(2 ml) was injected to destroy residual hydride. (The Dry Ice condenser prevents loss of any volatile reaction products in the stream of evolved hydrogen.) To the resulting reaction mixture was added simultaneously 4 ml of 5 *M* sodium acetate and 3 ml of 30% hydrogen peroxide. The flask was brought to room temperature and allowed to stir there for 1 hr. Anhydrous potassium carbonate was added to separate the water. The tetrahydrofuran phase was separated. The aqueous phase was extracted three times with ethyl ether. The combined organic phases were dried overnight over magnesium sulfate. The mixture was then analyzed using a 12-ft column of FFAP on Chromosorb W in the F & M 500 chromatograph.

The various compounds required for the glpc analysis of the products were either commercially available or were synthesized by standard methods. Their properties are summarized in Table IX.

Selective Reductions. XII. Explorations in Some Representative Applications of Aluminum Hydride for Selective Reductions

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Contribution from the Richard B. Wetherill Laboratory, Purdue University, Lafayette, Indiana 47907. *Received December 11, 1967*

Abstract: Previously, an extensive comparison of the reducing characteristics of lithium aluminum hydride and aluminum hydride had indicated that the latter reagent exhibits some interesting differences from those of the former, suggesting that aluminum hydride might find useful application for selective reductions. A number of such promising applications have been explored. Thus the reaction of aluminum hydride with alkyl and cycloalkyl halides is considerably slower than the reaction of lithium aluminum hydride with such halides. Consequently, aluminum hydride is very effective in reducing the carboxylic acid and carboxylic ester groups of halogen-containing derivatives without significant attack on the halogen. Similarly, aluminum hydride reacts only sluggishly with the nitro group, either aliphatic or aromatic, and therefore serves as a selective reagent to reduce other groups in the presence of the nitro grouping. Aluminum hydride proved to be an excellent reagent for the reduction of ketoximes and amides to amines. It is of special value in the reduction of nitriles to amines. Even in cases such as allyl cyanide and benzyl cyanide, where relatively acidic hydrogen in the α position introduces major difficulties with lithium aluminum hydride, or cinnamonitrile, where the conjugated double bond causes difficulties, aluminum hydride achieves the reduction of the nitrile group to the amine in satisfactory yield. The reaction of lithium aluminum hydride with enolizable keto esters is complex. The use of aluminum hydride in conjunction with sodium borohydride made possible the reduction of representative derivatives to the corresponding diol. The reduction of epoxides by aluminum hydride appears to be more rapid in some cases than the corresponding reduction by lithium aluminum hydride. Moreover, there is a greater tendency to open at the more substituted position. In some cases one can take advantage of this feature for synthetic purposes. Finally, the stereochemistry of reduction of ketones by aluminum hydride is very similar to that realized with lithium aluminum hydride. Thus aluminum hydride possesses a number of qualities which offer special advantages for the selective reduction of many groups in the presence of halogen or nitro substituents, for the reduction of oximes and amides to amines, and for the reduction of nitrile and other groupings in molecules containing relatively acidic enolizable hydrogen.

Previously, we reported the development of an exceedingly simple procedure for the preparation of solutions of aluminum hydride in tetrahydrofuran.[2] In this procedure a clear, standardized solution of lithium aluminum hydride was treated with the theoretical quantity of 100% sulfuric acid to precipitate lithium sulfate (eq 1).

$$2LiAlH_4 + H_2SO_4 \longrightarrow 2AlH_3 + 2H_2\uparrow + Li_2SO_4\downarrow \quad (1)$$

The reducing properties of this reagent were explored[2] and compared with those of lithium aluminum hydride under carefully standardized conditions (0°, tetrahydrofuran solution).[3] Significant differences in reducing characteristics were observed. It appeared that some of these differences might be made the basis for useful methods of achieving certain selective reductions. Accordingly, we undertook to explore some of these possibilities.[4]

Results and Discussion

For small-scale quantitative experiments, we used clear, filtered, standardized solutions of aluminum hydride in tetrahydrofuran. Such solutions were also used for some of the large-scale preparative reductions. However, we also established that satisfactory results could be realized merely by dissolving a weighed quantity of lithium aluminum hydride in tetrahydrofuran, followed by addition of 100% sulfuric acid to form the aluminum hydride, and then using these heterogeneous mixtures directly for the reductions. This simplified procedure has obvious advantages for reductions on a preparative scale. All experiments were performed under a nitrogen atmosphere, although tests (see Experimental Section) indicated that there was no major dis-

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[1] Graduate research assistant on a research grant, DA 31-124 ARO(D) 453, supported by the U. S. Army Research Office (Durham).

[2] H. C. Brown and N. M. Yoon, *J. Am. Chem. Soc.*, **88**, 1464 (1966).

[3] H. C. Brown, P. M. Weissman, and N. M. Yoon, *ibid.*, **88**, 1458 (1966).

[4] For comprehensive reviews, see (a) N. G. Gaylord, "Reduction with Complex Metal Hydrides," Interscience Publishers, Inc., New York, N. Y., 1956; (b) W. G. Brown, *Org. Reactions*, **6**, 469 (1951); V. M. Mićović and M. L. Mihailović, "Lithium Aluminum Hydride in Organic Chemistry," Naukna Knjiga, Belgrade, Yugoslavia, 1955. For a less detailed survey devoted especially to selective reductions, see H. C. Brown, "Hydroboration," W. A. Benjamin, Inc., New York, N. Y., 1962.

advantage in carrying the reactions out in the presence of dry air.

Reaction of Alkyl Halides with Aluminum Hydride and Lithium Aluminum Hydride. Our original standard list of substrates did not include any halogen derivatives.[2,3] However, other research under way in our laboratories soon made it clear that there were significant differences in the behavior of aluminum hydride and lithium aluminum hydride toward alkyl and cycloalkyl halides. Accordingly, we undertook a detailed comparison of the two reagents in this area. The results are summarized in Table I.

Table I. Reaction of Alkyl Halides with Aluminum Hydride and Lithium Aluminum Hydride in Tetrahydrofuran at 25°

		Hydride used for reduction[b]	
Compound[a]	Time, hr	AlH_3	$LiAlH_4$
n-Butyl chloride	0.25	0	0.15
	12	0.20	0.61
	24	0.24	0.82
	48		1.04
n-Butyl bromide	0.25		0.78
	0.5	0.06	0.92
	1.0		0.97
	3.0	0.25	0.98
	24	0.53	
	48	0.59	
n-Butyl iodide	0.25		1.00
	0.5		1.01
	3.0	0.5[c]	
	6.0	0.78[c]	
sec-Butyl bromide	0.25	0.02	0.10
	6.0	0.15	0.47
	24	0.25	0.94
	32		1.04
t-Butyl bromide	0.25	0	0.02
	12	0.1	0.16
	48	0.16	0.24
Cyclopentyl bromide	0.25	0.02	0.08
	6.0	0.23	0.57
	24	0.31	1.01
Cyclohexyl bromide	0.25	0	0.11
	3.0	0.04	0.23
	12	0.08	0.27
	24		0.31

[a] 10.0 mmol of compound to 13.3 mmol of aluminum hydride or 10 mmol of lithium aluminum hydride. The solutions were 0.25 *M* in compound, 1.00 *M* in "hydride." [b] Mmol of "hydride"/mmol of compound. [c] White precipitate was observed.

It is of interest that the reaction with lithium aluminum hydride exhibits the typical characteristics of a bimolecular SN2 displacement reaction. Thus the rate of reaction decreases markedly from the iodide to the bromide to the chloride. Similarly the rate decreases from *n*-BuBr to *sec*-BuBr to *t*-BuBr. Moreover, cyclohexyl bromide is considerably slower than cyclopentyl bromide, and the latter is comparable to *sec*-butyl bromide.[5]

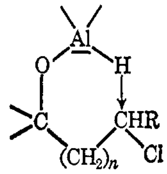
It is evident that the reaction of aluminum hydride with these alkyl and cycloalkyl halides is considerably slower than the corresponding reactions of lithium aluminum hydride. This suggested that aluminum hydride might be valuable for the reduction of various functional groups without significant concurrent attack of reactive halogen substituents present in the molecule. Accordingly, this possibility was explored.

Selective Reduction of Functional Groups in the Presence of Halogen Substituents. In particular, the clean reduction of halogen-substituted carboxylic acids and esters by lithium aluminum hydride has offered difficulties in the past.[6,7] Thus the yield of 2-chloroethanol from chloroacetic acid has been reported to be 13[6] and 5%.[7]

Since carboxylic acids are reduced more rapidly by aluminum hydride than by lithium aluminum hydride,[2] whereas halogen is attacked less readily by the former reagent, aluminum hydride clearly promises major advantages for such reductions. Indeed, the reagent was tested with three pairs of halogen acids and esters. The results are summarized in Table II.

It is evident that the yields are excellent, so that the use of aluminum hydride overcomes many of the difficulties previously experienced with lithium aluminum hydride.

In the course of this study, we observed that the yields of the halohydrins decreased, with prolongation of the reaction time, much more rapidly than anticipated from the results in Table I. Thus the yield of 3-bromo-1-butanol decreased 27% in 2.5 hr (from 87% in 0.5 hr to 60% in 3.0 hr), whereas *sec*-butyl bromide exhibited only 25% reaction in the much longer reaction time of 24 hr at the higher temperature, 25°. This observation supports Eliel's conclusion that a cyclic intramolecular mechanism must be largely responsible for the loss of halogen[7,8] (2).



(2)

Mixed hydride (1:1 $LiAlH_4$-$AlCl_3$) has also been applied to this problem.[9] With this reagent both acid chloride and ester could be reduced in good yield, but the highest yield realized from carboxylic acids was 50% with 3-bromopropionic acid. It would appear that both the more convenient preparation of the reagent and the higher yields with carboxylic acids make aluminum hydride the reagent of choice for such reductions.

Selective Reduction of Functional Groups in the Presence of Nitro Substituents. It had been observed that both 1-nitropropane, as a representative of an aliphatic nitro derivative, and nitrobenzene, as a representative of an aromatic nitro derivative, both reacted relatively slowly with aluminum hydride,[2] whereas the corresponding reactions with lithium aluminum hydride[3] were much faster. In both compounds the reduction of the nitro group was accompanied by hydrogen evolution, and in the case of nitrobenzene this was also accompanied by an intense color change, from pale yellow to dark green.

The relative sluggishness of the reaction of aluminum hydride with both of these types of nitro groups sug-

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[5] A detailed study of such SN2 displacement reactions with lithium aluminum hydride and sodium borohydride is underway with S. Krishnamurthy and will be reported shortly. We are indebted to Mr. Krishnamurthy for assistance with the present experiments.

[6] C. E. Sroog, C. M. Chih, F. A. Short, and H. M. Woodburn, *J. Am. Chem. Soc.*, **71**, 1710 (1949).

[7] E. L. Eliel and J. T. Traxler, *ibid.*, **78**, 4049 (1956).

[8] E. L. Eliel, *Record Chem. Progr.*, **22**, 129 (1961).

[9] R. F. Nystrom, *J. Am. Chem. Soc.*, **81**, 610 (1959).

Table II. Selective Reduction of Halogen Acids and Esters with Aluminum Hydride in Tetrahydrofuran at 0°

Compound[a]	AlH_3/compd	Time, hr	Product[b]	AlH_3 yield, %[b]	$LiAlH_4$ yield, %	Ref
Chloroacetic acid	2.00	0.25	2-Chloroethanol	69	13	6
					5	7
Ethyl chloroacetate[c]	1.33	0.25	2-Chloroethanol	83	37	6
3-Chloropropionic acid	2.00	0.25	3-Chloropropanol	89 (61)[e]	21	7
Ethyl 3-chloropropionate[c]	1.33	0.25	3-Chloropropanol	100		
3-Bromobutyric acid	2.00	0.25	3-Bromobutanol	81		
		0.5		87[d]		
Ethyl 3-bromobutyrate	1.33	0.25	3-Bromobutanol	93.5		
		0.5		86		

[a] The solutions were 0.25 *M* in compound. [b] Products were identified and estimated by glpc analysis. [c] White precipitate were observed. [d] The yield decreased to 60% in 3.0 hr. [e] Isolated yield.

Table III. Selective Reduction of Functional Groups in the Presence of the Nitro Group with Aluminum Hydride in Tetrahydrofuran at 0°

Compound[a]	AlH_3/compd	Time, hr	Product	AlH_3 yield,[b] %	$LiAlH_4$ yield, %	Ref
Methyl 4-nitropentanoate	2.0	3.0	4-Nitropentanol	80	61	10
p-Nitrobenzoyl chloride	1.0	0.5	*p*-Nitrobenzyl alcohol	92		
Ethyl *p*-nitrobenzoate	2.0	3.0	*p*-Nitrobenzyl alcohol	68	40	11

[a] The solutions were 0.25 *M* in compound. [b] Isolated yield.

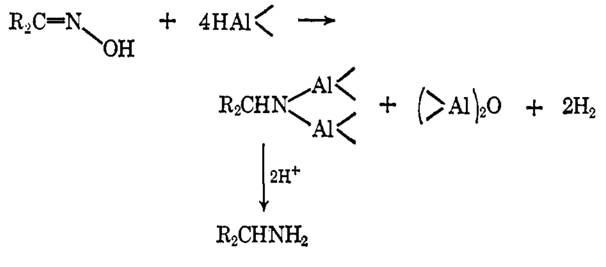
Table IV. Reduction of Representative Ketoximes with Aluminum Hydride in Tetrahydrofuran at 65°

Compound[a]	AlH_3/ compd	Time, hr	Product	AlH_3 yield,[b,c] %	$LiAlH_4$ yield, %	Ref
Cyclohexanone oxime	2.0	0.5	Cyclohexylamine	94 (85)	71[h]	10
					61[i]	10
					48[j]	11
Cyclopentanone oxime	2.0	0.5	Cyclopentylamine	92 (63)[d]	33	10
			Piperidine	(7)[d]		
2-Methylcyclohexanone oxime	2.0	0.5	2-Methylcyclohexylamines[e]	97	53	10
Norcamphor oxime	2.0	0.5	2-Norbornylamines[e]	92		
Acetophenone oxime	2.0	0.5	α-Phenylethylamine	82	56, 43[g]	10,12
			N-Ethylaniline	4.3[f]	16[g]	10

[a] The solutions were 0.25 *M* in compound. [b] Yields were estimated by titration. [c] Figures in parentheses were isolated yields. [d] 70% of amines were isolated, of which 10% of piperidine was identified and estimated by pmr. [e] In other experiments these oximes were reduced at 0° and the isomeric distribution was determined to be 70:30 *cis*-:*trans*-2-methylcyclohexylamine and 37:63 *exo*-:*endo*-norbornylamine. [f] N-Ethylaniline was identified and estimated by glpc. [g] A yield of 61% α-phenylethylamine and 6% N-ethylaniline was realized in tetrahydrofuran in an experiment carried out in the present study (see Table V). [h] In THF. [i] In Et_2O. [j] With $LiAlH_4 \cdot 0.33AlCl_3$.

gested that aluminum hydride could be used to reduce other groups selectively in the presence of such groups. This was tested with three representative derivatives. The results are summarized in Table III, together with related data for reductions with lithium aluminum hydride.[10,11] It is evident that quite satisfactory yields were realized.

Reduction of Ketoximes to Amines. Although lithium aluminum hydride has been used successfully for the reduction of oximes to amines, the reaction usually requires 3–8 hr in refluxing ether, and the yields are only moderate to low.[10–15] Five representative ketoximes were chosen and reduced with aluminum hydride in refluxing tetrahydrofuran. The reductions were all complete within 0.5 hr, using 2 mol of aluminum hydride/mol of compound (50% excess "hydride" over that theoretically required). The reaction mixtures remained clear and colorless. Four "hydrides" were consumed per mol of oxime—two for reduction and two for hydrogen evolution, as indicated by the over-all reaction 3.



(3)

The results are summarized in Table IV and compared with results for reductions with lithium aluminum hydride taken from the literature.

The formation of both α-phenylethylamine and N-ethylaniline from the reduction of acetophenone oxime was interesting and we examined it in more detail. Reduction of the oxime by lithium aluminum hydride in tetrahydrofuran was undertaken. There was an immediate evolution of 1 mol of hydrogen on mixing

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(10) H. Feuer and T. J. Kucera, *J. Am. Chem. Soc.*, **77**, 5740 (1955).

(11) H. Felkin, *Compt. Rend.*, **230**, 305 (1950).

(12) D. R. Smith, M. Maienthal, and J. Tipton, *J. Org. Chem.*, **17**, 294 (1952).

(13) M. Ferles, *Z. Chem.*, **6**, 224 (1966).

(14) C. R. Walter, Jr., *J. Am. Chem. Soc.*, **74**, 5158 (1952).

(15) M. N. Rerick, C. H. Trottier, R. A. Daignault, and J. D. DeFoe, *Tetrahedron Letters*, 629 (1963).

the reagents at room temperature. Hydrogen evolution then became very slow, even in refluxing tetrahydrofuran. After 1.5 hr under these conditions, 0.6 mol of additional hydrogen had been evolved and a precipitate formed. No additional hydrogen was then evolved. The isomeric distributions observed in the products by use of the various reducing agents are summarized in Table V.

Table V. Rearrangements in the Reduction of Acetophenone Oxime with Aluminum Hydride and Lithium Aluminum Hydride

Reagent	α-Phenyl-ethylamine	N-Ethyl-aniline	Ref
AlH_3	95	5	*a*, *b*
$LiAlH_4$ in THF	91	9	*a*, *c*
$LiAlH_4$ in Et_2O	78–80	20–22	15
$LiAlH_4$–$AlCl_3$, 1:4 in Et_2O	2–4	96–98	15

[a] Present study. [b] Total yield 86.3% for AlH_3 in 0.5 hr at 65°. [c] Total yield 67% for $LiAlH_4$ in 3 hr at 65°.

It is evident that aluminum hydride gives the least rearrangement of all the reagents examined with this oxime. Therefore, both the high yield in a relatively short reaction time (Table IV) and the low rearrangement (Table V) appear to make aluminum hydride the reagent of choice for the reduction of such ketoximes.

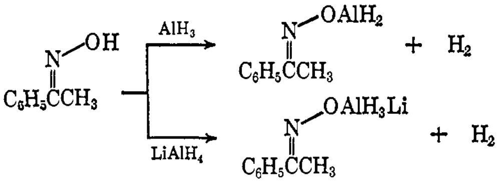
It was not a primary objective of the present study to concern itself with the mechanism of the reductions. However, the observation that aluminum hydride gives the least rearrangement among the various reagents examined was of interest. This can be combined with a number of earlier observations to suggest a reasonable course for the reaction which accounts for the observed differences between aluminum hydride and lithium aluminum hydride in these reductions.

1. In the reaction of *n*-hexylamine with lithium aluminum hydride, 2 mol of hydrogen/mol of amine is evolved immediately.[3] However, in the corresponding reaction with aluminum hydride only 1 mol of hydrogen is evolved rapidly, with evolution of the second being very slow.[2]

2. Hexanenitrile and benzonitrile react faster with aluminum hydride than with lithium aluminum hydride.[2,3] Also, pyridine undergoes reaction at a moderate speed with aluminum hydride, but only very slowly with lithium aluminum hydride.

3. A yellow color was observed in the reactions of benzonitrile with lithium aluminum hydride and with aluminum hydride. In the reactions with pyridine there was observed a faint green color with lithium aluminum hydride and a yellow color with aluminum hydride.

We therefore suggest that the first step is the reaction of the oxime with either aluminum hydride or lithium aluminum hydride to give a derivative, as indicated in (4). On the basis of the previous observations, it would appear that many carbon–nitrogen double and triple bonds are much more susceptible to attack by aluminum hydride than by lithium aluminum hydride. Consequently, we suggest that the intermediate A reacts much faster with aluminum hydride, through an addition to the carbon–nitrogen double bond, to form the amine ultimately, as shown in (5), whereas the corresponding reaction of lithium aluminum hydride involves an attack on the nitrogen–oxygen bond, as shown in (6).



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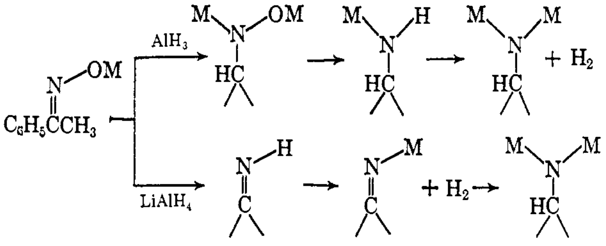

(5)

(6)

According to this interpretation, the relatively slow reaction of lithium aluminum hydride with the initial intermediate affords it opportunity to undergo a Beckmann rearrangement, leading ultimately for the formation of N-ethylaniline.[16]

Reduction of Amides to Amines. Six representative amides were selected and reduced with aluminum hydride in tetrahydrofuran at 0–25°. The four *t*-amides in the group, N,N-dimethyl-, N,N-diethyl-, N,N-diisopropylbenzamide, and N,N-dimethylcinnamide, were all reduced to the corresponding amines within 0.5 hr, in essentially quantitative yields. The reduction of the *sec*-amide, N-methylbenzamide, was considerably slower, but the yield was still very high. The primary amide, benzamide, exhibited both a slow reaction and a reduced yield, 76–82%. The results are summarized in Table VI.

Lithium aluminum hydride has also been applied to such reductions.[17,18] However, there appears to be a competition between the rupture of the carbon–oxygen bond, leading to amine, and the rupture of the carbon–nitrogen bond, leading to alcohol. Thus it was shown that the amount of rupture of the carbon–nitrogen bond is varied by changes in the amount of hydride, the temperature of the reaction, the mode of addition, and the reaction time, as well as by structural differences in the substrate.[18,19] For example, Mićović and Mihailović reported that in the reductions of N,N-dimethylbenzamide benzyl alcohol is obtained in 15% yield when the reduction is carried out with the theoretical amount of hydride, in 13% yield when the reduction is carried out at 0°, whereas no alcohol is formed under so-called normal conditions (1 hr at 34° with 25–30% excess hydride). Furthermore, the many studies on aldehyde synthesis *via* the partial reduction of *t*-amides suggest that this competition is markedly influenced by both the steric and electronic characteristics of the amide groups.[19] It appears, therefore,

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(16) See K. Kitahonoki, K. Kotera, Y. Matsukawa, S. Miyazaki, T. Okada, H. Takahashi, and Y. Takano, *Tetrahedron Letters*, 1059 (1965), for a discussion of the related rearrangement of benzylketoximes to aziridines in the reduction with lithium aluminum hydride in tetrahydrofuran.

It should be pointed out that it has been argued that the production of secondary amines in these reductions involve a rearrangement of a hydroxylamine intermediate, rather than a Beckmann rearrangement of the ketoxime (see ref 15).

(17) H. Uffer and E. Schlitter, *Helv. Chim. Acta*, **31**, 1397 (1948).

(18) V. M. Mićović and M. L. Mihailović, *J. Org. Chem.*, **18**, 1190 (1953).

Table VI. Reduction of Representative Amides with Aluminum Hydride in Tetrahydrofuran

Compound[a]	Mode of addn	Temp, °C	AlH_3/compd	Time, hr	Product	AlH_3 yield,[b,c] %	$LiAlH_4$ yield, %	Ref
Benzamide	N	25	2.00	12	Benzylamine	82[d]		
	R	25	2.00	24		76[e]		
N-Methylbenzamide[f]	N	25	1.33	24	N-Methylbenzylamine	95.5 (89)		
N,N-Dimethylbenzamide[g]	N	0	1.33	1.0	N,N-Dimethylbenzylamine	98		
	N	25	1.33	0.5		98		
	N	25	1.33	1.0		97		
	R[i]	0	0.33	1.0		47		
N,N-Dimethylcinnamide[g]	N	0	1.33	0.5	N,N-Dimethylcinnamylamine	94	0	18
	R	0	1.33	0.5		93 (70)		
	N[j]	0	0.76	1.0		(73)		
N,N-Diethylbenzamide[g]	N	0	1.33	0.5	N,N-Diethylbenzylamine	97	92[h]	18
	N	0	1.33	1.0		97 (93)		
	N	25	2.66	12		96		
	N	65	1.33	0.5		96		
N,N-Diisopropylbenzamide[g]	N	0	1.33	0.5	N,N-Diisopropylbenzylamine	97 (88)		

[a] The solutions were 0.25 *M* in compound. [b] Yields were estimated by titration. [c] Figures in parentheses were isolated yields. [d] The reaction mixture was slightly yellow. [e] The reaction mixture was yellow. [f] The reaction mixture was slightly turbid. [g] White precipitate was observed immediately. [h] Mićović and Mihailović[18] reported 13% benzyl alcohol at 0°, but no alcohol in refluxing ether with 25–30% excess $LiAlH_4$. [i] 0.85 H^- was used per mole of compound. [j] 1.87 H^- was used per mole of compound.

Table VII. Reduction of Nitriles with Aluminum Hydride in Tetrahydrofuran at 25°

Compound[a]	AlH_3/compd	Time, hr	Product	AlH_3 yield,[b] %	$LiAlH_4$ yield, %	Ref	$LiAlH_4$–$AlCl_3$ yield, %	Ref
Capronitrile	1.33	1.0	*n*-Hexylamine	91.3	63	22	75[j]	22
3-Butenonitrile	1.33	1.0	3-Butenylamine	83.3 (55)[c]	0	24		
Phenylacetonitrile	1.33	3.0	2-Phenylethylamine	94.2 (77)	46	22	83,[j] 50[k]	22, 13
Diphenylacetonitrile	1.33	0.5	2,2-Diphenylethylamine	97.7 (91)	61	22	91[j]	22
Cinnamonitrile	1.33	0.5	Cinnamylamine Hydrocinnamylamine	78.2 (39.4)[d] (8.6)				
	2.00	1.0	Cinnamylamine Hydrocinnamylamine	(56)[e,g](50)[e] (4) (13)	0[f,h]			
Benzonitrile	1.33	1.0	Benzylamine	96.8[i]	72	23	88[k]	13

[a] The solutions were 0.25 *M* in compound. [b] Yields were estimated by titration. [c] Figures in parentheses were isolated yields. [d] The reaction mixture turned orange. [e] The reaction mixture turned yellow. [f] The reaction mixture turned dark red. [g] At 0°. [h] After stripping off the solvent, yellow solids were observed for two cases where $LiAlH_4$/compound ratios were 2.00 and 1.00. [i] 95.5% by glpc. [j] $LiAlH_4$–$AlCl_3$, 1:1. [k] $LiAlH_4$–$AlCl_3$, 3:1.

that aluminum hydride is the reagent of choice for the conversion of amides into amines.[20]

Reduction of Nitriles to Amines. In our stoichiometry studies[2] we were impressed by the observation that no hydrogen was evolved in the reaction of capronitrile with aluminum hydride, whereas 24 mol % hydrogen was evolved in the corresponding reaction with lithium aluminum hydride.[3] Such hydrogen evolution, representing attack by the nucleophilic reagent on the active hydrogen of the α position, is believed to be responsible for the decreased yields encountered in the reduction of aliphatic nitriles by lithium aluminum hydride.[21]

This difficulty has been overcome by the use of mixed hydride for the reduction.[22] However, it appeared that aluminum hydride might offer a convenient alternative, with special advantages in systems where the substrate might be sensitive to the presence of a strong Lewis acid. Accordingly, we subjected six selected nitriles to reduction with aluminum hydride. Excellent yields were realized. The results are summarized in Table VII, together with related data for reductions with lithium aluminum hydride[23] and mixed reagent.[22]

To illustrate the advantages of the present approach we recently required 3-butenylamine.[24] An attempt to reduce 3-butenonitrile with lithium aluminum hydride gave a negligible yield of the desired amine. Consequently, we relied on a several-step synthesis, involving synthesis of the benzenesulfonate, treatment of this derivative with sodium azide to form 3-butenyl azide, followed by lithium aluminum hydride reduction of the azide to the amine.[25] Certainly, the simple reduction of 3-butenonitrile to 3-butenylamine in 1 hr at 25° offers considerable in both convenience and economy of time.

Reduction of Enolizable Keto Esters to Diols. It has been reported that highly enolizable keto esters, such as 2-carbethoxycyclopentanone, give only a small amount of the desired diols.[26,27] The major product is a complex mixture of unsaturated alcohols (7).

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(19) N,N-Disubstituted amides can be reduced to aldehydes in excellent yields with lithium ethoxyaluminohydrides. See H. C. Brown and A. Tsukamoto, *J. Am. Chem. Soc.*, **83**, 4549 (1961); **86**, 1079 (1964), and references therein.

(20) Diborane also gave excellent yields of amines from amides, but cannot be used for olefinic compounds, such as N,N-dimethylcinnamide: H. C. Brown and P. Heim, *ibid.*, **86**, 3566 (1964).

(21) L. H. Amundsen and L. S. Nelson, *ibid.*, **73**, 242 (1951); L. M. Soffer and E. W. Parrotta, *ibid.*, **76**, 3580 (1954); L. M. Soffer and M. Katz, *ibid.*, **78**, 1705 (1956).

(22) R. F. Nystrom, *ibid.*, **77**, 2544 (1955).

(23) R. F. Nystrom and W. G. Brown, *ibid.*, **70**, 3738 (1948).

(24) H. C. Brown and M. K. Unni, *ibid.*, **90**, 2902 (1968).

(25) E. Renk and J. D. Roberts, *ibid.*, **83**, 878 (1961).

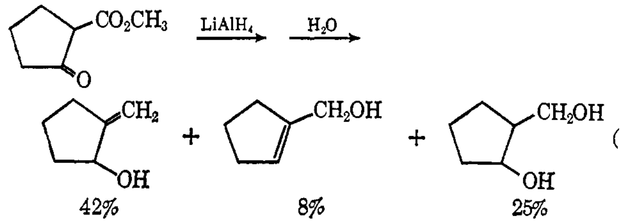
(26) E. Buchta and H. Bayer, *Ann.*, **573**, 227 (1951).

(27) A. S. Dreiding and J. A. Hartman, *J. Am. Chem. Soc.*, **75**, 939 (1953).

Table VIII. Reduction of Enolizable Keto Esters with Aluminum Hydride at 0° and with Sodium Borohydride at 25° in Tetrahydrofuran

Compound[a]	AlH_3/compd	Time, hr	Product[b]	AlH_3 yield,[b] %	$LiAlH_4$ yield, %	Ref
Ethyl acetoacetate	1.33	0.5	1,3-Butanediol	63[c]	30	26
	1.33	0.5		69.5[d]		
	2.00	0.5		67.7[d]		
2-Carbethoxycyclopentanone	2.00	0.5	2-Methylolcyclopentanol	82.5[c]	22	26
	2.00	0.5		78.5[d]	25	27

[a] The solutions were 0.25 *M* in compound. [b] Products were isolated by distillation and identified by glpc and pmr. [c] Hydrolyzed with THF-H_2O (1:1) and treated with equimolar sodium borohydride dissolved in 3 *M* NaOH for 1 hr. [d] Hydrolyzed with 2-propanol and treated with equimolar sodium borohydride for 2 hr.



(7)

Although such enolizable keto esters were not included in our stoichiometry study,[2] a number of related observations suggested that reduction of such esters by aluminum hydride should produce the corresponding keto alcohols. These observations are as follows.

1. Aluminum hydride does not evolve hydrogen in the reaction with nitriles which contain relatively active hydrogen in the α position.

2. Aluminum hydride does not attack the double bond in the reaction with cinnamyl derivatives.[2,28]

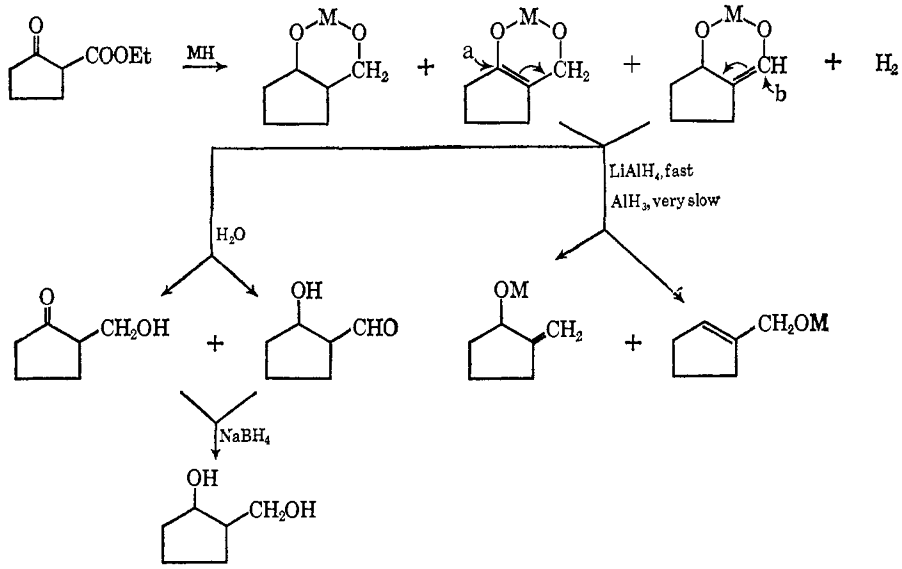
3. In the reaction of isopropenyl acetate with aluminum hydride, the rate and the stoichiometry suggested that the reduction proceeds to give an aluminum derivative of the enol form of acetone, relatively stable to further reduction by the reagent.[2] This is in marked contrast to the behavior of lithium aluminum hydride.[3]

Accordingly, once the intermediate is produced in the reaction with aluminum hydride, the simultaneous addition of water and sodium borohydride should convert the intermediate first into the keto alcohol, and then into the desired diol.

This possibility was tested for two keto esters, ethyl acetoacetate and 2-carbethoxycyclopentanone. In both cases the corresponding diols were obtained in greatly improved yields. The results are summarized in Table VIII.

A possible mechanism which accounts for these results is outlined in (8).

These considerations also suggest that it should be possible to utilize aluminum hydride for the selective reduction of the carbethoxy group in enolate salts, without attack on the enolate function. This would provide a convenient route to keto alcohols, such as the conversion of 2-carbethoxycyclopentanone into 2-methylolcyclopentanone. However, we did not test this possibility.



(8)

Reduction of Epoxides. Previously we had observed that reduction of four representative epoxides, 1,2-butylene oxide, styrene oxide, cyclohexene oxide, and 1-methyl-1,2-cyclohexene oxide, by either lithium aluminum hydride[3] or aluminum hydride[2] were very rapid, being complete within 1 hr at 0°. For three of the four epoxides the products were identical, involving essentially 100% attack of hydride at the less substituted center to give the corresponding secondary or tertiary alcohols. In the case of styrene oxide we observed that aluminum hydride gave a significant amount of opening at the secondary position to yield 27% of the primary alcohol, 2-phenylethanol.

We decided to explore this phenomenon in more detail to see if we could achieve such an inverted opening of the epoxide ring in systems where such an opening would be helpful synthetically. 1,2-Butylene oxide, styrene oxide, 1-phenylcyclohexene oxide, 1-phenylcyclopentene oxide, and norbornene oxide were selected for study. These same epoxides were subjected to

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[28] M. J. Jorgensen, *Tetrahedron Letters*, 559 (1962).

Table IX. Reduction of Representative Epoxides in Tetrahydrofuran

Compound[a]	Hydride[b]	Temp, °C	Time, hr	Product[c]	Total yield,[c] %
1,2-Butylene oxide	$LiAlH_4$	25	1.0	100% *sec*-butyl alcohol	93
	AlH_3	25	1.0	100% *sec*-butyl alcohol	99
	AlH_3–$2AlCl_3$	0	1.0[d]	100% *sec*-butyl alcohol	71
Styrene oxide	$LiAlH_4$	0	0.5	96% α- and 4% β-phenylethanol	92
	$LiAlH_4$	25	1.0	98% α- and 2% β-phenylethanol	98.5
	AlH_3	0	1.0	76% α- and 24% β-phenylethanol	98
	AlH_3	25	1.0	73% α- and 27% β-phenylethanol	100
	AlH_3–$2AlCl_3$	0	1.0	9.2% α- and 90.8% β-phenylethanol	92.5
1-Phenylcyclohexene oxide	$LiAlH_4$	0	48.0	100% 1-phenylcyclohexanol	98
	AlH_3	0	6.0	64% 1- and 36% *cis*-2-phenylcyclohexanol	97
1-Phenylcyclopentene oxide	$LiAlH_4$	0	24		*f*
	$LiAlH_4$	25	24	87% 1- and 13% *cis*-2-phenylcyclopentanol	94
	AlH_3	0	24	9% 1- and 91% *cis*-2-phenylcyclopentanol	100
Norbornene oxide	$LiAlH_4$	25	240	100% *exo*-2-norbornanol	8
	$LiAlH_4$	65	96	100% *exo*-2-norbornanol	73
	$LiAlH_4$ (DG)	100	24	100% *exo*-2-norbornanol	98
	AlH_3	25	96	69% *exo*-2- and 31% 7-norbornanol	84
	AlH_3	65	12	51% *exo*-2-, 48% 7-, and 1% *endo*-2-norbornanol	80
	AlH_3–$2AlCl_3$	0	3[e]		0

[a] The solutions were 0.25 *M* in compound. [b] Hydride/compound were all 1:1 molar ratio. [c] Products were identified and estimated by glpc. [d] 1.0 "hydride" used for reduction per mole of compound. [e] 0.9 "hydride" used for reduction per mole of compound. [f] 42% H^- used.

mixed hydride, AlH_3–$2AlCl_3$, for comparison. The results are summarized in Table IX.

In the case of 1,2-butylene oxide all three reagents gave essentially only *sec*-butyl alcohol. There is evidently no tendency in this system to open at the secondary position rather than undergo attack by hydride at the primary position.

Again styrene oxide gave partial reduction at the benzylic position, 25%, with aluminum hydride, and this increases to 91% with the mixed hydride. In the case of 1-phenylcyclohexene oxide, the reduction at the tertiary position increases to 36% with aluminum hydride. Finally, the reduction at the tertiary position of 1-phenylcyclopentene oxide by aluminum hydride becomes the dominant reaction, yielding only 9% of the tertiary alcohol and 91% of *cis*-2-phenylcyclopentanol,[29] isomerically pure.

It is evident that in selected systems aluminum hydride can be used to achieve an opening of the epoxide ring that is contrary to that observed with lithium aluminum hydride. Of course, such openings by "mixed hydrides" have long been recognized.[8] Nevertheless, there are many systems where the use of the milder agent, aluminum hydride, would be strongly preferred.

The results with *exo*-norbornene oxide were quite unexpected. The reaction of the epoxide with lithium aluminum hydride was amazingly slow. Thus, in 240 hr at 25° lithium aluminum hydride produced only 8% *exo*-norbornanol. This compares with 100% reduction of cyclohexene oxide in 1 hr at 0°.[3] Doubtless this is an indication of the marked resistance of the norbornane structure to SN2 reactions.[30] The reduction could be speeded up considerably in refluxing tetrahydrofuran (65°) and in diglyme at 100°, without altering the nature of the reaction. The latter modification would appear to possess promise synthetically for the reduction of such bicyclic oxides.

The reduction of norbornene oxide by aluminum hydride is considerably more facile, requiring 96 hr at 25° or 12 hr at 65° for complete reduction. However, the product is no longer the *exo*-norbornanol exclusively. Indeed, at 65° the product contains 48% 7-norbornanol and provides a relatively simple route to this derivative.

It is apparent then that reduction of epoxides by lithium aluminum hydride possesses all the characteristics of a relatively clean SN2 reaction, involving attack of the epoxide and transfer of hydride at the least hindered position.[31] The use of aluminum hydride introduces an electrophilic component, in which there occurs a competitive transfer of hydride at the more substituted center, especially when it is benzylic in nature capable of stabilizing an electron deficiency. The formation of *cis*-2-phenylcyclohexanol and *cis*-2-phenylcyclopentanol, without evidence of the *trans* isomer, in the reduction of the corresponding oxides by aluminum hydride, makes it clear the transfer of hydride to the tertiary center must involve a Walden inversion at that center. Finally, the rearrangement observed in the reduction of norbornene oxide by aluminum hydride again supports the conclusion that the use of this reagent involves an electrophilic component.

We are presently engaged in a study of the reduction of such epoxides by diborane, sodium borohydride, and mixtures of the two reagents.[32] Consequently, a detailed discussion of the mechanisms of these reductions is best deferred until the entire subject can be discussed as a unit.

Stereochemistry of Ketone Reductions by Aluminum Hydride. The reduction of cyclic and bicyclic ketones by lithium aluminum hydride and its derivatives has been thoroughly studied.[33–36] Consequently it was of

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(29) P. T. Lansbury, D. J. Scharf, and V. A. Pattison, *J. Org. Chem.*, **32**, 1748 (1967). The same observation was reported, but it was also reported that when the turbid solution, presumably containing Li_2SO_4, was used, the results were similar to the $LiAlH_4$–$AlCl_3$ (3:1) reduction. These authors did not note the formation of tertiary alcohol.

(30) J. P. Schaefer and D. S. Weinberg, *J. Org. Chem.*, **30**, 2635 (1965).

(31) However, attention is called to the formation of 2–4% of 2-phenylethanol from styrene oxide and 13% of *cis*-2-phenylcyclopentanol from 1-phenylcyclopentene oxide.

(32) Research in progress.

Table X. Stereochemistry of Reduction of Representative Cyclic and Bicyclic Ketones

Ketone[a]	Product	AlH_3	$LiAlH_4$[b]	LiAlH(O-*t*-Bu)$_3$[b]	LiAlH(OMe)$_3$[b]
2-Methylcyclopentanone	*trans/cis*	79/21	76/24	72/28	56/44
2-Methylcyclohexanone	*trans/cis*	73.5/26.5	76/24	70/30	31/69
4-*t*-Butylcyclohexanone	*trans/cis*	87/13	89/11	89.7/10.3	
Norcamphor	*exo/endo*	7/93	11/89	7/93	2/98
Apocamphor	*exo/endo*	91/9	90/10[c]		
Camphor	*exo/endo*	90/10	92/8	93/7	99/1

[a] The solutions were 0.25 *M* in compound. [b] Reference 33. [c] R. Howe, E. C. Friedrich, and S. Winstein, *J. Am. Chem. Soc.*, **87**, 379 (1965).

interest to explore whether the results with aluminum hydride would exhibit any significant difference. The results are summarized in Table X.

The similarity in the stereochemical results in reductions by aluminum hydride and lithium aluminum hydride is remarkable. Indeed, of the four reagents only lithium trimethoxyaluminohydride appears to give results that are significantly different. The precise reason for this similarity in results is not yet clear and discussion will be deferred.

Obviously, there would be no point to the use of aluminum hydride for the reduction of such simple ketones, when lithium aluminum hydride gives the same stereochemical results. However, in more complex derivatives, where other groups may be present that are susceptible to attack, the use of aluminum hydride can be advantageous. However, sodium borohydride[37] gives almost identical stereochemical results, so that it would doubtless be the reagent of choice in the reduction of such ketones.

Conclusions

Major differences in reducing characteristics have been observed between sodium borohydride, a "basic" reducing agent, and diborane, an "acidic" reducing agent. The differences between lithium aluminum hydride and aluminum hydride are much smaller. However, this study has turned up significant differences which indicate aluminum hydride to be a useful reagent for (1) the reduction of carboxylic acid and ester groups in the presence of reactive halogen substituents; (2) the reduction of reducible functional groups in the presence of nitro substituents; (3) the reduction of ketoximes to amines; (4) the reduction of amides to amines; (5) the reduction of nitriles, especially those with active α hydrogen, to amines; (6) the reduction of enolizable keto esters; and (7) the reduction of certain selected epoxides.

Experimental Section

Materials. For the most part the compounds used were commercial products of highest purity available. In some cases, the compounds were synthesized, and the procedures are described at the place where the reductions of these compounds are reported.

We were indebted to Professor P. T. Lansbury for sending us a sample of 1-phenylcyclopentene oxide and its procedure of preparation and to Professor H. Feuer for supplying us with methyl 4-nitropentanoate. The lithium aluminum hydride was 95+% material from the Ventron Corporation (Metal Hydrides Division). For the quantitative experiments tetrahydrofuran (THF) was treated with a slight excess of the lithium aluminum hydride necessary to react with the active hydrogen impurities and then distilled from the reagent. For some of the preparative runs lithium aluminum hydride was dissolved directly into Baker's Reagent Grade THF and the turbid solution used directly for preparation of the aluminum hydride.

Preparation of Lithium Aluminum Hydride Solution in Tetrahydrofuran (THF) and Standardization. Solutions of lithium aluminum hydride in THF were prepared by adding an excess of the hydride to dry THF (freshly distilled from a slight excess of lithium aluminum hydride) and stirring the mixture for at least 2 hr under a dry nitrogen atmosphere. The resulting solution was then filtered under a slight positive nitrogen pressure through a 2-in. bed of tightly packed Celite prepared on a sintered glass disk previously sealed into a large cylinder for enclosing the solution.

In this way clear to slightly turbid yet quite homogeneous solutions of the reagent were prepared and stored in a 1-l. flask with a rubber septum syringe inlet.

In one typical preparation, 50 g (1.25 mol) of lithium aluminum hydride (95+% pure, Metal Hydrides Inc.) was added to 800 ml of THF (dried as described previously). After following the above procedure, a crystal-clear 1.55 *M* solution was obtained. The hydride concentration was determined by injecting aliquots of the solution into the hydrolyzing mixture, consisting of a 1:1 mixture of 2 *N* aqueous sulfuric acid and THF, and measuring the hydrogen evolved.

Prepared in this manner and vigorously protected from atmospheric moisture, these solutions of lithium aluminum hydride appeared to be stable indefinitely.

Preparation of Aluminum Hydride Solution in THF. By means of a hypodermic syringe, 51.6 ml of 1.55 *M* lithium aluminum hydride (80 mmol) and 68.4 ml of THF were introduced into a 300-ml flask fitted with an inlet part, rubber syringe cap, and magnetic stirring bar, and connected to a gas meter *via* the reflux condenser and a Dry Ice trap. To this solution, 3.94 g (2.14 ml) of 100% sulfuric acid (specific gravity 1.839) (40 mmol) was added slowly by means of a syringe, while stirring the solution vigorously at room temperature. (Usually the flask was immersed in a cold water bath to minimize possible reaction of the hydride with the THF at higher temperatures.) There was evolved 79.7 mmol of hydrogen, and the solution was permitted to stir for 1 hr, then allowed to stand at room temperature to permit the lithium sulfate precipitate to settle. (It was usually convenient to allow the solution to stand overnight.) The clear supernatant solution was removed with a syringe and the hydride concentration determined; 1.96 "hydride"/ml was found, whereas 1.97 "hydride"/ml was expected. The concentration of aluminum hydride was usually slightly lower than the expected value; thus we obtained 1.96, 1.86, 1.92 for the "hydride"/ml in three separate preparations where a value of 1.97 was calculated.

This clear solution was used for all reductions studied, except in the case of large-scale preparations. The aluminum hydride solution was also filtered using the same technique as in the case of the lithium aluminum hydride solutions, and the clear solution was then stored in a cold room (−2 to −4°). We could store such solutions for 1 week without significant change in the hydride concentration (see following discussion).

Stability of Aluminum Hydride Solution in THF. The stability of aluminum hydride solutions in THF was examined by following the change in hydride concentration with time. The change observed in the hydride concentration of clear aluminum hydride

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(33) H. C. Brown and H. R. Deck, *J. Am. Chem. Soc.*, **87**, 5620 (1965).

(34) W. G. Dauben, G. J. Fonken, and D. S. Noyce, *ibid.*, **78**, 2579 (1956); W. G. Dauben, E. J. Blanz, Jr., J. Jiv, and R. A. Micheli, *ibid.*, **78**, 3762 (1956).

(35) E. L. Eliel and M. N. Rerick, *ibid.*, **82**, 1367 (1960); H. Haubenstock and E. L. Eliel, *ibid.*, **84**, 2363 (1962).

(36) D. C. Ayres and R. Sawdaye, *Chem. Commun.*, 527 (1966); *J. Chem. Soc.*, 581 (1967).

(37) H. C. Brown and J. Muzzio, *J. Am. Chem. Soc.*, **88**, 2811 (1966).

Table XI. Stability of Aluminum Hydride Solution in Tetrahydrofuran at Various Temperatures

Temp, °C	Time, hr 0	0.5	1.0	3.0	6.0	12.0	24.0	48.0	72.0
0	2.78[a]	2.78	2.78	2.78			2.78	2.78	2.76
	(100)[b]	(100)	(100)	(100)			(100)	(100)	(99)
25	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.00	0.98
	(100)	(100)	(100)	(100)	(100)	(100)	(100)	(98)	(96)
50	1.02	1.00	1.01	1.01	1.00		0.94	0.87	0.80
	(100)	(98)	(99)	(99)	(98)		(92)	(85)	(78.5)
65	1.81	1.79	1.74	1.61	1.37	1.18	0.99		
	(100)	(99)	(96)	(89)	(75.6)	(65.2)	(54.7)		
65[c]	1.91	1.85	1.81	1.6	1.33	1.11	0.87		
	(100)	(97)	(95)	(84)	(70)	(58.2)	(45.6)		

[a] Mmoles of "hydride"/ml of solution. [b] Figures in parentheses are percentage of concentration, compared with initial (0 hr) concentration. [c] The solution was refluxed in the presence of Li_2SO_4.

Table XII. Loss of Hydride from Lithium Aluminum Hydride and Aluminum Hydride Solution in THF in the Presence of Air at 25°

	Time, hr 0	0.5	1.0	3.0	6.0	12.0	24.0	48.0
$LiAlH_4$, M (in H^-)	0.99	0.98	0.98	0.97	0.97	0.93	0.82	0.59
% H^-	(100)	(99)	(99)	(98)	(98)	(94)	(83)	(60)
AlH_3, M (in H^-)	0.97	0.96	0.96	0.94	0.93	0.9	0.84	0.59
% H^-	(100)	(99)	(98)	(97)	(96)	(93)	(87)	(61)

solutions at 0, 25, and 50° and in the absence and presence of lithium sulfate in refluxing THF (65°) are summarized in Table XI.

Behavior of THF Solutions of Lithium Aluminum Hydride and Aluminum Hydride toward Air. Standard solutions of lithium aluminum hydride and aluminum hydride in THF (approximately 1.00 M in hydride) were prepared and subjected to the following tests at room temperature.

1. Aliquots (2 ml) of the above solutions were removed by syringe and discharged through air into an evaporating dish. These solutions did not catch fire, indicating that such solutions are not spontaneously inflammable.

2. Aliquots (5 ml) of the above solutions were placed in evaporating dishes and allowed to stand exposed to the open air. Except for a slight warming of the solutions, no other significant change was immediately observed. Evaporation of the solvent from the aluminum hydride solution was complete in about 30 min, leaving a powdery white residue which exhibited no hydride activity on treatment with water. On the other hand, the lithium aluminum hydride solution formed a film on the surface and this reduced the rate of evaporation of the solvent. Many large bubbles of gas, presumably hydrogen, could be observed under the surface. The whole mass became gelatinous and eventually dried to a white powder and milky thin film in about 2 hr. This experiment was repeated with more concentrated solutions, aluminum hydride (2.8 M in H^-) and lithium aluminum hydride (6.2 M in H^-). However, the results were similar.

3. A flask and a condenser (protected by a drying tube) were flushed with dry air; 50 ml of a standard solution (1.0 M in hydride) of each was introduced into the flask and allowed to stand exposed to the dry air; Aliquots were removed and analyzed for residual hydride. The observed decreases in the hydride concentrations are summarized in Table XII.

Destruction of Excess Aluminum Hydride. At the end of the reaction, the excess hydride was destroyed with a 1:1 mixture of THF and water. Thus when 0.4 mol of aluminum hydride was used in the reaction, 50 ml of $THF \cdot H_2O$ (1:1) mixture was added regardless of the hydride consumption.

This corresponds to a 15% excess for the following stoichiometry, assuming $n = 3$ (*i.e.*, that no hydride had been utilized for reaction).

$$AlH_n(OR)_{3-n} + 3H_2O \longrightarrow (3 - n)ROH + Al(OH)_3 + nH_2$$

After this initial hydrolysis, isolation of the products utilized procedures which varied in accordance with the characteristics of the products.

a. Alkaline Products. To the hydrolyzed reaction mixture, which originally contained 0.4 mol of aluminum hydride, 20 g of sodium hydroxide dissolved in 150 ml water was added with constant stirring. The bulky aluminum hydroxide soon coagulated. The clear supernatant solution was decanted and the residual mass was extracted twice with 100 ml of ether. The extraction of amines by this procedure was essentially complete, as indicated by the following data. For the small-scale reductions (10 mmol) of cyclohexanone oxime and acetophenone oxime, the extent of the extraction of the corresponding amines was checked by titration. Approximately 95% of the recovered amine was present in the decanted tetrahydrofuran layer, with only a 1 or 2% of additional amine provided by the ether extractions.

b. Neutral Products. For the alcohols, produced in the reductions of epoxides and ketones, the reaction mixtures were hydrolyzed with an excess of 1:1 mixture of THF and water.

The aqueous layer was saturated with potassium carbonate, and the clear THF layer was separated. This THF layer contained essentially all alcoholic products as shown by glpc analysis for the representative alcohols. These are summarized in Table XIII.

Table XIII. Recovery of Representative Alcohols from Lithium Aluminum Hydride and Aluminum Hydride Reduction Mixtures[a]

Alcohol	Recovery of alcohol, % $LiAlH_4$	AlH_3	Internal glpc standard
n-Butyl alcohol	97.5	98.6	Toluene
sec-Butyl alcohol	100	99.3	Toluene
Cyclohexanol	97.2	96	*sec*-Butylbenzene
1-Methylcyclohexanol	99.3	99.6	*n*-Propylbenzene
2-Methylcyclohexanols	100	98.2	*n*-Propylbenzene
α-Phenylethanol	100	100	Benzyl alcohol
β-Phenylethanol	100	98.9	Benzyl alcohol
exo-2-Norbornanol	100	100	Cyclohexanol
7-Norbornanol	97	100	Cyclohexanol

[a] Alcohols were treated with $LiAlH_4$ or AlH_3 in THF solution at room temperature. After 30 min, the mixture was worked up as described and the internal glpc standard was added. The THF layer was subjected to glpc and compared with synthetic mixture of the corresponding alcohols and the standard.

General Procedure Used for Hydride Reductions. The following general procedure was used for the quantitative studies. The reaction flask was dried in an oven and cooled down in a dry nitrogen atmosphere. The flask was equipped with rubber syringe cap, magnetic stirring bar, and a reflux condenser which is connected to an inverted gas buret *via* a Dry Ice vapor trap. All reductions were carried out in this dry nitrogen atmosphere, although the tests previously described indicated that the presence of dry air in the reaction vessel offers no major difficulties.

To transfer substances, hypodermic syringes were used for small-scale reductions, and a dropping funnel was used for preparative-scale reductions.

Reductions in the Presence of Halogen Substituents. Ethyl 3-chloropropionate was conveniently prepared by the following procedure. A solution of 3-chloropropionic acid (0.5 mol, 55 g) in absolute ethanol (50 ml) was saturated with dry hydrogen chloride with the aid of the Brown and Brown gas apparatus.[38] The absorption was fast at the beginning, causing the solution to warm up, and then continued slowly for about 2 hr (total uptake of hydrogen chloride was 0.36 mol). The solution was diluted with 200 ml of ether, washed with dilute sodium bicarbonate solution and water, and dried over anhydrous magnesium sulfate. Analysis by glpc showed only one peak. After stripping off the ether with a rotary evaporator, distillation yielded 55 g (80% yield) of ethyl 3-chlorobutyrate, bp 96–97° (35 mm), $n^{20}\text{D}$ 1.4259 (lit.[39] $n^{20}\text{D}$ 1.4269).

The following procedure for the reduction of ethyl 3-chloropropionate is representative of the small-scale quantitative studies of the reduction of the six compounds examined (Table II). Aluminum hydride, 6.66 mmol in 15 ml of tetrahydrofuran, was introduced into the reaction flask, placed in an ice bath, and flushed with dry nitrogen. The ester, contained in dry tetrahydrofuran previously cooled to 0° (5 ml of 1.0 *M* solution), was added to the hydride solution with moderate stirring. The formation of a white precipitate was observed immediately. After 15 min, the reaction mixture was hydrolyzed with 3 ml of the THF–H_2O (1:1) mixture. 1-Octanol (5 ml of 1 *M* solution) was added as an internal standard. The tetrahydrofuran layer was dried over anhydrous magnesium sulfate. Glpc analysis of the solution indicated a quantitative yield of 3-chloro-1-propanol. In another run, a 98% yield was indicated after 30 min.

The following procedure for the reduction of 3-chloropropionic acid on a preparative scale is representative. A 1-l., three-necked flask was equipped with a reflux condenser, a mechanical stirrer, and a thermometer adapter equipped with a rubber septum which was used as an inlet tube. In the flask was placed 500 ml of THF (Baker AR), and 16 g (0.4 mol) of lithium aluminum hydride (95+%, Metal Hydrides Inc.) was added in five portions while the solution was gently stirred. The stirring was continued for 1 hr. The flask was immersed in an ice bath, and the solution was vigorously stirred as 19.6 g (10.7 ml) of 100% sulfuric acid was added dropwise by means of hypodermic syringe through the rubber septum. The addition was completed in 20 min, and 408 mmol of hydrogen was evolved as indicated by the gas meter which was connected to the top of the reflux condenser (400 mmol was expected). The solution was stirred for 1 hr and placed in an ice-salt bath. To this aluminum hydride solution, which has considerable suspended material (the impurities present in the lithium aluminum hydride and the lithium sulfate precipitate), there was added slowly over 30 min 21.7 g (0.2 mol) of 3-chloropropionic acid dissolved in 50 ml of THF, previously cooled down to 0°. During the addition, a total of 0.204 mol of hydrogen was evolved, and the temperature of the solution was maintained at 2° or below. After stirring for 15 min more, the excess hydride was cautiously destroyed with 50 ml of the 1:1 mixture of THF and water. The precipitate was filtered off, treated with 150 ml of water, and then washed twice with 100 ml of THF, and the combined THF extracts were dried, first with anhydrous sodium sulfate and then with anhydrous magnesium sulfate. After stripping off the THF with a rotary evaporator, 3-chloropropanol was isolated by distillation: 11.5 g (61% yield), bp 59–60° (9 mm), $n^{21}\text{D}$ 1.4450 (3-chloropropanol purchased from Matheson Coleman and Bell exhibited the same refractive index) (lit.[40,41] bp 63–64° (16 mm), $n^{20}\text{D}$ 1.4469).

Alternate procedures were explored for the work-up of the reaction mixture following the reaction. In one case the reaction mixture was treated with a saturated solution of potassium sodium tartrate to give the soluble complex of aluminum. In another, the mixture was treated with water followed by saturated potassium carbonate solution. The yields realized were 51 and 58%, respectively. The 58% yield realized in the potassium carbonate procedure is slightly less than the 61% realized in the original procedure. However, the simplicity of the procedure has much to recommend it. To the hydrolyzed reaction mixture was added 80 g of potassium carbonate dissolved in 200 ml of water with constant stirring. The grayish precipitate initially formed was converted into a finer white precipitate. This precipitate was filtered off and washed twice with 50-ml portions of THF. The combined THF extracts were then treated as described above.

Reduction in the Presence of the Nitro Substituent. The following reduction of methyl 4-nitropentanoate illustrates the practicality of utilizing aluminum hydride for reduction of other more easily reducible functional groups in the presence of a nitro substituent. To 10 mmol of aluminum hydride in 15 ml of THF, there was added over 5 min 0.806 g (5 mmol) of methyl 4-nitropentanoate dissolved in 5 ml of THF. During the addition, the flask was maintained in an ice–salt bath (−10°). There was observed an immediate evolution of 1.1 mmol of hydrogen (22%). However, this did not continue (presumably due to reaction with active hydrogen). The reaction mixture became very viscous. (A gelatinous precipitate was observed when the ratio of aluminum hydride to compound was 1:1.) After 3 hr at 0°, the reaction mixture was treated with 5 ml of 20% phosphoric acid containing 0.4 g of urea.[10] The THF layer was decanted, the aqueous layer was twice extracted with 10 ml of ether, and the combined extracts were dried over anhydrous sodium sulfate. The solvents were removed with a rotary evaporator. No ester was present in the product, as indicated by the ir spectra. 4-Nitropentanol was distilled *in vacuo:* 0.53 g (80% yield), bp 89–92° (1 mm), $n^{21}\text{D}$ 1.4469 (lit.[10] bp 90–92° (1 mm), $n^{20}\text{D}$ 1.4479).

Reduction of Amides. The reduction of N,N-diisopropylbenzamide is described as a representative of the procedure used to reduce amides. N,N-Diisopropylbenzamide, 2.05 g (10 mmol), dissolved in 10 ml of THF, was added to 13.3 mmol of aluminum hydride in 30 ml of THF at 0°. After 30 min, the reaction mixture was hydrolyzed with 5 ml of THF–H_2O (1:1) mixture. The voluminous precipitate of aluminum hydroxide thus formed was readily coagulated into a pasty mass of relatively small volume by adding 1 g of sodium hydroxide pellets dissolved in 30 ml of water and stirring, yielding a clear solution containing the amine. This solution was decanted. The extraction of amine was essentially complete after two washings with ether. The combined extract was diluted to 100 ml and the amount of amine present determined by titration of aliquots.

a. Estimation of Amine by Titration. To 5 ml of the amine solution, there was added 10 ml of 0.067 *N* HCl. This was thoroughly shaken and then titrated with 0.05 *N* Na_2CO_3 using methyl red as an indicator. At least two titrations were carried out for the determination of each amine; 3.75 and 3.70 ml of 0.05 *N* Na_2CO_3 were needed in the case of N,N-diisopropylbenzylamine, which correspond to 96.5 and 97% yields of amine.

b. Isolation. The amine solution (50 ml, corresponding to 5 mmol of amide) was subjected to the rotary evaporator and the residue distilled *in vacuo*, bp 100–102° (25 mm). There was obtained 0.84 g of N,N-diisopropylbenzylamine, 88% yield (identified by pmr).

Reduction of Oximes. The following reduction of cyclohexanone oxime to cyclohexylamine on a preparative scale is illustrative of such reductions. To 300 ml of a 0.67 *M* lithium aluminum hydride (0.2 mol) solution in THF, contained in a 1-l. flask equipped with rubber syringe septum and reflux condenser, 9.8 g (0.1 mol, 5.35 ml) of 100% sulfuric acid was added dropwise in 10 min, while the solution was vigorously stirred in a cold water bath by means of a magnetic stirrer. Hydrogen (0.206 mol) was evolved and lithium sulfate formed as a white precipitate. The stirring was continued for an additional hour. To this solution at room temperature was added slowly 11.3 g (0.1 mol) of cyclohexanone oxime dissolved in 50 ml of THF. Hydrogen was evolved and there was a vigorous exothermic reaction which caused the THF to reflux. The refluxing was continued for 0.5 hr. The total hydrogen evolved was 0.19 mol. The reaction mixture was hydrolyzed with 50 ml of the usual 1:1 mixture of THF and water, followed by the addition of 10 g of sodium hydroxide dissolved in 100 ml of water. The original voluminous precipitate coagulated into a much smaller gelatinous mass. The THF solution was decanted and the gelatinous mass was washed with three portions of 100 ml of ether. The combined extracts were dried over anhydrous potassium carbonate. Fractional distillation through a 20-cm Widmer column gave 8.4 g (85% yield) of cyclohexylamine: bp 130–131° (744 mm), $n^{20}\text{D}$ 1.4574 (lit.[42,43] bp 132–133° (744 mm), $n^{24}\text{D}$ 1.4575). The ir spectrum was identical with that of Sadtler No. 845.

The following experiments report our comparison of the reduction of acetophenone oxime with aluminum hydride and lithium aluminum hydride.

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[38] C. A. Brown and H. C. Brown, *J. Org. Chem.*, **31**, 3989 (1966); H. C. Brown and M.-H. Rei, *ibid.*, **31**, 1090 (1966).

[39] E. Schjanberg, *Z. Phys. Chem.*, **172**, 230 (1935).

[40] R. Lespieau, *Bull. Soc. Chim. France*, (5) 7, 254 (1940).

[41] C. W. Gayler and H. M. Waddle, *J. Am. Chem. Soc.*, **63**, 3358 (1941).

[42] G. S. Hiers and R. Adams, *Ber.*, **59**, 170 (1926).

[43] O. Wallach, *Ann.*, **343**, 46 (1905).

a. Aluminum Hydride. Acetophenone oxime (5 mmol) dissolved in 5 ml of THF was added to 10 mmol of aluminum hydride (30 mmol of "hydride") in 15 ml of THF and refluxed for 30 min. Hydrogen (10.2 mmol) was evolved during the reaction and 10.3 mmol of "hydride" was used for reduction as revealed by the residual hydride analysis.

b. Lithium Aluminum Hydride. Acetophenone oxime (5 mmol) dissolved in 5 ml of THF was added to 7.5 mmol of lithium aluminum hydride (30 mmol of "hydride") in 15 ml of THF. Hydrogen (4.9 mmol) was evolved practically instantaneously. The hydrogen evolution then continued only very slowly in refluxing THF. The reaction mixture gradually turned yellow and after 1 hr became turbid. After 1.5 hr, the total hydrogen evolution was 8 mmol and showed no further increase in the total reaction time of 3 hr. A total of 9 mmol of "hydride" was utilized for reduction.

c. Products. These two reduction mixtures were worked up as indicated in the reduction of N,N-diisopropylbenzamide. Titrations showed 81% of amine for the reduction by aluminum hydride, and 61% of amine for the reduction by lithium aluminum hydride. Glpc analysis showed the presence of 4.3 and 6% of N-ethylaniline, respectively, in the major product, α-methylbenzylamine. Since N-ethylaniline is neutral to methyl red,[44] the titration values correspond only to yields of α-methylbenzylamine.

Reduction of Nitriles. The ready reduction of nitriles containing relatively acidic hydrogen in the α positions is illustrated by the following preparative-scale conversion of diphenylacetonitrile into benzhydrylamine. A 1-l., three-necked flask was equipped with a reflux condenser, a mechanical stirrer, and a dropping funnel. The gas outlet tube on the condenser was attached to a Dry Ice trap, and then to a gas meter. The flask was placed in an ice bath, and 10.65 g (0.266 mol, 95+% pure) of lithium aluminum hydride dissolved in 500 ml of THF was placed in the flask.

Then 13.03 g (7.1 ml) of 100% sulfuric acid was slowly added through the dropping funnel over 15 min, while the solution was vigorously stirred. The stirring was continued for an additional hr. The total hydrogen collected was 0.266 mol. To this aluminum hydride solution, 38.64 g (0.2 mol) of diphenylacetonitrile dissolved in 50 ml of THF was slowly introduced over 30 min through a dropping funnel. During the addition of the nitrile only a slight evolution of hydrogen was observed (5.6 mmol, 2.8%). After stirring for 30 min more, the hydride was carefully destroyed with 50 ml of 1:1 mixture of THF and water. Stirring was continued as 15 g of sodium hydroxide in 150 ml of water was added to coagulate the precipitate aluminum hydroxide. The clear THF solution was decanted, and the remaining mass was extracted twice with 100-ml portions of ether. The combined extracts were dried over anhydrous potassium carbonate. The solvents were removed on a rotary evaporator. On cooling, the residual viscous liquid was transformed into a light yellowish solid: 32.55 g (91% yield), mp 43–44.5° (lit.[45] mp 44–45°).

The following procedure illustrates the reduction of 3-butenonitrile into 3-butenylamine. The preparation of aluminum hydride and the reduction procedure were the same as described for the reduction of diphenylacetonitrile. Lithium aluminum hydride, 2.65 g (66 mmol), 100 ml of THF, and 1.78 ml of 100% sulfuric acid (33 mmol) were used to prepare 66 mmol of aluminum hydride in THF solution. To this solution 3.36 g (50 mmol) of 3-butenonitrile dissolved in 10 ml of THF was added slowly. A light yellow color developed. However, no appreciable hydrogen evolution was noticed. After the usual work-up, the amine solution was treated with 30 ml of 2 *N* hydrochloric acid (60 mmol). The water layer was concentrated to a viscous mass. Ethyl ether was added, followed by saturated potassium hydroxide solution. The ether solution was dried over anhydrous potassium carbonate and distilled through a 20-cm Widmer column to obtain the 3-butenylamine: 1.95 g (55% yield), bp 76–77° (746 mm) (lit.[25] bp 75–77°).

The following procedure was followed for the reduction of cinnamonitrile. To 66 mmol of aluminum hydride solution, prepared as in the previous preparation, was added 6.46 g (50 mmol) of cinnamonitrile dissolved in 10 ml of THF at 0°. The reaction mixture soon became yellow and changed to light orange color. After 1 hr, the reaction mixture was worked up as described in the reduction of diphenylacetonitrile. Distillation *in vacuo* gave 3.18 g (48% yield) of a colorless liquid, bp 93–95° (4 mm), leaving a considerable amount of an orange-red viscous residue, which solidified on cooling. Pmr examination of this colorless distillate showed that cinnamylamine was contaminated with 18% of hydrocinnamylamine.

In another run, 2 mol of a clear aluminum hydride solution was used per mol of the nitrile. In this case the yield of amine increased to 60%, and the contamination of the saturated amine decreased to 6%. In this preparation the reaction mixture exhibited the yellow color and failed to undergo the change to orange, as noted in the experiment using the 1.33:1 ratio.

In order to compare the relative effectiveness of lithium aluminum hydride with aluminum hydride in this reduction, two identical reactions were carried out at 25°. In the reduction involving lithium aluminum hydride, no yield of amine was realized—only a yellow solid material was present after stripping off the solvent. On the other hand, the comparable aluminum hydride experiment provided a 63% yield of amines which contained an 80:20 mixture of cinnamylamine to hydrocinnamylamine. These results indicate both that aluminum hydride is the prefered reagent for this type of reduction and that the reduction is preferably carried out at 0°, rather than 25°.

Reduction of Enolizable Keto Esters to Diols. The following reduction of 2-carbethoxycyclopentanone is representative. To 10 mmol of aluminum hydride in 15 ml of THF, there was added 0.78 g (5 mmol) of 2-carbethoxycyclopentanone dissolved in 5 ml of THF at 0°. After 30 min, the reaction mixture was hydrolyzed with a 1:1 mixture of THF and water, and then treated with 5 mmol of sodium borohydride dissolved in 5 ml of 3 *N* sodium hydroxide for 1 hr at room temperature. The reaction mixture was hydrolyzed with a 1:1 mixture of dilute sulfuric acid (2 *N*) and THF. The aqueous layer was then saturated with potassium carbonate and thoroughly extracted with THF. The combined THF extract was concentrated with a rotary evaporator, and 2-methylolcyclopentanol was recovered by distillation *in vacuo:* 0.48 g (82.5% yield), bp 102–103° (2 mm). The compound was identified by pmr. When the reaction mixture was hydrolyzed with isopropyl alcohol and then treated with sodium borohydride in this alcohol for 2 hr at room temperature, a 78.5% yield was obtained. However, in this case, the presence of 1.5% of an impurity was observed in the product by glpc analysis, presumably 2-methylolcyclopentanone.

Reduction of Epoxides. Normally, lithium aluminum hydride would appear to be the reagent of choice for the reduction of epoxides. However, in some cases, where the molecule may contain groups which are relatively stable to aluminum hydride, or where strongly basic conditions should be avoided, the use of aluminum hydride may be advantageous. The following procedure for the reduction of 1,2-butylene oxide illustrates the procedure followed for the reduction of a simple epoxide.

To 5 mmol of aluminum hydride in 15 ml of THF, 5 mmol of 1,2-butylene oxide dissolved in 5 ml of THF was added at room temperature and permitted to react at room temperature for 1 hr. Toluene (5 mmol) was added as an internal standard, and the reaction mixture was hydrolyzed with the usual 1:1 mixture of THF and water. After saturating the aqueous layer with potassium carbonate, the clear THF layer was separated and dried over anhydrous magnesium sulfate. Glpc analysis indicated a 99% yield of *sec*-butyl alcohol free from *n*-butyl alcohol.

The reduction of highly substituted epoxides can be considerably slower. However, in some cases the use of aluminum hydride gives a markedly different product than lithium aluminum hydride, so that the slow reaction time may not be a handicap. Such a reduction is the conversion of 1-phenylcyclopentene oxide into *cis*-2-phenylcyclopentanol.[29] The following procedure is representative.

To 5 mmol of aluminum hydride in 15 ml of THF, 5 mmol of 1-phenylcyclopentene oxide dissolved in 5 ml of THF was added at 0° and permitted to react at 0° for 24 hr. (In a separate study, we found that the reduction was complete in 24 hr as indicated by one hydride uptake.) Benzyl alcohol (5 mmol) was added as an internal standard, and the reaction mixture was hydrolyzed with the usual 1:1 mixture of THF and water. After saturating the aqueous layer with potassium carbonate, the clear THF layer was separated and dried over anhydrous magnesium sulfate. Glpc analysis (150-ft, Carbowax 20M capillary column) indicated a quantitative yield of alcohols, consisting of 9% of 1-phenylcyclopentanol and 91% of *cis*-2-phenylcyclopentanol.

The reduction of norbornene oxide is very slow with lithium aluminum hydride in the usual solvents (ether or THF) and considerably faster with aluminum hydride. The following procedure describes a typical reduction of norbornene oxide.

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[44] That N-propylaniline is neutral to methyl red was shown in ref 12.

[45] R. F. Nystrom, *J. Am. Chem. Soc.*, 77, 2544 (1955).

To 15 mmol of aluminum hydride dissolved in 45 ml of THF, 15 mmol of *exo*-norbornene oxide dissolved in 15 ml of THF was added at room temperature and permitted to react at room temperature. The reaction was followed by measuring the residual hydride of aliquots of the reaction mixture. After 4 days, the reduction was complete as indicated by one hydride uptake per mol of compound. To 8 ml of the reaction mixture (2 mmol of compound), 2 mmol of cyclohexanol was added as an internal standard, and the reaction mixture was hydrolyzed with the usual 1:1 mixture of THF and water. After saturating the aqueous layer with potassium carbonate, the clear THF was separated and dried over anhydrous magnesium sulfate. Glpc analysis indicated an 84% yield of alcohols which contained a 69:31 mixture of *exo*-2-norbornanol to 7-norbornanol.

At elevated temperature norbornene oxide is converted in reasonable yield to 7-norbornanol. The following describes the procedure used.

To 10.3 mmol of aluminum hydride dissolved in 30 ml of THF, 10 mmol of *exo*-norbornene oxide dissolved in 10 ml of THF was added at room temperature and refluxed for 12 hr. After adding 10 mmol of cyclohexanol as an internal standard, the reaction mixture was worked up exactly the same as above. Glpc analysis indicated no *exo*-norbornene oxide and an 80% yield of alcohols which contained a 51:48 mixture of *exo*-2-norbornanol to 7-norbornanol and contaminated with less than 1% of *endo*-2-norbornanol. Since the same sample of *exo*-norbornene oxide gave only *exo*-2-norbornanol when reduced with lithium aluminum hydride, this contamination of *endo*-2-norbornanol did not come from *endo*-norbornene oxide which might have been contaminated with *exo*-norbornene oxide.

Finally, we observed that lithium aluminum hydride in diglyme at 100° reduces norbornene oxide relatively rapidly, without rearrangement. This procedure would appear to have many advantages for the reduction of bicyclic epoxides.

To 5 mmol of lithium aluminum hydride in 15 ml of diglyme, 5 mmol of *exo*-norbornene oxide dissolved in 5 ml of diglyme was added at room temperature. The reaction mixture was kept at 100° for 24 hr. After adding 5 mmol of naphthalene as an internal standard, the reaction mixture was worked up exactly the same as above. Glpc analysis indicated 98% yield of *exo*-2-norbornanol with no contamination by 7-norbornanol.

Reduction of Ketones. Again, there appears to be no major advantage to the use of aluminum hydride for the reduction of ketones, except possibly in cases where it is desirable to avoid the presence of a strongly alkaline reagent. The following procedure describes the use of aluminum hydride for the reduction of camphor.

To 6.66 mmol of aluminum hydride in 15 ml of THF, 5 mmol of *d*-camphor dissolved in 5 ml of THF was added at 0°. The reaction was over in 15 min, as indicated by one hydride uptake. The reaction mixture was worked up the same as epoxides and analyzed by glpc on a 25% glycerol column on Firebrick. Isoborneol and borneol were identified by comparing with authentic samples. The ratio of isoborneol to borneol was 90:10.

Trimethylmetal Halide Elimination from Trimethylsilylmethyl- and Trimethyltinmethyl-Substituted *gem*-Dihalocyclopropanes

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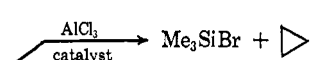
Abstract: The zinc chloride catalyzed elimination of trimethylchlorosilane or trimethyltin chloride from trimethylsilylmethyl- or trimethyltinmethyl-substituted *gem*-dihalocyclopropanes was found to give as organic products halogen-substituted 1,3-dienes. The fact that *cis*-1,1-dichloro-2-methyl-3-(trimethylsilylmethyl)cyclopropane readily gave *cis*-3-chloropiperylene in high yield and that *trans*-1,1-dichloro-2-methyl-3-(trimethylsilylmethyl)cyclopropane gave a 72:28 mixture of *cis*- and *trans*-3-chloropiperylene in only 7% yield after considerably longer reaction time provided some insight into the nature of the elimination process. An explanation in terms of disrotatory, stereospecific opening of the cyclopropane ring to an allylic cation from which the trimethylmetal group is lost to give the 1,3-diene is presented. Other conversions described include: 1,1-dichloro-2-(trimethylmetalmethyl)cyclopropane (metal = Si and Sn) to 2-chloro-1,3-butadiene, 1,1-dibromo-2-(trimethylsilylmethyl)cyclopropane to 2-bromo-1,3-butadiene, 1,1-dichloro-2-methyl-2-(trimethylsilylmethyl)cyclopropane to 2-chloro-3-methyl-1,3-butadiene, and 30:70 *cis*-:*trans*-1,1-dichloro-2-methyl-3-(trimethyltinmethyl)cyclopropane to 3:1 *cis*-:*trans*-3-chloropiperylene.

The elimination of trimethylhalosilane from β-haloethyl- and γ-halopropylsilicon compounds, reported first by Sommer, Whitmore, and their coworkers in the late forties, is by now a well-known reaction in organosilicon chemistry.[2] In some cases such eliminations occur simply when the compound in question is heated, *e.g.*, $Me_3SiCH_2CH_2Cl \rightarrow Me_3SiCl + CH_2{=}CH_2$, but, more generally, such reactions are promoted by Lewis acid catalysts or occur upon solvolysis (usually base catalyzed). Thus, for instance, Sommer and coworkers[3] have described the preparation of cyclopropane from γ-bromopropyltrimethylsilane in high yield.



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Our recent investigation of the addition of dihalocarbenes to the C=C bonds of allyl and vinyl compounds of silicon and tin[4,5] led to an interest in the chemistry of silicon- and tin-containing *gem*-dihalocyclopropanes and suggested that a study of the elimination reactions of compounds of type I might be of interest. From such compounds γ elimination of trimethylmetal halide is in principle possible, and we report here concerning this question.

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(1) National Institutes of Health Predoctoral Fellow, 1963–1967.

(2) C. Eaborn, "Organosilicon Compounds," Butterworths & Co. (Publishers) Ltd., London, 1960, pp 133–136, 139–140.

(3) L. H. Sommer, R. E. Van Strien, and F. C. Whitmore, *J. Am. Chem. Soc.*, **71**, 3056 (1949).

(4) D. Seyferth, J. M. Burlitch, R. J. Minasz, J. Y.-P. Mui, H. D. Simmons, Jr., A. J.-H. Treiber, and S. R. Dowd, *ibid.*, **87**, 4259 (1965).

(5) D. Seyferth, T. F. Jula, H. Dertouzos, and M. Pereyre, *J. Organometal. Chem.* (Amsterdam), **11**, 63 (1968).