1348, 1152, 1117 cm^{-1}; nmr (CCl_4) δ 1.1–2.3 (mult, 16 H); ms *m/e* (%) 152 (43), 123 (28), 109 (100), 96 (47), 95 (38), 83 (94), 81 (52), 67 (63), 55 (59), 41 (60). *Anal.* Calcd for $C_{10}H_{16}O$: 152.12011. Found: 152.11997.

Methylation of 2-Trimethylsiloxybicyclo[5.3.0]dec-1-ene (43). A solution of 2-trimethylsiloxybicyclo[5.3.0]dec-1-ene (56 mg, 0.25 mmol) in 3 ml of 1,2-dimethoxyethane with a few milligrams of triphenylmethane as an indicator was treated with methyllithium at 25° until a color persisted. Then methyl iodide (0.3 ml) was added and the mixture stirred for 2 min. Water was added and the product extracted with 2 × 50 ml portions of hexane. An oil, 29 mg (71%), was obtained upon evaporation of 1-methylbicyclo-[5.3.0]decan-2-one (**48**). The oil was a single spot by tlc on silica gel: ir (CCl_4) 1736, 1412, 1374 cm^{-1}; nmr (CCl_4) δ 1.13 (s) and 1.17 (s) total 3 H, cis and trans isomers; 1.2–2.3 (mult, 15 H); ms *m/e* (%) 166 (0.4), 151 (16), 110 (100), 95 (75), 81 (77), 68 (42), 67 (56), 55 (43), 41 (67). *Anal.* Calcd for $C_{11}H_{18}O$: 166.13576. Found: 166.13321.

Acknowledgment. We thank the National Science Foundation and the National Institutes of Health for their generous support of our programs. We also thank the National Science Foundation and the Wisconsin Alumni Research Foundation for support in the purchase of nmr and mass spectrometric facilities.

New Synthetic Reactions. A Versatile Cyclobutanone (Spiroannelation) and γ-Butyrolactone (Lactone Annelation) Synthesis[1]

Barry M. Trost*[2] and Mitchell J. Bogdanowicz

Contribution from the Department of Chemistry, University of Wisconsin, Madison, Wisconsin 53706. *Received February 23, 1973*

Abstract: The condensation of aldehydes and ketones with diphenylsulfonium cyclopropylide followed by acid treatment upon work-up leads directly to cyclobutanones in 44–97% yields *via* intermediate oxaspiropentanes. With cyclic ketones (a spiroannelation process), the reaction is highly stereoselective. With diphenylsulfonium 2-methylcyclopropylide, spiroannelation generates 3-methylcyclobutanones predominantly indicating preferential migration of the secondary carbon atom in the intermediate oxaspiropentane. Treatment of the cyclobutanones with basic hydrogen peroxide, sodium hypobromite, or hypochlorous acid effects smooth (82–100%) conversion to the corresponding γ-butyrolactones in which the more substituted carbon atom migrates exclusively and with retention of configuration. The high yields associated with these reactions and the ubiquitous nature of the carbonyl group make these methods valuable entries into cyclobutanones and γ-butyrolactones.

Examination of past and present literature shows the lack of a general method for the preparation of substituted cyclobutanones from aldehydes and ketones as starting materials. Nevertheless, many cyclobutanones have been prepared and described in the literature.[3,4] Basically, only a few of these methods are generally useful, some of which are summarized in Table I. The evolving utility of cyclobutanones as intermediates in synthesis led us to explore a method based on the ubiquitous carbonyl function. Our earlier finding of the formation of spiro[5.3]nonan-2-one in the quenching of the reaction of cyclopropyllithium and triphenylsulfonium fluoroborate with cyclohexanone suggested the use of cyclopropyl sulfur ylides.[5] This new cyclobutanone synthesis transforms a carbonyl carbon into the 2 carbon of a cyclobutanone ring through the intermediacy of an α-oxycyclopropylcarbinyl cation. An electrofugal center attached to the cyclopropane ring drastically modifies the chemical behavior of the latter. While the ready interconversion of cyclopropylcarbinyl, cyclobutyl, and homoallyl systems[6] causes product control of reactions proceeding by a cyclopropylcarbonium ion path to be frequently difficult, reactions involving oxycyclopropylcarbonium ion intermediates can be expected to be unidirectional. On the assumption that an oxycyclopropylcarbonium ion is the final stage of the acid catalyzed ring opening of an oxaspiropentane, the product of rearrangement of α-oxycyclopropylcarbinyl systems should be cyclobutanones. Some α-oxycyclopropylcarbinyl systems have been studied in recent years;[7–10] however, the applicability was limited due to the difficulties associated

(1) For preliminary reports of portions of this work, see (a) B. M. Trost and M. J. Bogdanowicz, *J. Amer. Chem. Soc.*, **93**, 3773 (1971); (b) M. J. Bogdanowicz and B. M. Trost, *Tetrahedron Lett.*, 923 (1973). This manuscript represents part X of this series.

(2) Camille and Henry Dreyfus Teacher–Scholar Grant Recipient.

(3) For a series of articles dealing with cyclobutanones, see (a) J. M. Conia and J. Gore, *Bull. Chim. Soc. Fr.*, 726, 735, 744, 752, 755, 763, 768, 773 (1963); (b) J. M. Conia and J. Salaun, *ibid.*, 1957 (1964); (c) J. M. Conia and C. Faget, *ibid.*, 1963 (1964); (d) J. M. Conia and J. Bore, *ibid.*, 1968 (1964); (e) J. M. Conia, H. Gore, J. Salaun, and L. Ripoll, *ibid.*, 1976, 1981 (1964); (f) J. M. Conia and J. Salaun, *ibid.*, 2747, 2751, 2755 (1965); (g) H. Audier, J. M. Conia, M. Fetizon, and J. Gore, *ibid.*, 787 (1967); (h) J. Gore, C. Djerassi, and J. M. Conia, *ibid.*, 950 (1967); (i) J. Gore, J. M. Denis, P. Leriverend, and J. M. Conia, *ibid.*, 2432 (1968); (j) J. Salaun and J. M. Conia, *ibid.*, 3730, 3735 (1968); (k) J. Salaun and J. M. Conia, *Chem. Commun.*, 1358 (1970); (l) J. M. Conia and J. R. Salaun, *Accounts Chem. Res.*, **5**, 33 (1972).

(4) For a comprehensive review of cyclobutane chemistry, see D. Seebach, S. Beckman, and H. Geiger in "Methoden der Organischen Chemie," Band IB, Teil 4, E. Mueller, Ed., Georg Thieme Verlag, Stuttgart, 1971.

(5) B. M. Trost, R. W. LaRochelle, and M. J. Bogdanowicz, *ibid.*, 3449 (1970).

(6) M. Hanack and H. J. Schneider, *Fortschr. Chem. Forsch.*, **8**, 554 (1967).

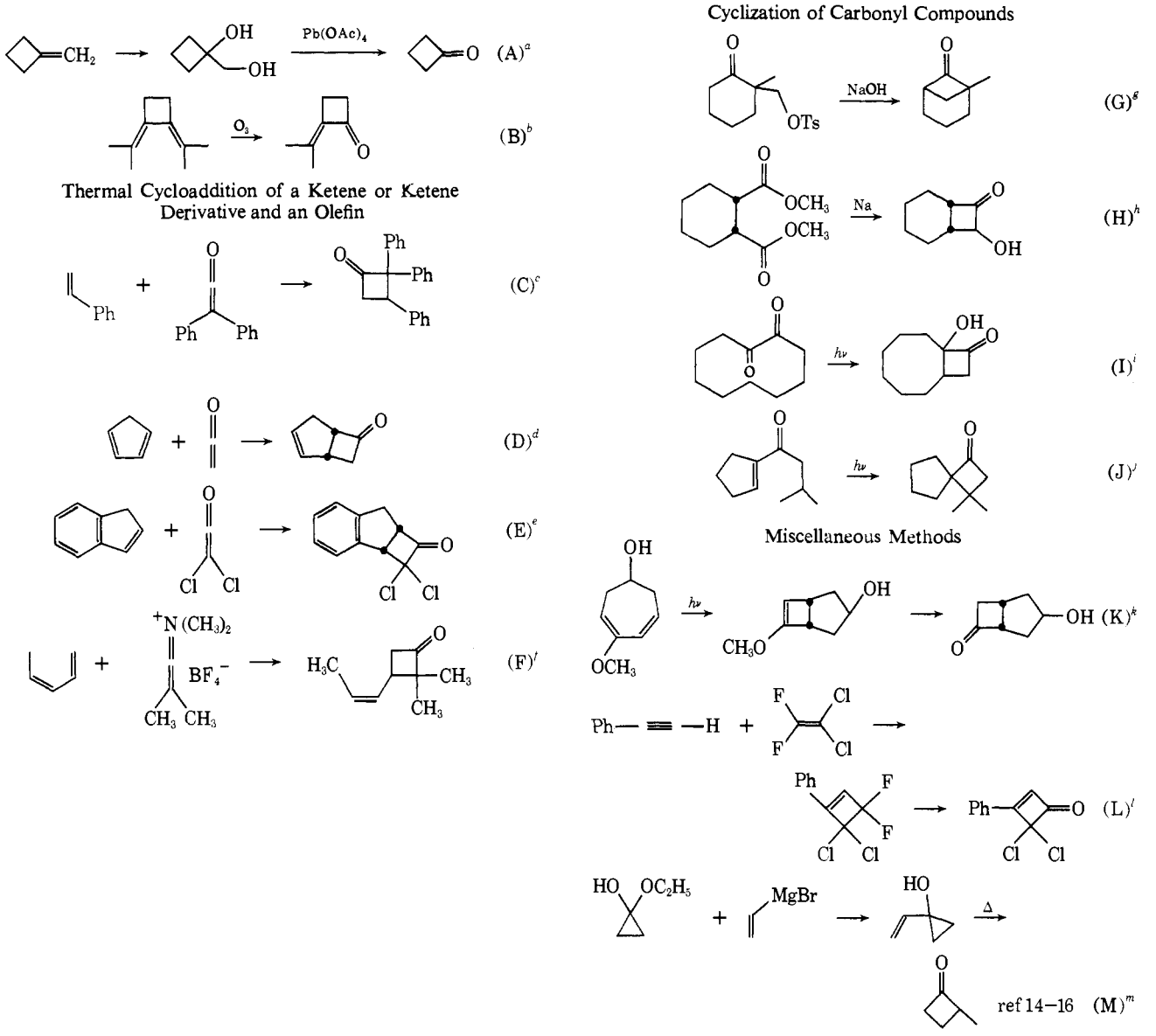
(7) H. H. Wasserman, R. E. Cochoy, and M. S. Baird, *J. Amer. Chem. Soc.*, **91**, 2376 (1969); H. H. Wasserman, H. W. Adickes, and O. E. de Ochoa, *ibid.*, **93**, 5586 (1971).

(8) J. R. Salaun and J. M. Conia, *Tetrahedron Lett.*, 2849 (1972).

(9) L. Crombie, M. L. Games, and D. J. Pointer, *J. Chem. Soc. C*, 1347 (1968); H. W. Thielmann and H. Hecker, *Justus Liebigs Ann. Chem.*, **728**, 158 (1969); N. J. Turro and R. B. Gagosian, *J. Amer. Chem. Soc.*, **92**, 2036 (1970); E. E. Wenkert, R. A. Mueller, E. J. Reardon, S. S. Sathe, D. J. Scharf, and G. Tosi, *ibid.*, **92**, 7428 (1970).

(10) H. H. Wasserman and D. C. Clagett, *ibid.*, **88**, 5368 (1966).

Table I. General Synthesis of Cyclobutanones. Oxidative Cleavage of Alkylidene Cyclobutanes



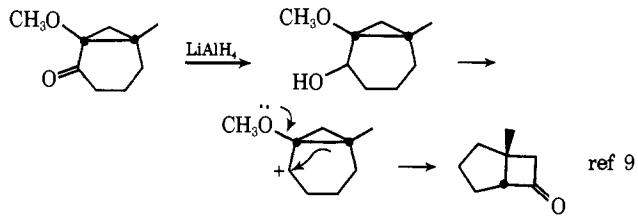
[a] J. D. Roberts and C. W. Sauer, *J. Amer. Chem. Soc.*, **71**, 3925 (1949). For direct cleavage of the olefin with ozone, see J. M. Conia, P. Leriverend, and J-L. Ripoll, *Bull. Soc. Chim. Fr.*, 1803 (1961). [b] S. V. Lebedeff, *Zh. Russ. Fiz-Khim. Obshchest.*, **43**, 820 (1911). [c] C. S. Marvel and M. I. Kohan, *J. Org. Chem.*, **16**, 741 (1951). [d] E. Vogel and K. Müller, *Justus Liebigs Ann. Chem.*, **615**, 29 (1958). [e] L. Ghosez, R. Montaigne, A. Roussel, H. VanLierde, and P. Molliet, *Tetrahedron*, **27**, 615 (1971). [f] J. Marchand-Brynaert and L. Ghosez, *J. Amer. Chem. Soc.*, **94**, 2870 (1972). [g] E. Wenkert and D. P. Strike, *J. Org. Chem.*, **27**, 1883 (1962). [h] A. C. Cope and E. C. Herrick, *J. Amer. Chem. Soc.*, **72**, 983 (1950). [i] W. H. Urry, D. J. Trecker, and D. A. Winey, *Tetrahedron Lett.*, 609 (1962). [j] A. B. Smith, A. M. Foster, and W. C. Agosta, *J. Amer. Chem. Soc.*, **94**, 5100 (1972). [k] O. L. Chapman, D. J: Pasto, and A. A. Grisworld, *ibid.*, **84**, 1213, 1220 (1962). [l] J. D. Roberts, G. B. Kline, and H. E. Simmons, *ibid.*, **75**, 4765 (1953). [m] H. H. Wasserman, R. E. Cochoy, and M. S. Baird, *ibid.*, **91**, 2376 (1969); H. H. Wasserman, H. W. Adickes, and O. E. de Ochoa, *ibid.*, **93**, 5586 (1971); J. R. Salaun and J. M. Conia, *Tetrahedron Lett.*, 2849 (1972).

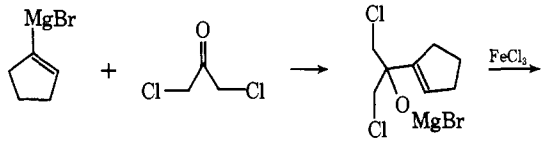
with their synthesis. A reaction in which α-oxycyclopropylcarbinyl systems play an important role is the acid-catalyzed rearrangement of cyclobutanones. The equilibration of bicyclic chloro ketone **1** to a mixture of **1**, **2**, and **3** in formic acid is rationalized adequately by invoking the intermediacy of an α-oxycyclopropylcarbinyl cation.

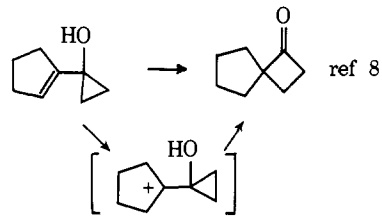
The facile synthesis of oxaspiropentanes[11] can be used in conjunction with the aforementioned rearrangement to produce a high yield cyclobutanone synthesis. Since this reaction provides the attachment of a spiro ring at a carbonyl carbon in a single step, the process is termed spiroannelation. The spiroannelation procedure can be utilized to prepare cyclobutanones *via* either an irreversible or reversible diphenylsulfonium cyclopropylide generation. Irreversible generation of ylide **5** was accomplished with sodium methylsulfinyl carbanion[12] in dimethoxyethane (DME) at −40° (method A, Table II). It has generally been found that reversible genera-

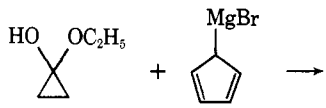
(11) (a) B. M. Trost and M. J. Bogdanowicz, *J. Amer. Chem. Soc.*, **95**, 5311 (1973); (b) M. J. Bogdanowicz and B. M. Trost, *Tetrahedron Lett.*, 887 (1972); (c) for the parent system, see J. R. Salaun and J. M. Conia, *Chem. Commun.*, 1579 (1971).

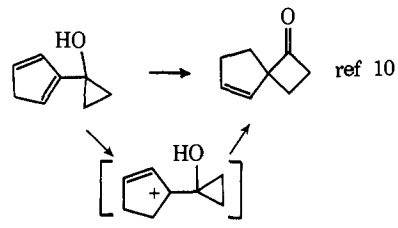
(12) E. J. Corey and M. Chaykovsky, *J. Amer. Chem. Soc.*, 87, 1345 (1965).

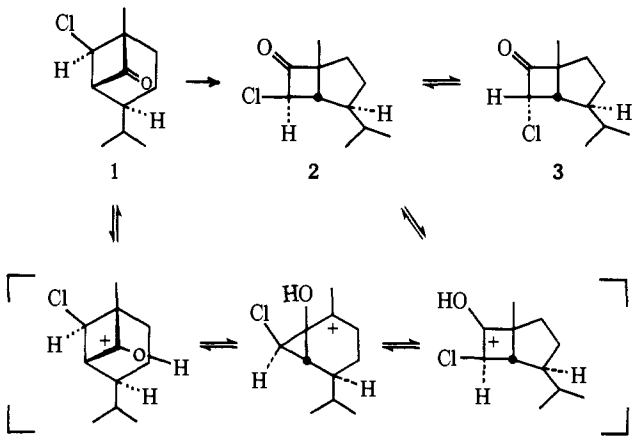










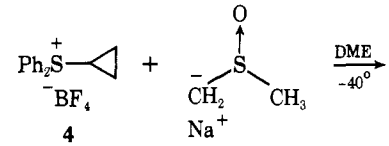


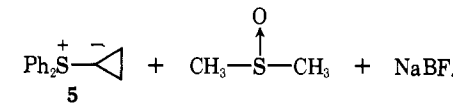
tion of ylide **5** utilizing powdered potassium hydroxide in dimethyl sulfoxide (DMSO) led to higher yields of cyclobutanone with much less experimental difficulty (method B, Table II).

Under reversible ylide formation conditions, a carbonyl compound reacts with **5** to give an epoxide, in this instance a specific class of epoxide, an oxaspiropentane. Upon working up the reaction mixture with aqueous acid the corresponding cyclobutanone is isolated directly. Alternatively, the oxaspiropentane may be isolated and subsequently rearranged quantitatively to the cyclobutanone under a variety of conditions. It should be emphasized that, in most instances, no attempt to maximize yields was made.

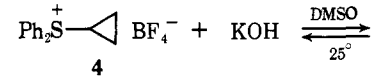
Generally, any Lewis acid has the potential to catalyze the rearrangement of oxaspiropentane to cyclobutanone. Protonic acids effect the rearrangement of oxaspiropentane **6** to cyclobutanone **7**. However, in

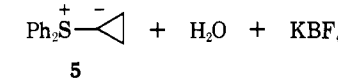
Irreversible

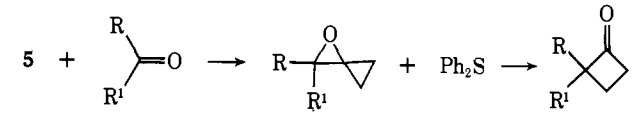


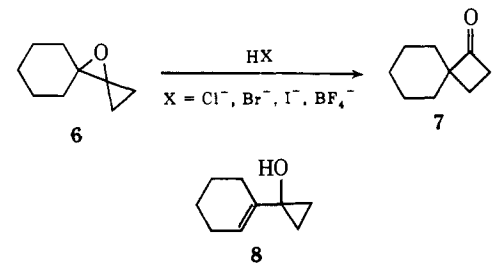


Reversible

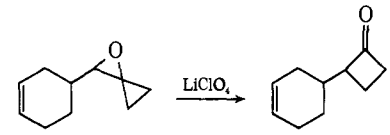








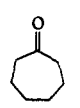
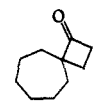
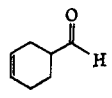
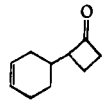
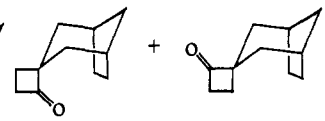
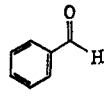
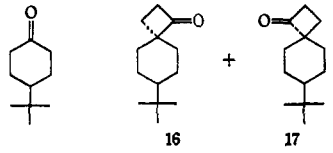
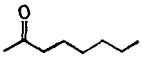
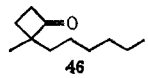
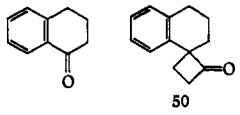
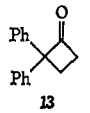
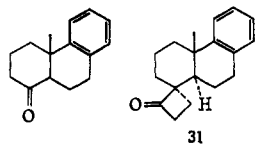
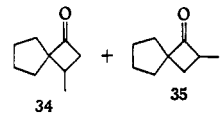
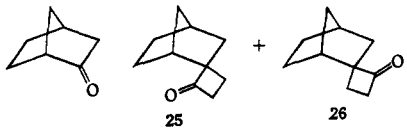
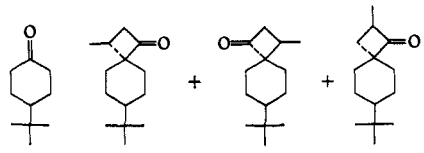
the case where the anion of the acid can act as a base (HX where X = halogen) some vinylcyclopropanol (**8**)[11] is observed. A nonnucleophilic counterion such as fluoroborate circumvents the generation of vinylcyclopropanol (**8**). Other methods may be employed to transform **6** to **7**; thus lithium bromide and hexamethylphosphorotriamide in benzene or lithium perchlorate in refluxing benzene quantitatively rearranges oxaspiropentanes to cyclobutanones.[13] The latter method is most generally applicable since the nonaqueous, nonnucleophilic medium minimizes any alternative reactions. It should be noted that when an oxaspiropentane such as **9**[11] is rearranged with lithium perchlorate in



refluxing benzene to cyclobutanone **10**, longer times are necessary. The decrease in reactivity of oxaspiropentanes derived from aldehydes is attributable to the decrease in relative stability of the α-oxycyclopropylcarbinyl cation generated in the ring opening. Oxaspiropentanes from aldehydes generate a secondary carbonium ion in contrast to oxaspiropentanes from ketones which generate a more stable tertiary cation. However, this difference is not drastic; tertiary oxaspiropentanes rearrange completely in 1 hr and secon-

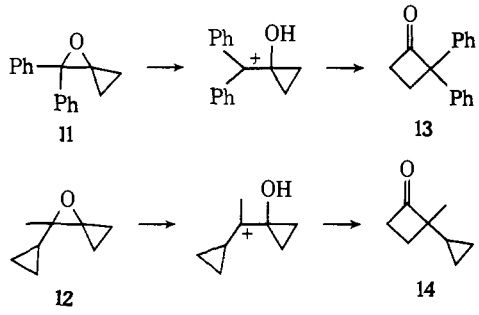
(13) B. Rickborn and R. M. Gerkin, *J. Amer. Chem. Soc.*, **93**, 1693 (1971).

Table II. Preparation of Cyclobutanones

Ketone or aldehyde	Cyclobutanone	% yield	Method	Ketone or aldehyde	Cyclobutanone	% yield	Method
	 14	86[a]	B		 51	90[a] (see text)	B[b]
	 10	87[a]	B		 52 53	44 (52:53, 65:35)	B
	 48	70 87[a]	A B		16 17	80[a] (see text)	B
	 47	59[a]	B				
	 46	92[a]	B		50	72[a]	B
	 13	75 91[a]	A B		31	78[a] (see text)	B
	 49	94[a]	B		 34 35	83[a] (23:24, 93:7)	B[b]
	 7	61 97[a]	A B				
	25 26	65 (25:26, (85:15) 92[a] (25:26, 82:18)	A B		42 43 44	95[a] (see text)	B[b]

[a] Isolated yields. [b] From diphenyl-2-methylcyclopropylsulfonium fluoroborate. [c] Method A: irreversible generation of the ylide with dimsyl anion in dimethoxyethane, vpc determined yields. Method B: reversible generation of the ylide with potassium hydroxide in dimethyl sulfoxide.

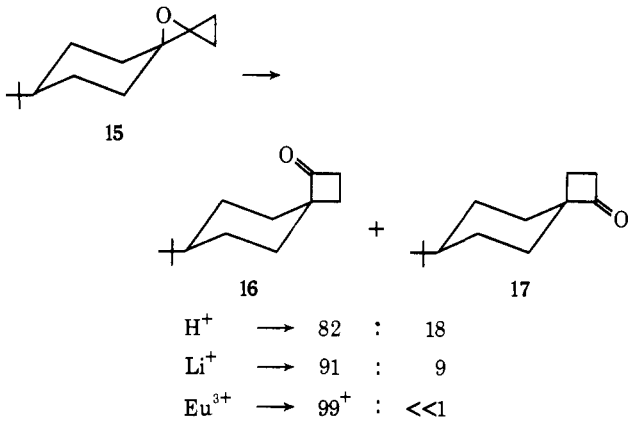
dary oxaspiropentanes in 4 hr with refluxing lithium perchlorate in benzene. On the other hand, substituents on the oxaspiropentane which increase the stability of the carbonium ion relative to a tertiary carbonium ion increase the reactivity of the oxaspiropentane. Thus, under the reaction conditions of their formation,



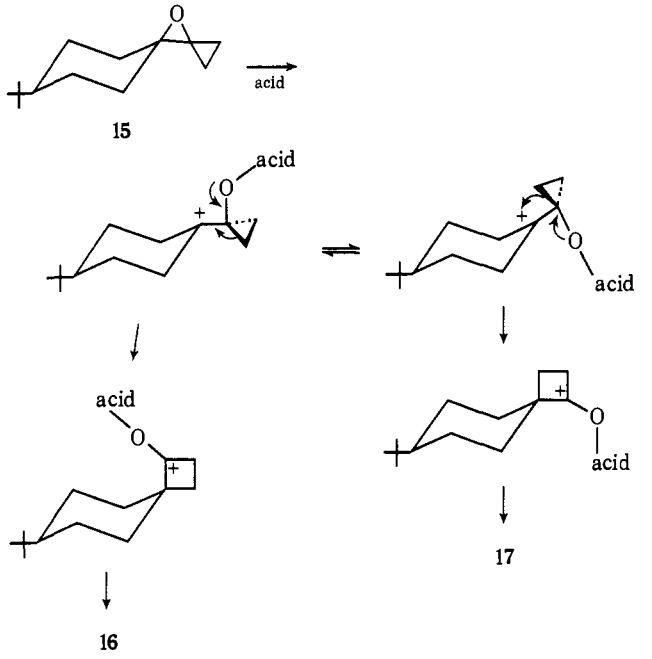
the oxaspiropentanes **11** and **12** are too labile for isolation; the corresponding cyclobutanones (**13** and **14**) are isolated instead. It is interesting to note that even though 2-phenyloxaspiropentane[11] has a stabilizing phenyl moiety, it is isolable due to the counterbalancing secondary center generated upon ring opening.

The stereochemical consequences of the rearrangement illustrate its rapidity relative to other processes, such as bond rotation. Oxaspiropentane **15**[14] is a crystalline solid (mp 26.5–27.0°) homogeneous *via* all the available analytical criteria. The assignment of the depicted stereochemistry rests on the anticipated preferential equatorial attack of ylide and the arguments presented below. In aqueous acids, **15** rearranges to a 82:18 mixture of **16** and **17**. On the other hand, lithium perchlorate in refluxing benzene is more selective, and

(14) E. J. Corey and T. Tauindranathan, *Tetrahedron Lett.*, 4753 (1971); Y. Tsuda, T. Tanno, A. Ukai, and K. Isobe, *ibid.*, 2009 (1971).

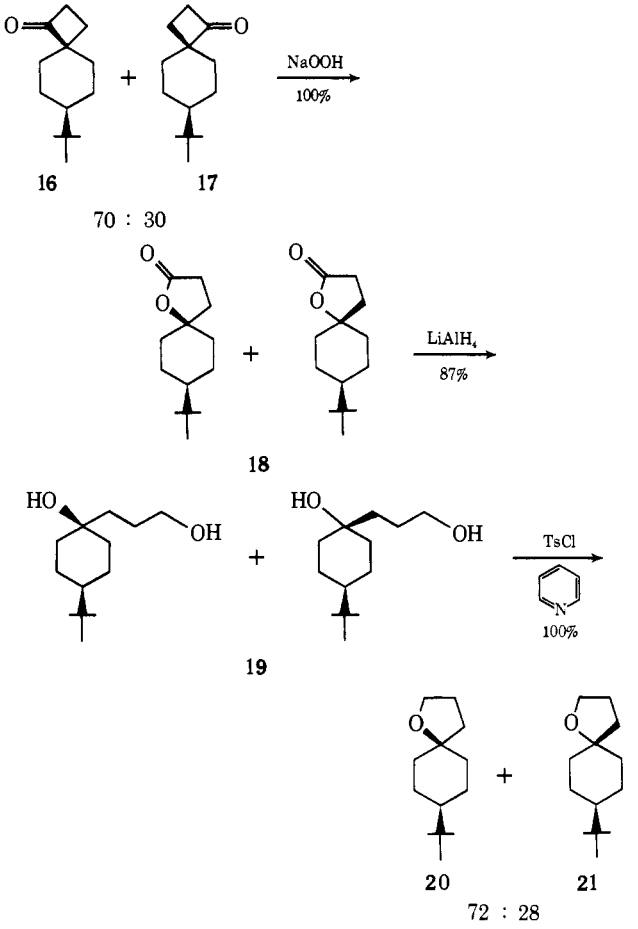


$Eu(fod)_3$[15] in deuteriochloroform at 37° was the most selective Lewis acid utilized. A rationalization for the differences observed with different Lewis acid catalysts resides in the nature of the oxygen–Lewis acid bond. The Lewis acid complexes with the epoxide oxygen with subsequent ring opening, developing a positive charge on carbon. The resulting α-oxycyclopropylcarbinyl cation can bond migrate to the cyclobutyl cation (which in this instance is a protonated cyclobutanone) with inversion at the migration terminus. Alternatively, the α-oxycyclopropylcarbinyl cation can rotate about the carbon–carbon bond to another conformer, which upon bond migration leads to cyclobutanone **17**. The different acids utilized change the relative rates of bond migration versus bond rotation. Lithium and europium form a more ionic bond with oxygen resulting in a greater negative charge on oxygen. The increased charge on oxygen enhances the bond migration relative to bond rotation. However, protonic acids form highly covalent bonds to oxygen minimizing the negative charge, allowing bond rotation to compete with bond migration.



The assignments of stereochemistry of **16** and **17** were based on subsequent transformations to a mixture of tetrahydrofurans **20** and **21** (Scheme I). Basic hydrogen peroxide oxidizes the mixture of **16** and **17** to a mixture of lactones **18**. The rearrangement has been shown to proceed *via* retention of configuration of the migrating carbon.[14] Lithium aluminum hydride reduction of lactone mixture **18** resulted in a mixture of diols **19**. Reaction of this diol mixture with *p*-toluenesulfonyl chloride in pyridine resulted in a mixture of tetrahydrofurans **20** and **21**. Analysis of this mixture by vpc[16] revealed the same ratio as in **16** and **17** within experimental error. To unambiguously determine which tetrahydrofuran can be assigned to the structure **20**, an independent synthesis of **20** was performed (see Scheme II). Allylmagnesium bromide addition to 4-*tert*-butylcyclohexanone produces two alcohols **22** and **23** in an approximately equimolar ratio.[17] Separation of these alcohols was accomplished by thin layer chromatography. The alcohol with the highest R_f was assigned the trans stereochemistry by comparison of its infrared spectrum to the infrared spectrum of an authentic sample of **22**.[18] Pure **22** upon hydroboration[19] resulted in a diol which cyclized with *p*-toluenesulfonyl chloride in pyridine to yield a single tetrahydrofuran. Mixed injection on a vpc[16] column of the mixture of **20** and **21** with pure **20** resulted in enhancement of the major isomer's peak.

Scheme I. Determination of the Stereochemistry of **16** and **17**



(15) The shift reagent utilized is tris(2,2-dimethyl-6,6,7,7,8,8,8-heptafluoro-3,5-octanedionato)europium: R. E. Rondeau and R. E. Sievers, *J. Amer. Chem. Soc.*, 93, 1522 (1971).

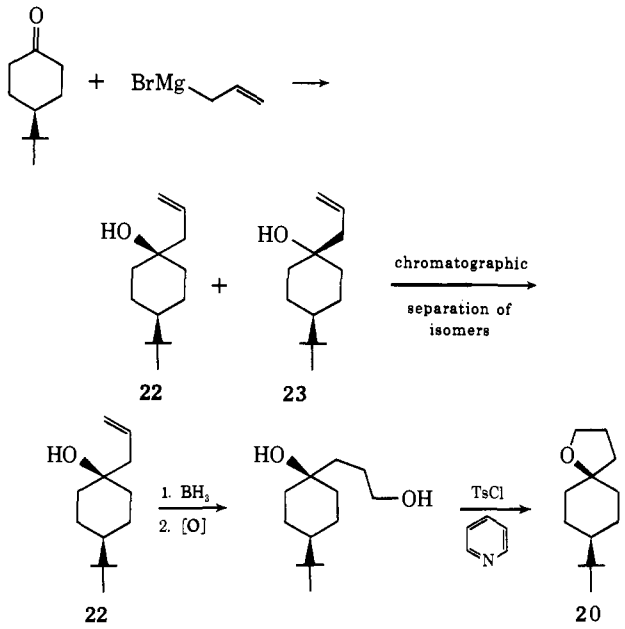
(16) Analyzed by vpc on a 11-ft 8% SE-30 column on Chromosorb W at 138°.

(17) J. Moulines and R. Lalande, *Bull. Chim. Soc. Fr.*, 1075 (1971).

(18) J. Adams, L. Hofmann, Jr., and B. M. Trost, *J. Org. Chem.*, 35, 1600 (1970).

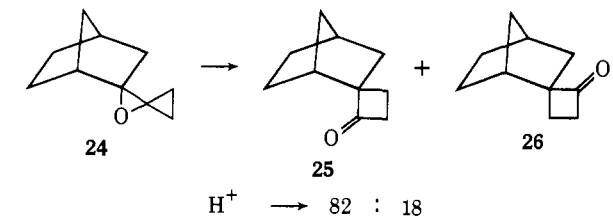
(19) H. C. Brown, "Hydroboration," W. A. Benjamin, New York, N. Y., 1967.

Scheme II. Preparation of **20**



22 23 22 20

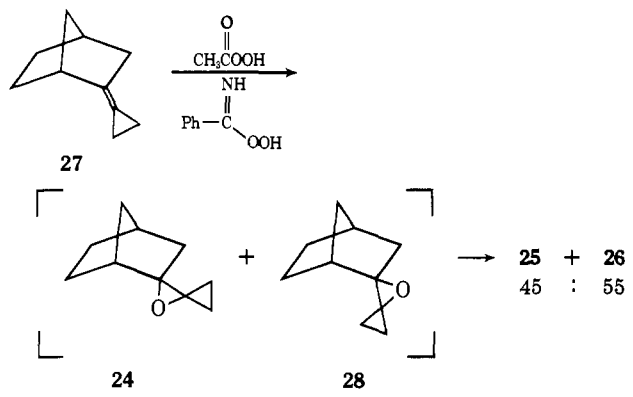
The difference in acids toward specificity in oxaspiropentane rearrangement previously described is also observed when **24**[11] is rearranged to **25** and **26**. An alternative synthesis of a mixture of **25** and **26** was accomplished from the epoxidation of 2-cyclopropylidenenorbornane (**27**)[20] with buffered peracetic acid[21] or perbenzimidic acid.[22] The oxaspiropentanes initially formed in the epoxidation reactions are labile to the conditions. In each case the same ratio of **25**:**26**, 45:55, was obtained. Exo nucleophilic attack on norcamphor is usually preferred. Therefore, ylide **5** should produce predominately dispiroepoxide **24**



24 25 26

$H^+ \longrightarrow$ 82 : 18

$Li^+ \longrightarrow$ 91 : 9



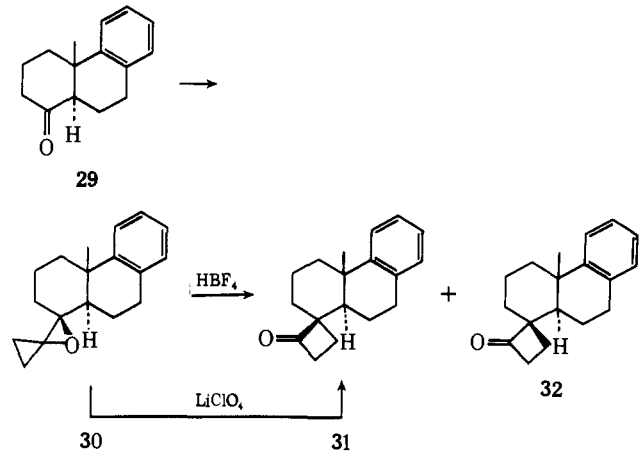
27

25 + 26
45 : 55

24 28

whereas epoxidation of olefin **27** would produce predominately **28**. The difference in cyclobutanone distribution from the two independent routes reflects this preference.

To further illustrate the synthetic utility of this stereoselective spiroannelation procedure, ketone **29** was converted to oxaspiropentane **30**. Subsequent rearrangement with aqueous tetrafluoroboric acid led to a 93:7 ratio of **31**:**32**. However, lithium perchlorate in refluxing benzene resulted in a single cyclobutanone **31**. Confirmation of the stereochemistry of **31** was obtained from europium(III) chemical shift data. The shift of the methylene unit next to the carbonyl was 185 Hz and that of the methyl singlet was 108 Hz. The large shift of the methyl singlet relative to the methylene is in accord with the structure **31** due to the close proximity of the carbonyl and methyl groups. Other evidence in support of the structures **31** and **32** comes from solvent shift studies in the nmr spectra of these cyclobutanones. The shifting of proton absorptions in the nmr with a change of solvent has been studied in great detail in the steroid field.[23] The studies indicate that in benzene the protons in front of the plane perpendicular to the carbonyl group have positive, or downfield shifts, while those behind the plane exhibit upfield or negative shifts relative to carbon tetrachloride. In compound **31** the methyl group lies in front of the plane perpendicular to the carbonyl; thus a positive shift is expected. Alternatively, compound **32** has the methyl group behind the plane of the carbonyl resulting in a negative shift. The shifts observed are in accord with the expected shifts (see Table III). Thus, by proper choice of reagents, the oxaspiropentane to cyclobutanone rearrangement is stereospecific.



29 30 31 32

Table III. Nmr Solvent Shifts (Hz) for the Methyl Singlet of **31** and **32**

Compd	CCl_4	Benzene-d_6	Benzene-d_6–CCl_4
31	74.5	81	+6.5
32	83.0	72	−11.0

The specificity of the oxaspiropentane to cyclobutanone rearrangement is further illustrated with the oxaspiropentanes derived from diphenylsulfonium 2-methylcyclopropylide. In this instance, the specificity lies in the migration of the more substituted bond in the

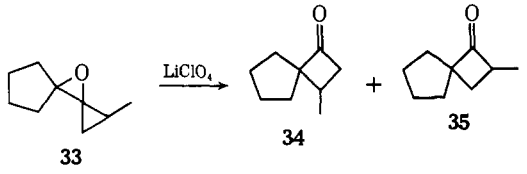
(20) Prepared from cyclopropyltriphenylphosphonium bromide and norbornanone: E. E. Schweizer, C. J. Berninger, and J. G. Thompson, *J. Org. Chem.*, **33**, 336 (1968). For epoxidations of alkylenecyclopropanes, also see J. R. Wiseman and H. F. Chan, *J. Amer. Chem. Soc.*, **92**, 4749 (1970); J. K. Crandall and D. R. Paulson, *J. Org. Chem.*, **33**, 991, 3291 (1968); and ref 3g.

(21) M. Korach, D. Nielson, and W. Rideout, *J. Amer. Chem. Soc.*, **82**, 4328 (1960).

(22) G. B. Payne, *Tetrahedron Lett.*, 763 (1962).

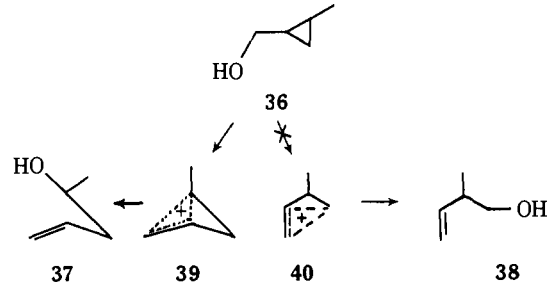
(23) D. H. Williams and N. S. Bhacca, *Tetrahedron*, **21**, 2021 (1965).

α-oxycyclopropylcarbinyl cation intermediate. Oxaspiropentane **33**[11] rearranges to **34** and **35** (93:7) with

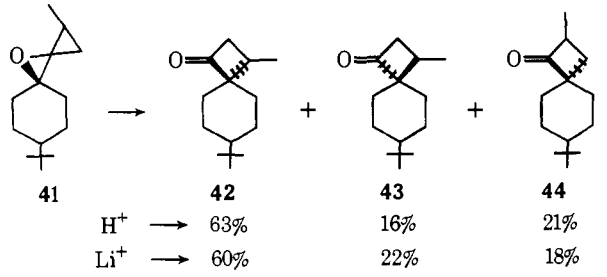


ratio **34** : **35** = 93 : 7

refluxing lithium perchlorate in benzene. An analogous cyclopropylcarbinol **36** solvolyzes in perchloric acid to



homoallyl alcohol **37** rather than **38**, suggesting the intermediate carbonium ion **39** is formed preferentially over carbonium ion **40**.[24] Thus, in cyclopropylcarbinyl cations, the carbon which can best stabilize a positive charge will migrate preferentially. Preferential bond migration is also observed when oxaspiropentane **41**[11]

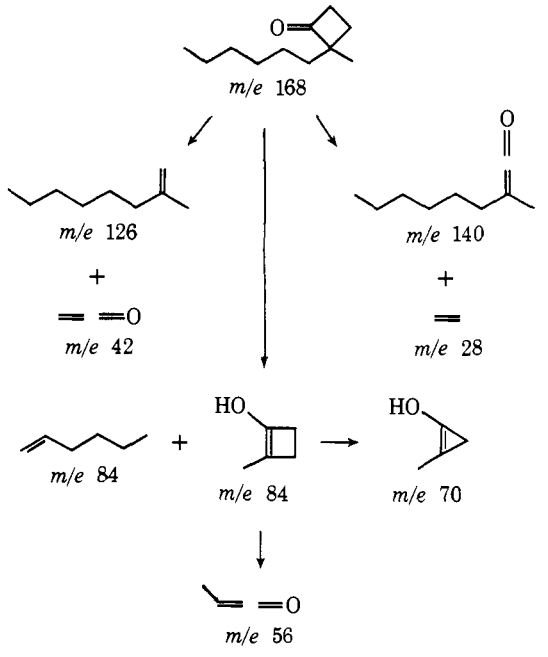


is rearranged with tetrafluoroboric acid or lithium perchlorate in benzene. Analysis of the mixture of **42**, **43**, and **44** by vpc affords distinct separation of the isomers. The order of elution, *i.e.*, **44**, **42**, then **43** is characteristic of their structures. Cyclobutanone **16**, where the carbonyl is axial (and therefore sterically congested), has a shorter retention time than cyclobutanone **17**. Also, 2-methylcyclobutanone **35** is retained less than 3-methylcyclobutanone **34**. Thus the two axial cyclobutanones **44** and **42** come out first in the order of their methyl substitution and equatorial cyclobutanone **43** comes out last.

More definitive structural proof arises from the characteristic mass spectral fragmentations. The major fragmentation pathway of a cyclobutanone is outlined in Scheme III.[3g] The fragmentation can be useful in determining the structure of a cyclobutanone. For example, 2-methyl- and 3-methylcyclobutanones can be distinguished from one another with the aid of high resolution mass spectrometry. Using the fragmentation shown in Scheme III, the expected fragmentations of cyclobutanones **42** and **43** are the loss of ketene ($M^+ - 42$) and propylene ($M^+ - 42$). Examination of the high

(24) M. Julia and Y. Noël, *Bull. Soc. Chim. Fr.*, 3742, 3749, 3756 (1968).

Scheme III. Fragmentation of 2-*n*-Hexyl-2-methylcyclobutanone in the Mass Spectrometer



resolution spectrum of each cyclobutanone resolves the two *m/e* 166 ions from the loss of C_2H_2O and C_3H_6. The *m/e* 166 ion for cyclobutanone **44** can only arise from loss of C_3H_6. The relative intensities of the $M^+ - C_3H_6$ to $M^+ - C_2H_2O$ ions are listed for the cyclobutanones **42**–**44** in Table IV. The exceedingly low

Table IV. High Resolution Mass Spectral Data for **42**, **43**, and **44**

Cyclobutanone	$(M^+ - C_3H_6)/(M^+ - C_2H_2O)$	$M^+ - C_3H_6$ ion Calcd 166.13576 Found:	$M^+ - C_2H_2O$ ion Calcd 166.17214 Found:
42	0.33	166.13570	166.17199
43	0.10	166.13599	166.17215
44	75	166.13570	166.17140

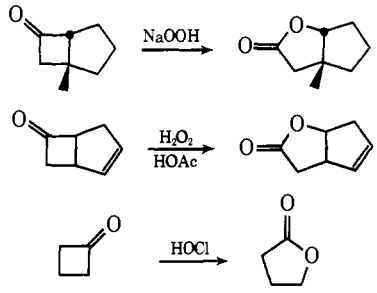
intensity of the $M^+ - C_2H_2O$ ion in the mass spectrum of **44** is in accord with that of a 2-methylcyclobutanone.

Characteristic absorption of the α protons in 2,2-disubstituted cyclobutanones is observed in their nmr spectra. Usually the protons appear as a finely split triplet (actually the AA′ part of AA′BB′ pattern) at δ 2.7–3.2. These data in conjunction with a strong carbonyl absorption between 1770–1780 cm^{-1} in the infrared spectrum are indicative of a 2,2-disubstituted cyclobutanone.

With the availability of cyclobutanones in a simple and high yield fashion from ketones, their application as intermediates in organic synthesis was deemed desirable. The high strain energy (~27 kcal/mol) should provide a driving force for many transformations. Indeed, for this reason cyclobutanones undergo unusually facile Baeyer–Villager oxidations[25] allowing the use of peroxide derivatives normally incapable of effecting such a

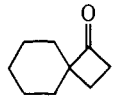
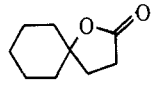
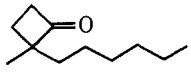
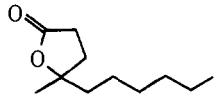
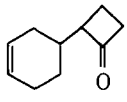
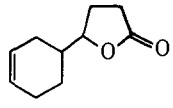
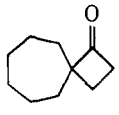
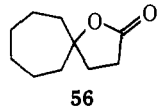
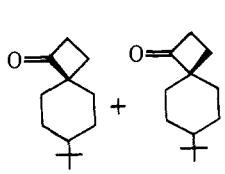
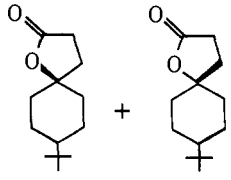
(25) For reviews, see C. H. Hassall, *Org. React.*, **9**, 73 (1957); H. O. House, "Modern Synthetic Reactions," W. A. Benjamin, New York, N. Y., 1965, pp 123–129.

transformation.[26-29] Coupling of facile cyclobutanone synthesis, spiroannelation, with the peroxide oxidation



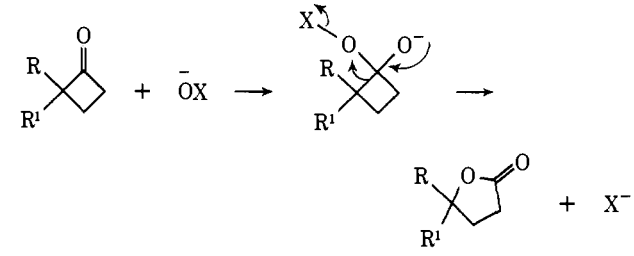
allows smooth conversion to the γ-butyrolactones in isolated overall yields of 57–92% from the starting ketone (Table V). All the methods utilized (hypochlorous acid, basic hydrogen peroxide, and sodium hypobromite) are specific for transforming cyclobutanones to γ-lactones. Larger rings are inert toward hypochlorous acid or basic hydrogen peroxide. However, with sodium hypobromite, bromination α to the carbonyl and cleavage reactions are possible with five membered or larger rings.[30] It should be noted that use of basic hydrogen peroxide as the rearranging reagent allows the presence of double bonds which would interfere with normal peracid methods.

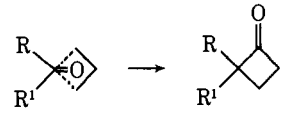
Table V. Lactone Annelation

Cyclobutanone	Lactonization reagent	γ-Lactone	% isolated yield
 7	HOCl	 45	90
	NaOOH		82
 46	NaOOH	 54	100
 10	NaOOH	 55	82
 51	NaOBr	 56	94
 16 17	NaOOH	 18	100

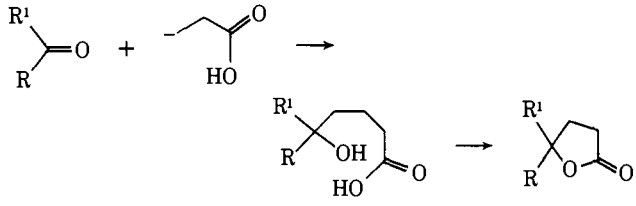
data in Table VI indicate the same order of migratory preferences (*i.e.*, tertiary > secondary > primary) as found in the peracid reaction. Furthermore, the migration occurs with retention of configuration at the migrating carbon.[14] Thus utilization of a 70:30 mixture of cyclobutanones **16** and **17** from spiroannelation of 4-*tert*-butylcyclohexanone led to a mixture of γ-butyrolactones which was converted (Scheme I) into a mixture of tetrahydrofurans possessing the same composition as starting materials. Since cyclobutanone **16** is the exclusive product of spiroannelation when europium(III) is employed to rearrange the precursor oxaspiropentane, this method of lactone annelation is consequently highly stereoselective.

Thus, with one facile procedure a carbonyl carbon is spiroannelated by a three-carbon unit to form a cyclobutanone. The process is highly efficient and stereoselective. The subsequent transformations of such compounds provide unusual synthetic versatility. One





such application involves creation of a synthon which reversed the electronic sense of a normal Michael acceptor, acrylic acid. The procedure incorporates spiroannelation and results in the addition of $^-$CCCOOH to a carbonyl partner. Since the product of the reaction



upon acidic work-up is a γ-lactone, the process is termed lactone annelation. The utility of this approach becomes more apparent by comparison to recently developed methods.[31-33] Thus, alkylation of metalated carboxylic acids with epoxides ultimately derived from a

(26) Cleavage of ketones with basic hydrogen peroxide or *tert*-butyl hydroperoxide has also been reported, but in very low yields; see K. Maruyama, *Bull. Chem. Soc. Jap.*, 33, 1516 (1960); 34, 102, 105 (1961); H. O. House and R. L. Wasson, *J. Org. Chem.*, 22, 1157 (1957); S. D. Levine *ibid.*, 31, 3189 (1966); D. L. Coffen and D. G. Korzan, *ibid.*, 36, 390 (1971); for a Baeyer–Villager of a strained cyclopentanone, see N. M. Weinshenker and R. Stephenson, *ibid.*, 37, 3741 (1972).

(27) Y. Tsuda, T. Tanno, A. Ukai, and K. Isobe, *Tetrahedron Lett.*, 2009 (1971).

(28) P. A. Grieco, *J. Org. Chem.*, 37, 2363 (1972).

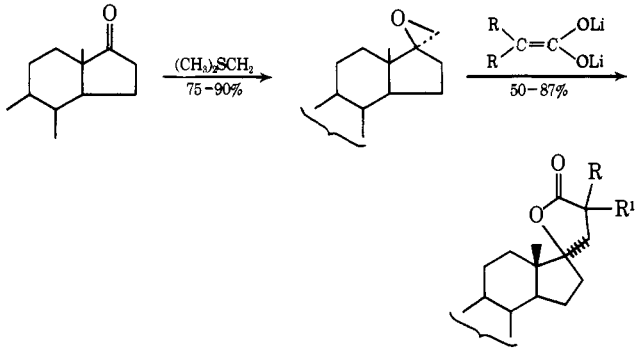
(29) J. A. Horton, M. A. Laura, S. M. Kalbag, and R. C. Petterson, *ibid.*, 34, 3366 (1969).

(30) R. Levine and J. R. Stephens, *J. Amer. Chem. Soc.*, 72, 1642 (1950).

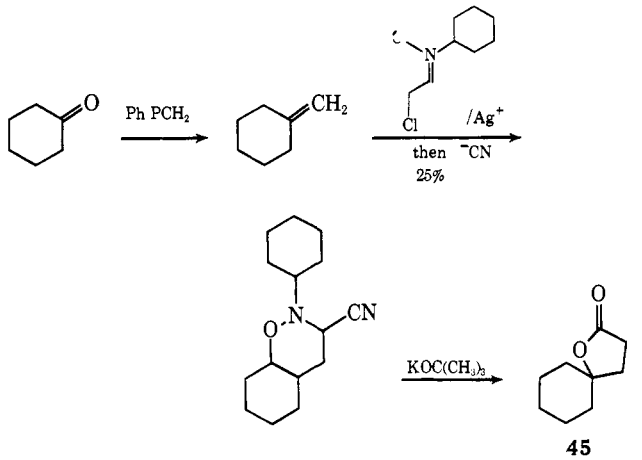
(31) P. L. Creger, *J. Org. Chem.*, 37, 1907 (1972).

(32) T. K. D. Gupta, D. Felix, U. M. Kempe, and A. Eschenmoser, *Helv. Chim. Acta*, 55, 2198 (1972).

(33) P. E. Eaton, G. F. Cooper, R. C. Johnson, and R. H. Mueller, *J. Org. Chem.*, 37, 1947 (1972).

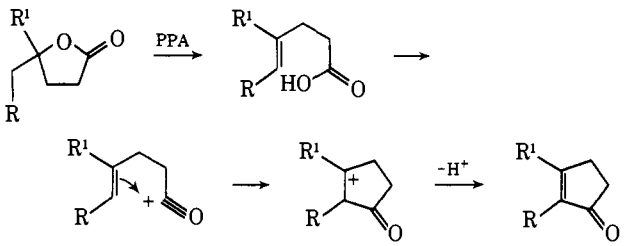


ketone generates the lactone in 38–78% yields,[31] whereas by the present method overall yields of 57–92% were obtained. Eschenmoser and coworkers[32] converted methylenecyclohexane into γ-butyrolactone **45** in



45

an overall yield of less than 20% in three steps compared with 80–88% in two steps by the present method. The inherent interest in γ-butyrolactones combined with their important utilization as precursors to cyclopentenones[33] renders lactone annelation an unusually useful procedure. More generally, the widespread applicability of the Michael reaction in organic synthesis bodes well for the utility of a process which inverts the normal electronic sense of the Michael acceptor.



Experimental Section

General. Melting points were taken on a Thomas-Hoover melting point apparatus and are uncorrected. Unless otherwise stated, infrared spectra were determined in carbon tetrachloride solution on a Beckman IR-8 spectrophotometer. Ultraviolet spectra were determined in 95% ethanol on a Cary Model 15 spectrometer. Nmr spectra were determined in carbon tetrachloride solution on Varian A60 or A60A spectrometers; chemical shifts are given in δ with TMS as the internal standard. Splitting patterns are designated as s, singlet; d, doublet; t, triplet; q, quartet; bs, broad singlet; mult, multiplet. Coupling constants are given in hertz. Mass spectra were taken on the AE1 MS 902 high resolution mass spectrometer or a Consolidated Electronic Corporation 103C mass spectrometer at an ionizing voltage of 70 eV and an ionizing current of 98 mA. All exact mass determinations were obtained on the MS-902 instrument. Analyses were performed by Spang Microanalytical Laboratories, Ann Arbor, Mich. Vpc analyses were performed on an Aerograph Model 90P instrument with a helium flow rate of 60 ml/min.

All experiments were carried out under an atmosphere of dry nitrogen unless noted otherwise. In experiments requiring dry solvents, ether, tetrahydrofuran, and dimethoxyethane were distilled from sodium–benzophenone. Methylene chloride and dimethyl sulfoxide were distilled from calcium hydride. Apparatus for experiments requiring dry conditions were dried either by flaming under reduced pressure or in a nitrogen stream, or drying in an oven at 120° for 12 hr.

During work-up of the reactions, general drying of the solvent was performed over anhydrous magnesium sulfate unless otherwise stated.

Thin layer or preparative thick layer plates were made of E. Merck AG Darmstadt silica gel PF-254 activated by drying for 2 hr at 140°. The general eluent was 10% ether in hexane unless described in the text. Removal of material from the silica gel was accomplished by successive washings with ether.

Generation of Diphenylsulfonium Cyclopropylide in DMSO with Potassium Hydroxide at 25°. Preparation of Cyclobutanones Directly. Under nitrogen, a solution of cyclopropyldiphenylsulfonium fluoroborate (3.92 g, 13.5 mmol) and 10 mmol of ketone in 30 ml of dimethyl sulfoxide was prepared at room temperature. In one portion powdered potassium hydroxide (1.12 g, 20 mmol) was added and the solution stirred 4 hr. The time depends on the reactivity of the ketone; benzaldehyde needs only 30 min while a hindered ketone such as diisopropyl ketones needs 24 hr. The reaction mixture was then poured onto cold aqueous 1 *M* tetrafluoroboric acid (25 ml) and extracted with 2 × 50 ml of ether. The ether was washed with water and then dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (a mixture of diphenyl sulfide and product) was either directly distilled to isolate the cyclobutanone or filtered through a column of silica gel using hexane–ether mixtures.

Alternatively, the reaction mixture may be extracted with 3 × 50 ml of hexane; the hexane was washed with 100 ml of saturated aqueous sodium bicarbonate and separated. Evaporation of the hexane *in vacuo* resulted in an oil which was dissolved in 100 ml of benzene. Lithium perchlorate (0.106 g, 1.0 mmol) was added and the mixture refluxed for 1 hr (except for the preparation of **10** where the time was 4 hr). Subsequently, the benzene solution was diluted with 4 equiv of hexane, filtered, and evaporated *in vacuo* to yield the respective cyclobutanones which were further purified in the usual manner. The yields of the various ketones are listed in Table VI.

Spectral Properties of the Cyclobutanones. Spiro[3.5]nonan-1-one (7): ir (CCl_4) 2944, 2941, 2862, 1773, 1449, 1393, 1155, 1120, 1057, 1040, 1020 cm^{-1}; nmr (CCl_4) δ 1.64 (bs, 10 H), 1.70 (t, J = 8.5 Hz, 2 H), 2.88 (t, J = 8.5 Hz, 2 H); ms *m/e* (%) 138 (7), 110 (12), 96 (20), 81 (77), 67 (100). *Anal.* Calcd for $C_9H_{14}O$: 138.10446. Found: 138.10440.

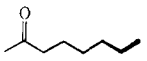
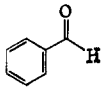
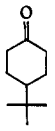
2-Phenylcyclobutanone (48): ir (CCl_4) 3077, 3040, 3008, 2967, 2941, 1786, 1605, 1495, 1449, 1387, 1285, 1221, 1198, 1065, 1028, 990, 694 cm^{-1}; nmr (CCl_4) δ 1.70–2.84 (very complex mult, 2 H), 2.85–3.28 (complex mult, 2 H), 4.43 (t (finely split), J = 9 Hz, 1 H), 7.20 (s, 5 H); ms *m/e* (%) 146 (15), 118 (14), 104 (100), 91 (14), 77 (24). *Anal.* Calcd for $C_{10}H_{10}O$: 146.07312. Found: 146.07573.

***endo*-4,7-Methanospiro[3.5]nonan-1-one (25)** was purified by collection from a 5 ft × 0.25 in. Carbowax 20M Chromosorb W column at 100°, retention time 14 min: ir (CCl_4) 2959, 2882, 1764, 1445, 1393, 1302, 1250, 1188, 1149, 1133, 1099, 1075, 1034 cm^{-1}; nmr (CCl_4) δ 1.15–2.14 (mult, 10 H), 2.30 (bs, 2 H), 2.67–3.08 (mult, 2 H); ms *m/e* (%) 150 (26), 122 (34), 108 (59), 93 (89), 79 (88), 66 (100). *Anal.* Calcd for $C_{10}H_{14}O$: 105.10446. Found: 150.10505.

***exo*-4,7-Methanospiro[3.5]nonan-1-one (26)** was collected from a 5 ft × 0.25 in. Carbowax 20M on Chromosorb W column at 100°, retention time 17 min: ir (CCl_4) 2960, 2880, 1773, 1443, 1393, 1302, 1250, 1129, 1111, 1036 cm^{-1}; nmr (CCl_4) δ 1.00–2.38 (mult, 12 H), 2.70–3.10 (mult, 2 H); ms *m/e* (%) 150 (27), 122 (20), 108 (48), 93 (66), 79 (74), 66 (100). *Anal.* Calcd for $C_{10}H_{14}O$: 150.10446. Found: 150.10497.

2,2-Diisopropylcyclobutanone (47) was purified by a thick layer chromatography: ir (CCl_4) 1772, 1397, 1366, 1241 cm^{-1}; nmr (CCl_4) δ 0.92 (d, J = 7 Hz, 6 H), 0.95 (d, J = 7 Hz, 6 H), 1.55–2.05 (mult, 4 H), 2.25–2.78 (mult, 2 H); ms *m/e* (%) 154 (11), 139 (6), 111 (49), 97 (39), 83 (68), 69 (100), 55 (82), 41 (81). *Anal.* Calcd for $C_{10}H_{18}O$: 154.13576. Found: 154.13583.

Table VI. Preparation of Cyclobutanones

Ketone	Wt, g (mmol)	4, g (mmol)	KOH, g (mmol)	Time, hr	Bp, °C (mm)	Wt, g (mmol)	% isolated yield
	3.84 (30.0)	10.99 (35.0)	2.80 (50.0)	18		4.64 (27.6)	92
	1.14 (10.0)	3.14 (10.0)	1.12 (20.0)	24		0.91 (5.9)	59
	1.06 (10.0)	3.14 (10.0)	1.12 (20.0)	0.5	80 (0.1)[a]	1.27 (8.7)	87
	2.10 (25.0)	7.85 (25.0)	2.80 (50.0)	3	25 (0.1)[a]	2.91 (23.5)	94
	0.98 (10.0)	3.92 (12.5)	1.12 (20.0)	4	34 (1.0)	1.33 (9.7)	97
	2.24 (20.0)	6.24 (20.0)	2.24 (40.0)	3		2.74 (18.0)	90
	3.65 (25.0)	9.42 (30.0)	2.80 (50.0)	17	120 (1.3)	3.19 (17.3)	69
	2.31 (15.0)	5.64 (18.0)	1.97 (35.0)	10		2.33 (12.0)	80
	1.10 (10.0)	3.14 (10.0)	2.80 (50.0)	10		1.38 (9.3)	92
	0.90 (7.3)	3.13 (10.0)	1.42 (25.0)	12	45 (0.2)	0.52 (32)	44

[a] Flash distilled, temperature indicates pot temperature.

4,5-Benzospiro[3.5]nonan-1-one (50): ir (CCl_4) 3079, 3333, 2941, 1783 cm^{-1}; nmr (CCl_4) δ 1.7–2.3 (mult, 6 H), 2.70 (bt, J = 5 Hz, 2 H), 2.9–3.3 (mult, AA'BB', 2 H), 7.00 (s, 4 H); ms *m/e* (%) 186 (30), 144 (100), 129 (54), 59 (50). *Anal.* Calcd for $C_{13}H_{14}O$: 186.10446. Found: 186.10601.

Spiro[3.4]octan-1-one (49): ir (CCl_4) 2959, 2874, 1779, 1443, 1395, 1253, 1111, 1045 cm^{-1}; nmr (CCl_4) δ 1.67 (bs, 8 H), 1.83 (t, J = 8 Hz, 2 H), 2.85 (t, J = 8 Hz, 2 H); ms *m/e* (%) 124 (13), 106 (2), 96 (18), 67 (100). *Anal.* Calcd for $C_8H_{12}O$: 124.08881. Found: 124.08589.

Spiro[3.6]decan-1-one (51): ir (CCl_4) 1779, 1393, 1087, 1042 cm^{-1}; nmr (CCl_4) δ 1.3–1.9 (mult, 14 H), 2.84 (t, J = 8.5 Hz, 2 H); ms *m/e* (%) 152 (9), 134 (11), 124 (14), 110 (11), 96 (20), 95 (74), 82 (100), 68 (56), 67 (68), 54 (65). *Anal.* Calcd for $C_{10}H_{16}O$: 152.12011. Found: 152.12034.

2-*n*-Hexyl-2-methylcyclobutanone (46): ir (CCl_4) 2976, 2941, 2870, 1779, 1391, 1373, 1054 cm^{-1}; nmr (CCl_4) δ 0.86 (t, J = 6 Hz, 3 H), 1.13 (s, 3 H), 1.2–1.4 (mult, 10 H), 1.5–2.0 (mult, AA'BB', 2 H), 2.7–3.1 (mult, AA'*BB'*, 2 H); ms *m/e* (%) 168 (3), 150 (8), 140 (4), 112 (12), 111 (10), 98 (11), 70 (34), 69 (37), 57 (32), 56 (100), 55 (38), 41 (48). *Anal.* Calcd for $C_{12}H_{20}O$: 168.15141. Found: 168.14979.

***endo*-5,8-Methanospiro[3.6]decan-1-one (52)** was collected from a 12 ft × 0.25 in. 5% Carbowax 20M on Chromosorb W column at 110°; retention time 11.2 min: ir (CCl_4) 1774, 1050 cm^{-1}; ms *m/e* (%) 164 (17), 136 (14), 122 (12), 107 (14), 93 (26), 80 (50), 66 (100). *Anal.* Calcd for $C_{11}H_{16}O$: 164.12011. Found: 164.12082.

***exo*-5,8-Methanospiro[3.6]decan-1-one (53)** was collected from a 12 ft × 0.25 in. Carbowax 20M on Chromosorb W column at 110°; retention time 13.4 min: ir (CCl_4) 1779, 1089, 1053 cm^{-1}; ms *m/e* (%) 164 (12), 136 (9), 122 (8), 107 (11), 93 (24), 80 (45), 66 (100). *Anal.* Calcd for $C_{11}H_{16}O$: 164.12011. Found: 164.12023.

Preparation of 2,2-Diphenylcyclobutanone (13). To a solution of benzophenone (1.82 g, 10 mmol) and cyclopropyldiphenylsulfonium fluoroborate (3.45 g, 11 mmol) in dimethyl sulfoxide (50 ml) was added powdered potassium hydroxide (1.12 g, 20 mmol). The mixture was stirred for 4 hr at 25°. The reaction mixture was then extracted with 2 × 150 ml of hexane. The hexane was washed with a saturated aqueous sodium bicarbonate solution (50 ml) and then dried over anhydrous sodium sulfate. The hexane was removed *in vacuo* to yield an oil. This oil was a mixture of 2,2-diphenylcyclobutanone and diphenyl sulfide. No acid was added for the rearrangement of the oxaspiropentane. Separation of the two components on silica gel PF-254 eluted with hexane resulted in 2.02 g (91%) of an oil. This oil was identical with the 2,2-diphenylcyclobutanone obtained previously (*vide infra*). 2,2-Diphenylcyclobutanone (**13**): ir (CCl_4) 3077, 3040, 2984, 2941, 1786, 1600, 1493, 1449, 1393, 1188, 1074, 1021, 1008, 905, 696 cm^{-1}; nmr (CCl_4) δ 2.86 (mult (AA'BB''), 4 H), 7.16 (s, 10 H); ms *m/e* (%) 222 (3), 194 (9), 180 (44), 105 (100), 77 (63). *Anal.* Calcd for $C_{16}H_{19}O$: 222.10446. Found: 222.10507.

Preparation of 2-Cyclopropyl-2-methylcyclobutanone (14). A solution of cyclopropylmethyl ketone (0.84 g, 10 mmol) and cyclopropyldiphenylsulfonium fluoroborate (3.14 g, 10 mmol) in 40 ml of dimethyl sulfoxide was treated with powdered potassium hydroxide (1.12 g, 20 mmol) and the mixture stirred at 25° for 4 hr. The reaction mixture was then extracted with 3 × 100-ml portions of hexane. The hexane was washed with a saturated aqueous sodium bicarbonate solution (100 ml) and then dried over anhydrous sodium sulfate. The hexane was removed *in vacuo* to yield an oil. This oil was a mixture of 2-cyclopropyl-2-methylcyclobutanone and diphenyl sulfide; no acid was used for rearrangement. Separation of the two components was effected on silica gel PF-254 eluted with hexane. An oil resulted (1.06 g, 8.6 mmol, 86%) which was a single compound by tlc on silica gel: ir (CCl_4) 3090, 1778, 1053,

1017 cm^{-1}; nmr (CCl_4) δ 0.1–1.0 (mult, 5 H), 1.21 (s, 3 H), 1.4–1.8 (mult, 2 H), 2.83 (mult, 2 H); ms *m/e* (%) 124 (1.5), 109 (2), 96 (19), 82 (29), 67 (100). *Anal.* Calcd for $C_8H_{12}O$: 124.08881. Found: 124.08871.

Preparation of *cis*- and *trans*-6-*tert*-Butylspiro[3.5]nonan-1-one (16 and 17). 6-*tert*-Butyl-3-oxadispiro[2.1.5.0]decane (513 mg, 2.64 mmol) was dissolved in 100 ml of ether. A 125-ml portion of 2 *M* tetrafluoroboric acid was added. This mixture was shaken for 10 min at 25° and then the ether was separated. The aqueous layer was washed with a 100-ml portion of ether. The two ether portions were combined and dried over anhydrous sodium sulfate. The ether was evaporated *in vacuo*, and 6-*tert*-butylspiro[3.5]nonan-1-one (547 mg, 2.81 mmol) was recovered with a crude yield of 100%: ir (CCl_4) 2967, 2882, 1776, 1475, 1441, 1391, 1379, 1366, 1350, 1116, 1053 cm^{-1}; nmr (CCl_4) δ 0.87 (s, 9 H), 1.2–2.2 (mult, 10 H), 2.86 (mult, *AA'BB'*, 2 H); ms *m/e* (%) 194 (5), 166 (6), 137 (5), 121 (11), 119 (28), 117 (28), 109 (14), 98 (11), 96 (31), 81 (26), 79 (11), 67 (12), 57 (100), 55 (18), 41 (32), 39 (14). *Anal.* Calcd for $C_{13}H_{22}O$: 194.16706. Found: 194.16783.

The recovered product, 6-*tert*-butylspiro[3.5]nonan-1-one, was analyzed by vpc, and the two stereoisomers were separated. An 11 ft × 0.25 in. 8% SE-30 on Chromosorb W column was used at 138°. The first peak (77%) had a retention time of 4.0 min. The second peak (23%) had a retention time of 5.2 min.

First peak, *cis*-6-*tert*-butylspiro[3.5]nonan-1-one (**16**): ir (CCl_4) 2959, 2882, 2857, 1773, 1477, 1447, 1393, 1366, 1294, 1239, 1121, 1054 cm^{-1}; ms *m/e* (%) 194 (17), 179 (5), 166 (12), 150 (9), 136 (8), 123 (8), 120 (9), 110 (11), 109 (20), 96 (46), 81 (31), 79 (12), 67 (22), 57 (100), 43 (8). *Anal.* Calcd for $C_{13}H_{22}O$: 194.16706. Found: 194.16719.

Second peak, *trans*-6-*tert*-butylspiro[3.5]nonan-1-one (**17**): ir (CCl_4) 2959, 2874, 1776, 1477, 1471, 1441, 1394, 1366, 1348, 1289, 1239, 1110, 1028 cm^{-1}; ms *m/e* (%) 194 (5), 166 (7), 137 (5), 123 (5), 120 (5), 110 (7), 109 (14), 96 (34), 81 (27), 79 (10), 67 (20), 57 (100), 41 (35). *Anal.* Calcd for $C_{13}H_{22}O$: 194.16706. Found: 194.16783.

Preparation of 2-(Cyclohex-3′-ene)cyclobutanone (10). 2-(Cyclohex-3′-ene)-1-oxaspiropentane (710 mg, 4.73 mmol) was dissolved in 10 ml of benzene. Anhydrous lithium perchlorate (100 mg) was added as a catalyst. The reaction was refluxed under nitrogen for 3 hr. (An earlier attempt was made with anhydrous lithium perchlorate (25 mg) with refluxing for only 1 hr. In this attempt mostly starting material was recovered.) The reaction was cooled to room temperature and 100 ml of hexane was added. The precipitated lithium perchlorate was filtered. The hexane was evaporated *in vacuo* leaving an 87.3% yield of 2-(cyclohex-3-ene)cyclobutanone (620 mg, 4.13 mmol): ir (CCl_4) 3040, 2994, 2924, 2849, 1779, 1435, 1391, 1366, 1232, 1175, 1139, 1078, 1041 cm^{-1}; nmr (CCl_4) δ 1.2–2.3 (mult, 9 H), 2.65–3.30 (mult, 3 H), 5.55 (bs, 2 H); ms *m/e* (%) 150 (18), 134 (6), 122 (40), 94 (9), 93 (29), 91 (19), 83 (8), 80 (76), 79 (100), 78 (56), 72 (25), 68 (9), 67 (100), 66 (33), 65 (37), 57 (7), 54 (83), 51 (12), 41 (22), 39 (44). *Anal.* Calcd for $C_{10}H_{14}O$: 150.10502. Found: 150.10446.

Preparation of 14β-Methyl-4α-(2′-oxospiracyclobutyl)-1,2,3,5,6,7-hexahydrophenanthrene and 14β-Methyl-4β-(2′-oxospiracyclobutyl)-1,2,3,5,6,7-hexahydrophenanthrene (31 and 32). A solution of 14β-methyl-4-oxo-1,2,3,5,6,7-hexahydrophenanthrene (**29**) (1.30 g, 6.1 mmol), cyclopropyldiphenylsulfonium fluoroborate (2.82 g, 9.0 mmol), and dimethyl sulfoxide (75 ml) was mixed. Powdered potassium hydroxide (1.12 g, 20 mmol) was added and the mixture stirred at 25°. After 4 hr the reaction mixture was extracted with 3 × 75 ml of hexane, washed with a saturated aqueous sodium bicarbonate solution (50 ml), and dried over anhydrous sodium sulfate. The hexane was evaporated *in vacuo* to yield an oil: nmr (CCl_4) δ 0.5–1.0 (mult, 4 H), 1.25 (s, 3 H), 1.3–2.5 (mult, 9 H), 2.73 (bt, J = 6 Hz), 6.9–7.3 (aromatic protons obscured by diphenyl sulfide).

This oil was dissolved in 100 ml of pentane and shaken with 50 ml of a 2 *M* aqueous tetrafluoroboric acid solution for 15 min. The pentane was separated, washed with 100 ml of water, and dried over anhydrous magnesium sulfate. The pentane was evaporated *in vacuo* and the resulting oil chromatographed on a silica gel PF-254 thin layer plate eluted with hexane. The cyclobutanone remained near the base line while the diphenyl sulfide was moved near the top. An oil was obtained, 1.49 g, 95.5%. This oil was rechromatographed on silica gel PF-254 eluted with 20% ether in hexane. Five bands were observed. The fourth band, R_f 0.7, consisted of 0.94 g (61%) of a crystalline solid (**31**), mp 55.5–56.0°: ir (CCl_4) 3077, 1770 cm^{-1}; nmr (CCl_4) δ 1.25 (s, 3 H), 1.3–2.5 (mult, 11 H), 2.5–3.05 (mult, 4 H), 6.8–7.2 (mult, 4 H); ms *m/e* (%) 254 (11.8), 239 (16), 226 (12), 212 (26), 197 (54), 183 (32), 141 (28), 43 (100). *Anal.* Calcd for $C_{18}H_{22}O$: 254.16705. Found: 254.16779.

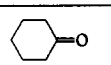
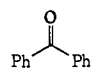
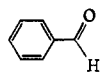
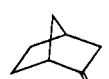
The third band, R_f 0.55, weighed 0.07 g (4.5%). This band was also a crystalline solid (**32**), mp 133–134°: ir (CCl_4) 3077, 1773 cm^{-1}; nmr (CCl_4) δ 1.39 (s, 3 H), 1.5–2.3 (mult, 11 H), 2.6–3.1 (mult, 4 H), 6.8–7.3 (mult, 4 H); ms *m/e* (%) 254 (19), 252 (35), 239 (18), 237 (26), 226 (100), 212 (99), 197 (76), 183 (40), 169 (95), 141 (96), 129 (94), 115 (70). *Anal.* Calcd for $C_{18}H_{22}O$: 254.16705. Found: 254.16799.

Band 2 was the other major band, 0.44 g, which by infrared analysis had no carbonyl but a strong hydroxyl group and cyclopropyl protons. This substance must be produced during rearrangement of the oxaspiropentane to the cyclobutanone. It is not a vinyl cyclopropanol, since treatment with acid did not produce the corresponding cyclobutanone.

Preparation of 14β-Methyl-4-(2′-oxospiracyclobutyl)-1,2,3,5,6,7-hexahydrophenanthrene (31). To a solution of 14β-methyl-4-oxo-1,2,3,5,6,7-hexahydrophenanthrene (**28**) (0.89 g, 4.18 mmol) and cyclopropylidiphenylsulfonium fluoroborate (1.57 g, 5.00 mmol) in dimethyl sulfoxide (50 ml) was added powdered potassium hydroxide (0.56 g, 10.0 mmol). This was stirred for 4 hr. The mixture was then extracted with 3 × 100 ml of hexane; the hexane was washed with 50 ml of an aqueous saturated sodium bicarbonate solution, dried over anhydrous sodium sulfate, and evaporated *in vacuo* to yield an oil. The oil was dissolved in 50 ml of benzene with 200 mg of anhydrous lithium perchlorate. This mixture was refluxed for 1 hr. Upon cooling to 25°, 200 ml of hexane was added and the solution filtered and evaporated *in vacuo*. The resulting oil was chromatographed on silica gel PF-254 eluted with hexane to remove diphenyl sulfide. The cyclobutanone obtained was crystalline and identical with the major isomer of the initial reaction where rearrangement was accomplished by tetrafluoroboric acid. The yield of cyclobutanone was 0.83 g (78%) (**31**).

Generation of Diphenylsulfonium Cyclopropylide with Dimsylsodium in Dimethoxyethane. A suspension of cyclopropylidiphenylsulfonium fluoroborate (314 mg, 1.00 mmol) in 10 ml of dry dimethoxyethane was cooled in a Dry Ice–chlorobenzene slush (*ca.* −40°). (It is important that the temperature not be lower than −45° for ylide generation. If it is, the dimethyl sulfoxide solution of dimsylsodium freezes with formation of chunks and precludes ylide formation.) Dimsylsodium (1.10 ml of 1.06 *M* dimethyl sulfoxide solution, 1.16 mmol) was added rapidly and a deep orange-yellow color developed. The suspended sulfonium salt was no longer present; the mixture appeared homogeneous. The resultant orange-yellow solution was mixed for 4 min at which time the desired ketone was added (1 mmol). This was stirred for 15 min at −45° then allowed to warm to room temperature over 30 min. Then 5.0 ml of aqueous 1 *M* tetrafluoroboric acid was added. This solution was extracted with 2 × 10-ml portions of ether. The ether was evaporated to yield the mixture for analysis. The aqueous layer was extracted with methylene chloride (10 ml) which resulted in less than 2% of starting sulfonium salt. The results are listed in Table VII.

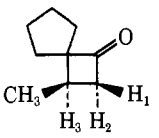
Table VII. Generation of Diphenylsulfonium Cyclopropylate with Methylsulfinyl Carbanion

Carbonyl compd	Wt, mg (1.0 mmol)	Int. standard, cycloheptanone, mg	Calcd wt, mg	% yield
	98	49.6	59.6	61
	182	68.4	136.5	75
	106	87.5	74.2	70
	110	62.7	71.5	65[a]

[a] Mixture of *endo*- (**25**) and *exo*- (**26**) 4,7-methanospiro[3.5]nonan-1-one in the ratio of 85:15.

Preparation of 3-Methylspiro[3.4]octan-1-one (34). A benzene (25 ml) solution of 1-methyl-3-oxadispiro[2.1.4.0]nonane (1.15 g, 0.83 mmol) was refluxed with lithium perchlorate (0.106 g, 1.0 mmol). After 1 hr, 300 ml of hexane was added and the solution filtered. Evaporation of the hexane *in vacuo* resulted in isolation of 1.14 g (99%) of **34** and **35**. Vpc analysis on a 5 ft × 0.25 in. 5% SE-30 column at 110° showed a 93:7 ratio of 3-methylspiro-[3.4]octan-1-one (**34**) and 2-methylspiro[3.4]octan-1-one (**35**) with respective retention times of 5.6 and 6.5 min.

3-Methylspiro[3.4]octan-1-one (**34**): ir (CCl_4) 1776, 1399, 1377



34

$J_{1,2}$ = 17 Hz
$J_{1,3}$ = 6 Hz
$J_{2,3}$ = 10 Hz

cm^{-1}; nmr (CCl_4) δ 1.15 (d, J = 7 Hz, 3 H), 1.70 (bs, 8 H), 2.0–2.7 (mult, 2 H), 3.0–3.5 (mult, 1 H). A 20 mol % europium shift study moves the protons next to the carbonyl downfield far enough to obtain coupling constants. Ms *m/e* (%): 138 (6), 96 (53), 67 (100). *Anal.* Calcd for $C_9H_{14}O$: 138.10446. Found: 138.10435.

2-Methylspiro[3.4]octan-1-one (**35**): ir (CCl_4) 1770, 1443, 1212 cm^{-1}; ms *m/e* (%) 138 (20), 96 (100), 82 (12), 67 (90). *Anal.* Calcd for $C_9H_{14}O$: 138.10446. Found: 139.10408.

Preparation of a Mixture of *cis*-6-*tert*-Butyl-3-methylspiro[3.5]-nonan-1-one (42), *trans*-6-*tert*-Butyl-3-methylspiro[3.5]nonan-1-one (43), and *cis*-6-*tert*-Butyl-2-methylspiro[3.5]nonan-1-one (44). A solution of 4-*tert*-butylcyclohexanone (1.54 g, 10.0 mmol) and diphenyl-2-methylcyclopropylsulfonium fluoroborate (3.28 g, 10.0 mmol) in 40 ml of dimethyl sulfoxide was treated with powdered potassium hydroxide (1.12 g, 20 mmol) and stirred at 25° for 4 hr. The reaction mixture was extracted with 3 × 150-ml portions of hexane; the hexane was washed with 100 ml of a saturated aqueous sodium bicarbonate solution, separated, and evaporated *in vacuo*. The resultant oil was dissolved in 50 ml of benzene and refluxed with lithium perchlorate (0.1 g) for 1 hr. Upon cooling, the benzene was diluted with 300 ml of hexane, filtered, and evaporated *in vacuo* to yield 1.97 g (9.5 mmol, 95%) of a mixture of **42**, **43**, and **44**. This mixture was separated on an 8 ft × 0.25 in. 5% Carbowax 20M on Chromosorb W column at 130°.

Peak 1, retention time 13 min, *cis*-6-*tert*-butyl-2-methylspiro-[3.5]nonan-1-one (**44**): ir (CCl_4) 1765, 1366, 1121, 975 cm^{-1}; ms *m/e* (%) 208 (4), 166 (59), 81 (40), 57 (100). *Anal.* Calcd for $C_{14}H_{24}O$: 208.18270. Found: 208.18216. Mass of ($M - C_3H_6$) ion Calcd: 166.13576. Found: 166.13570. Mass of ($M - C_2H_2O$) ion Calcd: 166.17214. Found: 166.17140. Ratio of ($M - C_3H_6$)/($M - C_2H_2O$) = 75.

Peak 2, retention time 17 min, *cis*-6-*tert*-butyl-3-methylspiro-[3.5]nonan-1-one (**42**): ir (CCl_4) 1767, 1393, 1366 cm^{-1}; nmr (CCl_4) δ 0.90 (s, 9 H), 1.15 (d, J = 6 Hz, 3 H), 1.2–2.2 (mult, 10 H), 2.50 (dd, J = 19 Hz, J = 7 Hz, 1 H), 3.16 (dd, J = 19 Hz, J = 11 Hz, 1 H); ms *m/e* (%) 208 (6), 166 (85), 110 (32), 57 (100). *Anal.* Calcd for $C_{14}H_{24}O$: 208.18270. Found: 208.18234. Mass of ($M - C_3H_6$) ion Calcd: 166.13576. Found: 166.13570. Mass of ($M - C_2H_2O$) ion Calcd: 166.17214. Found: 166.17199. Ratio of ($M - C_3H_6$)/($M - C_2H_2O$) = 0.33.

Peak 3, retention time 23 min, *trans*-6-*tert*-butyl-3-methylspiro-[3.5]nonan-1-one (**43**): ir (CCl_4) 1773, 1368 cm^{-1}; nmr (CCl_4) δ 0.87 (s, 9 H), 1.25 (d, J = 7 Hz), 1.2–1.9 (mult, 10 H), 2.38 (dd, J = 19 Hz, J = 5 Hz, 1 H), 3.25 (dd, J = 19 Hz, J = 12 Hz, 1 H); ms *m/e* (%) 208 (3), 166 (58), 110 (31), 57 (100). *Anal.* Calcd for $C_{14}H_{24}O$: 208.18270. Found: 208.18248. Mass of ($M - C_3H_6$) ion Calcd: 166.13576. Found: 166.13599. Mass of ($M - C_2H_2O$) ion Calcd: 166.17214. Found: 166.17215. Ratio of ($M - C_3H_6$)/($M - C_2H_2O$) = 0.10.

Preparation of 2-Cyclopropylidenenorbornane. Triphenylphosphonium cyclopropylide[20] was generated by treatment of a slurry of cyclopropyltriphenylphosphonium bromide (3.85 g, 10.0 mmol) in 20 ml of dimethoxyethane with dimsylsodium in dimethyl sulfoxide (5.0 ml of a 2.09 M solution, 10.0 mmol). The solution turned a deep orange and was mixed at 30° for 10 min. Then norcamphor (10.0 mmol), 1.10 g) in 1.0 ml of dimethoxyethane was added. The mixture was stirred at reflux temperature for 12 hr, 20 ml of water was added, and the mixture was extracted with 2 × 100 ml of hexane. The hexane was evaporated to yield an oil plus a solid which upon elution through a 1 × 12 in. silica gel column with hexane afforded an oil, 0.65 g, 49% (**27**): nmr (CCl_4) δ 0.90 (mult, 4 H), 1.00–1.75 (mult, 6 H), 1.83–2.25 (mult, 2 H), 2.25–2.50 (bs, 1 H), 2.76 (bs, 1 H); ir (CCl_4) 3065, 2967, 2884, 2857, 1786, 1179, 1093, 978 cm^{-1}; ms *m/e* (%) 134 (12), 119 (25), 105 (35), 93 (38), 92 (52), 93 (63), 79 (100), 66 (52). *Anal.* Calcd for $C_{10}H_{14}$: 134.10954. Found: 134.10831.

Epoxidation of 2-Cyclopropylidenenorbornane with Peracetic Acid. 2-Cyclopropylidenenorbornane (1.00 g) was dissolved in 10 ml of methylene chloride. After cooling this solution to 0°, 3 ml of 40% peracetic acid was added. When 5 min of stirring was completed, 25 ml of water was added, and the methylene chloride layer was separated and washed with a saturated aqueous sodium carbonate solution and then with water. The methylene chloride was dried and evaporated to yield 0.93 g (84%) of an oil. The oil was separated into its two components, *endo*- and *exo*-4,7-methanospiro[3.5]-nonan-1-one (**25** and **26**) on a 5 ft × 0.25 in. 5% Carbowax 20M on Chromosorb W column at 100° with retention times of 14 and 17 min, respectively. The ratio of **25** to **26** was 45:55. These cyclobutanones were identical in spectral and chromatographic properties with the cyclobutanones resulting from spiroannelation of norbornanone.

Epoxidation of 2-Cyclopropylidenenorbornane with Perbenzimidic Acid. To a solution of 2-cyclopropylidenenorbornane (0.421 g, 3.14 mmol) and benzonitrile (361 mg, 3.5 mmol) in 5 ml of methanol was added 54 mg of solid potassium bicarbonate. With stirring, 373 mg (3.5 mmol) of a hydrogen peroxide (30% aqueous) solution was added rapidly. After the mixture was stirred at room temperature for 12 hr, 25 ml of water was added and the mixture extracted with 3 × 25 ml of methylene chloride. The combined methylene chloride layers were dried and evaporated. Then 50 ml of hexane was added to precipitate the benzamide. After filtration and evaporation, 0.359 g (76%) of an oil was obtained. This oil proved to be a mixture of **25** and **26** in the ratio of 44:56 by vpc analysis on a 5 ft × 0.25 in. 5% Carbowax 20M on Chromosorb W column at 100°. The epoxides rearrange under the conditions of the reaction.

Rearrangement of 2-Cyclopropylidenenorbornane Oxide with Various Acids. A dimethyl sulfoxide (75 ml) solution of cyclopropyldiphenylsulfonium fluoroborate (3.14 g, 10.0 mmol) and norcamphor (1.10 g, 10 mmol) was treated with powdered potassium hydroxide (2.80 g, 50 mmol). After 10 hr the solution was extracted with 3 × 50 ml of pentane. The pentane solution was dried over anhydrous sodium sulfate and evaporated *in vacuo*. The resulting oil (2.190 g) was 63.5% oxaspiropentane by nmr analysis. This represents a yield of 92%.

The mixture of 2-cyclopropylidenenorbornane oxide and diphenyl sulfide was used in the subsequent rearrangements without separation.

A solution of the above mixture (0.300 g) in pentane (25 ml) was shaken for 10 min with 25 ml of the various acids listed in Table VIII. Each acid rearranged the oxaspiropentane to **25** and **26** in the percentages and yields listed. The separation of **25** and **26** was accomplished on a 5 ft × 0.25 in. 10% KOH, 10% Carbowax of Chromosorb W vpc column at 100°.

Table VIII

Acid	% **16**	% **17**	Recovered material, g (%)	Concn of acid, M
HBF_4	81	19	0.296 (98.6)	1
HI	82	18	0.281 (93.6)	0.5
HBr	82	18	0.292 (97.4)	1
HCl	82	18	0.290 (96.7)	1

Rearrangement of 2-Cyclopropylidenenorbornane Oxide with Lithium Perchlorate in Benzene. A mixture of 63.5% 2-cyclopropylidenenorbornane oxide and 36.5% diphenyl sulfide (0.175 g, 0.74 mmol of oxaspiropentane) was dissolved in 25 ml of benzene. Anhydrous lithium perchlorate (0.106 g, 1.0 mmol) was added and the mixture stirred for 2 hr. Water (25 ml) was added to the reaction mixture and the benzene layer was separated. After drying the benzene solution over anhydrous sodium sulfate and removing the benzene *in vacuo*, an oil was obtained, 0.167 g (95%). This oil was analyzed by vpc on a 5 ft × 0.25 in. 10% KOH and 10%

Carbowax 20M on Chromosorb W column at 100°. The relative yields of **25** and **26** are 91 and 9%, respectively.

Rearrangement of Cyclopropylidenecyclohexane Oxide with Various Acids. A solution of cyclohexanone (0.49 g, 5 mmol) and cyclopropyldiphenylsulfonium fluoroborate (1.57 g, 5 mmol) in dimethyl sulfoxide (15 ml) was treated with powdered potassium hydroxide (0.56 g, 10 mmol). After 2 hr, the reaction mixture was extracted with 2 × 35 ml of pentane. The pentane solution was dried and evaporated *in vacuo* to yield 1.2195 g of an oil. This oil was distilled at 26° (1 mm) to yield 0.5 g (80%) of cyclopropylidenecyclohexane oxide.

A solution of cyclopropylidenecyclohexane oxide (100 mg) in 25 ml of pentane was shaken with 25 ml of 1 *M* aqueous hydrochloric acid for 10 min. The pentane layer was separated, dried over anhydrous sodium sulfate, and evaporated *in vacuo* to yield 98 mg (98%) of an oil. This oil was analyzed by vpc,[16] which indicates only a single product. The product was identical in all respects with spiro[3.5]non-1-one (**7**). Similar experiments with tetrafluoroboric acid and hydrobromic acid gave spiro[3.5]nor-1-one in 97 and 99% yields, respectively.

A solution of cyclopropylidenecyclohexane oxide (130 mg) in benzene (10 ml) was treated with hexamethylphosphoramide (179 mg, 1.0 mmol) and lithium bromide (106 mg, 1.0 mmol). After the solution was stirred for 2 hr, water (20 ml) was added and the mixture extracted with ether. The ether layer was dried over anhydrous sodium sulfate and evaporated *in vacuo* to yield 224 mg of an oil; spiro[3.5]non-1-one was separated from this mixture of ketone and hexamethylphosphamide by extracting a pentane solution of the oil with 2 × 50 ml of water. The pentane was dried and evaporated *in vacuo* to yield 116 mg (89%) of spiro[3.5]non-1-one (**7**), which was a single spot on tlc.

Hypochlorous Acid Oxidation of Spiro[3.5]nonan-1-one (7). Acetic acid (4 ml) and 30 ml of water were added to 30 ml of 5.25% sodium hypochlorite (bleach). This solution was added quickly to spiro[3.5]nonanone (264 mg, 1.91 mmol). The solution was mixed for 18 min at room temperature under nitrogen. The hypochlorous acid was destroyed with 30 ml of a 10% sodium bisulfite solution. The product was extracted with five 40-ml portions of ether. The ether solution was washed with water. The water was backwashed with ether which was added to the original ether solution. The ether was dried over anhydrous magnesium sulfate and evaporated *in vacuo*. The recovered product had an acidic smell. The product was redissolved in hexane and washed with water. The water was backwashed with hexane which was added to the original hexane solution. The hexane was dried over anhydrous magnesium sulfate and evaporated *in vacuo*. The crude 1-oxaspiro-[4.5]decan-2-one (**45**)[33,34] (1.73 g, 90%) was a single compound by vpc on an 11 ft × 0.25 in. 8% SE-30 on Chromosorb W column at 138°: ir (CCl_4) 2959, 2874, 1777, 1449, 1218, 1189, 1147, 1126, 959 cm^{-1}; nmr (CCl_4) δ 1.65 (bs, 10 H), 2.0 (mult, *AA'BB'*, 2 H), 2.53 (mult, AA'*BB'*, 2 H); ms *m/e* (%) 154 (20), 125 (10), 112 (15), 111 (100), 105 (21), 97 (25), 85 (21), 83 (37), 81 (44), 71 (35), 69 (34), 67 (46), 57 (51), 41 (88). *Anal.* Calcd for $C_9H_{14}O$: 154.09937. Found: 154.09613.

Basic Hydrogen Peroxide Oxidation of Spiro[3.5]nonan-1-one (7). Spiro[3.5]nonan-1-one (289 mg, 2.09 mmol) was dissolved in 10 ml of methanol and stirred at room temperature under nitrogen. A 30% aqueous hydrogen peroxide solution (470 mg, 4.15 mmol) was added to the solution followed by 0.22 ml (2.04 mmol) of 9.28 *M* aqueous sodium hydroxide solution. After 2 hr, 20 ml of 10% aqueous hydrochloric acid was added to make the solution acidic. The product was extracted with four 40-ml portions of ether. The ether was dried over anhydrous magnesium sulfate and evaporated *in vacuo*. The crude yield of spiro[4.5]-1-oxadecan-2-one (266 mg, 1.72 mmol) was 83%. The spectral properties of the product were identical with the previous product (**45**).

Preparation of 4-Methyl-4-*n*-hexyl-γ-butyrolactone (54). 2-Methyl-2-*n*-hexylcyclobutanone (244 mg, 1.45 mmol) was dissolved in 10 ml of methanol and stirred at room temperature under nitrogen. A 30% aqueous hydrogen peroxide solution (443 mg, 3.63 mmol) was added to the methanol solution followed by 0.20 ml (1.86 mmol) of a 9.28 *M* aqueous sodium hydroxide solution. After 2 hr, 25 ml of a 10% aqueous hydrochloric acid solution was added resulting in an acidic solution (litmus). The product was extracted with four 40-ml portions of ether. The ether was dried over anhydrous magnesium sulfate and evaporated *in vacuo*. The product was dissolved in hexane and washed with water. The water was backwashed twice with hexane which was added to the original hexane solution. The hexane was dried over anhydrous magnesium sulfate and evaporated *in vacuo*. Vpc analysis of the crude 4-methyl-4-*n*-hexyl-γ-butyrolactone,[33,35] 277 mg (1.50 mmol) (100%), on an 11 ft × 0.25 in. 8% SE-30 on Chromosorb W at 140° confirmed its homogeneity: ir (CCl_4) 2959, 2890, 1779, 1458, 1381, 944 cm^{-1}; nmr (CCl_4) δ 0.90 (bt, J = 7 Hz), 3 H), 1.35 (s, 3 H), 1.2–1.6 (mult, 10 H), 1.7–2.1 (mult, *AA'BB'*, 2 H), 2.47 (mult, AA'*BB'*, 2 H); ms *m/e* (%) 184 (0.33), 169 (4), 114 (5), 100 (8), 99 (100), 69 (7), 55 (9), 43 (21), 41 (11), 39 (5). *Anal.* Calcd for $C_{11}H_{20}O_2$: 184.14632. Found: 184.14639.

Preparation of 4-(Cyclohex-3′-ene)-γ-butyrolactone (55). 2-(Cyclohex-3′-ene)cyclobutanone (400 mg, 2.66 mmol) was dissolved in 30 ml of methanol and stirred at room temperature under nitrogen. A 30% aqueous hydrogen peroxide solution (690 mg, 6.2 mmol) was added to the methanolic solution followed by 0.28 ml (2.6 mmol) of 9.28 *M* aqueous sodium hydroxide solution. After 2.5 hr, 50 ml of a 10% hydrochloric acid solution was added resulting in an acidic solution (litmus). The product was extracted with four 60-ml portions of ether. The ether was dried over anhydrous sodium sulfate and evaporated *in vacuo*. An oil, 360 mg (81.7%), resulted which was characterized without further purification as 4-(cyclohex-3′-ene)-γ-butyrolactone. Analysis by vpc on a 5 ft × 0.25 in. 5% SE-30 on Chromosorb W resulted in only one peak at 16.5 min: ir (CCl_4) 3040, 2924, 2849, 1786, 1404, 1332, 1175, 1048, 1022, 955, and 907 cm^{-1}; nmr (CCl_4) δ 1.2–2.6 (mult, 10 H), 4.2 (mult, 1 H), 5.6 (bs, 2 H); ms *m/e* (%) 166 (17), 135 (8), 131 (10), 120 (9), 110 (8), 106 (35), 104 (37), 97 (26), 93 (31), 91 (31), 86 (16), 85 (100), 81 (34), 79 (82), 78 (27), 77 (25), 67 (22), 60 (36), 57 (28), 54 (24), 53 (23), 51 (18), 44 (89), 41 (49). *Anal.* Calcd for $C_{10}H_{14}O_2$: 166.09937. Found: 166.09966.

Preparation of 1-Oxaspiro[4.6]undecan-2-one (56). To a cold (0°) solution of 8.8 g (0.22 mol) of sodium hydroxide in 36 ml of water was added 8.75 g (0.055 mol) of bromine. This mixture resulted in an approximate 1.3 *M* solution of sodium hypobromite. A 13-ml aliquot of this solution (16.9 mmol) was added to spiro-[3.6]decan-1-one (300 mg, 1.97 mmol) and stirred at 25° for 2.5 hr. Then 50 ml of a saturated aqueous sodium bisulfite solution was added to destroy the unreacted sodium hypobromite. The basic solution was extracted with ether to remove any unreacted ketone (<2 mg). The aqueous layer was acidified (litmus) with concentrated hydrochloric acid and extracted with ether. The resultant ether extract was dried over anhydrous magnesium sulfate and evaporated *in vacuo* to yield 311 mg (94%) of 1-oxaspiro[4.6]-undecan-2-one (**56**). This oil was purified by tlc for spectroscopic analysis: ir (CCl_4) 1775, 1381, 1238, 1359, 1222, 1119, 928 cm^{-1}; nmr (CCl_4) δ 1.4–2.2, (mult, 14 H), 2.51 (mult, 2 H); ms *m/e* (%) 168 (7), 149 (3), 125 (12), 111 (100), 98 (23), 95 (14), 82 (13), 68 (24), 55 (20), 44 (35). *Anal.* Calcd for $C_{10}H_{16}O_2$: 168.11502. Found: 168.11483.

Preparation of 1-Oxa-7-*tert*-butylspiro[4.5]decan-2-one (18). A solution of 6-*tert*-butylspiro[3.5]nonan-1-one (465 mg, 2.39 mmol) in 30 ml of methanol was stirred at 25° under nitrogen. A 30% aqueous hydrogen peroxide solution (646 mg, 5.69 mmol) was added to the methanol solution. Then 0.26 ml (2.41 mmol) of a 9.28 *M* aqueous sodium hydroxide solution was added. After 2 hr, 10 ml of 25% hydrochloric acid was added. The product was extracted with 4 × 60-ml portions of ether. The ether was dried over anhydrous sodium sulfate and evaporated *in vacuo*. The crude yield of 1-oxa-7-*tert*-butylspiro[4.5]decan-2-one (525 mg, 250 mmol) was approximately 100%: ir (CCl_4) 2959, 2874, 1776, 1443, 1366, 1326, 1280, 1220, 1188, 1160, 1121, 1050, 1001, 969, 951, 928, 899 cm^{-1}; nmr (CCl_4) δ 0.87 (s, 9 H), 1.0–2.1 (mult, 10 H), 2.28–2.62 (mult, *AA'BB'*, 2 H). The product of the reaction was analyzed by vpc on a 5 ft × 0.25 in. 5% SE-30 on Chromosorb W column at 150° to effect separation of the two stereoisomers with retention times of 14 min (80%) and 18 min (20%).

First peak, *syn*-1-oxa-7-*tert*-butylspiro[4.5]decan-2-one: ir (CCl_4) 2959, 2882, 2849, 1776, 1477, 1466, 1443, 1364, 1279, 1221, 1189, 1121, 1002, 969, 951, 929, 899 cm^{-1}; ms *m/e* (%) 210 (unobserved), 195 (7.2), 177 (1.5), 154 (18), 137 (78), 136 (41), 111 (13), 108 (12), 95 (33), 94 (100), 81 (32), 79 (14), 67 (14), 57 (75), 41 (58). *Anal.* Calcd for $C_{16}H_{19}O_2$: 195.13850. Found: 195.13943.

Second peak, *anti*-1-oxa-7-*tert*-butylspiro[4.5]decan-2-one: ir (CCl_4) 2959, 2874, 1776, 1477, 1466, 1447, 1366, 1330, 1283, 1220,

(34) M. F. Ansell, J. E. Emmett, and B. E. Grimwood, *J. Chem. Soc. C*, 141 (1969).

(35) J. H. Amin, S. G. Patnekar, H. H. Mathur, and S. C. Bhattacharya, *Indian J. Chem.*, 2, 14 (1964).

1200, 1171, 1120, 1050, 973, 899 cm^{-1}; ms *m/e* (%) 210 (1.60), 195 (4.3), 177 (2.7), 154 (22), 137 (8), 136 (13), 111 (20), 108 (5), 95 (16), 94 (20), 81 (16), 79 (8), 67 (10), 57 (100), 55 (26), 41 (47). *Anal.* Calcd for $C_{13}H_{22}O_2$: 210.16197. Found: 210.16190.

Reduction of 1-Oxa-7-*tert*-butylspiro[4.5]decan-2-one (18). 1-Oxa-7-*tert*-butylspiro[4.5]decan-2-one (398 mg, 1.89 mmol) was dissolved in 2 ml of dry, distilled ether. Lithium aluminum hydride (152 mg, 4.01 mmol) was added, followed by 5 ml of dry, distilled ether. The mixture was stirred at 0° under nitrogen. The ice bath was allowed to warm to room temperature, and after 7 hr wet ether followed by drops of water were added to destroy any excess lithium aluminum hydride. The water layer was separated and washed with two portions of ether. The ether layers were combined and dried over anhydrous sodium sulfate. The ether was evaporated *in vacuo*, and crude 4-*tert*-butyl-1-(3′-hydroxypropyl)-cyclohexan-1-ol (**19**) (348 mg, 1.64 mmol), a white solid, mp 83–92°, was recovered with a yield of 87%: ir (CCl_4) 3623, 3096–3546, 2950, 2874, 1534, 1466, 1441, 1364, 1259, 1095, 1053, 1010 cm^{-1}; nmr (CCl_4) δ 0.86 (s, 9 H), 1.0–1.8 (mult, 13 H), 3.0 (bs, 2 H), 3.54 (mult, 2 H); ms *m/e* (%) 214 (1.2), 196 (1.8), 181 (1.6), 155 (100), 115 (94), 102 (12), 97 (77), 81 (27), 79 (12), 69 (17), 57 (77), 55 (26), 41 (36).

Preparation of *cis*- (20) and *trans*- (21) 1-Oxa-7-*tert*-butylspiro-[4.5]decane. 4-*tert*-Butyl-1-(3′-hydroxypropyl)cyclohexan-1-ol (340 mg, 1.60 mmol) was dissolved in 4 ml of pyridine. This was stirred at 0° under nitrogen. *p*-Toluenesulfonyl chloride (340 mg, 1.7 mmol) was dissolved in 3 ml of pyridine and added dropwise to the solution. Stirring was continued for 1.5 hr at 0° and 1.5 hr at 25°. The solution was then poured on ice. The product was extracted with ether. The ether was washed with dilute hydrochloric acid and water. Both the dilute hydrochloric acid and water were backwashed with ether which was added to the original ether portion. The ether was dried over anhydrous sodium sulfate and evaporated *in vacuo*. A trace of pyridine remained with the crude spiro[4.5]-1-oxa-7-*tert*-butyldecane (363 mg, 1.73 mmol). The yield was approximately 100%: ir (CCl_4) 2959, 2874, 1536, 1471, 1443, 1366, 1259, 1095, 1048, 1009 cm^{-1}; nmr (CCl_4) δ 0.79 (s, 9 H), 0.85–1.9 (mult, 10 H), 3.63 (mult, *AA′BB′*, 2 H). The product was analyzed by vpc on an 11 ft × 0.25 in. 8% SE-30 on Chromosorb W column at 145°. The first peak (72%) had a retention time of 7.2 min; the second peak (28%) had a retention time of 8.9 min.

First peak, *cis*-1-oxa-7-*tert*-butylspiro[4.5]decane (**20**): ir (CCl_4) 2967, 2890, 2657, 1538, 1477, 1441, 1393, 1354, 1196, 1135, 1103, 1048 cm^{-1}; ms *m/e* (%) 197 (1.1), 196 (7.8), 181 (1.0), 139 (1.3), 125 (2), 98 (7), 97 (100), 84 (8.5), 57 (5), 55 (6). *Anal.* Calcd for $C_{13}H_{24}O$: 196,18270. Found: 196.18092.

Second peak, *trans*-1-oxa-7-*tert*-butylspiro[4.5]decane (**21**): ir (CCl_4) 2959, 2874, 1538, 1475, 1447, 1393, 1366, 1305, 1195, 1076 cm^{-1}; ms *m/e* (%) 197 (1.0), 196 (5.8), 181 (1.0), 139 (1.3), 125 (2.2), 98 (8), 97 (100), 84 (8.2), 57 (5.6), 55 (7.0). *Anal.* Calcd for $C_{13}H_{24}O$: 196.18270. Found: 196.18198.

Preparation of *cis*- (23) and *trans*- (22) 1-Allyl-4-*tert*-butylcyclohexan-1-ol. Allyl bromide (4.75 g, 39.2 mmol) in 22 ml of ether was added dropwise to magnesium (1.7 g, 70 mmol) in 15 ml of ether. This was stirred and allowed to reflux under nitrogen. When refluxing ceased, 4-*tert*-butylcyclohexanone (2.53 g, 16.4 mmol) dissolved in ether was added dropwise. The reaction was given 1 hr to complete. The mixture was then poured into a 34% aqueous ammonium chloride solution. The ether was separated and washed twice with water. After drying over anhydrous sodium sulfate the ether was evaporated *in vacuo*. The crude product, 1-allyl-4-*tert*-butylcyclohexan-1-ol (3.23 g, 16.5 mmol), was produced with a yield of about 100%. In a second run the yield was 88% crude product: ir (CCl_4) 3523, 3597, 3472, 3086, 1637, 1364, 912 cm^{-1}; nmr (CCl_4) δ 0.84 (s, 9 H), 1.0–1.9 (mult, 11 H), 2.13 (t, J = 7 Hz, 2 H), 4.85 (mult, 1 H), 5.10 (bs, 1 H), 5.5–6.0 (mult, 1 H).

The crude alcohol product had no carbonyl component. Separation of the alcohols was accomplished on a silica gel PF-254 thin layer plate eluted with 5% ether in hexane. Pure *trans*-1-allyl-4-*tert*-butylcyclohexan-1-ol (**22**) was the isomer with the largest R_f value. The stereochemistry was assigned by comparison of infrared spectra of authentic samples.[36] *trans*-1-Allyl-4-*tert*-butylcyclohexan-1-ol (**22**): ir (CCl_4) 3600, 3086, 2959, 2841, 1637, 1468, 1431, 1393, 1364, 1242, 1174, 1145, 1044, 992, 912 cm^{-1}. *cis*-1-Allyl-4-*tert*-butylcyclohexan-1-ol (**29**): ir (CCl_4) 3623, 3597, 3497, 3086, 2950, 2874, 1637, 1468, 1433, 1393, 1366, 1225, 1188, 1139, 1081, 1034, 987, 912 cm^{-1}.

Hydroboration of *trans*-1-Allyl-4-*tert*-butylcyclohexan-1-ol (22). 1-Allyl-4-*tert*-butylcyclohexan-1-ol (450 mg, 2.3 mmol) was dissolved in 2 ml of diglyme. Sodium borohydride (0.18 g, 4.5 mmol) dissolved in 20 ml of diglyme was added. The mixture was stirred at room temperature under nitrogen. Boron trifluoride ether complex (0.82 g, 6 mmol, 0.74 ml) was added dropwise over 1 min. Mixing was continued for 2.5 hr, and then 5 ml of water was added dropwise to destroy the boron trifluoride ether complex. Sodium hydroxide (0.56 g, 10 mmol) dissolved in 5 ml of water was added rapidly followed by dropwise addition of aqueous 30% hydrogen peroxide (0.5 g, 7 mmol). The reaction was mixed for an additional hour. The product was extracted with three 25-ml portions of ether. The ether was washed with five 50-ml portions of water and dried over anhydrous sodium sulfate. The ether was evaporated *in vacuo*, and the crude product, *trans*-4-*tert*-butyl-1-(propan-3-ol)cyclohexan-1-ol (487 mg, 2.3 mmol), was recovered with about 99% yield. This product was further treated with *p*-toluenesulfonyl chloride in pyridine without further purification. *trans*-4-*tert*-Butyl-1-(propan-3-ol)cyclohexan-1-ol (290 mg, 1.35 mmol) was dissolved in 4 ml of pyridine. While stirring under nitrogen, *p*-toluenesulfonyl chloride (340 mg, 1.70 mmol) in 3 ml of pyridine was added dropwise to the solution. After the mixture was stirred for 2 hr, 100 ml of water and 100 ml of ether were added. Upon separation of the ether layer, washing with 3 × 50 ml portions of 3 *N* hydrochloric acid, and evaporation *in vacuo*, 256 mg (97%) of an oil resulted. This oil was analyzed by vpc on an 11 ft × 0.25 in. 8% SE-30 on Chromosorb W column at 42°. The product was a single peak, *cis*-1-oxa-7-*tert*-butylspiro[4.5]decane (**20**). Addition of this pure sample to the previously obtained mixture of *cis*- and *trans*-1-oxa-7-*tert*-butylspiro[4.5]decane with subsequent vpc analysis resulted in enhancement of the major isomer. Thus, the major isomer is *cis*-1-oxa-7-*tert*-butylspiro[4.5]decane (72%) and the minor isomer is *trans*-1-oxa-7-*tert*-butylspiro[4.5]decane (28%).

Acknowledgment. We express our gratitude to the National Science Foundation and the National Institutes of Health for their generous support of our programs. We also express our thanks to the National Science Foundation and the Wisconsin Alumni Research Foundation whose funds provided the nuclear magnetic resonance and mass spectrometers used in this study.

(36) R. W. LaRochelle, B. M. Trost, and L. Krepski, *J. Org. Chem.*, **36**, 1126 (1971).