974).
376. T. H. Chan and K. T. Nwe, Tetrahedron Lett., **1973**, 3601.
377. R. B. Wetzel and G. L. Kenynon, J. Am. Chem. Soc., **96**, 5189 (1974).
378. T. H. Chan and B. S. Ong, J. Org. Chem., **39**, 1748 (1974).
379. T. H. Chan and K. T. Nwe, Phosphorus, **3**, 225 (1974).
380. G. A. Boswell, Jr., J. Org. Chem., **33**, 3699 (1968).
381. R. Huston, M. Rey, and A. S. Dreiding, Bull. Soc. Chim. Belg., **88**, 911 (1979).
382. A. Hassner and R. Fletcher, Tetrahedron Lett., **1970**, 5053.
383. J. Fajkoš, Chem. Listy, **52**, 2134 (1958) [C.A., **53**, 5344e (1959)].
384. J. Fajkoš, Collect. Czech. Chem. Commun., **24**, 2284 (1959).
385. M. E. Wolff, W. Ho, and R. Kwok, Steroids, **5**, 1 (1965).
386. J. Fajkoš and F. Šorm, Collect. Czech. Chem. Commun., **24**, 766 (1959).
387. J. Fajkoš and V. Šanda, Collect. Czech. Chem. Commun., **27**, 355 (1962).
388. J. Fajkoš and J. Joska, Collect. Czech. Chem. Commun., **27**, 1849 (1962).
389. R. Zurflüh and C. Tamm, Helv. Chim. Acta, **55**, 2495 (1972).
390. L. Sydnes and L. Skattebøl, Tetrahedron Lett., **1974**, 3703.
391. L. K. Sydnes and L. Skattebøl, Acta Chem. Scand., Ser. B, **32**, 632 (1978).
392. S. Miyano and H. Hashimoto, Bull. Chem. Soc. Jpn., **48**, 3665 (1975).
393. R. J. Bailey and H. Shechter, J. Am. Chem. Soc., **96**, 8116 (1974).
394. H. Terauchi, S. Takemura, and Y. Ueno, Chem. Pharm. Bull., **23**, 640 (1975).
395. F. E. Herkes, U.S. Pat. 3,876,711 (1975) [C.A., **83**, 9450t (1975)].
396. (a) G. J. Karabatsos and R. L. Shone, J. Org. Chem., **33**, 619 (1968); (b) S. Krishnamurthy and H. C. Brown, J. Org. Chem., **47**, 276 (1982); (c) B. H. Han and P. Boudjouk, Tetrahedron Lett., **23**, 1643 (1982).

397. M. Kraus and V. Ba E ant, *Proceedings of 5th International Congress on Catalysis, 1972* (publ. 1973), Vol. 2, p. 1073, North-Holland, Amsterdam, [C.A., **81**, 3188a (1974)].

398. M. Kraus, Collect. Czech. Chem. Commun., **37**, 3052 (1972).

399. I. Šimůnek and M. Kraus, Collect. Czech. Chem. Commun., **38**, 1786 (1973).

400. E. C. Ashby and J. J. Lin, J. Org. Chem., **43**, 1263 (1978).

401. S. Hayashi, T. Nakai, N. Ishikawa, D. J. Burton, D. G. Naae, and H. S. Kesling, Chem. Lett., **1979**, 983.

402. P. T. Lansbury and E. J. Nienhouse, J. Am. Chem. Soc., **88**, 4290 (1966).

403. P. T. Lansbury, E. J. Nienhouse, D. J. Scharf, and F. R. Hilfiker, J. Am. Chem. Soc., **92**, 5649 (1970).

404. R. I. Kruglikova, N. I. Rostova, and B. V. Unkovskii, *Tezisy Dokl.-Vses. Konf. Khim. Atsetilena, 5th 1975*, Metsuiereba, Tiflis, USSR, pp. 376–377 [C.A., **89**, 42301s (1978)].

405. A. Claesson and L. I. Olsson, J. Am. Chem. Soc., **101**, 7302 (1979).

406. W. P. Neumann, *The Organic Chemistry of Tin*, Wiley-Interscience, New York, 1970, Chap. "10".

407. R. C. Poller, *The Chemistry of Organotin Compounds*, Academic Press, New York, 1970, Chap. "7".

408. H. G. Kuivila, Synthesis, **1970**, 499.

409. A. R. Pinder, Synthesis, **1980**, 425.

410. R. O. Hutchins, D. Kandasamy, C. A. Maryanoff, D. Masilamani, and B. E. Maryanoff, J. Org. Chem., **42**, 82 (1977).

411. H. C. Brown and S. Krishnamurthy, J. Am. Chem. Soc., **95**, 1669 (1973).

412. S. Masamune, P. A. Rossy, and G. S. Bates, J. Am. Chem. Soc., **95**, 6452 (1973).

413. S. Masamune, G. S. Bates, and P. E. Georghiou, J. Am. Chem. Soc., **96**, 3686 (1974).

414. H. C. Brown and P. M. Weissman, Israel J. Chem., **1**, 430 (1963).

415. K. K. Chan, N. Cohen, J. P. DeNoble, A. C. Specian, Jr., and G. Saucy, J. Org. Chem., **41**, 3497 (1976).

416. H. J. Mayer, N. Rigassi, U. Schwieter, and B. C. L. Weedon, Helv. Chim. Acta, **59**, 1424 (1976).

417. S. R. Landor, B. J. Miller, J. P. Regan, and A. R. Tatchell, J. Chem. Soc., Chem. Commun., **1966**, 585.

418. S. R. Landor and N. Punja, Tetrahedron Lett., **1966**, 4905.

419. J. S. Cowie, P. D. Landor, S. R. Landor, and N. Punja, J. Chem. Soc., Perkin Trans. 1, **1972**, 2197.

420. S. R. Landor, B. J. Miller, J. P. Regan, and A. R. Tatchell, J. Chem. Soc., Perkin Trans. 1, **1974**, 557.
421. R. J. D. Evans, S. R. Landor, and J. P. Regan, J. Chem. Soc., Chem. Commun., **1965**, 397.
422. R. J. D. Evans, S. R. Landor, and J. P. Regan, J. Chem. Soc., Perkin Trans. 1, **1974**, 552.
423. R. Baudouy and J. Gore, Bull. Soc. Chim. Fr., Pt. 2, **1975**, 2159.
424. R. Baudouy and J. Gore, Synthesis, **1974**, 573.
425. J. Gore and R. Baudouy, Tetrahedron Lett., **1973**, 3361.
426. R. Baudouy and J. Gore, Bull. Soc. Chim. Fr., Pt. 2, **1975**, 2166.
427. R. Baudouy and J. Gore, Tetrahedron Lett., **1974**, 1593.
428. J. Gore and R. Baudouy, Tetrahedron Lett., **1974**, 3743.
429. S. R. Landor, E. S. Pepper, and J. P. Regan, J. Chem. Soc. (C), **1967**, 189.
430. M. *1* erný and J. Málek, Tetrahedron Lett., **1969**, 1739.
431. M. *1* erný and J. Málek, Collect. Czech. Chem. Commun., **35**, 1216 (1970).
432. M. *1* erný and J. Málek, Collect. Czech. Chem. Commun., **35**, 2030 (1970).
433. T. Kametani, S. P. Huang, M. Ihara, and K. Fukumoto, J. Org. Chem., **41**, 2545 (1976).
434. M. *1* erný and J. Málek, Collect. Czech. Chem. Commun., **35**, 3079 (1970).
435. J. Málek, unpublished results.
436. M. S. Chauhan, F. M. Dean, D. Matkin, and M. L. Robinson, J. Chem. Soc., Perkin Trans. 1, **1973**, 120.
437. L. H. Conover and D. S. Tarbell, J. Am. Chem. Soc., **72**, 3586 (1950).
438. J. F. Carroll, S. Kulkowit, and M. A. McKervey, J. Chem. Soc., Chem. Commun., **1980**, 507.
439. H. C. Brown and S. Krishnamurthy, J. Chem. Soc. Chem. Commun., **1972**, 868.
440. H. C. Brown, S. Krishnamurthy, and R. A. Coleman, J. Am. Chem. Soc., **94**, 1750 (1972).
441. H. C. Brown, S. Krishnamurthy, J. L. Hubbard, and R. A. Coleman, J. Organomet. Chem., **166**, 281 (1979).
442. S. Krishnamurthy and H. C. Brown, J. Org. Chem., **44**, 3678 (1979).
443. H. C. Brown, P. M. Weissman, and N. M. Yoon, J. Am. Chem. Soc., **88**, 1458 (1966).
444. S. Danishefsky, P. F. Schuda, and K. Kato, J. Org. Chem., **41**, 1081

(1976).

445. W. R. Roush and T. E. D'Ambra, J. Org. Chem., **46**, 5045 (1981).

446. K. Piatkowski and A. Siemieniuk, Pr. Nauk Inst. Chem. Org. Fiz. Politech. Wroclaw, **1970**, 53 [C.A., **78**, 97820p (1973)].

447. T. K. Jones and J. H. J. Peet, Chem. Ind. (London), **1971**, 995.

448. E. L. Eliel and D. W. Delmonte, J. Am. Chem. Soc., **80**, 1744 (1958).

449. (a) P. Ma, V. S. Martin, S. Masamune, K. B. Sharpless, and S. M. Viti, J. Org. Chem., **47**, 1378 (1982); (b) S. M. Viti, Tetrahedron Lett., **23**, 4541 (1982).

450. (a) N. Minami, S. S. Ko, and Y. Kishi, J. Am. Chem. Soc., **104**, 1109 (1982); (b) J. M. Finan and Y. Kishi, Tetrahedron Lett., **23**, 2719 (1982).

451. S. Terashima, M. Hayashi, and K. Koga, Tetrahedron Lett., **21**, 2733 (1980).

452. M. Hayashi, S. Terashima, and K. Koga, Tetrahedron, **37**, 2797 (1981).

453. M. Ogawa, M. Sugishita, M. Takagi, and T. Matsuda, Tetrahedron, **31**, 299 (1975).

454. E. L. Eliel and M. N. Rerick, J. Am. Chem. Soc., **82**, 1362 (1960).

455. E. C. Ashby and B. Cooke, J. Am. Chem. Soc., **90**, 1625 (1968).

456. E. Bengsch, M. Corval, and R. Viallard, Bull. Soc. Chim. Fr., Pt., 2, **1974**, 877.

457. S. Krishnamurthy, R. M. Schubert, and H. C. Brown, J. Am. Chem. Soc., **95**, 8486 (1973).

458. H. C. Brown and N. M. Yoon, J. Chem. Soc., Chem. Commun., **1968**, 1549.

459. M. *1* apka, V. Chvalovský, K. Kochloefl, and M. Kraus, Collect. Czech. Chem. Commun., **34**, 118 (1969).

460. M. Julia and A. Rouault, Bull. Soc. Chim. Fr., **1959**, 1833.

461. K. C. Nicolaou, S. P. Seitz, and M. R. Pavia, J. Am. Chem. Soc., **103**, 1222 (1981).

462. S. Danishefsky, T. Kitakara, P. F. Schuda, and S. J. Etheredge, J. Am. Chem. Soc., **98**, 3028 (1976).

463. S. Danishefsky, P. F. Schuda, T. Kitahara, and S. J. Etheredge, J. Am. Chem. Soc., **99**, 6066 (1977).

464. S. Krishnamurthy, J. Org. Chem., **46**, 4628 (1981).

465. C. S. Sell, Aust. J. Chem., **28**, 1383 (1975).

466. S. Yamaguchi, K. Kabuto, and F. Yasuhara, Chem. Lett., **1981**, 461.

467. Y. Yamamoto, H. Toi, A. Sonoda, and S. I. Murahashi, J. Am. Chem. Soc., **98**, 1965 (1976).

468. T. Harayama, M. Takatane, and Y. Inubushi, Chem. Pharm. Bull., **27**, 726 (1979).

469. R. Murphy and R. H. Prager, Aust. J. Chem., **29**, 617 (1976).

470. C. C. Leznoff and J. Y. Wong, Can. J. Chem., **51**, 3756 (1973).

471. J. Y. Wong, C. Manning, and C. C. Leznoff, Angew. Chem., **86**, 743 (1974).

472. F. Nerdel, H. Kaminski, and D. Frank, Tetrahedron Lett., **1967**, 4973.

473. G. Just and G. Reader, Tetrahedron Lett., **1973**, 1521.

474. K. Tsuda, S. Ikuma, M. Kawamura, R. Tachikawa, and T. Miyadera, Chem. Pharm. Bull., **10**, 865 (1962).

475. B. A. Pawson, K. K. Chan, J. DeNoble, R. J. L. Han, V. Piermattie, A. C. Specian, S. Srisethnil, P. W. Thrown, O. Bohoslovec, L. J. Machlin and E. Gabriel, J. Med. Chem., **22**, 1059 (1979).

476. O. *1* ervinka, P. Malo ‘ , and H. Procházková, Collect. Czech. Chem. Commun., **39**, 1869 (1974).

477. C. J. Reich, G. R. Sullivan, and H. S. Mosher, Tetrahedron Lett., **1973**, 1505.

478. H. S. Mosher, Tetrahedron, **30**, 1733 (1974).

479. R. Noyorr, I. Tomino, Y. Tanimoto, and M. Nishizawa, Koen Yoshishu-Tennen Yuki Kagobutsu Toronkai, 22nd, **1979**, 642 [C.A., **93**, 7696k (1980); C.A., **93**, 149842d (1980)].

480. J. V. Frosch, I. T. Harrison, B. Lythgoe, and A. K. Saksena, J. Chem. Soc., Perkin Trans. 1, **1974**, 2005.

481. W. Sucrow, Tetrahedron Lett., **1970**, 4725.

482. G. Büchi, B. Gubler, R. S. Schneider, and J. Wild, J. Am. Chem. Soc., **89**, 2776 (1967).

483. M. Nishizawa and R. Noyori, Tetrahedron Lett., **21**, 2821 (1980).

484. R. O. Hutchins and D. Kandasamy, J. Org. Chem., **40**, 2530 (1975).

485. S. Krishnamurthy and H. C. Brown, J. Org. Chem., **40**, 1864 (1975).

486. M. P. Paradisi, G. P. Zecchini, and G. Ortar, Tetrahedron Lett., **21**, 5085 (1980).

487. N. Finch, Fr. Pat. 1,563,495 (1969) [C.A., **72**, 54876v (1970)].

488. K. J. Rorig and H. A. Wagner, U.S. Pat. 3,412,094 (1968) [C.A., **70**, 68410j (1969)].

489. M. Julia, S. Julia, and C. Jeanmart, C.R. Acad. Sci., Ser. C., **250**, 4003 (1960).

490. M. Julia, Fr. Pat. 1,217,262 (1960) [C.A., **55**, 20995c (1961)].

491. M. Julia, S. Julia, and C. Jeanmart, Bull. Soc. Chim. Fr., **1961**, 1854.

492. T. H. Smith, A. N. Fujiwara, D. W. Henry, and W. W. Lee, J. Am. Chem.

Soc., **98**, 1969 (1976).

493. T. H. Smith, A. N. Fujiwara, W. W. Lee, H. Y. Wu, and D. W. Henry, J. Org. Chem., **42**, 3653 (1977).
494. L. D. Bergel'son and S. G. Batrakov, Izv. Akad. Nauk SSSR, Ser. Khim., **1963**, 1259 [C.A., **59**, 12637g (1963)].
495. J. Málek and M. *1* erny, Synthesis, **1973**, 53.
496. T. P. Johnston, A. T. Shortnacy, and R. H. James, J. Labelled Compd. Radiopharm., **15**, (Suppl. Vol.), 599 (1978).
497. H. L. Cohen, J. Polym. Sci., Polym. Chem. Ed., **13**, 745 (1975).
498. P. G. Pietta, P. F. Cavallo, K. Takahashi, and G. R. Marshall, J. Org. Chem., **39**, 44 (1974).
499. C. J. Reich, Ph.D. Dissertation, Stanford University, Stanford, California, 1976 [C.A., **87**, 38725z (1977)].
500. O. *1* ervinka, O. B lovský, and P. Adámek, Collect. Czech. Chem. Commun., **30**, 3462 (1965).
501. O.*1* ervinka and J. Fusek, Z. Chem., **8**, 145 (1968).
502. A. I. Meyers and P. M. Kendall, Tetrahedron Lett., **1974**, 1337.
503. S. Yamaguchi, F. Yasuhara, and K. Kabuto, Tetrahedron, **32**, 1363 (1976).
504. K. Saigo, M. Yamamoto, K. Morimura, and H. Nohira, Chem. Lett., **1979**, 545.
505. M. Schmidt, R. Amstutz, G. Crass, and D. Seebach, Chem. Ber., **113**, 1691 (1980).
506. O. *1* ervinka and A. Fábryová, Tetrahedron Lett., **1967**, 1179.
507. S. R. Landor, B. J. Miller, and A. R. Tatchell, Proc. Chem. Soc., **1964**, 227.
508. N. Baggett and P. Stribblehill, J. Chem. Soc., Perkin Trans. 1, **1977**, 1123.
509. U. Vallavi, P. Balzano, and V. Monterosso, Ann. Chim. (Rome), **65**, 91 (1975).
510. R. Haller and H. J. Schneider, Chem. Ber., **106**, 1312 (1973).
511. E. D. Lund and P. E. Shaw, J. Org. Chem., **42**, 2073 (1977).
512. H. K. Müller, J. Schuart, H. Baborowski, and E. Müller, J. Prakt. Chem., **315**, 449 (1973).
513. H. K. Müller, J. Schuart, and H. Baborowski, J. Prakt. Chem., **315**, 1045 (1973).
514. R. Haller and R. Rümmler, Arch. Pharm. (Weinheim, W. Germany), **306**, 510 (1973).
515. H. J. Schneider and R. Haller, Justus Liebigs Ann. Chem., **743**, 187 (1971).

516. H. J. Williams, J. Chem. Soc., Perkin Trans. 1, **1973**, 1852.
517. S. E. Ellzey, Jr. and C. H. Mack, J. Org. Chem., **27**, 2655 (1962).
518. C. R. Johnson and C. J. Stark, Jr., J. Org. Chem., **47**, 1196 (1982).
519. O. H. Wheeler and J. L. Mateos, Can. J. Chem., **36**, 1431 (1958).
520. H. R. Deck, Ph.D. Dissertation, Purdue University, Lafayette, Ind., 1963 [C.A., **61**, 14482 (1964)].
521. J. C. Richer, D. Perelman, and N. Baskevitch, Tetrahedron Lett., **1975**, 2627.
522. H. C. Brown and S. Krishnamurthy, J. Am. Chem. Soc., **94**, 7159 (1972).
523. J. Hooz, S. Akiyama, F. J. Cedar, M. J. Bennett, and R. M. Tuggle, J. Am. Chem. Soc., **96**, 274 (1974).
524. S. Krishnamurthy and H. C. Brown, J. Am. Chem. Soc., **98**, 3383 (1976).
525. R. Maurin and M. Bertrand, Bull. Soc. Chim. Fr., **1970**, 998.
526. Y. Senda, S. Mitsui, R. Ono, and S. Hosokawa, Bull. Chem. Soc. Jpn., **44**, 2737 (1971).
527. A. Barco, S. Benetti, G. P. Pollini, P. G. Baraldi, M. Guarneri, D. Simoni, and C. Gandolfi, J. Org. Chem., **46**, 4518 (1981).
528. R. Aries, Fr. Dem. 2,258,362 (1975) [C.A., **84**, 121282m (1976)].
529. J. C. Richer, M. A. Poirier, Y. Maroni, and G. Manuel, Can. J. Chem., **59**, 1303 (1981).
530. C. Agami, M. Fadlallah, and J. Levisalles, Tetrahedron, **37**, 903 (1981).
531. P. Benetton, A. Accary, C. Arnaud, and J. Huet, C. R. Acad. Sci., Ser. C. **283**, 359 (1976).
532. K. Mori, M. Ohki, K. Okada, Y. Takei, and M. Matsui, Agr. Biol. Chem., **37**, 2907 (1973) [C.A., **80**, 83309h (1974)].
533. K. Kabuto and H. Ziffer, J. Org. Chem., **40**, 3467 (1975).
534. K. Kabuto, H. Shindo, and H. Ziffer, J. Org. Chem., **42**, 1742 (1977).
535. (a) J. E. Bäckvall, K. Oshima, R. E. Palermo, and K. B. Sharpless, J. Org. Chem., **44**, 1953 (1979); (b) K. Suzuki, A. Ikegawa, and T. Mukaiyama, Chem. Lett., **1982**, 899.
536. S. Winstein and J. Sonnenberg, J. Am. Chem. Soc., **83**, 3235 (1961).
537. M. Walkowicz and C. Walkowicz, Rocz. Chem., **51**, 447 (1977) [C.A., **87**, 117467v (1977)].
538. M. Rey, S. Roberts, A. Dieffenbacher, and A. S. Dreiding, Helv. Chim. Acta, **53**, 417 (1970).
539. J. V. Paukstelis and Jar-lin Kao, J. Am. Chem. Soc., **94**, 4783 (1972).
540. S. P. Acharya and H. C. Brown, J. Am. Chem. Soc., **89**, 1925 (1967).
541. H. C. Brown and A. Suzuki, J. Am. Chem. Soc., **89**, 1933 (1967).
542. M. P. Zink, H. R. Wolf, E. P. Müller, W. B. Schweizer, and O. Jeger,

Helv. Chim. Acta, **59**, 32 (1976).
543. R. Zurflüh, E. N. Wall, J. B. Siddall, and J. A. Edwards, J. Am. Chem. Soc., **90**, 6224 (1968).
544. P. Briaucourt, J. P. Guetté, and A. Horeau, C.R. Acad. Sci., Ser. C, **274**, 1203 (1972).
545. C. H. Heathcock and D. Gray, Tetrahedron, **27**, 1239 (1971).
546. C. H. Heathcock and B. E. Ratcliffe, J. Org. Chem., **37**, 1298 (1972).
547. H. C. Brown and W. C. Dickason, J. Am. Chem. Soc., **92**, 709 (1970).
548. D. W. Theobald, Tetrahedron, **19**, 2261 (1963).
549. C. Agami, M. Fadlallah, and J. Levisalles, Tetrahedron, **37**, 909 (1981).
550. D. J. Humphreys and G. R. Proctor, J. Chem. Soc., Perkin Trans. 1, **1972**, 722.
551. A. L. Johnson, J. B. Stothers, and C. T. Tan, Can. J. Chem., **53**, 212 (1975).
552. G. Zweifel and H. C. Brown, J. Am. Chem. Soc., **86**, 393 (1964).
553. E. Fujita, T. Fujita, Y. Nagao, P. Coggan, and G. A. Sim, Tetrahedron Lett., **1968**, 4191.
554. E. Fujita, T. Fujita, and Y. Nagao, Tetrahedron, **25**, 3717 (1969).
555. S. P. Acharya and H. C. Brown, J. Org. Chem., **35**, 3874 (1970).
556. S. P. Acharya and H. C. Brown, J. Org. Chem., **35**, 196 (1970).
557. G. R. Wenzinger and J. A. Ors, J. Org. Chem., **39**, 2060 (1974).
558. W. Nagata, T. Wakabayashi, M. Narisada, Y. Hayase, and S. Kamata, J. Am. Chem. Soc., **93**, 5740 (1971).
559. M. Ando, G. Büchi, and T. Ohnuma, J. Am. Chem. Soc., **97**, 6880 (1975).
560. J. P. Kutney, U. Bunzli-Trepp, T. Honda, J. Katsube, and B. R. Worth, Helv. Chim. Acta, **61**, 1554 (1978).
561. J. P. Kutney, U. Bunzli-Trepp, K. K. Chan, J. P. de Souza, Y. Fujise, T. Honda, J. Katsube, F. K. Klein, A. Leutwiler, S. Morehead, M. Rohr, and B. R. Worth, J. Am. Chem. Soc., **100**, 4220 (1978).
562. L. de Vries, R. Heck, R. Piccolini, and S. Winstein, Chem. Ind. (London), **1959**, 1416.
563. R. D. Stolow and T. Groom, Tetrahedron Lett., **1968**, 4069.
564. K. Inoue, S. Ueda, Y. Shiobara, I. Kimura, and H. Inouye, J. Chem. Soc., Perkin Trans. 1, **1981**, 1246.
565. O. G. Plantema, H. de Koning, and H. O. Huisman, Recl. Trav. Chim. Pays-Bas, **95**, 120 (1976).
566. W. Carruthers and A. Orridge, J. Chem. Soc., Perkin Trans. 1, **1977**, 2411.

567. C. Iwata, T. Fusaka, T. Fujiwara, K. Tomita, and M. Yamada, J. Chem. Soc., Chem Commun., **1981**, 463.
568. M. Biollaz, G. Büchi, and G. Milne, J. Am. Chem. Soc., **92**, 1035 (1970).
569. J. J. Cawley and D. V. Petrocine, J. Org. Chem., **40**, 1184 (1975).
570. T. Y. R. Tsai, K. P. Nambiar, D. Krikorian, M. Botta, R. Marini-Bettolo, and K. Wiesner, Can. J. Chem., **57**, 2124 (1979).
571. S. Yamada, M. Kitamoto, and S. Terashima, Tetrahedron Lett., **1976**, 3165.
572. M. Kitamoto, K. Kameo, S. Terashima, and S. Yamada, Chem. Pharm. Bull., **25**, 1273 (1977).
573. S. Yamada and S. Terashima, Jpn. Kokai 77, 156,835 [C.A., **88**, 136199w (1978)].
574. M. E. Cain, J. Chem. Soc., **1964**, 3532.
575. M. F. Semmelhack, R. D. Stauffer, and A. Yamashita, J. Org. Chem., **42**, 3180 (1977).
576. J. E. Baldwin, R. C. Thomas, L. I. Kruse, and L. Silberman, J. Org. Chem., **42**, 3846 (1977).
577. P. L. Southwick, N. Latif, B. M. Fitzgerald, and N. M. Zaczek, J. Org. Chem., **31**, 1 (1966).
578. J. Durand and J. Huet, Bull. Soc. Chim. Fr., Pt. 2, **1978**, 428.
579. O. *1* ervinka, O. K | íE , and J. *1* ervenka, Z. Chem., **11**, 109 (1971).
580. O. *1* ervinka and O. K | íE , Collect. Czech. Chem. Commun., **38**, 294 (1973).
581. J. Huton, M. Senior, and N. C. A. Wright, Synth. Commun., **9**, 799 (1979).
582. C. Schmidt, K. L. Adams, and U. Fechner, Can. J. Chem., **52**, 1732 (1974).
583. R. S. Brinkmeyer and V. M. Kapoor, J. Am. Chem. Soc., **99**, 8339 (1977).
584. W. S. Johnson, R. S. Brinkmeyer, V. M. Kapoor, and T. M. Yarnell, J. Am. Chem. Soc., **99**, 8341 (1977).
585. J. P. Vigneron and J. M. Blanchard, Tetrahedron Lett., **21**, 1739 (1980).
586. S. R. Landor, B. J. Miller, and A. R. Tatchell, J. Chem. Soc. (C), **1971**, 2339.
587. P. A. Bartlett and W. S. Johnson, J. Am. Chem. Soc., **95**, 7501 (1973).
588. P. C. Traas, H. Boellens, and H. J. Takken, Recl. Trav. Chim. Pays-Bas, **95**, 57 (1976).
589. G. D. Prestwich, F. B. Whitfield, and G. Stanley, Tetrahedron, **32**, 2945 (1976).
590. R. L. Markezich, W. E. Willy, B. E. McCarry, and W. S. Johnson, J. Am.

Chem. Soc., **95**, 4414 (1973).

591. W. S. Johnson, B. E. McCarry, R. L. Markezich, and S. G. Boots, J. Am. Chem. Soc., **102**, 352 (1980).
592. N. Lander and R. Mechoulam, J. Chem. Soc., Perkin Trans. 1, **1976**, 484.
593. R. A. Finnegan and P. L. Bachman, J. Org. Chem., **30**, 4145 (1965).
594. D. Caine, P. C. Chen, A. S. Frobese, and J. T. Gupton, J. Org. Chem., **44**, 4981 (1979).
595. R. E. Ireland, M. I. Dawson, S. C. Welch, A. Hagenbach, J. Bordner, and B. Trus, J. Am. Chem. Soc., **95**, 7829 (1973).
596. K. E. Wilson, R. T. Seidner, and S. Masamune, J. Chem. Soc., Chem. Commun., **1970**, 213.
597. P. R. Story and S. R. Fahrenholtz, J. Am. Chem. Soc., **87**, 1623 (1965).
598. J. B. Wiel and F. Rouessac, J. Chem. Soc., Chem. Commun., **1976**, 446.
599. J. B. Wiel and F. Rouessac, Bull. Soc. Chim. Fr., Pt. 2, **1979**, 273.
600. E. J. Corey and J. Gorzynski Smith, J. Am. Chem. Soc., **101**, 1038 (1979).
601. M. F. Semmelhack and R. D. Stauffer, J. Org. Chem., **40**, 3619 (1975).
602. H. Haubenstock, J. Org. Chem., **37**, 656 (1972).
603. H. Haubenstock and P. Quezada, J. Org. Chem., **37**, 4067 (1972).
604. M. Vandewalle and E. Madeleyn, Tetrahedron, **26**, 3551 (1970).
605. (a) C. J. Sih, R. G. Salomon, P. Price, R. Sood, and G. Peruzzotti, J. Am. Chem. Soc., **97**, 857 (1975); (b) Teijin Ltd., Jpn. Kokai Tokkyo Koho 81, 123,932 [C. A., **96**, 68441g (1982)]; (c) M. Suzuki, T. Kawagishi, T. Suzuki, and R. Noyori, Tetrahedron Lett., **23**, 4057 (1982).
606. P. A. Grieco, N. Fukamiya, and M. Miyashita, J. Chem. Soc., Chem. Commun., **1976**, 573.
607. Z. G. Hajos, D. R. Parrish, and E. P. Oliveto, Tetrahedron Lett., **1966**, 6495.
608. Z. G. Hajos, D. R. Parrish, and E. P. Oliveto, Tetrahedron, **24**, 2039 (1968).
609. G. Saucy, R. Borer, and A. Fürst, Helv. Chim. Acta, **54**, 2034 (1971).
610. G. Saucy and R. Borer, Helv. Chim. Acta, **54**, 2121 (1971).
611. R. E. Ireland and D. M. Walba, Tetrahedron Lett., **1976**, 1071.
612. K. F. Cohen, R. Kazlauskas, and J. T. Pinhey, J. Chem. Soc., Perkin Trans. 1, **1973**, 2076.
613. G. Stork, G. A. Kraus, and G. A. Garcia, J. Org. Chem., **39**, 3459 (1974).
614. G. Stork and G. A. Kraus, J. Am. Chem. Soc., **98**, 2351 (1976).

615. R. Pappo and P. W. Collins, Tetrahedron Lett., **1972**, 2627.
616. R. Pappo and C. J. Jung, Ger. Offen. 2,321,984 (1973) [C.A., **80**, 26827b (1974)].
617. M. M. S. Bruhn and R. Pappo, Ger. Offen. 2,415,765 (1974) [C. A., **82**, 86119y (1975)].
618. R. Pappo and C. J. Jung, U.S. Pat. 3,969,391 (1976) [C. A., **86**, 55057e (1977)].
619. C. J. Sih, J. B. Heather, G. P. Peruzzotti, P. Price, R. Sood, and L. F. Hsu Lee, J. Am. Chem. Soc., **95**, 1676 (1973).
620. C. J. Sih, J. B. Heather, R. Sood, P. Price, G. P. Peruzzotti, L. F. Hsu Lee, and S. S. Lee, J. Am. Chem. Soc., **97**, 865 (1975).
621. C. J. Sih and J. B. Heather, U.S. Pat. 3,968,141 (1976) [C.A., **86**, 29416b (1977)].
622. H. Yamaoka, T. Hakucho, and K. Akiba, Heterocycles, **15** (spec. issue), 1159 (1981).
623. H. Cho and R. G. Harvey, J. Chem. Soc., Perkin Trans. 1, **1976**, 837.
624. R. G. Harvey, S. H. Goh, and C. Cortez, J. Am. Chem. Soc., **97**, 3468 (1975).
625. J. D. White, Tetrahedron Lett., **1974**, 2879.
626. J. D. White, J. F. Ruppert, M. A. Avery, S. Torii, and J. Nokami, J. Am. Chem. Soc., **103**, 1813 (1981).
627. W. Fleischhacker and H. Markut, Monatsh. Chem., **102**, 569 (1971).
628. W. Fleischhacker and H. Markut, Monatsh. Chem., **102**, 587 (1971).
629. E. L. Eliel and F. W. Nader, J. Am. Chem. Soc., **92**, 3045 (1970).
630. J. M. Sonney, P. Vogel, and U. Burger, Helv. Chim. Acta, **63**, 1016 (1980).
631. H. Felkin, Bull. Soc. Chim. Fr., **1951**, 347.
632. D. C. Wigfield and F. W. Gowland, Can. J. Chem., **55**, 3616 (1977).
633. J. Diekman and C. Djerassi, J. Org. Chem., **32**, 1005 (1967).
634. P. Gailochet, A. Caillet, and D. Bauer, Analysis, **2**, 597 (1973) [C.A., **79** 152469d (1973)].
635. K. K. Chan, A. C. Specian, Jr., and G. Saucy, J. Org. Chem., **43**, 3435 (1978).
636. K. K. Chan and G. Saucy, U.S. Pat. 4,029,678 (1977) [C.A., **88**, 38000e (1978)].
637. F. Kienzle and R. E. Minder, Helv. Chim. Acta, **61**, 242 (1978).
638. K. Mori, S. Tamada, M. Uchida, N. Mizumachi, Y. Tachibana, and M. Matsui, Tetrahedron, **34**, 1901 (1978).
639. F. T. Sher and G. A. Berchtold, J. Org. Chem., **42**, 2569 (1977).

640. K. Yamakawa, K. Nishitani, and K. Kasahara, Chem. Pharm. Bull., **27**, 953 (1979).
641. Personal communication, Professor R. Noyori, University of Nagoya, Japan.
642. A. F. Kluge, K. G. Untch, and J. H. Fried, J. Am. Chem. Soc., **94**, 7827 (1972).
643. Personal communication, Professor S. Terashima, University of Tokyo, Japan.
644. J. L. Hubbard and H. C. Brown, Synthesis, **1978**, 676.
645. H. C. Brown and R. A. Coleman, J. Am. Chem. Soc., **91**, 4606 (1969).
646. H. C. Brown, R. A. Coleman, and M. W. Rathke, J. Am. Chem. Soc., **90**, 499 (1968).
647. H. C. Brown, U.S. Pat. 3,752,860 (1973) [C.A., **79**, 92370c (1973)].
648. H. C. Brown, E. F. Knights, and R. A. Coleman, J. Am. Chem. Soc., **91**, 2144 (1969).
649. M. Vidal and P. Arnaud, Bull. Soc. Chim. Fr., **1972**, 675.
650. H. C. Brown, M. M. Rogi / , M. W. Rathke, and G. W. Kabalka, J. Am. Chem. Soc., **91**, 2150 (1969).
651. T. Gibson, Tetrahedron Lett., **23**, 157 (1982).
652. (a) E. Cesarotti, R. Ugo, and H. B. Kagan, Angew. Chem., **91**, 842 (1979); (b) R. Gabioud, G. Chapuis, and P. Vogel, J. Org. Chem., **47**, 3316 (1982).
653. N. H. Wilson, V. Peesapati, R. L. Jones, and K. Hamilton, J. Med. Chem., **25**, 495 (1982).
654. M. A. McKinney, S. W. Anderson, M. Keyes, and R. Schmidt, Tetrahedron Lett., **23**, 3443 (1982).
655. A. Padwa, T. J. Blacklock, P. H. J. Carlsen, and M. Pulwer, J. Org. Chem., **44**, 3281 (1979).
656. M. U. Bombala and S. V. Ley, J. Chem. Soc., Perkin Trans. 1, **1979**, 3013.
657. A. Ricci, R. Danieli, and G. Pirazzini, Gazz. Chim. Ital., **105**, 37 (1975).
658. K. Miyano, T. Sakai, and H. Hamano, Jpn. Kokai Tokkyo Koho 79, 22,370 [C.A., **90**, 203888b (1979)].
659. S. Makleit, S. Berényi, and R. Bognár, Acta Chim. Acad. Sci. Hung., **94**, 165 (1977) [C.A., **88**, 170362d (1978)].
660. S. Makleit, S. Berényi, and R. Bognár, Magy. Kem. Foly., **83**, 478 (1977) [C.A., **88**, 121484m (1978)].
661. W. A. Ayer, L. M. Browne, J. R. Mercer, D. R. Taylor, and D. E. Ward, Can. J. Chem., **56**, 717 (1978).
662. M. Malacria and J. Gore, J. Org. Chem., **44**, 885 (1979).

663. O. Rigassi and U. Schwieter, Ger. Offen. 2,032,906 (1971) [C.A., **74**, 124797n (1971)].
664. K. K. Chan and G. Saucy, U.S. Pat. 4,045,475 (1977) [C.A., **87**, 183979 (1977)].
665. H. Zak and U. Schmidt, Chem. Ber., **106**, 3652 (1973).
666. W. S. Johnson, T. A. Lyle, and G. W. Daub, J. Org. Chem., **47**, 161 (1982).
667. G. S. Groenewold and M. L. Gross, J. Labelled Compd. Radiopharm., **18**, 1809 (1981).
668. D. L. Coffen, D. A. Katonak, and F. Wong, J. Am. Chem. Soc., **96**, 3966 (1974)].
669. D. A. Frost and G. A. Morrison, J. Chem. Soc., Perkin Trans. 1, **1973**, 2159.
670. A. G. Causa, H. Y. Chen, S. Y. Tark, and H. J. Harwood, J. Org. Chem., **38**, 1385 (1973).
671. R. F. Borne, C. R. Clark, and J. M. Holbrook, J. Med. Chem., **16**, 853 (1973).
672. A. M. Mubarak and D. M. Brown, Tetrahedron Lett., **21**, 2453 (1980).
673. A. M. Mubarak and D. M. Brown, J. Chem. Soc., Perkin Trans. 1, **1982**, 809.
674. C. Béguin, Bull. Soc. Chim. Fr., **1969**, 372.
675. R. M. Williams and W. H. Rastetter, Tetrahedron Lett., **1979**, 1187.
676. R. M. Williams and W. H. Rastetter, J. Org. Chem., **45**, 2625 (1980).
677. (a) D. R. Williams, B. A. Barner, K. Nishitani, and J. G. Phillips, J. Am. Chem. Soc., **104**, 4708 (1982); (b) J. Better and S. Gatenbeck, Acta Chem. Scand., Ser. B, **33**, 235 (1979).
678. T. Jen, J. S. Frazee, M. S. Schwartz, K. F. Erhard, and C. Kaiser, J. Med. Chem., **20**, 1263 (1977).
679. B. S. Balgir, L. N. Mander, and S. T. K. Mander, Aust. J. Chem., **18**, 2459 (1973).
680. G. Just, T. J. Liak, Mu-Ill Lim, P. Potvin, and Y. S. Tsantrizos, Can. J. Chem., **58**, 2024 (1980).
681. R. E. Counsell, T. D. Smith, V. V. Ranade, O. P. D. Noronha, and P. Desai, J. Med. Chem., **16**, 684 (1973).
682. B. A. Pawson, H. C. Cheung, R. J. L. Han, P. W. Trown, M. Buck, R. Hansen, W. Bollag, U. Ineichen, H. Pleil, R. Rüegg, N. M. Dunlop, D. L. Newton, and M. B. Sporn, J. Med. Chem., **20**, 918 (1977).
683. G. Just and T. J. Liak, Can. J. Chem., **56**, 211 (1978).
684. J. W. Scott, D. R. Parrish, and G. Saucy, U.S. Pat. 4,026,907 (1977) [C.A., **87**, 184732r (1977)].

685. H. J. Liu, Z. Valenta, J. S. Wilson, and T. T. J. Yu, Can. J. Chem., **47**, 509 (1969).

686. D. R. Williams and K. Nishitani, Tetrahedron Lett., **21**, 4417 (1980).

687. N. Cohen, R. J. Lopresti, and G. Saucy, J. Am. Chem. Soc., **101**, 6710 (1979).

688. E. E. Galantay, Switz. Pat. 595,314 (1978) [C.A., **89**, 75279v (1978)].

689. W. McCrae, J. H. Fried, and J. Ansley, Ger. Offen. 1,910,186 (1969) [C.A., **72**, 55099f (1970)].

690. R. A. Partyka, R. T. Standridge, H. G. Howell, and A. T. Shulgin, U.S. Pat. 4,105,695 (1978) [C.A., **90**, 151799b (1979)].

691. I. Kubo, T. Kamikawa, and T. Kubota, Tetrahedron, **30**, 615 (1974).

692. (a) H. De Koning, A. Springer-Fidder, M. J. Moolenaar, and H. O. Huisman, Recl. Trav. Chim. Pays-Bas, **92**, 237 (1973); (b) A. Vystr / il, V. Pouzar, and V. K | e / ek, Collect. Czech. Chem. Commun., **38**, 3902 (1973).

693. C. Ireland and D. J. Faulkner, Bioorg. Chem., **7**, 125 (1978).

694. T. Kametani, Heterocycles, **17**, 463 (1982).

695. H. J. Kötzsch, Chem. Ber. **99**, 1143 (1966).

696. M. J. Drabicky, P. C. Myhre, C. J. Reich, and E. R. Schmittou, J. Org. Chem., **41**, 1472 (1976).

697. A. A. Bothner-By, J. Am. Chem. Soc., **73**, 846 (1951).

698. Y. Minoura and H. Yamaguchi, J. Polym. Sci., Part A-1, **6**, 2013 (1968).

699. P. S. Portoghese, J. Org. Chem., **27**, 3359 (1962).

700. P. Briaucourt and A. Horeau, C.R. Acad. Sci., Ser. C, **281**, 627 (1975).

701. M. *1* erný, J. Málek, M. *1* apka, and V. Chvalovský, Collect. Czech. Chem. Commun., **34**, 1025 (1969).

702. A. S. Angeloni, S. Marzocchi, and G. Scapini, Gazz. Chim. Ital., **107**, 421 (1977).

703. O. *1* ervinka, V. D \dek, and J. Šmidrkal, Z. Chem., **11**, 11 (1971).

704. O.*1* ervinka, O. B \lovský, and L. Korálová, Z. Chem., **9**, 448 (1969).

705. J. R. E. Hoover, G. L. Dunn, D. R. Jakas, L. L. Lam, J.J. Taggart, J. R. Guarini, and L. Phillips, J. Med. Chem., **17**, 34 (1974).

706. K. Saigo, S. Ogawa, S. Kikuchi, A. Kasahara, and H. Nohira, Bull. Chem. Soc. Jpn., **55**, 1568 (1982).

707. S. Terashima, K. Koga, and N. Tanno, Eur. Pat. Appl. 35,355 (1981) [C.A., **96**, 52036t (1982)].

708. R. Noyori, Ger. Offen. 2,940,336 (1980) [C.A., **94**, 30250g (1981)].

709. (a) O. *1* ervinka, and J. Fusek, Collect. Czech. Chem. Commun., **38**, 441 (1973); (b) W. Francke and W. Mackenroth, Angew. Chem., **94**, 704

(1982).
710. R. Aries, Fr. Dem. 2,259,823 (1975) [C.A., **84**, 90143k (1976)].
711. O. Štrouf, J. Fusek, and O. *1* ervinka, Collect. Czech. Chem. Commun., **39**, 1044 (1974).
712. R. Agnemo and G. Gellerstedt, Acta Chem. Scand., Ser. B, **33**, 337 (1979).
713. R. Zurflüh, L. L. Dunham, V. L. Spain, and J. B. Siddall, J. Am. Chem. Soc., **92**, 425 (1970).
714. F. Yasuhara and S. Yamaguchi, Tetrahedron Lett., **21**, 2827 (1980).
715. J. P. Guetté and A. Horeau, Bull. Soc. Chim. Fr., **1967**, 1747.
716. O. *1* ervinka, O. B \ lovský, A. Fábryová, V. Dudek, and K. Grohman, Collect. Czech. Chem. Commun., **32**, 2618 (1967).
717. R. Annunziata, M. Cinquini, and F. Cozzi, J. Chem. Soc., Perkin Trans. 1, **1979**, 1687.
718. R. Andrisano, A. S. Angeloni, and S. Marzocchi, Tetrahedron, **29**, 913 (1973).
719. L. D. Tomina, E. I. Klabunovskii, Yu. I. Petrov, I. A. Rubtsov, and E. M. Cherkasova, Izv. Akad. Nauk SSSR, Ser. Khim., **1973**, 857 [C.A., **79**, 41817w (1973)].
720. H. Meyer and D. Seebach, Justus Liebigs Ann. Chem., **1975**, 2261.
721. D. Seebach and H. Meyer, Angew. Chem., **86**, 40 (1974).
722. S. Chimichi and R. Nesi, J. Chem. Soc., Perkin Trans. 1, **1979**, 2215.
723. E. L. Eliel, J. K. Koskimies, and B. Lohri, J. Am. Chem. Soc., **100**, 1614 (1978).
724. O. *1* ervinka, V. Suchan, and B. Masa | , Collect. Czech. Chem. Commun., **30**, 1693 (1965).
725. R. C. Lamb, L. P. Spadafino, R. G. Webb, E. B. Smith, W. E. McNew, and J. G. Pacifici, J. Org. Chem., **31**, 147 (1966).
726. L. Colombo, C. Gennari, C. Scolastico, F. Aragozzini, and C. Merendi, J. Chem. Soc., Perkin Trans. 1, **1980**, 2549.
727. C. A. Kingsbury and D. C. Best, Bull. Chem. Soc. Jpn., **45**, 3440 (1972).
728. M. Faurie, C. Malardeau, and G. Mousset, Bull. Soc. Chim. Fr., Pt. 2, **1979**, 177.
729. Y. Kasuya, M. Watanabe, and H. Hamano, Jpn. Kokai 72, 20, 132 [C.A., **77**, 151657k (1972)].
730. H. Hamano and S. Okuda, Chem. Pharm. Bull., **22**, 1348 (1974).
731. H. Hamano and S. Okuda, Chem. Pharm. Bull., **26**, 833 (1978).
732. A. Murai, K. Takahashi, H. Taketsuru, and T. Masamune, J. Chem. Soc., Chem. Commun., **1981**, 221.

733. O. *1* ervinka and O. B \lovský, Z. Chem., **7**, 226 (1967).
734. R. J. Stoodley, Tetrahedron, **31**, 2321 (1975).
735. L. Angiolini, P. C. Bizzarri, G. Scapini, and M. Tramontini, Tetrahedron, **37**, 2137 (1981).
736. S. Yamaguchi, J. A. Dale, and H. S. Mosher, J. Org. Chem., **37**, 3174 (1972).
737. A. Horeau, H. B. Kagan, and J. P. Vigneron, Bull. Soc. Chim. Fr., **1968**, 3795.
738. T. R. Govindachari, K. R. Ravindranath, and N. Viswanathan, J. Chem. Soc., Perkin Trans. 1, **1974**, 1215.
739. E. H. Gold and E. Babad, U.S. Pat. 3,956,390 (1976) [C.A., **85**, 62788b (1976)].
740. (a) M. Yanagiya, F. Matsuda, K. Hasegawa, and T. Matsumoto, Tetrahedron Lett., **23**, 4039 (1982); (b) A. Kasal and L. Kohout, Collect. Czech. Chem. Commun., **47**, 130 (1982).
741. J. F. Tocanne and C. Asselineau, Bull. Soc. Chim. Fr., **1968**, 2103.
742. T. Kametani, K. Kigasawa, M. Hiiragi, N. Wagatsuma, T. Kohagizawa, and H. Inoue, Heterocycles, **14**, 775 (1980).
743. R. Haller and R. Rümmler, Arch. Pharm. (Weinheim, W. Germany), **306**, 431 (1973).
744. P. F. Beal, F. H. Lincoln, Jr., and J. E. Pike, U.S. Pat. 3,435,053 (1969) [C.A., **71**, 49770f (1969)].
745. O. *1* ervinka, K. Bláha, Jr., A. Fábryová, R. Fink, D. van der Helm, and J. Po | ádek, Collect. Czech. Chem. Commun., **44**, 2946 (1979).
746. J. Weichet and L. Bláha, Czech, Pat. 188,846 (1981) [C.A., **96**, 123073r (1982)].
747. C. Temple, Jr., J. D. Rose, and J. A. Montgomery, Chem. Ind. (London), **1971**, 883.
748. (a) C. Temple, Jr., J. D. Rose, and J. A. Montgomery, J. Pharm. Sci., **61**, 1297 (1972) [C.A., **77**, 101279t (1972)]; (b) P. F. Beal, III, F. H. Lincoln, Jr., and J. C. Babcock, Fr. Pat. 1,521,715 (1968) [C.A., **71**, 80793g (1969)]; (c) P. F. Beal, III, J. C. Babcock, and F. H. Lincoln, Jr., J. Am. Chem. Soc., **88**, 3131 (1966).
749. J. Gutzwiller and M. R. Uskokovi / , Helv. Chim. Acta, **56**, 1494 (1973). /
750. G. Grethe, J. Gutzwiller, H. L. Lee, and M. R. Uskokovi / , Helv. Chim. Acta, **55**, 1044 (1972).
751. H. Yuki, T. Nakao, and N. Setoguchi, Jpn. Kokai 77, 156,853 [C.A., **88**, 152405r (1978)].
752. H. Newman, J. Org. Chem., **39**, 100 (1974).
753. K. Wiesner, P. T. Ho, D. Chang, and J. F. Blount, Experientia, **28**, 766

(1972).
754. R. C. Schulz and H. Mayerhöfer, Angew. Chem., **80**, 236 (1968).
755. H. C. Brown and F. G. M. Vogel, Justus Liebigs Ann. Chem., **1978**, 695.
756. L. D. Quin and J. H. Somers, J. Org. Chem., **37**, 1217 (1972).
757. W. S. Briggs and C. Djerassi, J. Org. Chem., **33**, 1612 (1968).
758. L. I. Zakharkin and N. V. Grandberg, Izv. Akad. Nauk SSSR, Ser. Khim., **1976**, 2612 [C.A., **86**, 120831u (1977)].
759. H. Christol, D. Duval, and G. Solladié, Bull. Soc. Chim. Fr., **1968**, 4151.
760. E. N. Marvell and R. Rusay, J. Org. Chem., **42**, 3336 (1977).
761. D. J. Kosman and L. H. Piette, J. Chem. Soc., Chem. Commun., **1969**, 926.
762. M. Gates and J. L. Zabriskie, Jr., J. Org. Chem., **39**, 222 (1974).
763. R. E. Ireland and F. R. Brown, Jr., J. Org. Chem., **45**, 1868 (1980).
764. W. S. Johnson and J. K. Crandall, J. Org. Chem., **30**, 1785 (1965).
765. B. Belleau and P. Cooper, J. Med. Chem., **6**, 579 (1963).
766. R. H. Burnell, A. Humblet, J. Pelletier, and S. Badripersaud, Can. J. Chem., **58**, 1243 (1980).
767. L. A. Van Royen, R. Mijngheer, and P. J. De Clercq, Tetrahedron Lett., **23**, 3283 (1982).
768. J. C. Richer and R. Bisson, Can. J. Chem., **47**, 4399 (1969).
769. L. Dolejš and F. Šorm, Tetrahedron Lett., **1959**, 1.
770. L. Dolejš and F. Šorm, Collect. Czech. Chem. Commun., **25**, 1837 (1960).
771. G. E. Gream, M. H. Laffer, and A. K. Serelis, Aust. J. Chem., **31**, 835 (1978).
772. A. Morimoto, T. Okutani, and K. Masuda, Chem. Pharm. Bull., **21**, 228 (1973).
773. N. A. Starkovsky, A. A. Carlson, and F. Johnson, J. Org. Chem., **31**, 2516 (1966).
774. M. Matsui, S. Katsube, and E. Murayama, Jpn. Pat. 74, 28,750 [C.A., **82**, 111668m (1975)].
775. F. Johnson, A. A. Carlson, and N. A. Starkovsky, J. Org. Chem., **31**, 1327 (1966).
776. M. Suzuki, Chem. Pharm. Bull., **8**, 778 (1960).
777. L. N. Mander and L. T. Palmer, Aust. J. Chem., **32**, 823 (1979).
778. R. L. Clarke, S. J. Daum, P. E. Shan, T. G. Brown, Jr., G. E. Groblewski, and W. V. O'Connor, J. Med. Chem., **10**, 593 (1967).
779. L. Novotný, C. Tabaciková-Wlotzka, V. Herout, and F. Šorm, Collect. Czech. Chem. Commun., **29**, 1922 (1964).

780. T. Okuda, Chem. Pharm. Bull., **7**, 259 (1959).
781. T. Okuda, Chem. Pharm. Bull., **7**, 671 (1959).
782. J. Fried, M. M. Mehra, W. L. Kao, and C. H. Lin, Tetrahedron Lett., **1970**, 2695.
783. H. H. Inhoffen, W. Kreiser, and M. Nazir, Justus Liebigs Ann. Chem., **755**, 1 (1972).
784. W. Kreiser and H. A. F. Heinemann, Justus Liebigs Ann. Chem., **1976**, 1222.
785. J. Kraemer, H. E. Radunz, D. Orth, M. Baumgarth, and P. Bruneau, Ger. Offen. 2,513,371 (1976) [C.A., **86**, 55069k (1977)].
786. H. E. Radunz, J. Kraemer, M. Baumgarth, and D. Orth, Ger. Offen. 2,422,924 (1975) [C.A., **84**, 121284p (1976)].
787. K. Mori, Tetrahedron Lett., **1973**, 723.
788. K. Mori, Tetrahedron, **30**, 1065 (1974).
789. R. B. Woodward, E. Logusch, K. P. Nambiar, K. Sakan, D. E. Ward, B. W. Au-Yeung, P. Balaram, L. J. Browne, P. J. Card, C. H. Chen, R. B. Chênevert, A. Fliri, K. Frobel, H. J. Gais, D. G. Garratt, K. Hayakawa, W. Heggie, D. P. Hesson, D. Hoppe, I. Hoppe, J. A. Hyatt, D. Ikeda, P. A. Jacobi, K. S. Kim, Y. Kobuke, K. Kojima, K. Krowicki, V. J. Lee, T. Leutert, S. Malchenko, J. Martens, R. S. Matthews, B. S. Ong, J. B. Press, T. V. Rajan Babu, G. Rousseau, H. M. Sauter, M. Suzuki, K. Tatsuta, L. M. Tolbert, E. A. Truesdale, I. Uchida, Y. Ueda, T. Uyehara, A. T. Vasella, W. C. Vladuchick, P. A. Wade, R. M. Williams, and H. N. C. Wong, J. Am. Chem. Soc., **103**, 3213 (1981).
790. J. B. Lambert and H. W. Mark, J. Am. Chem. Soc., **100**, 2501 (1978).
791. C. H. DePuy and P. R. Story, J. Am. Chem. Soc., **82**, 627 (1960).
792. N. H. Werstiuk, G. Timmins, and F. P. Cappelli, Can. J. Chem., **58**, 1738 (1980).
793. S. Saito, T. Moriwake, K. Takeuchi, and K. Okamoto, Bull. Chem. Soc. Jpn., **51**, 2634 (1978).
794. W. S. Trahanovsky, P. J. Flash, and L. M. Smith, J. Am. Chem. Soc., **91**, 5068 (1969).
795. C. J. Michejda and D. Von Riesen, J. Org. Chem., **37**, 3021 (1972).
796. R. Baker and L. K. Dyall, J. Chem. Soc. (B), **1971**, 1952.
797. V. Novák and J. Závada, Collect. Czech. Chem. Commun., **27**, 1224 (1962).
798. P. R. Brook, A. J. Duke, J. G. Griffiths, S. M. Roberts, M. Rey, and A. S. Dreiding, Helv. Chim. Acta, **60**, 1528 (1977).
799. R. P. Fraser and S. O'Farrell, Tetrahedron Lett., **1962**, 1143.
800. J. B. Lambert, J. W. Hamersma, A. P. Jovanovich, F. R. Koeng, S. A.

Sweet, and P. J. Kucinski, J. Am. Chem. Soc., **92**, 6372 (1970).

801. M. Walkowicz, H. Kuczy ski, and C. Walkowicz, Bull, Acad. Pol. Sci., Sec. Sci. Chim., **19**, 531 (1971) [C. A., **76**, 13665g (1972).].
802. H. C. Brown and W. J. Hammar, Tetrahedron, **34**, 3405 (1978).
803. H. Krieger and K. Manninen, Suomen Kemistilehti (B), **38**, 175 (1965) [C.A., **64**, 6520 (1966)].
804. J. B. Stothers, C. T. Tan, and K. C. Teo, Can. J. Chem., **54**, 1211 (1976).
805. A. A. Youssef, M. E. Baum, and H. M. Walborsky, J. Am. Chem. Soc., **81**, 4709 (1959).
806. C. Arnaud, A. Accary, and J. Huet, C. R. Acad. Sci., Ser. C, **285**, 325 (1977).
807. P. Vogel, Chimia (Aarau), **31**, 53 (1977).
808. J. M. Sonney and P. Vogel, Helv. Chim. Acta, **63**, 1034 (1980).
809. J. W. Wilt and R. Niinemae, J. Org. Chem., **45**, 5402 (1980).
810. K. E. Harding, J. W. Trotter, and L. M. May, J. Org. Chem., **42**, 2715 (1977).
811. W. T. Wipke and G. L. Goeke, J. Am. Chem. Soc., **96**, 4244 (1974).
812. A. G. Fallis, Can. J. Chem., **53**, 1657 (1975).
813. T. Sato, Y. Goto, and T. Fujisawa, Tetrahedron Lett., **23**, 4111 (1982).
814. P. A. Grieco, Y. Yokoyama, G. P. Withers, F. J. Okuniewicz, and C. L. J. Wang, J. Org. Chem., **43**, 4178 (1978).
815. Y. Hayakawa, Y. Baba, S. Makino, and R. Noyori, J. Am. Chem. Soc., **100**, 1786 (1978).
816. M. Gaitonde, P. A. Vatakencherry, and S. Dev, Tetrahedron Lett., **1964**, 2007.
817. K. Mori and M. Sasaki, Tetrahedron, **36**, 2197 (1980).
818. S. J. Daum, C. M. Martini, R. K. Kullnig, and R. L. Clarke, J. Org. Chem., **37**, 1665 (1972).
819. (a) K. Takeda and S. Yamamoto, Chem. Pharm. Bull., **20**, 314 (1972); (b) personal communication, Dr. K. Takeda, Shionogi & Co., Ltd., Osaka, Japan.
820. H. Kuczy ski, K. Piatkowski, A. Hendrich, and A. Kubik, Tetrahedron Lett., **1967**, 2371.
821. R. Howe, E. C. Friedrich, and S. Winstein, J. Am. Chem. Soc., **87**, 379 (1965).
822. G. E. Gream, D. Wege, and M. Mular, Aust. J. Chem., **27**, 567 (1974).
823. A. F. Regan, Tetrahedron, **25**, 3801 (1969).
824. C. W. Jefford, S. M. Evans, U. Burger, and W. Wojnarowski, Chimia

(Aarau), **25**, 413 (1971).

825. A. Gandini, F. Bondavalli, P. Schenone, and G. Bignardi, Ann. Chim. (Rome), **62**, 188 (1972).
826. D. Huckle, I. M. Lockhart, and N. E. Webb, J. Chem. Soc. (C), **1971**, 2252.
827. J. Barry, H. B. Kagan, and G. Snatzke, Tetrahedron, **27**, 4737 (1971).
828. D. J. Beames and L. N. Mander, J. Chem. Soc., Chem. Commun., **1969**, 498.
829. D. J. Beames, J. A. Halleday, and L. N. Mander, Aust. J. Chem., **25**, 137 (1972).
830. A. J. Bellamy and G. H. Whitham, Tetrahedron, **24**, 247 (1968).
831. A. J. Bellamy, W. Crilly, J. Farthing, and G. M. Kellie, J. Chem. Soc., Perkin Trans. 1, **1974**, 2417.
832. I. Ito, N. Tomiyoshi, K. Nakamura, S. Azuma, M. Izawa, F. Maruyma, M. Yanagiya, H. Shirahama, and T. Matsumoto, Tetrahedron Lett., **23**, 1721 (1982).
833. J. V. Paukstelis and B. W. Macharia, Tetrahedron, **29**, 1955 (1973).
834. D. Kimchi and S. Bien, J. Chem. Soc., **1961**, 5345.
835. J. Martin, W. Parker, B. Shroot, and T. Stewart, J. Chem. Soc. (C), **1967**, 101.
836. A. A. Akhrem, L. I. Ukhova, and A. N. Sergeeva, Vestsi Akad. Navuk BSSR, Ser. Khim. Navuk, **1975** (4), 53 [C.A., **83**, 178116v (1975)].
837. R. M. Dodson, J. R. Lewis, W. P. Webb, E. Wenkert, and R. D. Yousefyeh, J. Am. Chem. Soc., **83**, 938 (1961).
838. A. B. Daruwala, J. E. Gearien, W. J. Dunn, III, P. S. Benoit, and L. Bauer, J. Med. Chem., **17**, 819 (1974).
839. C. F. Barfknecht, D. E. Nichols, D. B. Busterholz, J. P. Long, J. A. Engelbrecht, J. M. Beaton, R. J. Bradley, and D. C. Dyer, J. Med. Chem., **16**, 804 (1973).
840. C. G. Chavdarian, S. L. Woo, R. D. Clark, and C. H. Heathcock, Tetrahedron Lett., **1976**, 1769.
841. M. S. Allen, N. Darby, P. Salisbury, E. R. Sigurdson, and T. Money, Can. J. Chem., **57**, 733 (1979).
842. J. S. Roberts and C. Thomson, J. Chem. Soc., Perkin Trans. 2, **1972**, 2129.
843. D. E. Nichols, C. F. Barfknecht, J. P. Long, R. T. Standridge, H. G. Howell, R. A. Partyka, and D. C. Dyer, J. Med. Chem., **17**, 161 (1974).
844. N. Ototani, T. Kato, and Y. Kitahara, Bull. Chem. Soc. Jpn., **40**, 1730 (1967).
845. R. C. Cambie and R. C. Hayward, Aust. J. Chem., **28**, 225 (1975).

846. Y. Tsuda, K. Yoshimoto, T. Yamashita, and M. Kaneda, Chem. Pharm. Bull., **29**, 3238 (1981).
847. D. H. R. Barton, S. D. Géro, and C. D. Maycock, J. Chem. Soc., Chem. Commun., **1980**, 1089.
848. (a) S. Torii, T. Inokuchi, and K. Kawai, Bull. Chem. Soc. Jpn., **52**, 861 (1979); (b) personal communication of Professor S. Torii, Okayama University, Okayama, Japan.
849. A. A. Akhrem, L. I. Ukhova, and A. N. Sergeeva, Vestsi Akad. Navuk BSSR, Ser. Khim. Navuk, **1975** (5), 75 [C.A., **84**, 16652j (1976)].
850. K. Hanaya, S. Kitamoto, H. Kudo, and S. Mitsui, Nippon Kagaku Kaishi, **1978**, 238 [C.A., **88**, 151761 (1978)].
851. J. A. Marshall and R. D. Royce, Jr., J. Org. Chem., **47**, 693 (1982).
852. G. L. Hodgson, D. F. MacSweeney, and T. Money, J. Chem. Soc., Perkin Trans. 1, **1973**, 2113.
853. C. R. Eck, G. L. Hodgson, D. F. MacSweeney, R. W. Mills, and T. Money, J. Chem. Soc., Perkin Trans. 1, **1974**, 1938.
854. G. L. Hodgson, D. F. MacSweeney, R. W. Mills, and T. Money, J. Chem. Soc., Chem. Commun., **1973**, 235.
855. L. Dolejš and V. Herout, Collect. Czech. Chem. Commun., **27**, 2654 (1962).
856. Council of Scientific and Industrial Research (India), Indian Pat. 136,944 (1975) [C.A., **93**, 150054e (1980)].
857. J. W. Clark-Lewis and D. P. Cox, Aust. J. Chem., **29**, 191 (1976).
858. E. Dynesen, Acta Chem. Scand., Ser. B, **30**, 371 (1976).
859. M. Prystaš, L. Kalvoda, and F. Šorm, Collect. Czech. Chem. Commun., **41**, 1426 (1976).
860. A. Ardon-Jimenez and T. G. Halsall, J. Chem. Soc., Perkin Trans. 1, **1978**, 1461.
861. Y. Harigaya, K. Yotsumoto, S. Takamatsu, H. Yamaguchi, and M. Onda, Chem. Pharm. Bull., **29**, 2557 (1981).
862. W. Nagata, H. Itazaki, K. Okada, T. Wakabayashi, K. Shibata, and N. Tokutake, Chem. Pharm. Bull., **23**, 2867 (1975).
863. W. Nagata, Jpn. Kokai 75, 19,756 [C.A., **83**, 114234y (1975)].
864. J. C. Richer and A. Rossi, Can. J. Chem., **50**, 1376 (1972).
865. H. Bretscheider, K. Hohenlohe-Oehringen, and K. Grassmayr, Monatsh. Chem., **103**, 1523 (1972).
866. J. S. Baran, U.S. Pat. 3,476,773 (1969) [C.A., **72**, 13001n (1970)].
867. D. Taub, R. D. Hoffsommer, C. H. Kuo, H. L. Slates, Z. S. Zelawski, and N. L. Wendler, Tetrahedron, **29**, 1447 (1973).
868. D. Taub, R. D. Hoffsommer, C. H. Kuo, H. L. Slates, Z. S. Zelawski, and

N. L. Wendler, J. Chem. Soc., Chem. Commun., **1970**, 1258.
869. W. T. Borden and E. J. Corey, Tetrahedron Lett., **1969**, 313.
870. K. G. Holden, B. Hwang, K. R. Williams, J. Weinstock, M. Harman, and J. A. Weisbach, Tetrahedron Lett., **1968**, 1569.
871. S. R. Jensen, A. Kjaer, and B. J. Neilsen, Acta Chem. Scand., **27**, 2581 (1973).
872. H. Sugihara, K. Ukawa, H. Kuriki, M. Nishikawa, and Y. Sanno, Chem. Pharm. Bull., **25**, 2988 (1977).
873. P. J. Kocienski, B. Lythgoe, and D. A. Roberts, J. Chem. Soc., Perkin Trans. 1, **1980**, 897.
874. Y. Kitahara, T. Kato, and M. Kishi, Chem. Pharm. Bull., **16**, 2216 (1968).
875. N. B. M. Arts, A. J. H. Klunder, and B. Zwanenburg, Tetrahedron, **34**, 1271 (1978).
876. P. E. Schueler and Y. E. Rhodes, J. Org. Chem., **39**, 2063 (1974).
877. W. L. Dilling, C. E. Reinecke, and R. A. Plepys, J. Org. Chem., **34**, 2605 (1969).
878. J. A. Pincock and L. M. Druet, Tetrahedron Lett., **21**, 3251 (1980).
879. H. R. Känel, H. G. Capraro, and C. Ganter, Helv. Chim. Acta, **65**, 1032 (1982).
880. J. Altman, E. Babad, J. Itzchaki, and D. Ginsburg, Tetrahedron, Suppl. 8, **22**, 279 (1966).
881. A. J. H. Klunder, J. W. M. Schellekens, and B. Zwanenburg, Tetrahedron Lett., **23**, 2807 (1982).
882. J. S. H. Kueh, M. Mellor, and G. Pattenden, J. Chem. Soc., Perkin Trans. 1, **1981**, 1052.
883. V. I. Lantvoev, Zh. Org. Khim., **12**, 2361 (1976).
884. D. Caine, H. Deutsch, S. T. Chao, D. G. Van Derveer, and J. A. Bertrand, J. Org. Chem., **43**, 1114 (1978).
885. J. Parello, Bull. Soc. Chim. Fr., **1968**, 1117.
886. I. Granoth, Y. Segall, and H. Leader, J. Chem. Soc., Perkin Trans. 1, **1978**, 465.
887. Y. Segall, R. Alkabets, and I. Granoth, J. Chem. Res. (S), **1977**, 310.
888. D. Calmes, L. Gorrichon-Guigon, P. Maroni, A. Accary, R. Barret, and J. Huet, Tetrahedron, **37**, 879 (1981).
889. M. Mousseron-Canet and J. C. Guilleux, Bull. Soc. Chim. Fr., **1966**, 3858.
890. H. Greuter, H. Schmid, and G. Fráter, Helv. Chim. Acta, **60**, 1701 (1977).
891. H. Greuter, G. Fráter, and H. Schmid, Helv. Chim. Acta, **55**, 526 (1972).

892. G. Fráter, Helv. Chim. Acta, **57**, 172 (1974).
893. H. Greuter and H. Schmid, Helv. Chim. Acta, **55**, 2382 (1972).
894. H. Rischke, J. D. Wilcock, and E. Winterfeldt, Chem. Ber., **106**, 3106 (1973).
895. A. L. Campbell, H. N. Leader, C. L. Spencer, and J. D. McChesney, J. Org. Chem., **44**, 2746 (1979).
896. S. K. Balasubramanian, Tetrahedron, **12**, 196 (1961).
897. M. Ando, K. Tajima, and K. Takase, Chem. Lett., **1978**, 617.
898. M. Ando and K. Takase, Tetrahedron, **33**, 2785 (1977).
899. K. Yakamawa, K. Nishitani, and K. Azusawa, Heterocycles, **9**, 499 (1978).
900. P. Deslongchamps, U. O. Cheriyan, Y. Lambert, J. C. Mercier, L. Ruest, R. Russo, and P. Soucy, Can. J. Chem., **56**, 1687 (1978).
901. M. Suchý and H. Khash, Collect. Czech. Chem. Commun., **27**, 2925 (1962).
902. O. D. Dailey, Jr., and P. L. Fuchs, J. Org. Chem., **45**, 216 (1980).
903. H. W. Gschwend, J. Am. Chem. Soc., **94**, 8430 (1972).
904. D. Lednicer and D. E. Emmert, J. Org. Chem., **34**, 1151 (1969).
905. D. Lednicer, U.S. Pat. 3,539,596 (1970) [C.A., **74**, 125926r (1971)].
906. T. Harayama, M. Takatani, and Y. Inubushi, Chem. Pharm. Bull., **28**, 2394 (1980).
907. R. E. Ireland, P. Bey, K. F. Cheng, R. J. Czarny, J. F. Moser, and R. I. Trust, J. Org. Chem., **40**, 1000 (1975).
908. E. J. Corey, R. B. Mitra, and H. Uda, J. Am. Chem. Soc., **85**, 362 (1963).
909. B. Hanquet, R. Guilard, and P. Fournari, Bull. Soc. Chim. Fr., Pt. 2, **1977**, 571.
910. F. B. Whitfield and G. Stanley, Aust. J. Chem., **30**, 1073 (1977).
911. E. H. White, S. Eguchi, and J. N. Marx, Tetrahedron, **25**, 2099 (1969).
912. S. G. Levine, I. Y. Chen, A. T. McPhail, and P. Coggon, Tetrahedron Lett., **1971**, 3459.
913. A. K. Banerjee, Tetrahedron, **35**, 1247 (1979).
914. W. S. Johnson, M. I. Dawson, and B. E. Ratcliffe, J. Org. Chem., **42**, 153 (1977).
915. T. Matsumoto, K. Miyano, S. Kagawa, S. Yu, J. Ogawa, and A. Ichihara, Tetrahedron Lett., **1971**, 3521.
916. M. F. Semmelhack, S. Tomoda, and K. M. Hurst, J. Am. Chem. Soc., **102**, 7567 (1980).
917. J. M. Luteijn and A. de Groot, Tetrahedron Lett., **23**, 3421 (1982).
918. P. Sundararaman and W. Herz, J. Org. Chem., **42**, 806 (1977).

919. Y. Segall, R. Alkabets, and I. Granoth, J. Chem. Res. (M), **1977**, 3541.

920. S. F. Lee, G. M. Sathe, W. W. Sy, P. T. Ho, and K. Wiesner, Can. J. Chem., **54**, 1039 (1976).

921. G. Adam and T. V. Sung, Tetrahedron, **34**, 717 (1978).

922. J. W. Huffman and J. J. Gibbs, J. Org. Chem., **39**, 2501 (1974).

923. H. J. E. Loewenthal, J. Chem. Soc., **1961**, 1421.

924. H. J. E. Loewenthal and P. Rona, J. Chem. Soc., **1961**, 1429.

925. E. Fujita, T. Fujita, H. Katayama, M. Shibuya, and T. Shingu, J. Chem. Soc. (C), **1970**, 1674.

926. R. E. Ireland, S. W. Baldwin, D. J. Dawson, M. I. Dawson, J. E. Dolfini, J. Newbould, W. S. Johnson, M. Brown, R. J. Crawford, P. F. Hudrlik, G. H. Rasmussen, and K. K. Schmiegel, J. Am. Chem. Soc., **92**, 5743 (1970).

927. W. H. Gerwick, W. Fenical, and M. U. S. Sultanbawa, J. Org. Chem., **46**, 2233 (1981).

928. J. A. Giles, J. N. Schumacher, S. S. Mims, and E. Bernasek, Tetrahedron, **18**, 169 (1962).

929. Y. Kitahara, T. Kato, M. Funamizu, and N. Otoya, Jpn. Pat 71 22,017 [C.A., **75**, 88385m (1971)].

930. T. Ibuka, K. Tanaka, and Y. Inubushi, Chem. Pharm. Bull., **22**, 907 (1974).

931. T. Ibuka, K. Tanaka, and Y. Inubushi, Tetrahedron Lett., **1972**, 1393.

932. R. L. Cargill, T. A. Bryson, L. M. Krueger, J. V. Kempf, and T. C. McKenzie, J. Org. Chem., **41**, 4096 (1976).

933. W. Herz, R. N. Mirrington, H. Young, and Y. Y. Lin, J. Org. Chem., **33**, 4210 (1968).

934. O. E. Edwards and R. S. Rosich, Can. J. Chem., **46**, 1113 (1968).

935. Z. Rappoport and J. Greenblatt, J. Am. Chem. Soc., **101**, 1343 (1979).

936. A. S. Kende, M. L. King, and D. P. Curran, J. Org. Chem., **46**, 2826 (1981).

937. (a) D. Becker, L. R. Hughes, and R. A. Raphael, J. Chem. Soc., Perkin Trans. 1, **1977**, 1674; (b) M. Ando, A. Akahane, H. Yamaoka, and T. Takahase, J. Org. Chem., **47**, 3909 (1982).

938. M. Ribi, A. Chang Sin-Ren, H. P. Küng, and C. H. Eugster, Helv. Chim. Acta, **52**, 1685 (1969).

939. T. Ohnuma, T. Oishi, and Y. Ban, J. Chem. Soc., Chem. Commun., **1973**, 301.

940. J. Shavel, Jr., U.S. Pat. 2,975,184 (1961) [C.A., **55**, 15516e (1961)].

941. M. Laing, K. H. Pegel, L. P. L. Piacenza, L. Phillips, and E. S. Waight, Tetrahedron Lett., **1973**, 3043.

942. M. R. Nair, S. Hilgard, J. Klinot, K. Waisser, and A. Vystr / il, Collect.

Czech. Chem. Commun., **41**, 770 (1976).
943. E. Aufderhaar, J. E. Baldwin, D. H. R. Barton, D. J. Faulkner, and M. Slaytor, J. Chem. Soc. (C), **1971**, 2175.
944. T. Norin and B. Winell, Acta Chem. Scand., **26**, 2289 (1972).
945. T. Norin and B. Winell, Acta Chem. Scand., **26**, 2297 (1972).
946. E. Klinotová, J. Beneš, and A. Vystr / il, Collect. Czech. Chem. Commun., **40**, 2861 (1975).
947. J. Meinwald, J. K. Crandall, and P. G. Gassman, Tetrahedron, **18**, 815 (1962).
948. D. Davalian, P. J. Garrat, and R. Riguera, J. Org. Chem., **42**, 368 (1977).
949. N. Harada, N. Ochiai, K. Takada, and H. Uda, J. Chem. Soc., Chem. Commun., **1977**, 495.
950. A Krebs, W. Rüger, and W. U. Nickel, Tetrahedron Lett., **22**, 4937 (1981).
951. D. W. H. MacDowell and F. L. Ballas, J. Org. Chem., **39**, 2239 (1974).
952. R. E. Ireland, and J. A. Marshall, J. Org. Chem., **27**, 1620 (1962).
953. T. Terasawa and T. Okada, J. Chem. Soc., Perkin Trans. 1, **1979**, 990.
954. J. M. Bec, J. Durand, and J. Huet, Bull. Soc. Chim. Fr., **1972**, 4344.
955. Z. G. Hajos and D. R. Parrish, J. Org. Chem., **39**, 1612 (1974).
956. D. Behr, I. Wahlberg, and C. R. Enzell, Acta Chem. Scand., Ser. B, **31**, 793 (1977).
957. J. B. Hendrickson and J. S. Farina, J. Org. Chem., **45**, 3361 (1980).
958. P. Jefferson, E. McDonald, and P. Smith, Tetrahedron Lett., **1978**, 585.
959. (a) J. N. Gardner, B. A. Anderson, and E. P. Oliveto, J. Org. Chem., **34**, 107 (1969); (b) M. E. Garst, V. A. Roberts, and C. Prussin, J. Org. Chem., **47**, 3969 (1982).
960. H. C. Kluender and G. P. Peruzzotti, Tetrahedron Lett., **1977**, 2063.
961. M. N. Galbraith and D. H. S. Horn, J. Chem. Soc., Chem. Commun., **1972**, 113.
962. E. J. Cragoe, Jr., and O. Woltersdorf, Jr., *Ger. Offen.* 2,448,393 (1975) [C.A., **83**, 114066v (1975)].
963. W. L. Parker and R. B. Woodward, J. Org. Chem., **34**, 3085 (1969).
964. K. Yamakawa, T. Satoh, N. Ohba, R. Skaguchi, S. Takita, and N. Tamura, Tetrahedron, **37**, 473 (1981).
965. F. Bohlmann, H. J. Förster, and C. H. Fischer, Justus Liebigs Ann. Chem., **1976**, 1487.
966. J. Vrko / , V. Herout, and F. Šorm, Collect. Czech. Chem. Commun., **28**, 1084 (1963).

967. (a) B. M. G. Gaveby, J. C. Huffman, and P. Magnus, J. Org. Chem., **47**, 3779 (1982); (b) K. Yamakawa, K. Nishitani, and A. Yamamoto, Chem. Lett., **1976**, 177.
968. P. De Clercq and M. Vandewalle, J. Org. Chem., **42**, 3447 (1977).
969. E. Dynesen, Acta Chem. Scand., Ser. B, **29**, 77 (1975).
970. K. Inoue, S. Ueda, Y. Shiobara, and H. Inouye, Tetrahedron Lett., **21**, 621 (1980).
971. E. W. Colvin, J. Martin, W. Parker, R. A. Raphael, B. Shroot, and M. Doyle, J. Chem. Soc., Perkin Trans. 1, **1972**, 860.
972. W. L. Meyer, R. A. Manning, P. G. Schroeder, and D. C. Shew, J. Org. Chem., **42**, 2754 (1977).
973. R. K. Boeckman, Jr., J. P. Bershas, J. Clardy, and B. Solheim, J. Org. Chem., **42**, 3630 (1977).
974. C. H. Kuo and D. Taub, Fr. Pat. 1,511, 392 (1968) [C.A., **70**, 88095p (1969)].
975. C. H. Kuo, D. Taub, and N. L. Wendler, Chem. Ind. (London), **1966**, 1340.
976. C. H. Kuo, D. Taub, and N. L. Wendler, J. Org. Chem., **33**, 3126 (1968).
977. A. V. Platonova, S. N. Ananchenko, and I. V. Torgov, Izv. Akad. Nauk SSSR, Ser. Khim., **1974**, 1581; [C.A., **81**, 152493y (1974)].
978. M. Nara, S. Terashima, and S. Yamada, Tetrahedron, **36**, 3171 (1980).
979. G. Haffer, U. Eder, G. Sauer, and R. Wiechert, Chem. Ber., **108**, 2665 (1975).
980. A. L. Johnson, J. Med. Chem., **15**, 360 (1972).
981. T. Terasawa and T. Okada, J. Chem. Soc., Perkin Trans. 1, **1978**, 576.
982. T. Terasawa and T. Okada, J. Org. Chem., **46**, 381 (1981).
983. J. S. Bindra, A. T. Neyyrapally, R. C. Gupta, V. P. Kamboj, and N. Anand, J. Med. Chem., **18**, 921 (1975).
984. H. Yamaguchi, Y. Harigaya, and M. Onda, Chem. Pharm. Bull., **30**, 569 (1982).
985. L. M. Kogan, V. E. Gulaya, B. Lacoume, and I. V. Torgov, Izv. Akad. Nauk SSSR, Ser. Khim., **1970**, 1356; [C.A., **74**, 13319p (1971)].
986. G. D. Searle Co., Neth. Appl. 6,512,786 (1966) [C.A., **65**, 5506a (1966)].
987. R. Pappo, U.S. Pat. 3,337,542 (1967) [C.A., **68**, 29947d (1968)].
988. L. N. Mander, G. J. Potter, S. G. Pyne, and M. Woolias, Aust. J. Chem., **34**, 1913 (1981).
989. S. V. Bhat, B. S. Bajwa, H. Dornauer, and N. J. de Souza, J. Chem. Soc., Perkin Trans. 1, **1982**, 767.
990. M. Mervi / , Y. Ben-David, and E. Ghera, Tetrahedron Lett., **22**, 5091 (1981).

991. M. Mervi / and E. Ghera, J. Am. Chem. Soc., **99**, 7673 (1977).
992. G. Ghera, Y. Ben-David, and D. Becker, Tetrahedron Lett., **1977**, 463.
993. J. S. Baran, D. D. Langford, C. D. Liang, and B. S. Pitzele, J. Med. Chem., **17**, 184 (1974).
994. G. V. Baddeley, A. J. Bealing, P. R. Jefferies, and R. W. Retallack, Aust. J. Chem., **17**, 908 (1964).
995. M. Balci and W. M. Jones, J. Am. Chem. Soc., **102**, 7607 (1980).
996. C. E. Hatch III, J. S. Baum, T. Takashima, and K. Kondo, J. Org. Chem., **45**, 3281 (1980).
997. Y. Takamura, M. Kunitomo, T. Masui, and M. Terashima, Chem. Ind. (London), **1972**, 168.
998. R. J. P. Corriu and C. Guerin, J. Organomet. Chem., **144**, 165 (1978).
999. H. Wynberg and B. Marsman, J. Org. Chem., **45**, 158 (1980).
1000. K. E. Hine and R. F. Childs, J. Am. Chem. Soc., **95**, 3289 (1973).
1001. K. E. Hine and R. F. Childs, J. Chem. Soc., Chem. Commun., **1972**, 144.
1002. K. R. Kopecky and C. Levine, Can. J. Chem., **59**, 3273 (1981).
1003. I. Elphimoff-Felkin and P. Sarda, Tetrahedron, **33**, 511 (1977).
1004. W. R. Roush and A. P. Spada, Tetrahedron Lett., **23**, 3773 (1982).
1005. L. Novák, G. Baán, J. Marosfalvi, and C. Szántay, Chem. Ber., **113**, 2939 (1980).
1006. P. C. Traas, H. Boelens, and H. J. Takken, Synth. Commun., **6**, 489 (1976).
1007. V. V. Veselovskii and A. M. Moiseenkov, Synthesis, **1974**, 58.
1008. P. Wilder, Jr., A. R. Portis, Jr., G. W. Wright, and J. M. Shepherd, J. Org. Chem., **39**, 1636 (1974).
1009. R. J. Armstrong, R. F. C. Brown, F. W. Eastwood, and M. E. Romyn, Aust. J. Chem., **32**, 1767 (1979).
1010. H. O. House and C. J. Blankley, J. Org. Chem., **33**, 53 (1968).
1011. J. W. Wheeler and R. H. Chung, J. Org. Chem., **34**, 1149 (1969).
1012. W. Cocker, K. J. Crowley, and K. Srinivasan, J. Chem. Soc., Perkin Trans. 1, **1973**, 2485.
1013. Y. Asaka, T. Kamikawa, and T. Kubota, Tetrahedron Lett., **1972**, 1597.

.
1014 P. F. Schuda, H. L. Ammon, M. R. Heimann, and S. Bhattacharjee, J. Org. Chem., **47**, 3434 (1982).
1015 N. Lander, Z. Ben-Zvi, R. Mechoulam, B. Martin, M. Nordqvist, and S. Agurell, J. Chem. Soc., Perkin Trans. 1, **1976**, 8.
1016 G. R. Kieczykowski and R. H. Schlessinger, J. Am. Chem. Soc., **100**, 1938 (1978).
1017 J. A. Marshall and S. F. Brady, Tetrahedron Lett., **1969**, 1387.
1018 J. A. Marshall and S. F. Brady, J. Org. Chem., **35**, 4608 (1970).
1019 T. Kato and H. Kondo, Bull. Chem. Soc. Jpn., **54**, 1573 (1981).
1020 Toray Industries Ltd., Jpn. Kokai Tokkyo Koho 81 122, 322 [C.A., **96**, 51871z (1982)].
1021 R. A. Finnegan and P. L. Bachman, J. Org. Chem., **36**, 3196 (1971).
1022 M. Matsui, T. Kitahara, and K. Takagi, Jpn. Kokai Tokkyo Koho 79 48,738 (1979) [C.A., **91**, 174903r (1979)].
1023 J. Lafontaine, M. Mongrain, M. Sergent-Guay, L. Ruest, and P. Deslongchamps, Can. J. Chem., **58**, 2460 (1980).
1024 M. Ando, S. Sayama, and K. Takase, Chem. Lett., **1979**, 191.
1025 P. W. Collins, E. Z. Dajani, D. R. Driskill, M. S. Bruhn, C. J. Jung, and R. Pappo, J. Med. Chem., **20**, 1152 (1977).
1026 D. J. Dawson and R. E. Ireland, Tetrahedron Lett., **1968**, 1899.
1027 M. R. Roberts and R. H. Schlessinger, J. Am. Chem. Soc., **103**, 724 (1981).
1028 G. Fráter, Helv. Chim. Acta, **61**, 2709 (1978).
1029 S. Torii, H. Tanaka, and Y. Kobayashi, J. Org. Chem., **42**, 3473 (1977).
1030 R. K. Hill, M. G. Fracheboud, S. Sawada, R. M. Carlson, and S. J. Yan, Tetrahedron Lett., **1978**, 945.
1031 R. Mechoulam, N. Lander, and S. Dikstein, Br. Pat. Appl. 2,027,021 (1980) [C.A., **95**, 80289a (1981)].
1032 A. Asselin, M. Mongrain, and P. Deslongchamps, Can. J. Chem., **46**, 2817 (1968).
1033 J. W. Clark-Lewis and M. M. Mahandru, Aust. J. Chem., **24**, 563 (1971).

.
1034 J. Nickel, E. Seeger, W. Engel, G. Engelhardt, and A. Eckenfels, Ger. . Offen. 2,047,804 (1972) [C.A., **77**, 34157m (1972)].
1035 L. I. Zakharkin, A. P. Pryanishnikov, and V. V. Guseva, U.S.S.R Pat. . 734,185 (1980) [C.A., **93**, 185843p (1980)].
1036 J. W. Clark-Lewis and D. C. Skingle, Aust. J. Chem., **20**, 2169 (1967). .
1037 P. LeRoy Enderson and D. A. Brittain, Switz. Pat. 609,663 (1979) [C.A., . **90**, 203673c (1979)].
1038 M. Lounasmaa and M. Puhakka, Acta Chem. Scand., Ser. B, **32**, 216 . (1978).
1039 M. Lounasmaa and M. Puhakka, Planta Med., **34**, 180 (1978) [C.A., . **90**, 38821 (1979)].
1040 R. J. Stoodley and N. S. Watson, J. Chem. Soc., Perkin Trans. 1, **1973**, . 2105.
1041 M. Matsui, T. Kitahara, K. Sakakibara, H. Yonehara, and S. Takeuchi, . Jpn. Pat. 73 30,274 [C.A., **80**, 36986s (1974)].
1042 P. A. Grieco, T. Takigawa, S. L. Bongers, and H. Tanaka, J. Am. Chem. . Soc., **102**, 7587 (1980).
1043 P. H. Nelson and K. G. Untch, U.S. Pat. 3,975,540 (1976) [C.A., **86**, . 72296z (1977)].
1044 L. E. Friedrich and R. A. Cormier, J. Org. Chem., **36**, 3011 (1971). .
1045 A. Mondon and H. Witt, Chem. Ber., **103**, 1522 (1970). .
1046 T. C. Kung and C. D. Gutsche, J. Org. Chem., **43**, 4069 (1978). .
1047 K. Psotta and A. Wiechers, Tetrahedron, **35**, 255 (1979). .
1048 S. Torii, H. Tanaka, and Y. Kobayashi, Ger. Offen. 2,824,843 (1979) . [C.A., **90**, 203548v (1979)].
1049 K. Mori and M. Matsui, Tetrahedron Lett., **1965**, 2347. .
1050 A. Ogiso and I. Iwai, Chem. Pharm. Bull., **12**, 820 (1964). .
1051 G. R. Allen, Jr. and M. J. Weiss, J. Org. Chem., **30**, 2904 (1965). .
1052 B. Voigt, G. Adam, N. S. Kobrina, E. P. Serebryakov, and N. D. Zelinskii, . Z. Chem., **17**, 372 (1977).
1053 I. A. Gurvich, N. S. Kobrina, and V. F. Kucherov, Izv. Akad. Nauk SSSR,

. Ser. Khim., **1969**, 1805 [C.A., **72**, 3103h (1970)].
1054 B. N. Ravi and D. J. Faulkner, J. Org. Chem., **43**, 2127 (1978).
.
1055 K. Sakai and S. Amemya, Jpn. Kokai 73 68,550 [C.A., **80**, 70422g
. (1974)].
1056 Upjohn Co., Neth, Pat. Appl. 6,611,478 (1967) [C.A., **68**, 2633m (1968)].
.
1057 M. H. Beale and J. MacMillan, J. Chem. Soc., Perkin Trans. 1, **1980**,
. 877.
1058 M. Fétizon, F. J. Kakis, and V. Ignatiadou-Ragoussis, J. Org. Chem., **38**,
. 1732 (1973).
1059 Anon, Jpn. Kokai 75, 130,732 [C.A., **85**, 142808y (1976)].
.
1060 A. Ichihara, R. Kimura, S. Yamada, and S. Sakamura, J. Am. Chem.
. Soc., **102**, 6353 (1980).
1061 Y. Konishi, M. Kawamura, Y. Iguchi, Y. Arai, and M. Hayashi,
. Tetrahedron, **37**, 4391 (1981).
1062 Warner-Lambert Pharmaceutical Co., Fr. Pat. M2784 [C.A., **62**, 13195c
. (1965)].
1063 E. Chan, S. R. Putt, H. D. H. Showalter, and D. C. Baker, J. Org. Chem.,
. **47**, 3457 (1982).
1064 P. Condran, Jr., M. L. Hammond, A. Mourino, and W. H. Okamura, J.
. Am. Chem. Soc., **102**, 6259 (1980).
1065 K. Takahashi, S. Shibata, S. Yano, M. Harada, H. Saito, Y. Tamura, and
. A. Kumagai, Chem. Pharm. Bull., **28**, 3449 (1980).
1066 S. Shibata, A. Kumagai, M. Harada, S. Yano, H. Saito, and K.
. Takahashi, Br. Pat. Appl. 2,075,835 (1981) [C.A., **96**, 143114h (1982)].