threo-1,2,3-Tribromo-1-phenylpropane (**3**) was purified by preparative liquid–solid chromatography employing a 0.0125 in. × 2 ft Corasil II column at a flow rate of 1.0 ml/min. The eluting solvent was *n*-hexane. The retention times for **2** and **3** were 2.6 and 2.1 min, respectively. In this manner pure **3** was obtained as a clear oil: nmr ($CDCl_3$) τ 2.68 (s, 5 H, ArH), 4.47 (d, 1 H, J = 4 Hz, ArCHBr), 5.65 (m, 1 H, C-2 H), 6.20 (m, 2 H, C-3 H); ir 695 (s, sh), 1220 (m, sh), 1435 (m, sh), 1450 (m, sh), 1495 cm^{-1} (m, sh); mass spectrum m/e 354 (M^+), 356 ($M^+ + 2$), 358 ($M^+ + 4$), 360 ($M^+ + 6$), 375, 377, and 379 ($C_9H_9Br_2^+$), 169 and 171 ($C_6H_5CHBr^+$), 117 (base peak, $M^+ - Br_3$). *Anal.* Calcd for $C_9H_9Br_3$: C, 30.28; H, 2.54; Br, 67.17. Found: C, 30.58; H, 2.57; Br, 67.06.

Stability of Ring-Opening Products to Reaction Conditions.—1,3-Dibromo-1-phenylpropane (200 mg) in 5 ml of a 0.25 M Br_2–$CHCl_3$ solution was allowed to stand at room temperature in the dark for 40 hr. Flash evaporation of the solvent and Br_2 yielded a clear oil which was determined to be the starting 1,3-dibromophenylpropane by comparative nmr and ir analysis.

2 (200 mg) in 5 ml of a 0.25 M Br_2–$CHCl_3$ solution was allowed to stand for 40 hr in the dark at room temperature. Flash evaporation of the solvent yielded a white, crystalline solid, mp 122–125°, which was determined to be the starting **2** by comparative nmr analysis.

Acknowledgment.—This work was supported in part by a grant from the National Science Foundation. We gratefully acknowledge their support.

Registry No.—**1**, 4392-24-9; **2**, 42334-76-9; **3**, 42334-77-0; phenylcyclopropane, 873-49-4.

Stereochemistry of Reduction of Substituted Cyclohexanones with Triisobutylaluminum and Diisobutylaluminum Hydride

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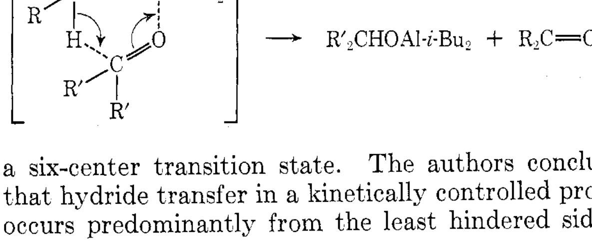
The reduction of 3,3,5-trimethylcyclohexanone and 4-*tert*-butylcyclohexanone with diisobutylaluminum hydride (DIBAH) and with triisobutylaluminum (TIBA) has been examined in ether and in benzene. Reduction of these ketones with DIBAH in 1:1 stoichiometry produces the epimeric alcohols in quantitative yield. The isomer ratio of the product mixture is essentially independent of solvent and reactant stoichiometry. On the other hand, reduction of these ketones with TIBA is more selective and is accompanied by some (~5%) formation of aluminum enolate. The isomer ratio of the product mixture is essentially independent of solvent, but dependent on the reactant stoichiometry and the initial concentration of TIBA. Evidence is presented which indicates that the epimeric ratio of alcohol products is influenced by the degree of association of TIBA, complex formation between TIBA and the aluminum alkoxide formed, and isomer equilibration by a Meerwein–Ponndorf–Verley pathway.

Since the reduction of chloral to 2,2,2-trichloroethanol by treatment with triethylaluminum etherate was first noted,[1] organoaluminum compounds have been investigated in considerable detail as reducing agents for a wide variety of organic functional groups. Although the reaction of organoaluminum reagents with carbonyl compounds can afford mixtures of alkylated and reduced products, the primary mode of reaction is that of reduction when the organometallic reagent has an available hydrogen at a branched β position,[2] or contains aluminum–hydrogen bonds.[3] Despite intensive investigation over a period of several decades, surprisingly little is presently known about the factors influencing the stereochemistry of reduction. The present study was undertaken with a twofold purpose in mind: (1) to systematically examine triisobutylaluminum (TIBA) and diisobutylaluminum hydride (DIBAH) as potential stereoselective reagents for the reduction of carbonyl compounds, and (2) to delineate the experimental parameters affecting the stereochemistry of reduction, particularly the effect of reactant stoichiometry on stereochemistry in hydrocarbon solvent.

Reduction of 2-methylcyclohexanone with DIBAH leads to predominant formation of *cis*-2-methylcyclohexanol, the least stable of the two expected alcohols.[4] However, because of the conformational mobility of 2-methylcyclohexanone, stereochemical interpretation of this result is at best uncertain. Furthermore, the isomer ratio of the product mixture was determined by measurement of density, a technique considerably less accurate than modern gas chromatographic methods. Haubenstock and Davidson[5] found that the composition of the product mixture obtained by reduction of 3,3,5-trimethylcyclohexanone with TIBA in benzene at 42° was dependent on the ratio of reactants. When TIBA was present in excess, the product mixture contained 96% of the least stable alcohol, *trans*-3,3,5-trimethylcyclohexanol. In the presence of excess ketone the isomeric ratio of the product mixture changed with time, approaching pure *cis*-3,3,5-trimethylcyclohexanol after 31 hr at 42°. This was attributed to thermodynamically controlled isomer equilibration *via* a Meerwein–Ponndorf–Verley type reduction involving



(1)

a six-center transition state. The authors concluded that hydride transfer in a kinetically controlled process occurs predominantly from the least hindered side of

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[1] H. Meerwein, G. Hinz, H. Majert, and H. Sonke, *J. Prakt. Chem.*, **147**, 226 (1936).

[2] K. Zeigler in "Organometallic Chemistry," H. Zeiss, Ed., Reinhold, New York, N. Y., 1960, Chapter 5.

[3] W. L. Everson and E. M. Ramirez, *Anal. Chem.*, **37**, 806 (1965).

[4] L. I. Zakharkin and I. M. Khorlina, *Izv. Akad. Nauk SSSR, Otd. Khim. Nauk.*, 1144 (1961); *Chem. Abstr.*, **55**, 27135*e* (1961).

[5] H. Haubenstock and E. B. Davidson, *J. Org. Chem.*, **28**, 2772 (1963).

the ketone, affording *trans*-3,3,5-trimethylcyclohexanol as the major product.

Teisseire and coworkers[6] have reported the reduction of several terpenoid ketones with excess TIBA in hydrocarbon solvent. In agreement with the work of Haubenstock and Davidson,[5] hydride transfer was observed in all cases to occur predominantly from the least hindered side of the substrate, leading to the thermodynamically less stable alcohol. Since TIBA was employed in excess, equilibration of the product mixture was not observed. In those cases where comparative data were reported, reduction with TIBA was found to be more stereoselective than reduction with DIBAH, leading in the former case to a higher proportion of the less stable alcohol.

Recently we reported that a dramatic change in stereochemistry takes place when 4-*tert*-butylcyclohexanone is allowed to react with trimethylaluminum in benzene if the R_3Al:ketone ratio is changed from 1:1 to 2:1,[7] whereas no change in stereochemistry is involved in ether solvent under the same conditions. It was suggested that the reaction in 1:1 ratio proceeds *via* a four-center transition state whereas the reaction in 2:1 ratio proceeds *via* a six-center transition state. Since there is reason to believe that reaction of a ketone with diisobutylaluminum hydride proceeds *via* a four-center transition state and reaction with triisobutylaluminum proceeds *via* a six-center transition state,[8] it was considered particularly important to evaluate the stereochemistry of diisobutylaluminum hydride and triisobutylaluminum reduction of 4-*tert*-butylcyclohexanone in benzene solvent. Based on the stereochemical results observed in the reaction of **1** and **2** with $(CH_3)_3Al$ it was anticipated that diisobutylaluminum hydride would reduce 4-*tert*-butylcyclohexanone in benzene predominantly from the least hindered side of the molecule (equatorial attack to produce the axial alcohol) in 1:1 ratio with an increasing amount of axial attack as the R_2AlH:ketone ratio is changed to 2:1. It was further anticipated that the stereochemistry of triisobutylaluminum reduction in benzene would be independent of stoichiometry and that reduction with both reducing agents would be independent of stoichiometry in ether solvent.

Eliel and Senda[9] have suggested that, in the absence of other factors, attack on the carbonyl group in an asymmetric environment occurs predominantly from the sterically least hindered side. The importance of stereoselective attack of reducing agents on a carbonyl group from the least hindered side of the molecule is obvious. In this way the least stable alcohol is always formed which is the most difficult isomer to obtain. The most stable isomer, of course, can be easily obtained by equilibration of the epimeric alcohol mixture.

Results and Discussion

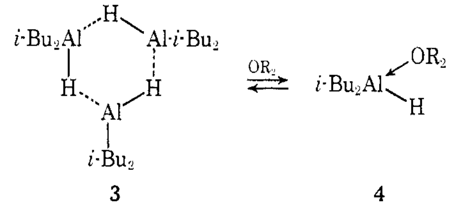
Table I summarizes the results obtained for reduction of 3,3,5-trimethylcyclohexanone (**1**) and 4-*tert*-butylcyclohexanone (**2**) with DIBAH. In each case, only the two expected reduction products were observed which together quantitatively account for the ketone consumed during reaction. It is evident from the data that reduction occurs in 1:1 stoichiometry. Failure to detect ketone after reaction with excess DIBAH indicates that formation of an aluminum enolate does not occur under these conditions, since quenching of the enolate would regenerate the ketone. As expected, a greater proportion of axial alcohol is obtained during reduction of 3,3,5-trimethylcyclohexanone than in the case of 4-*tert*-butylcyclohexanone, since axial attack is more hindered in the former case than in the latter.[10] Somewhat surprisingly, however, the stereochemistry of reduction is essentially independent of the nature of the solvent employed and not significantly influenced by reaction stoichiometry. Spectroscopic investigation[11] has shown that DIBAH exists as a cyclic hydrogen-bridged trimer (**3**) in the absence of donor solvents, but forms moderately stable 1:1 adducts (**4**) which exist in equilibrium with the associated species when aliphatic ethers are present. It is therefore likely that reduction in either solvent proceeds with prior formation of a complex analogous to the complex observed spectroscopically during reduction of benzophenone with TIBA.[8]

TABLE I[a]

REDUCTION OF 3,3,5-TRIMETHYLCYCLOHEXANONE (1) AND 4-*tert*-BUTYLCYCLOHEXANONE (2) WITH DIISOBUTYLALUMINUM HYDRIDE

					Products, %	
Expt	Ketone	Solvent	DIBAH, mmol	Ketone recovered, %	Axial alcohol	Equatorial alcohol
1	**1**	Ether	0.5	56	70	30
2	**1**	Ether	1.0	17	69	31
3	**1**	Ether	2.0	0	74	26
4	**1**	Ether	5.0	0	75	26
5	**1**	Benzene	0.5	56	67	33
6	**1**	Benzene	1.0	7	68	32
7	**1**	Benzene	2.0	0	73	27
8	**1**	Benzene	5.0	0	77	23
9	**2**	Ether	0.5	51	25	75
10	**2**	Ether	1.0	0	28	72
11	**2**	Ether	2.0	0	29	71
12	**2**	Ether	5.0	0	26	74
13	**2**	Benzene	0.5	48	32	68
14	**2**	Benzene	1.0	5	30	70
15	**2**	Benzene	2.0	0	34	66
16	**2**	Benzene	5.0	0	31	69

[a] All runs employed 1.0 mmol of ketone and 10.0 ml of solvent; reaction time was 2 hr at 0° in ether and 2 hr at 22° in benzene; quenched with 5% HCl.



3 **4**

When 4-*tert*-butylcyclohexanone was allowed to react with trimethylaluminum in benzene solvent, dramatic changes occurred in the stereochemistry when

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[6] (a) P. Teisseire, A. Galfre, M. Plattier, and B. Corbier, *Recherches*, **15**, 52 (1966); P. Teisseire, A. Galfre, M. Plattier, and B. Corbier, *ibid.*, **16**, 59 (1967); (c) P. Teisseire, P. Roullier, and A. Galfre, *ibid.*, **16**, 68 (1967); (d) P. Teisseire, A. Galfre, M. Plattier, P. Roullier, and B. Corbier, *ibid.*, **16**, 119 (1967).

[7] E. C. Ashby, S. H. Yu, and P. V. Roling, *J. Org. Chem.*, **37**, 1918 (1972).

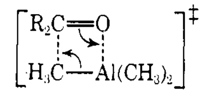
[8] E. C. Ashby and S. H. Yu, *J. Org. Chem.*, **35**, 1034 (1970).

[9] E. Eliel and Y. Senda, *Tetrahedron*, **26**, 2411 (1970).

[10] H. O. House, "Modern Synthetic Reactions," W. A. Benjamin, Menlo Park, Calif., 1972, pp 54–68.

[11] E. G. Hoffman, *Z. Elektrochem.*, **61**, 1014 (1957).

the organoaluminum compound to ketone ratio was >1:1.[7] Under these circumstances a higher proportion of product resulted from transfer of a methyl group to the most hindered (axial) side of the substrate molecule. Kinetic evidence has been presented to support the idea that this is a result of a change in mechanism.[12] When excess trimethylaluminum is present, alkylation proceeds by a consecutive bimolecular reaction possibly *via* a six-center transition state (**6**) rather than the four-center transition state (**5**) postulated for the case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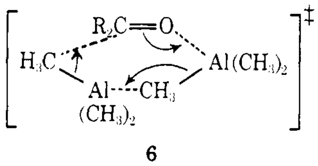
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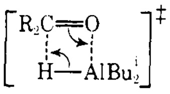
when equimolar quantities of reactants are employed. Although a similar change in mechanism is conceptually possible for ketone reduction with DIBAH (**7**, **8**), the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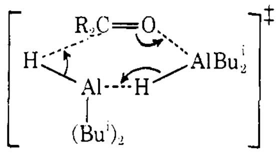
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data in Table I fail to supply evidence for its occurrence. The isomeric ratio of the product mixture is essentially independent of reactant ratio, and the small changes that are noted are in the direction opposite to that observed for alkylation with trimethylaluminum.

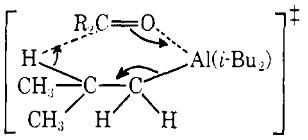
TABLE II[a]

REDUCTION OF 3,3,5-TRIMETHYLCYCLOHEXANONE (**1**) AND 4-*tert*-BUTYLCYCLOHEXANONE (**2**) WITH TRIISOBUTYLALUMINUM

Expt	Ketone	Solvent	TIBA, mmol	Ketone recovered, %	Products, %: Axial alcohol	Products, %: Equatorial alcohol
17	**1**	Ether	0.5	40	63	37
18	**1**	Ether	1.0	5	67	33
19	**1**	Ether	2.0	5	86	14
20	**1**	Ether	5.0	2	90	10
21	**1**	Benzene	0.5	54	82	18
22	**1**	Benzene	1.0	8	90	10
23	**1**	Benzene	2.0	3	90	10
24	**1**	Benzene	5.0	2	93	7
25	**2**	Ether	0.5	52	14	86
26	**2**	Ether	1.0	11	35	65
27	**2**	Ether	2.0	12	36	64
28	**2**	Ether	5.0	10	44	56
29	**2**	Benzene	0.5	42	30	70
30	**2**	Benzene	1.0	11	39	61
31	**2**	Benzene	2.0	3	40	60
32	**2**	Benzene	5.0	3	41	59

[a] All runs employed 1.0 mmol of ketone and 10.0 ml of solvent; reaction time was 2 hr at 0° in ether and 2 hr at 22° in benzene; quenched with 5% HCl.

The results obtained in the reduction of **1** and **2** with TIBA (Table II) are qualitatively similar to the results using DIBAH; *i.e.*, reduction of **1** involves predominant equatorial attack and reduction of **2** involves predominant axial attack with either TIBA or DIBAH. Since the reduction of ketones by TIBA is known to be first order in both ketone and TIBA and since the stereochemistry of reduction of **1** and **2** by DIBAH is not only similar to that observed for TIBA but also independent of stoichiometry, it is plausible that both reactions proceed *via* similar transition states, namely **8** and **9**. Although it was anticipated that the reaction of DIBAH with ketone would proceed *via* **7** at 1:1 stoichiometry and *via* **8** at 2:1 stoichiometry, it is not unreasonable to suggest that the reaction proceeds *via* **8** at all stoichiometries for two reasons: first, hydrogen is a much stronger bridging group than methyl (see **5** and **6**) and, secondly, if equilibrium 2 does not lie entirely to the right and pathway 4 is more rapid than pathway 3, then the reaction would be expected to proceed *via* pathway 4 involving transition state **8**.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$$R_2C{=}O + R'_2AlH \rightleftharpoons \underset{\text{(complex)}}{R_2C{=}O\cdots AlR_2H} \qquad (2)$$

$$\text{complex} \longrightarrow [\mathbf{7}]^{\ddagger} \longrightarrow \text{product} \qquad (3)$$

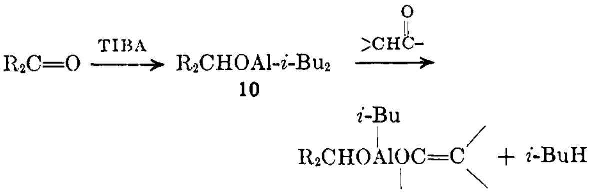
$$\text{complex} + R_2AlH \longrightarrow [\mathbf{8}]^{\ddagger} \longrightarrow \text{product} \qquad (4)$$

In agreement with previous reports, reduction with TIBA apparently proceeds in 1:1 stoichiometry. In all cases only the two expected reduction products were observed which together quantitatively account for the ketone consumed during reaction. Since the reduction reaction is rapid on the time scale of these experiments (Table III), recovery of ketone even when a fivefold excess of TIBA is employed provides compelling evidence for formation of an aluminum enolate. Ziegler, *et al.*,[13] have demonstrated that dialkylalkoxyaluminum compounds can abstract acidic protons from carbonyl-containing molecules, resulting in formation of an aluminum enolate. The enolization accompanying reduction with TIBA can then be explained as proton abstraction by the initially formed reduction product, diisobutylaluminum alkoxide.[8] Since DIBAH is far

TABLE III

TIME DEPENDENCE OF PRODUCT ISOMER RATIO FOR REDUCTION OF 3,3,5-TRIMETHYLCYCLOHEXANONE WITH TRIISOBUTYLALUMINUM

Time, min	Axial alcohol, %	Equatorial alcohol, %	Unreacted ketone, mmol
3	72	28	0.26
10	68	32	0.25
20	67	33	0.26
120	66	34	0.19
240	66	34	0.23


$$R_2C{=}O \xrightarrow{\text{TIBA}} \underset{\mathbf{10}}{R_2CHOAl\text{-}i\text{-}Bu_2} \xrightarrow{>CHC(=O)-} R_2CHOAl(i\text{-}Bu)OC{=}C< + i\text{-}BuH \qquad (5)$$

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[12] E. C. Ashby, J. Laemmle, and H. M. Neumann, *J. Amer. Chem. Soc.*, **90**, 5179 (1968).

[13] K. Zeigler, K. Schneider, and J. Schneider, *Justus Liebigs Ann. Chem.*, **623**, 9 (1959).

more reactive than TIBA toward ketones,[12] the aluminum alkoxide **10** is more able to compete with TIBA than with DIBAH for unreacted ketone. Consequently, enolization is observed during reduction with TIBA but not with DIBAH. In agreement with the results of previous workers,[5,6] comparison of Tables I and II demonstrates that the less reactive reducing agent, TIBA, is somewhat more selective than the more reactive one, DIBAH.

The most striking feature of Table II is that the stereochemistry of reduction with TIBA is apparently dependent on the ratio of reactants. In the presence of excess ketone, a higher proportion of the more stable equatorial alcohol is obtained. Several factors which might contribute toward this variation in stereochemistry were examined. The first of these is equilibration by a Meerwein–Ponndorf–Verley type reduction as previously observed over relatively long periods of time by Haubenstock and Davidson.[5] To determine whether equilibration of this type contributes significantly in determining the isomer ratios reported in Table II, 3,3,5-trimethylcyclohexanone (*ca.* 1.0 mmol) in ether was allowed to react with TIBA (*ca.* 0.75 mmol) and the stereochemical progress of the reaction was monitored by periodic withdrawal of samples. The results are summarized in Table III. Isomer equilibration does occur, and *cis*-3,3,5-trimethylcyclohexanol is continually produced at the expense of the trans isomer. However, even in the presence of 25 mol % of 3,3,5-trimethylcyclohexanone, equilibration is slow relative to the time scale of the reduction experiments (Table II). Consequently, other factors might be sought, operating in conjunction with isomer equilibration, to explain the variation of product composition with reactant ratio.

Since all the reduction experiments employed the same volume of solvent, the concentration of TIBA varied from 0.05 to 0.5 *M*. The change in stereochemistry might reflect differences in the state of association of the reducing agent. There is some diasgreement in the literature concerning the degree of association of TIBA in benzene and in ether. Cryoscopic and other studies have indicated that TIBA is monomeric in both solvents over the concentration range of present interest.[14] However, more recent calorimetric studies have demonstrated considerable association of TIBA.[15] It might be expected that, because of increased steric requirement of an associated species, greater selectivity and hence a higher proportion of *trans*-3,3,5-trimethylcyclohexanol would result when the initial TIBA concentration is greater. Because of enhanced coordination ability of ether, it would be anticipated that such an effect might be more pronounced in benzene than in ether. Inspection of Tables I and II shows that a greater proportion of equatorial attack generally does occur when the solvent is benzene. To test the effect of association of the reducing agent on the stereochemistry of reduction, several experiments were conducted in which equimolar quantities of reactants were employed, but the amount of ether solvent and hence the degree of association of TIBA was varied. Table IV summarizes the results of these experiments.

TABLE IV[a]

EFFECT OF INITIAL TRIISOBUTYLALUMINUM CONCENTRATION ON REDUCTION OF 3,3,5-TRIMETHYLCYCLOHEXANONE

Expt	[TIBA]	Axial alcohol, %	Equatorial alcohol, %	Ether, ml
33[b]	1.0	65	35	1
34	0.2	68	32	5
35	0.1	67	33	10
36	0.05	62	38	20
37	0.025	58	42	40

[a] All runs employed 1.0 mmol of ketone and 1.0 mmol of TIBA. [b] Because of poor mixing and considerable heating, this result could not be consistently reproduced and should be taken *cum grano salis.*

Clearly, the stereochemistry of reduction of 3,3,5-trimethylcyclohexanone with TIBA does depend on the initial concentration of the reducing agent. At high concentration where considerable association of TIBA is expected, there is a greater preference for hydride transfer from the least hindered equatorial side of the substrate, leading to a higher proportion of *trans*-3,3,5-trimethylcyclohexanol. However, this effect is relatively minor over the range of initial TIBA concentration employed in the reduction experiments, and cannot be solely responsible for the stereochemical variation reported in Table II.

Another factor of potential stereochemical consequence is possible complex formation between the initially formed dialkylalkoxyaluminum and TIBA. In those cases where TIBA is not in excess, a complex such as **11** (joined *via* an alkoxy bridging group) might

$$R_2C{=}O \xrightarrow{\text{TIBA}} \underset{\mathbf{10}}{R_2CHOAl\text{-}i\text{-}Bu_2} \overset{\text{TIBA}}{\rightleftharpoons} \underset{\mathbf{11}}{R_2CHOAl\text{-}i\text{-}Bu_2\cdot i\text{-}Bu_3Al}$$

be the active reducing species leading to a different stereochemical result. *A priori*, formation of such a complex might seem unlikely, since, even in the presence of donor solvents, aluminum alkoxides such as **10** exhibit a very strong tendency to self-associate into unreactive dimers and/or trimers.[12] On the other hand, formation of stable mixed alkoxy–alkyl bridged systems of empirical formula $R_2AlOR\cdot AlR_3$ are known.[16] Therefore, one cannot discount the possibility of reduction by a small equilibrium concentration of a complex such as **11**. The extent of such reduction would depend on the ability of the complex to compete with TIBA for ketone, and hence on the ratio of TIBA to ketone. To test the significance of reduction by a complex such as **11**, 3,3,5-trimethylcyclohexanone was reduced in ether with a reagent formed by premixing 3,3,5-trimethylcyclohexanol (35% trans) with 2 equiv of TIBA. After correcting for the isomeric composition of the reagent, it was found that 60% hydride transfer to the ketone was from the equatorial side. In a parallel experiment, reduction with TIBA under identical conditions resulted in 66% hydride transfer from the equatorial side of the ketone. This result suggests that a definite but small fraction of the stereochemical variation in reduction of ketones with TIBA

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(14) (a) E. G. Hoffmann, *Justus Liebigs Ann. Chem.*, **629**, 104 (1960); (b) R. Koster and P. Binger, *Advan. Inorg. Chem. Radiochem.*, **7**, 263, (1965).

(15) M. B. Smith, *J. Organometal. Chem.*, **22**, 273 (1970).

(16) E. C. Ashby, J. Laemmle, and G. Parris, *J. Organometal. Chem.*, **19**, 24 (1969).

may be attributed to intervention by a complex such as **11**.

Thus it appears that the dependence of the isomeric composition of the product mixture obtained by reduction of 3,3,5-trimethylcyclohexanone or 4-*tert*-butylcyclohexanone with TIBA cannot be attributed to a single cause. At least three minor factors are operative: isomeric equilibration *via* a Meerwein-Ponndorf-Verley type reduction, association of the reducing agent, and complexation of TIBA by the initially formed aluminum alkoxide. Greatest selectivity is attained when TIBA is employed in excess and the reduction is performed in concentrated solution.

Experimental Section

Manipulations of air-sensitive compounds were performed either in a Kewaunee inert atmosphere box or by employing special bench-top techniques.[17] Reagents were transferred in flame-dried syringes which were cooled under nitrogen. Products were analyzed by glc utilizing a 20-ft column packed with 5% Carbowax 20M on Chromosorb G and a Hewlett-Packard Model 700 chromatograph. Ethyl benzoate was employed as internal standard in reduction of 3,3,5-trimethylcyclohexanone, and analyses were performed at 135°. Retention times for ketone, axial alcohol, and equatorial alcohol were 16.0, 25.2, and 31.1 min, respectively. For reduction of 4-*tert*-butylcyclohexanone, 3,3,5-trimethylcyclohexanone was used as internal standard and analyses were performed at 150°. Retention times for ketone, axial alcohol, and equatorial alcohol were 22.6, 25.9, and 31.0 min, respectively.

Materials.—Reagent-grade ether and benzene were refluxed for 24 hr over $LiAlH_4$ and $NaAlH_4$, respectively, distilled through a 3-ft Vigreux column, and stored over sodium-lead alloy (J. T. Baker dri-Na) in a nitrogen atmosphere. Standard solutions of diisobutylaluminum hydride and triisobutylaluminum were prepared from the aluminum compounds as received (Ethyl Corp.). Aluminum analysis of the solutions by EDTA titration were in all cases satisfactory. Hydrolysis of an aliquot and analysis of the gases evolved indicated the presence of 2.7% active hydride in the triisobutylaluminum. 3,3,5-Trimethylcyclohexanone (Chemical Samples Co., 99%) was distilled through a 2-ft glass helices column and the middle fraction was used in this study. 4-*tert*-Butylcyclohexanone (Frinton Laboratories) was sublimed prior to use.

General Procedure for Reduction.—A 50-ml erlenmeyer flask containing a magnetic stirring bar was flame dried and allowed to cool under vacuum in the entry port of an inert atmosphere box. After transfer of the flask into the box, it was sealed with a rubber septum, removed from the box, and connected by means of a needle to a nitrogen-filled manifold equipped with an oil-filled bubbler. A solution of the appropriate ketone (1.00 mmol, *ca.* 1 ml of 1 *M* solution) was introduced into the reaction vessel followed by sufficient solvent to bring the final volume to 10.0 ml except in those cases where TIBA concentration was being studied. Stirring was initiated and the flask was immersed in a water bath at 0° for the reactions to be carried out in ether or at 22° for those to be carried out in benzene. After the flask had come to temperature equilibrium, a solution (*ca.* 1 *M*) of the appropriate organoaluminum reagent was introduced, allowed to react for 2.0 hr, and then quenched by addition of *ca.* 0.5 ml of 5% HCl. Internal standard was added and the product mixture was analyzed by glc.

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Registry No.—**1**, 873-94-9; **2**, 98-53-3; diisobutylaluminum hydride, 1191-15-7; triisobutylaluminum, 100-99-2; axial 3,3,5-trimethylcyclohexanol, 767-54-4; equatorial 3,3,5-trimethylcyclohexanol, 933-48-2; axial 4-*tert*-butylcyclohexanol, 937-05-3; equatorial 4-*tert*-butylcyclohexanol, 937-06-4.

[17] D. F. Shriver, "The Manipulation of Air-Sensitive Compounds," McGraw-Hill, New York, N. Y. 1969.

The Stereochemistry of Electroreductions. IV. Carbon–Sulfur Single Bonds[1]

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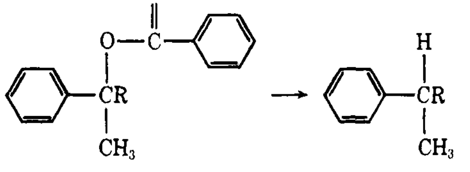
The stereochemistry of the electroreduction of optically active ethyl 2-phenylmercaptopropionate was investigated. Reaction proceeds with the formation of ethyl 2-phenylpropionate of low optical activity (2–4% stereospecificity–inversion of configuration being observed).

In an earlier paper,[1c] we reported the stereochemical features of the electroreduction of atrolactic acid derivatives. Controlled potential electrolysis of both *O*-benzoylatrolactic acid (I) and methyl *O*-benzoylatrolactate (II) resulted in cleavage of the carbon–oxygen bond and subsequent carbon–hydrogen bond formation (see Scheme I). The stereochemical results indicated that the reduction proceeded with almost complete loss of optical activity.

These results were in contrast to earlier reported reductions of cyclopropyl halides[1a,b] in which moderately high stereospecificities (56% inversion to 38% retention) were found. Also, Czochralska found that the electrochemical reduction of 2-chloro-2-phenylpropionic acid proceeded with a very high degree of stereospecificity (77% to 92% inversion of configuration).[2]

SCHEME I



I, R = COOH
II, R = $COOCH_3$

The present paper reports the results obtained in a study of the stereochemistry of the electroreduction of carbon–sulfur single bond substrates. It was thought

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[1] For earlier papers in this series see (a) R. Annino, R. E. Erickson, J. Michalovic, and B. McKay, *J. Amer. Chem. Soc.*, **88**, 4424 (1966); (b) R. E. Erickson, R. Annino, M. D. Scanlon, and G. Zon, *ibid.*, **91**, 1767 (1969); (c) R. E. Erickson and C. M. Fischer, *J. Org. Chem.*, **35**, 1604 (1970).

[2] B. Czochralska, *Chem. Phys. Lett.*, **1**, 239 (1967). We have attempted to repeat Czochralska's work but have been unsuccessful. Yields of the expected product were on the order of 50% and essentially no optical activity was found in the product mixture.