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Transfer Reactions Involving Boron. V. Reactions of the Intermediate Organoboranes Formed by Hydroboration of Enol Ethers[1]

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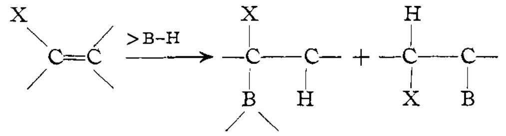
The intermediate organoborane formed in the hydroboration of ethoxystyrene has been shown to undergo competitive transfer and elimination reactions. Both reactions are markedly catalyzed by the addition of the Lewis acid, boron trifluoride. Studies with the hydroboration intermediate from ethoxycyclohexene and 4-*t*-butylethoxycyclohexene indicate that the uncatalyzed elimination is *cis* and the catalyzed elimination is *trans*. Hydroboration of 4-*t*-butylethoxycyclohexene in the presence of boron trifluoride reveals a reversal in the direction of addition of BH.

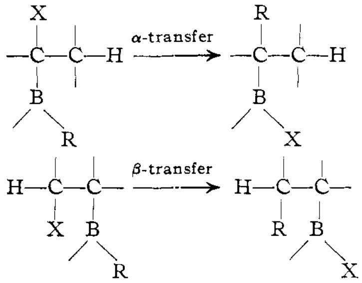
Introduction

The hydroboration of a heterosubstituted olefin (I) may result in the formation of an α-substituted organoborane (II) or a β-substituted organoborane (III). The stability of II and III, with respect to subsequent reactions leading to more stable intermediates, is dependent on the nature of the substituent X and the stereochemistry of the adduct. Prior to the investigations initiated in these laboratories, adducts of type III had been proposed as intermediates in the hydroboration of systems in which X is halogen, oxygen, silicon, and boron (in the dihydroboration of acetylenes), whereas the mention of adducts of type II were quite rare, the examples being silicon and boron (see above). Systems in which X was halogen, chlorine, the type III adducts underwent a very rapid elimination to give olefins.[3] Hydroboration of divinyl ether,[4] X = oxygen, with *t*-butylborane resulted in the formation of a relatively stable organoborane, the stability of which would appear to be due to steric factors. Adducts of type III in which X is silicon[4,5] and boron[1] are stable relative to any spontaneous reaction. Studies on the hydroboration of enethiol ethers[6] have revealed that substantial quantities of adducts of type II are formed in addition to those of type III. In these studies a new mode of relieving the "instability" of adducts of both types II and III was observed, that reaction being proposed as an intramolecular transfer reaction involving the migration of a hydrogen or substituted carbon atom from boron to carbon with the X group, RS–, migrating from carbon to boron as in α- and β-transfer.[7]



I II III

Certain simple rules were proposed to predict the stability of heterosubstituted organoboranes of types II and III[6b] but the factors leading to elimination *vs.* the transfer reactions could not be ascertained. This article reports an attempt to try to determine a few of the factors leading to transfer *vs.* elimination reactions in the hydroboration of enol ethers, a reaction in which both transfer and elimination reactions were proposed to occur.[6a]



X = C_6H_5S–; R = H or substituted carbon

Results

Hydroboration of β-Ethoxystyrene (IV).—The results from the hydroboration of β-ethoxystyrene under various conditions are listed in Table I. In experiments 1, 2, and 3 the hydroborations were carried out at 0° and the reaction mixtures maintained at 0° for the lengths of time indicated before hydrolysis and oxidation. Experiments 4, 5, and 6 were similar to 1, 2, and 3 except that the temperature was maintained at 25° Experiment 7 gives the observed results when boron trifluoride was added after the hydroboration step and experiment 8 lists the results when the hydroboration was carried out in the presence of boron trifluoride. Experiments 7 and 8 appeared to be much more exothermic than experiments 1–6. In addition to the products listed in Table I under experiments 7 and 8, a fair amount (approximately 15%) of a very high boiling material was formed. Oxidation of this material with chromic acid produced an apparent mixture of neutral compounds which absorbed in the infrared at 5.84 and 5.95 μ in carbon tetrachloride solution. Adequate separation of the oxidized mixture could not be accomplished. It is believed that these high boiling materials were produced by acid-catalyzed α- and β-carbon transfer reactions producing dimeric products of similar structure.[6b]

Hydroboration of Ethoxycyclohexene (V).—Hydroboration of ethoxycyclohexene in tetrahydrofuran produced an intermediate organoborane (R_2BH) which proved to be stable in refluxing tetrahydrofuran for a

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[1] For part IV see D. J. Pasto, *J. Am. Chem. Soc.*, **86**, 3039 (1964).

[2] National Institutes of Health Predoctoral Fellow.

[3] M. F. Hawthorne and J. A. Dupont, *J. Am. Chem. Soc.*, **80**, 5830 (1958); P. Binger and R. Köster, *Tetrahedron Letters*, **No. 4**, 156 (1961).

[4] M. F. Hawthorne, *J. Am. Chem. Soc.*, **83**, 2541 (1961).

[5] D. Seyferth, *J. Inorg. Nucl. Chem.*, **7**, 152 (1958); B. M. Mikhailov and T. A. Shchegoleva, *Izv. Akad. Nauk SSSR*, 546 (1959).

[6] (a) D. J. Pasto and J. L. Miesel, *J. Am. Chem. Soc.*, **84**, 4991 (1962); (b) D. J. Pasto and J. L. Miesel, *ibid.*, **85**, 2118 (1963).

[7] Although an elimination reaction could not be detected as occurring in the 1-phenyl-1-phenylmercaptopropene case, it appears that some elimination does compete with the transfer reaction in other cases (ref. 6).

Table I

Hydroboration of β-Ethoxystyrene

Expt.	Time	$C_6H_5CHOHCH_2OC_2H_5$	$C_6H_5CH_2CH_2OH$	$C_6H_5CHOHCH_3$	$C_6H_5CH{=}CH_2$	$C_6H_5CH_2CH_2OC_2H_5$	Starting material
1[a]	7 sec.	60	1.0	2.0	0.5	2.0	20
2[a]	10 min.	59	5.0	6.0	.4	2.0	15
3[a]	60 min.	59	10.0	10.0	.5	2.0	5
4[b]	15 min.	22.5	40	10.5	2.8	8.0	..
5[b]	60 min.	11.9	48	13.4	1.4	3.8	..
6[b]	120 min.	11.5	64	15	1.4	4.7	..
7[c]	10 sec.	22	7.0	11.2	11.9	2.0	10
8[d]	10 sec.	33	8.6	12.8	12.7	2.0	10

[a] Reaction temperature 0°. [b] Reaction temperature 25°. [c] Boron trifluoride etherate added to the hydroboration mixture at 0°. [d] Hydroboration carried out in the presence of boron trifluoride.

period of 2 hr. Hydrolysis and oxidation produced *trans*-2-ethoxycyclohexanol and trace amounts of cyclohexyl ethyl ether and cyclohexanol (see Table II, experiment 9). Hydroboration of V followed by the addition of boron trifluoride produced a very exothermic reaction which on hydrolysis and oxidation gave a substantial yield of cyclohexanol, a small amount of cyclohexyl ethyl ether, and a greatly reduced yield of the hydroxyether (see Table II, experiment 10). Hydroboration of V in the presence of boron trifluoride produced, after hydrolysis and oxidation, cyclohexanol and cyclohexyl ethyl ether. The cyclohexyl ethyl ether was produced in substantially greater yield than in the hydroboration experiments carried out in the absence of boron trifluoride (see Table II, experiment 11). Cyclohexene was detected in substantial quantities in both experiments involving the use of boron trifluoride but not in the hydroboration in the absence of boron trifluoride.

Table II

Hydroboration of Ethoxycyclohexene

Product	Experiment		
	9[a]	10[b]	11[c]
Cyclohexanol	Trace	24	47
Cyclohexyl ethyl ether	Trace	3	21
trans-2-Ethoxycyclohexanol	77	16	..
Cyclohexene	..	Present	Present
"Hydrides" used	0.95	1.19	1.40

[a] Hydroboration of V in tetrahydrofuran. [b] Hydroboration of V in tetrahydrofuran followed by the addition of boron trifluoride and allowing to stand at 0° for 5 min. before hydrolysis and oxidation. [c] Hydroboration of V in tetrahydrofuran in the presence of boron trifluoride and allowing to stand at 0° for 5 min. before hydrolysis and oxidation.

Hydroboration of 4-*t*-Butylethoxycyclohexene (VI).—Hydroboration of VI in tetrahydrofuran at 0° produced an intermediate organoborane mixture which proved to be stable in refluxing tetrahydrofuran for 2 hr. Hydroboration, followed by hydrolysis and oxidation, resulted in the formation of *cis*- and *trans*-4-*t*-butylethoxycyclohexane, axial and equatorial *t*-butylcyclohexanols, and two hydroxyethers for which the method of structure elucidation is presented below. Oxidation of a small portion of the crude reaction mixture with an excess of dichromate in acid solution, followed by gas–liquid chromatographic (g.l.c.) analysis on a 30-ft. Carbowax column, showed the presence of 4-*t*-butylcyclohexanone with only a trace of the 3-isomer present. This indicates that the axial and equatorial *t*-butylcyclohexanol fractions were comprised of mostly the *cis*- and *trans*-4-*t*-butylcyclohexanols, respectively. The yields are listed in Table III, experiment 12.

The structures of the two hydroxyethers were determined in the following manner. Chromatographic separation of the mixture on Florisil gave, in the order of elution from the Florisil column, a crystalline hydroxyether which proved to be identical with the second hydroxyether peak in the gas–liquid chromatogram and a liquid hydroxyether identical with the first hydroxyether peak in the gas–liquid chromatogram. The nuclear magnetic resonance spectrum of the crystalline hydroxyether[8] VII displayed an intense singlet representing the *t*-butyl group at -51 c.p.s. from tetramethylsilane (TMS). The ethyl group appeared as an A_3XY pattern with δ_{CH_3} -67, δ_{H_X} -205, and δ_{H_Y} -207 c.p.s., $J_{CH_3H_X} \simeq J_{CH_3H_Y} \simeq 6.9$, and $J_{H_XH_Y} \simeq 15$ c.p.s. The tertiary proton (on the cyclohexyl carbon bearing the ethoxyl group), absorption appeared at -194 c.p.s. with a band half-width (band width at half-peak height) of 7.1 c.p.s. The tertiary carbinol proton absorption appeared at -230 c.p.s. with a band half-width of 8.2 c.p.s. The band half-widths of both tertiary protons, compared with the band half-widths for the analogous protons in the second hydroxyether VIII, would indicate that both protons are equatorial.[9] Similarly, the position of the absorption bands for the tertiary protons would suggest that the tertiary protons in VII are equatorial, the equatorial protons usually absorbing at lower field.[9,10] The position of absorption of the tertiary carbinol proton of VII is, however, significantly different from the expected value calculated by the method of Eliel and co-workers.[10,11] Oxidation of hydroxyether VII gave ketoether IX with carbonyl absorption in the infrared at 5.82 μ. The n.m.r. spectrum showed *t*-butyl absorption at -56 c.p.s. and ethyl absorption as an apparent A_3X_2 system with δ_{CH_3} -71 and δ_{CH_2} -202 c.p.s. with $J_{CH_3CH_2} = 7$ c.p.s. The terti-

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[8] N. A. LeBel and R. F. Czaja (*J. Org. Chem.*, **26**, 4768 (1961)) isolated a crystalline hydroxyether (m.p. 95–97°) from the treatment of *cis*-2-chloro-*trans*-4-*t*-butylcyclohexanol with ethoxide. The structure of this hydroxyether was assigned as *trans*-2-ethoxy-*cis*-5-*t*-butylcyclohexanol (VII) on the basis of its infrared spectrum and the chemistry involved. The structure of VII is rigorously confirmed by n.m.r. and subsequent chemical conversions described in this article and by comparison of these properties with those of the only other possible *trans*-2-ethoxy-4-*t*-butylcyclohexanol isolated in this work.

[9] R. U. Lemieux, R. H. Kullnig, H. J. Bernstein, and W. G. Schneider, *J. Am. Chem. Soc.*, **80**, 6098 (1958).

[10] E. L. Eliel, M. H. Gianni, Th. H. Williams, and J. B. Stothers, *Tetrahedron Letters*, **No. 4**, 741 (1962).

[11] The apparent shielding of this proton would not appear to be due to shielding by the adjacent ethoxyl group. The tertiary carbinol proton in VIII resonates at the expected field strength[10] and would be expected to experience the same degree of shielding by the ethoxyl as the carbinol proton in VII, as both protons have the same relative orientation with respect to the ethoxyl group if VII is considered to be in the diaxial chair conformation. The anomaly then appears to lie in VII and may be due to distortion of the cyclohexane ring and contribution from forms other than that represented as VII.

ary proton on the carbon to which the ethoxyl group is bonded appeared at −206 c.p.s. with a band half-width of 6.8 c.p.s. The spectral properties, compared with those of the ketone X obtained from hydroxyether VIII, indicate that the ethoxyl is axial and the ketone has the structure IX. Treatment of IX with sodium ethoxide at 30° for 10 min. resulted in isomerization of IX to X.

The liquid hydroxyether VIII displayed a singlet at −53 c.p.s. in the n.m.r. representing the *t*-butyl protons. The ethyl group absorption appeared as an A_3XY pattern with δ_{CH_3} −71, δ_{H_X} −206, and δ_{H_Y} −222 c.p.s., $J_{CH_3H_X} \simeq J_{CH_3H_Y}$ 7.1 and $J_{H_XH_Y} = 8.7$ c.p.s. The tertiary proton on carbon bearing the ethoxyl appears at −183 c.p.s. with a band half-width of approximately 24 c.p.s., and the carbinol proton appears at −201 c.p.s. with a band half-width of 26 c.p.s. The n.m.r. data are consistent with the diequatorial hydroxyether VIII. The axial tertiary protons on the carbons bearing ethoxyl and hydroxyl are at higher field[9,10] than their counterparts in VII and the bands are much broader due to greater coupling with the adjacent protons as expected.[9] The position of the carbinol proton (−201 c.p.s.) is in excellent agreement with the position calculated (−200 c.p.s.) according to Eliel and co-workers.[10] In addition the greater dissimilarity between the methylene protons of the ethyl group in VIII with respect to VII is consistent owing to the closer proximity of the hydroxyl and ethoxyl functions in VIII. Oxidation of VIII gave a crystalline ketoether X which displayed carbonyl absorption at 5.78 μ. The tertiary proton on carbon bearing the ethoxyl absorbed at −174 c.p.s. with a band half-width of 16 c.p.s. while the ethyl group appeared as an A_3XY system with δ_{CH_3} −44, δ_{H_X} −157, and δ_{H_Y} −179 c.p.s. with $J_{CH_3H_X} \simeq J_{CH_3H_Y} = 6.2$ and $J_{H_XH_Y} = 7.2$ c.p.s. The proton on the carbon bearing the ethoxyl appeared at −174 c.p.s. with an apparent band half-width of 17 c.p.s. The spectral data are consistent for the ketoether having structure X. The carbonyl maximum of X occurs as shorter wavelength than IX which is consistent with other axially and equatorily 2-substituted cyclohexanones[12] in which the substituent is a halogen atom. The position of the tertiary proton resonance in X, at higher field than in IX, and the broader band half-width is consistent with the ethoxyl being in an equatorial position. The greater dissimilarity of the methylene protons of the ethyl group in X indicates a close proximity to a polar functional group. The structures of VII, VIII, IX, and X, and the chemical conversions are illustrated in Fig. 1.

The hydroboration of VI followed by the addition of boron trifluoride produced a rather exothermic reaction. Hydrolysis and oxidation produced (see Table III, experiment 13) 4-*t*-butylcyclohexene, *cis*- and *trans*-4-*t*-butylethoxycyclohexane, axial and equatorial *t*-butylcyclohexanol fractions, and the two hydroxyethers VII and VIII. Oxidation of a portion of the mixture followed by gas–liquid chromatographic analysis showed the derived *t*-butylcyclohexanones to be 58% 4- and 42% 3-*t*-butylcyclohexanone.

Hydroboration of VI in the presence of boron trifluoride resulted in the formation of the products indicated above except the yield of *trans*-4-*t*-butylethoxycyclohexane was substantially increased and the hydroxyether VII was absent (see Table III, experiment 14). Oxidation and analysis of the *t*-butylcyclohexanones showed 88% 4- and 12% 3-*t*-butylcyclohexanone.

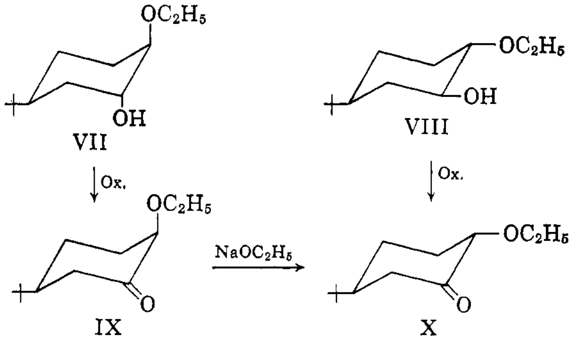

Figure 1.

TABLE III

HYDROBORATION OF 4-*t*-BUTYLETHOXYCYCLOHEXENE

Product	Experiment 12[a]	13[b]	14[c]
4-*t*-Butylcyclohexene	..	11	7.5
cis-4-*t*-Butylethoxycyclohexane	1.5	1.8	1.7
trans-4-*t*-Butylethoxycyclohexane	1.2	7.4	18
t-Butylcyclohexanol (axial)	2.8	7.0	31
t-Butylcyclohexanol (equatorial)	4.3	11	18
Hydroxyether VIII	46	48	21
Hydroxyether VII	38	10	..
Alcohol composition (4-isomer)[d]	99	58	88
Attack at the 1-position, %	10	..	64

[a] Hydroboration of VI in tetrahydrofuran at 0° and allowed to stand at room temperature 2 hr. [b] Hydroboration of VI in tetrahydrofuran at 0° followed by the addition of boron trifluoride at 0° with stirring for 10 min. [c] Hydroboration of VI in the presence of boron trifluoride in tetrahydrofuran at 0° with stirring for 10 min. [d] Determined by oxidation of a portion of the crude reaction mixture followed by gas–liquid chromatographic analysis for 3- and 4-*t*-butylcyclohexanone.

Discussion

A possible reaction scheme for the formation of products from β-ethoxystyrene (IV) is illustrated in Fig. 2. Hydroboration of IV may occur in either direction giving rise to a mixture containing the α-ethoxyorganoborane XI and the β-ethoxyorganoborane XII. Consider first the possible reaction paths available to the α-ethoxyl derivative XI. Rearrangement *via* the α-hydrogen transfer mechanism[6] would result in the formation of an intermediate organoborane which would give 2-phenylethanol on hydrolysis and oxidation. One may also visualize an α-elimination, either uncatalyzed or base-catalyzed, giving rise to a carbene which might rearrange to olefin (styrene) or react with solvent to give 2-phenylethanol. However, no evidence has been obtained under the present experimental conditions which would suggest such a mechanistic pathway is in operation. Intermediate XI which does not proceed to rearranged products undergoes a base-catalyzed hydrolysis during work-up leading to saturated ether,[13] no oxidation product, phenylacetaldehyde, having been observed in the reaction product mixture.

The reaction paths available to intermediate XII include a β-hydrogen transfer,[6] ultimately leading to 1-phenylethanol, and a β-elimination giving styrene.

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(12) E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, p. 24X.

(13) This is analogous to the base-catalyzed hydrolysis of similar α-derivatives in the sulfur series.[6] In this particular case some saturated ether might arise by hydrolysis of a benzyl carbon–boron bond, as in XII, but from the data obtained with V and VI the base-catalyzed hydrolysis of the α-ethoxyl derivatives would appear to occur much more rapidly than a benzyl carbon–boron hydrolysis in XII would be expected to occur.

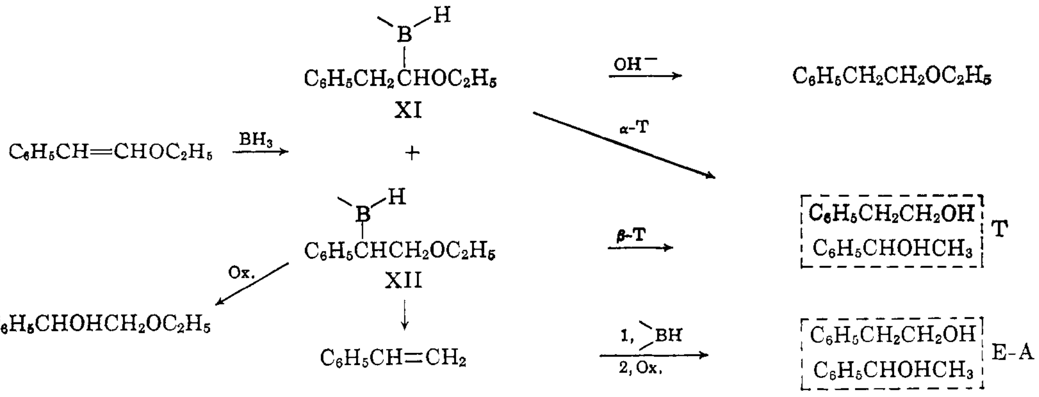

Figure 2.

The styrene, in the presence of excess >B–H, would be expected to undergo subsequent hydroboration giving 1- and 2-phenylethanol after hydrolysis and oxidation.

Distinction between the operation of the transfer mechanism and the elimination–addition mechanism should be possible based on the relative yields of the two isomeric alcohols formed as final products provided the concentration of intermediates of type XI and XII and the rates of α- and β-transfer do not fortuitously lead to a ratio of products identical with that obtained by hydroboration of the corresponding olefin. β-Ethoxystyrene was chosen for this study in anticipation that the hydroboration of IV would lead predominantly to intermediate XII, owing to the mesomeric interaction of the double bond with the ether oxygen, which, if the transfer mechanisms were operative, would be expected to lead to an alcohol fraction rich in 1-phenylethanol.[14] In contrast, product formation *via* an elimination–addition process would give an alcohol mixture in which 2-phenylethanol is the predominant product.

The contrasting pathways are illustrated in Fig. 2, the products of each pathway bracketed and indicated by T for transfer and E–A for the elimination–addition process. The ratio of 2-phenylethanol to 1-phenylethanol formed *via* transfer reactions cannot be predicted, but the ratio formed *via* the E–A process should be 4:1 or reasonably close to that value.[15]

The hydroboration of IV in tetrahydrofuran at 0° and maintaining the reaction mixture at 0°, experiments 1, 2, and 3 in Table I, produced an alcohol mixture in which 1-phenylethanol was formed in slight excess over the 2-isomer. The alcohol mixture in these cases *cannot* be formed entirely *via* the E–A process but must have been extensively formed *via* the hydrogen transfer mechanism. However, the results of experiments 4, 5, and 6 in Table I carried out at 25° are in distinct contrast to the results obtained at 0°. The 2- to 1-isomer ratios in these experiments are approximately 4:1, indicating that most of the alcohol mixture had been formed *via* the E–A path.

The results of the hydroborations of IV at 0 and 25° did not, however, compare well with the results previously reported[6] for the *in situ* hydroboration of IV in diglyme in which boron trifluoride was added to a diglyme solution of IV and sodium borohydride. In fact it proved difficult to obtain reproducible results using the *in situ* generation method. From these results it appeared obvious that the boron trifluoride might be catalyzing the reactions involving intermediates XI and XII. Addition of boron trifluoride to the hydroboration mixture of IV, experiment 7 of Table I, produced a highly exothermic reaction which, after hydrolysis and oxidation after a very short reaction time, produced substantially higher yields of the elimination product styrene and hydrogen transfer products 1- and 2-phenylethanol, with the 1-isomer in excess. It is obvious that both the transfer and elimination reactions are highly catalyzed by the Lewis acid boron trifluoride.[16] Hydroboration of IV in the presence of boron trifluoride, experiment 8 in Table I, gave results similar to those of experiment 7. In experiments of type 7 and 8 a substantial amount, approximately 15%, of a relatively nonvolatile material was isolated which is believed to have been formed by carbon-transfer reactions[6] which were also catalyzed by the boron trifluoride.[17]

The uncatalyzed elimination reaction appears to be highly temperature dependent. This would suggest that the mechanism of the elimination involves a four-centered transition state leading to a *cis* elimination. To the author's knowledge the mechanism and stereochemistry of the uncatalyzed elimination reaction has not been determined.[18]

To investigate further the stereochemistry of the elimination reaction the hydroboration of ethoxycyclohexene (V) was undertaken. Hydroboration of V produced primarily a *trans*-2-ethoxycyclohexylborane intermediate (XIII) which was stable in refluxing tetrahydrofuran (66°) for 2 hr. In this system the ethoxyl and boron groups cannot interact leading to a four-centered transition state for elimination owing to stereochemical problems. This experiment also mitigates against the possibility of the intermediate organoborane self-catalyzing its own destruction *via* the transfer and elimination reactions. Hydrolysis and oxidation of the reaction mixture produced *trans*-2-ethoxycyclo-

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[14] The rate of α-transfer in sulfur-containing systems[6] appeared to be only slightly faster than the rate of β-transfer.

[15] H. C. Brown and G. Zweifel, *J. Am. Chem. Soc.*, **82**, 4708 (1960); see also ref. 16.

[16] It was determined in a control experiment that the presence of boron trifluoride during the hydroboration of styrene does not alter the ratio of the products formed. In the absence of boron trifluoride the crude alcohol mixture, before distillation, was composed of 88% 2-phenylethanol and 12% 1-phenylethanol, and 88.5 and 11.5%, respectively, in the presence of boron trifluoride.

[17] The reactions carried out in the absence of boron trifluoride are referred to as "uncatalyzed" reactions although the intermediate organoboranes may be of sufficient Lewis acid strength to self-catalyze the elimination and transfer reactions. This does not appear to be the case (see later discussion concerning the hydroboration of V and VI).

[18] Utilizing the simple rules proposed to predict the instability of hetero-substituted organoboranes[6] a *cis* elimination would have been expected.

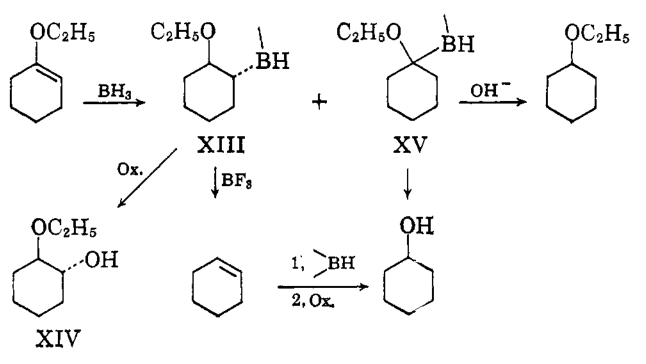

Figure 3.

hexanol (XIV) with trace amounts of cyclohexanol and cyclohexyl ethyl ether. Treatment of the hydroboration intermediate with boron trifluoride, experiment 10 in Table II, resulted in a substantial decrease in the yield of XIV and an increase in cyclohexanol and cyclohexene. The Lewis acid catalyzed elimination in this case must, therefore, occur in a *trans* fashion.

The hydroboration of V in the presence of boron trifluoride caused not only a disappearance of XIV and increase in cyclohexanol, but also in a substantial increase in the yield of cyclohexyl ethyl ether (see experiment 11, Table II). This would indicate that a greater percentage of attack by boron occurred at carbon atom 1 in the presence of boron trifluoride, experiment 11, than in experiment 9. Unfortunately the extent of this reversal of addition cannot be fully determined in that the cyclohexanol can be formed by an E–A process and hydrogen transfer in an intermediate of type XV between which no distinction can be made. Figure 3 illustrates the reactions involving V. The hydroboration of 4-*t*-butylethoxycyclohexene (VI) was therefore undertaken utilizing the *t*-butyl group as a handle in determining the course of the reactions.

The hydroboration of 4-*t*-butylethoxycyclohexene in tetrahydrofuran results in the formation of the products listed in experiment 12 of Table III. The saturated ethers arise by base-catalyzed hydrolysis, with retention of stereochemistry,[19] of the stereoisomeric intermediates XVI and XVII formed by the addition of B–H *cis* and *trans*, respectively, with respect to the *t*-butyl group (see Fig. 4). Hydrogen transfer reactions involving XVI and XVII, also believed to occur with retention in this system, result ultimately in the formation of *cis*- and *trans*-4-*t*-butylcyclohexanol, respectively. Hydroboration with the introduction of the boron at position 2 can occur either *cis* or *trans* with respect to the *t*-butyl group giving intermediates XVIII and XIX, respectively. In the absence of a strong Lewis acid these intermediates are stable with respect to both elimination and transfer reactions, as is evidenced by the fact that the product distribution does not change with time when the hydroboration mixture is refluxed in tetrahydrofuran for up to 2 hr. and that the *t*-butylcyclohexanol fraction did not contain any of the 3-isomers.[20]

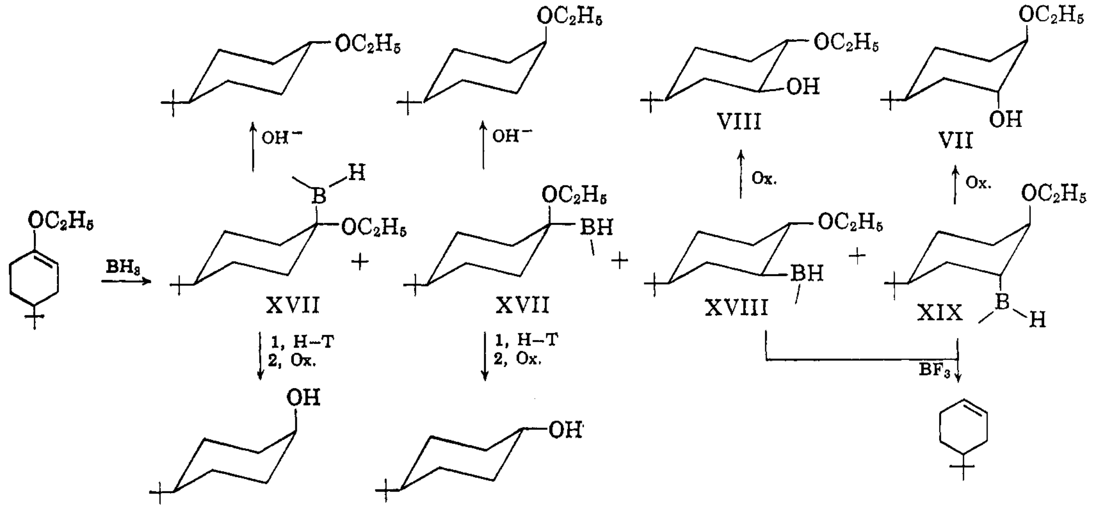

Figure 4.

Addition of boron trifluoride after the hydroboration step resulted in the formation of the products listed under experiment 13, Table III. A very noticeable increase in the yield of olefin and the alcohols occurred. The yield of diequatorial hydroxyether VIII remained unchanged, whereas the amount of diaxial compound surviving greatly decreased. The 4-*t*-butylcyclohexene thus appears to have been formed almost exclusively from XIX. The *t*-butylcyclohexanol fractions consisted of 58% 4- and 42% 3-*t*-butylcyclohexanol isomers, indicating that a substantial portion of the alcohol fraction was derived by hydroboration of 4-*t*-butylcyclohexene.[21] The composition of the alcohol mixture, being similar to that obtained by hydroboration of the olefin, indicates that β-hydrogen transfer is not occurring to a significant extent. This is undoubtedly caused by steric problems.

The more rapid acid-catalyzed elimination of XIX with respect to XVIII is not unexpected. The axial leaving groups are well oriented to provide maximum orbital overlap during olefin formation, whereas the equatorial substituents are not. Ample analogies are available in base-catalyzed eliminations in cyclohexyl

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(19) A. J. Weinheimer and W. E. Marsico, *J. Org. Chem.*, **27**, 1926 (1962).

(20) Unfortunately, analysis of the mixture of the four isomeric 3- and 4-*t*-butylcyclohexanols could not be accomplished by g.l.c. techniques. The analysis could be performed satisfactorily, as shown by carrying out a control analysis with a known mixture, by determining the ratio of axial to equatorial alcohol by g.l.c. followed by chromic acid oxidation to the 3- and 4-*t*-butylcyclohexanones and analysis by g.l.c. From these data one can calculate the composition of the alcohol mixture.

(21) The hydroboration of 4-*t*-butylcyclohexene in tetrahydrofuran at 0° leads to the formation of an alcohol mixture containing approximately 45% axial and 55% equatorial alcohols. Oxidation of the crude reaction mixture and analysis by g.l.c. indicated the presence of 50% 3- and 50% 4-*t*-butylcyclohexanone. The hydroboration of 4-*t*-butylcyclohexene will be the subject of a subsequent publication.

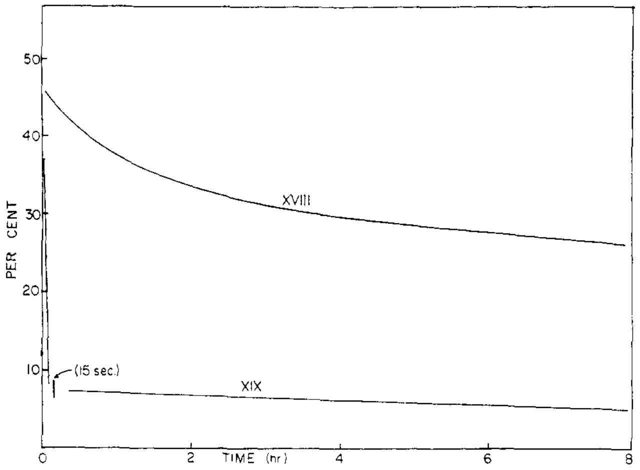
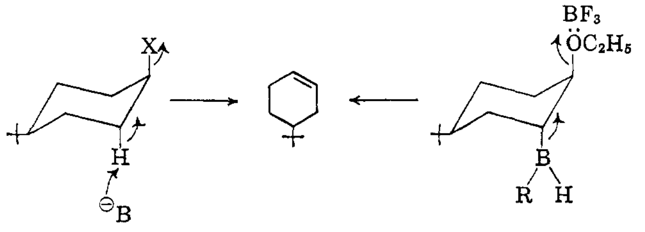


Fig. 5.—BF-catalyzed elimination of XVIII and XIX.

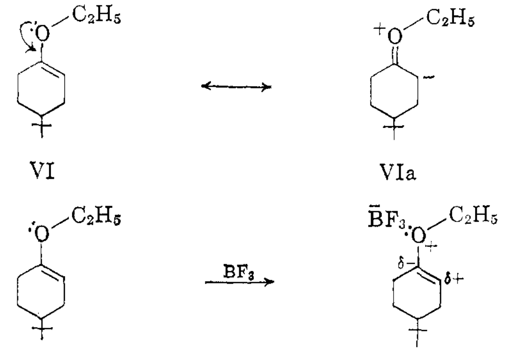
systems in which the axial derivatives undergo base-catalyzed eliminations more rapidly than the equatorial derivatives.[22] Relatively few examples involving acid-catalyzed eliminations have appeared and in these cases the elimination proceeds more rapidly when the leaving groups are in the axial position.[23] Caglioti and co-workers have observed the elimination of the elements of $>BOCH_3$ and $>BOAc$ from intermediates derived from the hydroboration of steroidal enol ethers and enol acetates (apparently the diequatorial derivatives are predominantly formed in these reactions) by refluxing with propionic acid or acetic anhydride for 1 to 4 hr.[24] The over-all electron flow in both the acid- and base-catalyzed eliminations is the same and is illustrated below. Intermediate XVIII does undergo



an acid-catalyzed elimination but at a much slower pace. Figure 5 shows the relative rates of disappearance of intermediates XVIII and XIX in the presence of boron trifluoride.

Hydroboration of VI in the presence of boron trifluoride resulted in the formation of the products listed in experiment 14 in Table III. Significant increases in the yields of *trans*-4-*t*-butylethoxycyclohexane and the isomeric *t*-butylcyclohexanols are observed with a substantial decrease in the yield of hydroxyether VIII and an absence of hydroxyether VII. A dramatic change in the composition of the alcohol mixture also occurred in that 88% of the alcohol mixture was *cis*- and *trans*-4-*t*-butylcyclohexanol. Only a small portion, approximately 25% of the total, of the alcohol fraction was formed by hydroboration of the intermediate 4-*t*-butylcyclohexene, the remainder of which must have been formed by a hydrogen transfer involving intermediates XVI and XVII. Summing the yields of the products formed from addition of boron to the 1-carbon atom, giving XVI and XVII, indicates that 64% of the hydroboration must have occurred in this fashion. Comparison of this value with the 10% addition of boron to the 1-carbon atom in experiment 12 in the absence of boron trifluoride reveals a dramatic reversal in the direction of B–H addition in the presence of boron trifluoride.

The reversal in the direction of addition of B–H can be rationalized in the following manner. The direction of B–H is highly dependent on steric and electronic factors. The electron distribution in VI is influenced by the mesomeric interaction of the nonbonded pair of electrons on the ether oxygen with the double bond giving the resonance structure VIa. The resulting



VIb

resonance hybrid will have a high electron density on the 2-carbon atom. Addition of B–H, polarized as $\overset{\delta+\ \delta-}{\searrow B{-}H}$ will result in the attachment of the boron atom at carbon atom 2. In the presence of boron trifluoride, the nonbonded pair of electrons on the other oxygen may complex in a Lewis acid–base manner tying down the mobility of the electron pair. The net result is that resonance structure VIa will not be possible and the effect of forming the complex will introduce an inductive effect toward the ether oxygen which will result in the electron distribution illustrated in VIb. Addition of B–H to VIb would be expected to occur with the attachment of the boron to carbon atom 1.

It seems rather remarkable that in a reaction mixture containing VI, boron trifluoride, and tetrahydrofuran in a mole ratio of approximately 1:1:20 such a dramatic reversal in the direction of addition is observed. The solvent tetrahydrofuran would be expected to be much more basic than VI. The amount of VI complexed with boron trifluoride would be expected to be relatively small; nonetheless the hydroboration of VI would appear to proceed *via* VIb. One way in which to rationalize these results would be that the rate of hydroboration of VIb is much more rapid than with uncomplexed VI.

The following mechanisms can be written for the transfer and elimination reactions utilizing intermediate XII. The uncatalyzed transfer mechanism, i, is similar to that proposed earlier for the sulfur analogs.[6] The mechanism for the acid-catalyzed β-transfer, ii, is tentatively written as shown. Although postulating the intermediacy of a cationic boron species

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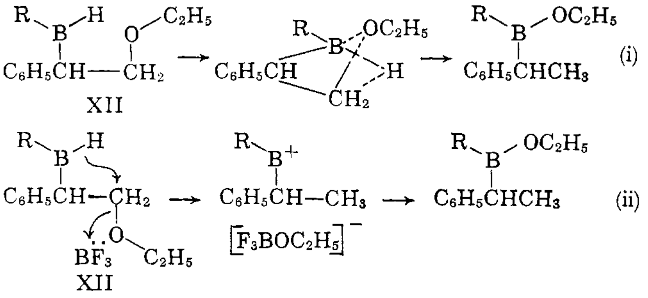
[22] See E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, pp. 227–228.

[23] M. G. Vavon, *Bull. soc. chim. France*, [4] **49**, 937 (1931); see also D. H. R. Barton, *Experientia*, **6**, 316 (1950).

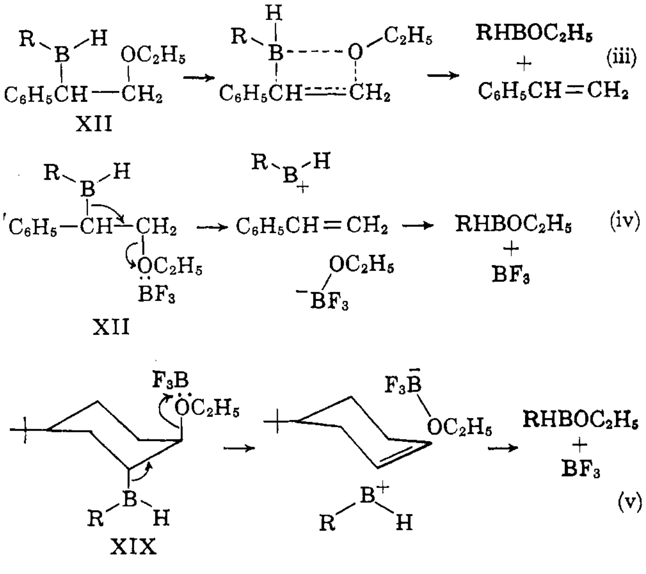
[24] L. Caglioti, G. Cainelli, G. Maina, and A. Selva, *Gazz. chim. ital.*, **92**, 309 (1962).

may be questionable, the cation may be stabilized by solvation with the electron donor solvent tetrahydrofuran.[25]

The mechanism of the uncatalyzed elimination, iii, would appear to proceed *via* a four-centered transition state leading to *cis* elimination as illustrated with XII. The stability of the *trans*-2-alkoxycyclohexylboranes derived from V and VI and the apparent high temperature dependence on the course of the reaction are in agreement with this proposal. The acid-catalyzed elimination with XII would appear to be *trans*, mechanism iv, by analogy with the observed eliminations in the derivatives from V and VI, mechanism v.



The present work indicates that certain precautions should be exercised in the hydroboration of heterosubstituted olefins and in the interpretation of the results obtained.



Experimental

All melting points are corrected values. Microanalyses were performed by the Schwarzkopf Microanalytical Laboratory, Woodside 77, N. Y. The nuclear magnetic resonance spectra were determined on a Varian HR-60 high resolution spectrometer. The determination of yields employing gas–liquid chromatography was accomplished by the addition of an internal standard and calculated using predetermined relative retention volumes.

Hydroboration of Ethoxystyrene.—To solutions of 3.00 g. (0.020 mole) of ethoxystyrene in 20 ml. of tetrahydrofuran was added 13.1 ml. of 1.53 *M* borane in tetrahydrofuran. The reaction mixtures were maintained at a constant temperature, 0 or 25°. After the indicated reaction time had elapsed (see Table I) the reaction mixture was hydrolyzed by the addition of 15 ml. of 20% sodium hydroxide (50% excess) and oxidized with 3 ml. of 30% hydrogen peroxide (50% excess). The oxidized sample was diluted with 200 ml. of water and extracted with four 75-ml. portions of ether. The extract was washed with water and saturated sodium chloride and dried over magnesium sulfate. The solvent was carefully removed under reduced pressure and the crude product analyzed by g.l.c. on a Carbowax column at 160°. The results are presented in Table I, experiments 1 through 6.

Hydroboration of Ethoxystyrene in the Presence of Boron Trifluoride.—A tetrahydrofuran solution of borane (10 ml. of 1.53 *M*) was rapidly added to a solution of 2.26 g. (0.0153 mole) of ethoxystyrene and 2.07 g. (0.0153 mole) of boron trifluoride etherate maintained at close to 0°. The reaction mixture was stirred for 10 sec. and was hydrolyzed, oxidized, and analyzed as described above. The results are presented in Table I, experiment 7.

Treatment of the Hydroboration Reaction Mixture of Ethoxystyrene with Boron Trifluoride Etherate.—To the hydroboration mixture derived from 2.26 g. (0.0153 mole) of ethoxystyrene and 10 ml. of 1.53 ml. of borane in tetrahydrofuran at 0° was rapidly added 2.07 g. (0.0153 mole) of boron trifluoride etherate. The reaction mixture was stirred for 10 sec. at 0° and hydrolyzed, oxidized, and analyzed as described above. The results are presented in Table I, experiment 8.

Hydroboration of Ethoxycyclohexene. A.—A solution of 2.80 g. (0.0222 mole) of ethoxycyclohexene in 5 ml. of tetrahydrofuran was added to 20 ml. of 0.74 *M* borane in tetrahydrofuran at 0° and allowed to stand for 2 hr. Hydrolysis with a 20% excess of base and measurement of the hydrogen evolved indicated utilization of 0.95 "hydride" per olefin. The hydrolyzed mixture was oxidized with a 20% excess of 30% hydrogen peroxide. The crude product was poured into water and extracted with two portions of ether and the extract dried over magnesium sulfate. Evaporation of the solvent and distillation of the crude product gave 2.50 g. which, on analysis by g.l.c. on a Carbowax column, contained 97% *trans*-2-ethoxycyclohexanol and trace amounts of cyclohexanol and cyclohexyl ethyl ether (Table II, experiment 9).

B.—Addition of boron trifluoride etherate (0.0115 mole) to the hydroboration mixture, from 0.0115 mole of ethoxycyclohexene and 0.00765 mole of borane, in tetrahydrofuran at 0°, followed by stirring for 5 min. (exothermic reaction) and basic hydrolysis, indicated the utilization of 1.19 "hydrides" per olefin. Oxidation and analysis as above showed the presence of cyclohexene (not determined quantitatively), cyclohexyl ethyl ether (3%), cyclohexanol (24%), and *trans*-2-ethoxycyclohexanol (16%) (Table II, experiment 10).

C.—Hydroboration of ethoxycyclohexene (0.0111 mole) with borane (0.0074 mole) in tetrahydrofuran in the presence of boron trifluoride etherate (0.0111 mole) for 5 min. at 0° followed by hydrolysis indicated the utilization of 1.40 "hydrides" per olefin. Analysis of the crude product after oxidation indicated the presence of cyclohexane (not determined quantitatively), cyclohexanol (46%), and cyclohexyl ethyl ether (21%) (Table II, experiment 11).

Hydroboration of 4-*t*-Butylethoxycyclohexene.—A solution of 1.55 g. (8.52 mmoles) of 4-*t*-butylethoxycyclohexene in 5 ml. of tetrahydrofuran was slowly added to 5.1 mmoles of borane in tetrahydrofuran at 0° and stirred for 0.5 hr.[26] The reaction mixture was hydrolyzed with a 20% excess of base and oxidized with a 20% excess of hydrogen peroxide. The mixture was poured into 100 ml. of water and the crude product was extracted with two 75-ml. portions of ether. The extract was dried over magnesium sulfate and the solvent was carefully removed under reduced pressure. The gas–liquid chromatogram of the crude product showed the presence of *cis*- and *trans*-4-*t*-butylcyclohexyl ethyl ether, axial and equatorial *t*-butylcyclohexanol, and two

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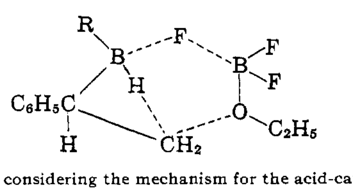
[25] It is possible to write a transition state in which boron trifluoride acts as a transfer bridge eliminating the necessity of postulating the intermediacy of the cationic boron species. This latter possibility would not appear feasible when considering the mechanism for the acid-catalyzed elimination of XIX. A more detailed study of the Lewis acid dependence and the stereochemistry involved in appropriately deuterium labeled substrates is under way and should clarify the more intimate details of the mechanisms involved.



[26] An earlier experiment indicated that hydroboration proceeded to the dialkylborane stage. In experiments with 4-*t*-butylethoxycyclohexene a 20% excess of borane in tetrahydrofuran based on the formation of dialkylboranes was used.

hydroxyethers identified as 1 and 2 in order of their appearance in the gas–liquid chromatogram.

A portion (approximately 100 mg.) of the crude product was dissolved in 5 ml. of acetone and oxidized at 0° with an excess of chromic acid. The reaction mixture was poured into water and extracted with three portions of ether. Evaporation of the solvent and analysis of the oxidized mixture by g.l.c. on a 30-ft. Carbowax column at 225° showed only a trace of 3-*t*-butylcyclohexanone.[27]

The remainder of the crude reaction mixture from the hydroboration of 4-*t*-butylethoxycyclohexene was chromatographed on a 25 × 2.5 cm. Florisil column set with 50% petroleum ether–benzene. Fractions 20 to 73, eluted with 90% benzene–petroleum ether to 20% chloroform–benzene, proved identical with hydroxyether 2 (VII). Recrystallization from petroleum ether gave colorless needles, m.p. 96.8–97.2°.[8] The n.m.r. spectrum of hydroxyether (VII) displayed the following characteristic peaks: *t*-butyl at −51 c.p.s. (from tetramethylsilane); ethyl group as an A_3XY pattern with δ_{CH_3} −67, δ_{HX} −205, and δ_{HY} −207 c.p.s. with $J_{HXHY} \simeq 15$ and $J_{CH_3CH_2} = 6.9$ c.p.s.; >C*H*-OC_2H_5 at −194 c.p.s. with band half-width of 7.1 c.p.s. and >C*H*OH at −230 c.p.s. with band half width of 8.2 c.p.s.

Anal. Calcd. for $C_{12}H_{24}O_2$: C, 71.95; H, 12.08. Found: C, 72.04; H, 12.18.

Fractions 76 to 89, eluted with 40 to 60% chloroform–benzene, were identical with hydroxyether 1 (VIII). The fractions were combined and molecularly distilled at 70° at 0.20 mm. giving a viscous liquid. The n.m.r. spectrum of hydroxyether 1 displayed the following characteristic peaks: *t*-butyl at −53 c.p.s.; ethyl group as an A_3XY pattern with δ_{CH_3} at −71 (triplet), δ_{HX} −206, and δ_{HY} −222 c.p.s. with $J_{CH_8CHXY} = 7.1$ and $J_{HXHY} = 8.7$ c.p.s.; >C*H*OC_2H_5 at −183 c.p.s. with band half-width of 24 c.p.s. and >C*H*OH at 201 c.p.s. with band half-width of 26 c.p.s.

Anal. Calcd. for $C_{12}H_{24}O_2$: C, 71.95; H, 12.08. Found: C, 72.25; H, 12.32.

The relative retention volumes of all components were determined and the yield of products was calculated. These values are listed in Table III, experiment 12.

Oxidation of Hydroxyether VII.—To a solution of 110 mg. of hydroxyether 2 in 10 ml. of acetone at 0° was added a slight excess of dichromate in 20% sulfuric acid. The reaction mixture was poured into 50 ml. of water and was extracted with two portions of ether. Evaporation of the solvent, after drying over magnesium sulfate, gave 100 mg. of a liquid (IX) which was purified by molecular distillation at 60–65° at 0.55 mm. The infrared spectrum of the product in carbon tetrachloride displayed very sharp carbonyl absorption at 5.82 μ. The n.m.r. spectrum displayed characteristic peaks at: *t*-butyl −56 c.p.s.; ethyl group as an A_3X_2 pattern with δ_{CH_3} −71 and δ_{CH_2} −202 c.p.s. with $J = 7$ c.p.s., and >C*H*OC_2H_5 at −206 c.p.s. with band half-width of 6.8 c.p.s.

Anal. Calcd. for $C_{12}H_{22}O_2$: C, 72.68; H, 11.18. Found: C, 72.98; H, 11.37.

Treatment of 10 mg. of ketoether IX in 2 ml. of 10% sodium ethoxide in ethanol at room temperature for 10 min., followed by recovery of the organic material by ether extraction after dilution with water, produced a ketoether (X) with a retention time identical with that observed for the ketoether derived from hydroxyether VIII.

Oxidation of Hydroxyether VIII.—A 130-mg. portion of hydroxyether 1 was oxidized as described above for hydroxyether VII giving 117 mg. of a ketoether X which was purified by sublimation at 50° and 0.5 mm. giving colorless crystals with m.p. 54–56°. The infrared spectrum in carbon tetrachloride displayed carbonyl absorption at 5.78 μ. The n.m.r. spectrum displayed the following characteristic peaks: *t*-butyl at −44 c.p.s.; ethyl group as an A_3XY pattern with δ_{CH_3} −54, δ_{HX} −157, and δ_{HY} −179 c.p.s. with $J_{CH_3CH_8} = 6.2$ and $J_{HXHY} = 7.2$ c.p.s.; >C*H*-OC_2H_5 at −174 c.p.s. with an apparent half-width of 17 c.p.s.

The gas–liquid chromatogram showed the presence of small amounts of two impurities. The analytical sample was purified by preparative gas–liquid chromatography.

Anal. Calcd. for $C_{12}H_{22}O_2$: C, 72.68; H, 11.18. Found: C, 72.73; H, 11.20.

Treatment of the Hydroboration Product of 4-*t*-Butylethoxycyclohexene with Boron Trifluoride Etherate.—A solution of 0.42 g. (2.30 mmoles) of olefin in 4 ml. of tetrahydrofuran was added to 1 ml. of 1.53 *M* borane in tetrahydrofuran at 0°. The reaction mixture was stirred for 10 min. and 0.42 g. (3 mmoles) of boron trifluoride etherate was added and allowed to stand for 3 min. The mixture was hydrolyzed, oxidized, and worked up as described above. The crude product was analyzed by g.l.c. and the results are presented in Table III, experiment 13.

In a separate experiment, aliquots of the reaction mixture, after addition of the boron trifluoride etherate, were periodically removed, hydrolyzed, oxidized, and the crude product analyzed by g.l.c. The results are presented in Fig. 5.

Hydroboration of 4-*t*-Butylethoxycyclohexene in the Presence of Boron Trifluoride.—To a solution of 2.02 g. (0.011 mole) of olefin and 1.57 g. (0.011 mole) of boron trifluoride etherate in 5 ml. of tetrahydrofuran at 0° was added 10 ml. of 0.74 *M* borane in tetrahydrofuran. The reaction mixture was stirred for 10 min., hydrolyzed, oxidized, and the crude product analyzed by g.l.c. The results are presented in Table III, experiment 14.

Acknowledgment.—The authors wish to thank Professor E. L. Eliel and his research collaborators for samples of authentic materials used in g.l.c. analysis in the *t*-butylcyclohexyl series. The authors also wish to thank the National Institutes of Health for a predoctoral fellowship to C. C. C. (fellowship number 1-F1-GM-21-333-01).

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[27] The reliability of this method for the determination of 3- *vs.* 4-*t*-butylcyclohexanols in such mixtures was demonstrated by the oxidation of a mixture of 3- and 4-*t*-butylcyclohexanol of weight ratio 1.09 to a mixture of 3- and 4-*t*-butylcyclohexanone, weight ratio 1.10, as determined by g.l.c.

[Contribution from the Basic Research Laboratories, Toyo Rayon Co., Ltd., Kamakura, Japan]

Organic Syntheses by Means of Noble Metal Compounds. VIII.[1] Catalytic Carbonylation of Allylic Compounds with Palladium Chloride

By Jiro Tsuji, Jitsuo Kiji, Shinzo Imamura, and Masanobu Morikawa

Received May 11, 1964

The reaction of allyl chloride and allyl alcohol with carbon monoxide in ethanol to form ethyl 3-butenoate by the catalytic action of palladium chloride was studied. Other allylic compounds react in the same way. It was found that in benzene solution allyl acetate forms 3-butenoic acetic anhydride, and allyl ether yields 3-butenoic anhydride by addition of carbon monoxide to the allylic carbon.

Introduction

Extensive studies on catalytic carbonylation of allyl chloride with nickel carbonyl and its related reactions have been carried out by Chiusoli.[2] Later, π-allylnickel halide, which is assumed to be an intermediate of the carbonylation of allyl chloride, was synthesized from an allyl halide and nickel carbonyl.[3] Its carbonylation was carried out in methanol, and

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[1] Part VII: J. Tsuji, M. Morikawa, and J. Kiji, *J. Am. Chem. Soc.*, in press.

[2] G. P. Chiusoli, *Chim. Ind.* (Milan), **41**, 503 (1959).

[3] E. O. Fischer and G. Bürger, *Z. Naturforsch.*, **16b**, 77 (1961); *Chem. Ber.*, **94**, 2409 (1961).