ml of a 1.00 M solution of sodium borohydride and 40 mmoles of boron trifluoride diglymate, providing 20% excess hydride. On completion of the reaction, checked by gas chromatographic examination for residual olefin, 150 mmoles of 1-decene (or other displacing olefin) was added and the flask (with adequate protection from atmospheric oxygen) was connected to the distillation assembly and brought to a rapid boil (the temperature in the flask was approximately 160°). The time for the appearance of the first drop of distillate was noted and considered as time zero. Individual fractions of 1.0, 2.0, 2.0 ml, etc., were collected in tared vials, weighed, and examined by gas chromatographic examination. The individual time for each fraction was noted and the times given in Table I represent the total elapsed time between the appearance of the first drop and the point at which the appearance of olefin became quite slow.

In the case of trisubstituted olefins hydroboration proceeds rapidly only to the dialkylborane stage. For these olefins, the procedure was varied to use 150 mequiv of hydride per 100 mmoles of olefin and 200 mmoles of 1-decene (or other olefin) for the displacement.

The recovery procedure was tested by introducing 100 mmoles of 1-pentene over a 3-hr period into refluxing diglyme. A 90% recovery was achieved. The yields reported in Tables I and II are actual yields and are not corrected for such normal operating losses.

Displacement Procedure with Isomerization. The hydroboration procedure was carried out precisely as described above. Following completion of the hydroboration, the reaction mixture was heated under gentle reflux for 1 hr to achieve isomerization. The reaction mixture was cooled to room temperature, the 1-decene was added, the flask was attached to the distillation assembly, and the displacement was carried out as described above.

Conversion of 3-Ethyl-2-pentene into 3-Ethyl-1-pentene. The following procedure is representative of those used to achieve the contrathermodynamic isomerization of olefins. 3-Ethyl-2-pentene, from the dehydration of triethylcarbinol,[4] was hydroborated in the usual manner, using 9.8 g, 100 mmoles, of the olefin, 30 mmoles of sodium borohydride, and 40 mmoles of boron trifluoride in diglyme. The reaction product was heated at gentle reflux for 1 hr. Then 21 g (150 mmoles) of 1-decene was injected by means of a syringe and the olefin formed was distilled through the Todd micro column. Over a period of 6 hr, five fractions were collected: 0.68, 1.62. 1.66, 1.63, and 1.52 g. Over another 9 hr, 0.86 g more was collected. The total yield was 7.97 g, 82% of theory. The gas chromatographic analysis established the composition to be 98% of 3-ethyl-1-pentene and 2% of 3-ethyl-2-pentene.

Organoboranes. V. The Thermal Cyclization of Dialkylboranes. A Convenient Synthesis of 2,4,4-Trimethyl-1,5-pentanediol and Related 1,5-Diols[1]

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Contribution from the Richard B. Wetherill Laboratory of Purdue University, Lafayette, Indiana. *Received October 16, 1965*

Abstract: The isomerization of bis(2,4,4-trimethyl-3-pentyl)borane under the usual conditions results in the evolution of hydrogen and the formation of a boron heterocycle in addition to the usual primary alkyl derivative. Oxidation of the reaction mixture provides 2,4,4-trimethyl-1,5-pentanediol and 2,4,4-trimethyl-1-pentanol in close to a 1:1 mole ratio. The results reveal that under isomerization conditions dialkylboranes with five carbon atoms or more undergo an intramolecular substitution to produce the boron heterocycle and hydrogen. The reaction is especially facile in cases where primary hydrogen is available at the 5 position. Two general procedures were developed to achieve this cyclization: (1) the trialkylborane is first equilibrated with diborane to the dialkylborane stage, and then cyclized; (2) the olefin is reacted in a 1:1 ratio with thexylborane to produce the monoalkylthexylborane, which is then cyclized. The latter procedure provides more effective utilization of the starting olefin.

The hydroboration of internal olefins, followed by isomerization, generally provides the primary alkyl derivatives in yields of 90% or better.[4,5] Oxidation provides the primary alcohol[4,6] and displacement of the terminal olefin,[6] both in excellent yields.

However, in the case of 2,4,4-trimethyl-2-pentene, it was noted that the yields were consistently lower, in the neighborhood of 60%.[5,6] Investigation soon revealed that the dialkylborane was undergoing a facile cyclization, with evolution of hydrogen, to produce a boron heterocycle. Oxidation of this heterocyclic provided the glycol, 2,4,4-trimethyl-1,5-pentanediol.

This phase of our study was completed prior to 1960. At that time a number of publications appeared dealing with the thermal decomposition of trialkylboranes with the simultaneous formation of heterocyclic boron derivatives.[7,8] At that time we debated whether to continue our explorations in this area. However, for synthetic purposes there appeared to be definite advantages to our approach, based upon a deliberate synthesis of the dialkylborane. The latter offers the possibility of a 50% conversion of the initial olefin into the boron heterocycle, whereas the synthesis *via* the thermal decomposition of the trialkylborane possesses a natural limit of 33% conversion.[9] Accordingly, we decided to continue our examination of this approach. Indeed, we later discovered that the use of thexylborane[10] provides a means of converting suitable ole-

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(1) Based in part on a thesis submitted by Kenneth J. Murray in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

(2) Research assistant on funds provided by the Ethyl Corp.

(3) Postdoctorate research associate on a grant (PRF 1718-A4) provided by the Petroleum Research Fund administered by the American Chemical Society.

(4) H. C. Brown and B. C. Subba Rao, *J. Am. Chem. Soc.*, **81**, 6434 (1959).

(5) H. C. Brown and G. Zweifel, *ibid.*, **88**, 1433 (1966).

(6) H. C. Brown and M. V. Bhatt, *ibid.*, **88**, 1440 (1966).

(7) P. F. Winternitz and A. A. Carotti, *ibid.*, **82**, 2430 (1960).

(8) R. Köster and G. Rotermund, *Angew. Chem.*, **72**, 138, 563 (1960); R. Köster and G. Schomberg, *ibid.*, **72**, 567 (1960).

(9) R. Köster, W. Larbig, and G. Rotermund, *Ann.*, **682**, 21 (1965).

(10) G. Zweifel and H. C. Brown, *J. Am. Chem. Soc.*, **85**, 2066 (1963).

fins into monoalkylthexylboranes suitable for cyclization with a theoretically possible 100% conversion of the olefin.

Results

It was soon observed that sodium borofluoride, normally present in reaction mixtures prepared by the usual internal hydroboration, interfered with the quantitative isolation of the diol. Accordingly, practically all of the experiments here reported were carried out in the absence of this salt, achieving the hydroboration by diborane generated externally.

Isomerization–Cyclization of Bis(2,4,4-trimethyl-3-pentyl)borane. 2,4,4-Trimethyl-2-pentene was hydroborated in the ratio of two olefins per BH_3, and the reaction mixture was heated for 4 hr at 160°. Oxidation provided a 70% conversion of the olefin into the primary alcohol and a 23.5% conversion into a diol, bp 132–133° (8.5 mm), $n^{20}D$ 1.4565. The analysis corresponded to that expected for a C_8 diol. Finally, the assignment of structure as 2,4,4-trimethyl-1,5-pentanediol was based on infrared and nmr spectra and comparison with other known isomers.

It was noted that there was still residual hydride at the end of the 4-hr heating period. Consequently, the reaction was repeated and the heating period was extended. In 19 hr there was realized a yield of 79 mmoles of the diol, out of the 100 theoretically possible for the proposed reaction.

The results are summarized in Table I.

Table I. Isomerization–Cyclization of Bis(2,4,4-trimethyl-3-pentyl)borane[a]

Time, hr	Hydrogen, mmoles[b] Isomn	Hydrol	Alcohol, mmoles Gc[c]	Isol	Diol, mmoles Gc[d]	Isol
4	84	33	140	110	47	45
8	106	10	110		73	68
19	105	0	107		79	75

[a] 200 mmoles of 2,4,4-trimethyl-2-pentene to 100 mmoles of BH_3, heating in diglyme at 160° (reflux). [b] Hydrogen evolved during isomerization–cyclization stage and during hydrolysis, prior to oxidation. [c] Carbowax 1540 at 100°. [d] Silicon–sorbitol at 150°.

Cyclization of Dialkylborane. The hydroboration of most simple olefins proceeds directly to the trialkylborane stage, without stopping at the desired intermediate dialkylborane stage. Consequently, the above isomerization–cyclization procedure would appear to be restricted to the relatively few trisubstituted olefins which do form such dialkylboranes easily.[11] However, it has been demonstrated that trialkylboranes can be equilibrated with diborane in tetrahydrofuran to the dialkylborane stage.[12] Accordingly, we undertook to test the possibility that similar equilibration in diglyme solution would provide a convenient route to the desired dialkylboranes and thus to the boron heterocycle.

Accordingly, 66.7 mmoles of tris(2,2,4-trimethyl-1-pentyl)borane was heated for 20 hr at 160° in refluxing diglyme. Oxidation provided 166 mmoles of alcohol and 17 mmoles of diol. On the other hand, when the trialkylborane was treated with sufficient diborane to form the dialkylborane, prior to the heating period, there was realized, in 8 hr, 118 mmoles of alcohol and 70 mmoles of diol, identical with the product of the isomerization–cyclization reaction. Indeed, the yields of both the alcohol and diol are very similar to those realized in the latter reaction for the same reaction period (Table I).

Consequently, we attempted to apply this reaction to other olefins. However, they proved to be much more resistant to the cyclization step than the 2,4,4-trimethylpentyl system. Thus, in 24 hr, 1-pentene and 1-hexene yielded only about half the amount of diols previously realized in 8 hr. Cyclohexene was even slower, yielding only 15 mmoles of diol. The difficulty clearly appeared to be in the cyclization stage, since the evolution of hydrogen from the refluxing solution was much slower than was observed in the original system.

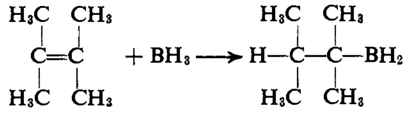
Increasing the reaction temperature by going over to refluxing triglyme (210°) greatly decreased the time required for complete reaction. After 2,4,4-trimethyl-1-pentene was hydroborated, equilibrated, and cyclized for only 1 hr in the triglyme medium, hydrogen evolution ceased, and oxidation yielded 93 mmoles of alcohol and 77 mmoles of diol. A similar reaction was performed on 1-pentene, but the reflux temperature of 210° could not be maintained. The reflux temperature dropped slowly to 168° in 13 hr, and oxidation yielded 102 mmoles of alcohol and 68 mmoles of glycol.

The difficulties encountered in isolating the glycols from triglyme suggested an attempt to achieve the cyclization at 200° in the absence of a solvent. In this procedure the olefin was hydroborated in tetrahydrofuran with a solution of diborane in the solvent, the reaction mixture was heated for 2 hr at 60° to achieve equilibration,[12] the solvent was removed by distillation, and the product was heated at 200° for approximately 2 hr. Again the reaction proceeded quite well with 2,4,4-trimethyl-1-pentene and more sluggishly with the other olefins.

In all cases other than the original olefin, the diols appeared to be mixtures of isomers, similar to those described by Köster and his co-workers.[9]

These results are summarized in Table II.

Cyclization of Monoalkylthexylborane. The hydroboration of the tetrasubstituted olefin, 2,3-dimethyl-2-butene, proceeds rapidly to the monoalkylborane stage, and slowly beyond[11] (eq 1). This highly useful intermediate has been given the common name, thexylborane.



$$(CH_3)_2C{=}C(CH_3)_2 + BH_3 \longrightarrow H{-}C(CH_3)_2{-}C(CH_3)_2{-}BH_2 \qquad (1)$$

Thexylborane reacts readily with less hindered olefins to produce monoalkylthexylboranes.[10] Further reaction to utilize the last available hydride is possible, but relatively slow, so that the addition is readily controlled to provide the desired dialkylborane (eq 2).

It should be noted that the thexyl group has no carbon atom in a 1,5 position with respect to the boron atom. Consequently, there should be no competition from this group for the desired cyclization.

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(11) H. C. Brown and A. W. Moerikofer, *J. Am. Chem. Soc.*, **84**, 1478 (1962).

(12) H. C. Brown, A. Tsukamoto, and D. B. Bigley, *ibid.*, **82**, 4703 (1960).

Table II. Cyclization of Dialkylboranes Produced by Equilibration[a]

Olefin (200 mmoles)	Solvent	Temp, °C	Time, hr	Hydrogen,[b] mmoles Cyclizn	Hydrol	Alcohol, mmoles Gc[c]	Diol, mmoles Gc[d]	Isol	Total recovery, %
2,4,4-Trimethyl-1-pentene[e]	DG	160	20	19	0	166	17		92
	DG	160	8	98	9	118	70	65	94
	TG	210	1	107	0	93	77	41	90
	Neat	200	1	100	0	88	72	69	80
1-Pentene	DG	160	24	72	21	155		33	94
	TG	210–168	13	99	0	102		68	85
1-Hexene	DG	160	24	72	6	150		32	91
	Neat	200	1.5	68	0	143	20	20	82
1-Dodecene	Neat	200	1.5	71	0	157		20	87
Cyclohexene	DG	160	24	66	23	159	15	14	87
	Neat	200	2.5	66	0	113	14	16	64
4-Methylcyclohexene	Neat	200	2.5	62	0	138		11	74

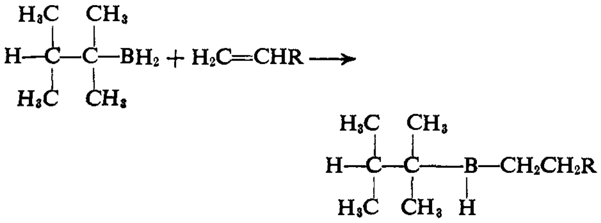
[a] 200 mmoles of olefin hydroborated and equilibrated with 100 mmoles of BH_3. [b] Hydrogen evolved during cyclization stage and during hydrolysis, prior to oxidation. [c] Carbowax 1540. [d] Silicone–sorbitol. [e] First run was a blank: 200 mmoles of olefin with 66.7 mmoles of BH_3.

Table III. Cyclization of Dialkylboranes from Thexylborane[a]

Olefin (100 mmoles)	Time, hr	Hydrogen, mmoles	Alcohols, mmoles[b] 2,3-Dimethyl-1-butanol	Olefin alcohol	Diols,[b] mmoles	Total recovery, %
2,4,4-Trimethyl-1-pentene	1	65	90	36	42	78
	2	73	89	34	49	83
	10	100	90	8	81	89
1-Pentene	10	90	88	30	55	85
4-Methyl-1-pentene	10	93	92	15	68	83
1-Hexene	10	70	95	43	40[d]	83
1-Octene	10	62	96	76	20[d]	96

[a] 100 mmoles of olefin hydroborated in tetrahydrofuran with 100 mmoles of thexylborane, the solvent removed, and the monoalkylthexylborane heated at 200° for the indicated time. [b] All yields by gas chromatographic analysis, 10% Carbowax 20M. [c] Three diols. [d] Four diols.

Accordingly, thexylborane was treated with 2,4,4-trimethyl-1-pentene and the product was heated to 200°. From 100 mmoles of olefin, 81 mmoles of the diol was obtained after oxidation. Moreover, 1-pentene yielded 55% of the 1,5-pentanediol, apparently



$$\mathrm{H{-}\overset{H_3C}{\underset{H_3C}{C}}{-}\overset{CH_3}{\underset{CH_3}{C}}{-}BH_2 + H_2C{=}CHR \longrightarrow H{-}\overset{H_3C}{\underset{H_3C}{C}}{-}\overset{CH_3}{\underset{CH_3}{C}}{-}\underset{H}{B}{-}CH_2CH_2R} \quad (2)$$

isomerically pure by the gas chromatographic examination. Similarly, 4-methyl-1-pentene provided an even better yield, 68%, of 4-methyl-1,5-pentanediol, again isomerically pure.

On the other hand, the reaction proceeded much more sluggishly with 1-hexene and 1-octene. Gas chromatographic examination of the products from these olefins revealed the presence of three hexanediols and four octanediols, with 70% of the products being the 1,4- and 1,5-diol isomers.

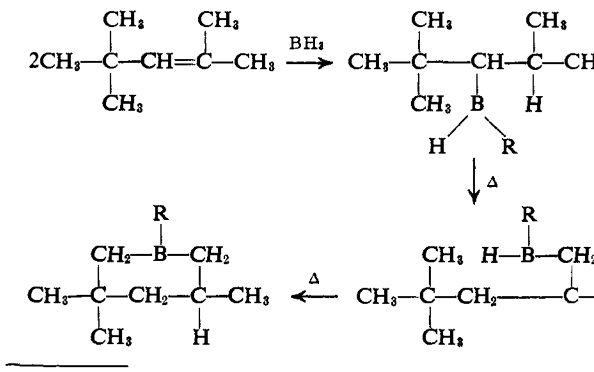
Consequently, it is quite clear that this procedure provides a satisfactory procedure for the ready synthesis of pure 1,5-diols in molecules which have primary hydrogen in a 1,5 relationship to the boron, but is not suitable for the preparation of pure diols from other structures.

The experimental results are summarized in Table III.

Discussion

It has been noted that in the hydroboration of the highly hindered olefin, di-*t*-butylethylene, the reaction tends to stop at the monoalkylborane stage.[13] On heating, the product, 2,2,5,5-tetramethyl-3-hexylborane, readily undergoes ring closure to form a boron heterocycle which can be oxidized into the corresponding diol.[13]

It is evident that the diol obtained *via* the hydroboration–isomerization of 2,4,4-trimethyl-2-pentene must arise from a related sequence of reactions. The initially formed secondary dialkylborane isomerizes into the primary dialkylborane. This places the three methyl groups at the quaternary center in an ideal position to react with the boron–hydrogen linkage (eq 3).



(3)

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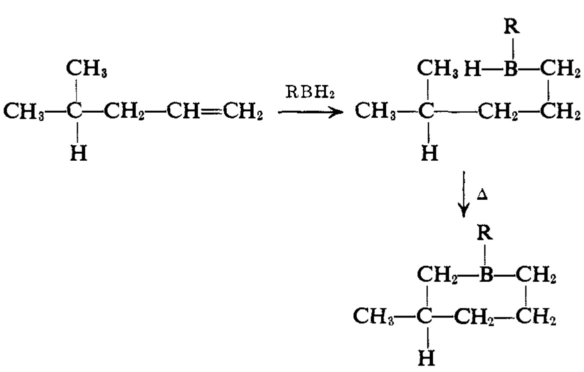
[13] T. J. Logan and T. J. Flautt, *J. Am. Chem. Soc.*, 82, 3446 (1960).

In attempting to generalize the reaction, the equilibration technique provided some success. However, the evidence is that equilibration does not proceed simply to the desired dialkylborane.[12] Consequently, the lower yields realized may, in part, be due to the fact that some of the products formed undergo other reactions than the desired one.

It is probable that this difficulty could be overcome by a detailed study of the equilibration reaction. Such a study may well provide the knowledge to control the equilibration to achieve the synthesis of pure mono- or dialkylborane at will. Such control would be helpful for many applications, and we are undertaking such a study.

However, the use of thexylborane provides a simple, direct synthesis of essentially pure dialkylborane. Moreover, a readily available olefin is substituted for the product to be converted into the heterocycle. Consequently, the maximum possible conversion to the desired product rises from 33% for the trialkylborane,[9] to 50% for the dialkylborane, to 100% for the monoalkylthexylborane route (eq 4).



(4)

A further advantage of the monoalkylthexylborane route is the isomeric purity of the various 1,5-pentanediols obtained. Both the trialkylborane[9] and the dialkylborane routes yield mixtures of isomers. The precise reason for this difference in the products is not known at present. Possibly the presence of the large thexyl group in the heterocycle (4) protects the system from isomerization of the ring.

The considerable difference in the reactivity of structures containing primary hydrogen in a 1,5 relationship to the boron substituent is of considerable interest. Attack by carbonium ions[14] or free radicals[15] greatly favors tertiary and secondary hydrogens over primary. Perhaps it should not be considered unexpected that the boron–hydrogen bond, with its hydridic character, prefers the primary hydrogen over secondary.

We have not explored the application of this reaction to terpenes or steroids. However, it appears promising as a means of introducing substituents into *gem*-dimethyl or angular methyl groups situated in a suitable location to a neighboring double bond.

In the present study we used alkaline hydrogen peroxide to convert the product into the corresponding diol as a convenient means of establishing the structure of the boron heterocycle. However, boron alkyls are subject to many other chemical transformations of interest in synthetic chemistry. Consequently, this cyclization reaction should find far greater application than merely as a synthetic route to the diol.

Experimental Section

Materials. Diglyme, triglyme, tetrahydrofuran, and boron trifluoride etherate were purified as previously described.[16] Sodium borohydride 98%, from Metal Hydrides Inc. was used without purification. All olefins used were Phillips pure grade, 99%, with the exception of 2,4,4-trimethyl-2-pentene, which was 95%. All operations were carried out under an inert atmosphere of nitrogen.

Isomerization–Cyclization of the Dialkylborane from 2,4,4-Trimethyl-2-pentene. Sodium borohydride (3.4 g, 90 mmoles), 2,4,4-trimethyl-2-pentene (22.4 g, 200 mmoles), and 90 ml of diglyme were mixed in a 300-ml, three-neck, round-bottom flask equipped with a thermometer, reflux condenser, and pressure-equalizing separatory funnel. The reflux condenser was equipped with an acetone trap to catch any diborane that might escape, and the trap then led to a Dry Ice trap which led to a gas meter.

To the stirred solution, 120 mmoles of boron trifluoride in diglyme was added over a period of 1 hr. The reaction mixture was then heated at 160° for 18 hr. During this period, 99 mmoles of hydrogen gas was liberated. The reaction mixture now was cooled to room temperature and treated with 10 ml of water followed by 15 ml of 6 *M* sodium hydroxide. No hydrogen was evolved. Then the mixture was oxidized at 90 to 100° with 32 ml of 30% hydrogen peroxide (vigorous reaction!). (The oxidation was carried through at somewhat higher temperature than normal because the heterocycle appeared to be less reactive than the usual organoborane.)

The water was distilled off and the precipitated borax was removed. The clear yellow filtrate was distilled, removing the diglyme and 2,4,4-trimethyl-1-pentanol, and leaving a less volatile residue. Gas chromatographic examination showed 126 mmoles of the alcohol. Distillation of the residual liquid in a micro distillation apparatus yielded 5.14 g, 35 mmoles, of a C_8 diol, bp 132–133° (8.5 mm), $n^{20}D$ 1.4565.

Anal. Calcd for $C_8H_{18}O_2$: C, 65.75; H, 12.62. Found: C, 66.06; H, 12.32.

The di-*p*-nitrobenzoate melted at 122–123° after three recrystallizations from chloroform.

Anal. Calcd for $C_{22}H_{24}N_2O_8$: C, 55.45; H, 5.44; N, 6.30. Found: C, 59.30; H, 5.33; N, 6.50.

The dibenzoate boiled at 226–228° (0.4 mm), $n^{22}D$ 1.5328.

Anal. Calcd for $C_{22}H_{26}O_4$: C, 74.55; H, 7.39. Found: C, 74.48; H, 7.19.

The glycol is nine times more soluble in ether than in water, so ether extraction from aqueous solution is feasible in the absence of sodium fluoroborate.

The results are summarized in Table I.

Structure. The infrared spectrum of the diol shows primary (9.6 μ) but not secondary or tertiary alcohol absorption. The region where secondary alcohol absorption should occur (9.0 μ) was established using 2,4,4-trimethyl-3-pentanol and 2,4,4-trimethyl-1,3-pentanediol as models. There were no strong bands in the region from 7.50 to 9.25 μ, where the isopropyl groups (8.60 μ) of 2,4,4-trimethyl-3- and -5-pentanols and the *t*-butyl groups (7.9–81 μ) of the corresponding -1-pentanol and -1,3-pentanediol absorb.

Finally, the nmr spectrum revealed a peak (in ppm from tetramethylsilane) at 4.70 attributed to hydroxyl protons, at 3.02 attributed to the methylol groups, a doublet at 1.51 attributed to the central methylene group, and a split peak at 0.79 attributed to the methyl protons. Because of the spin–spin coupling of the protons on the adjacent carbon atoms, the resonance due to the tertiary proton was lost as fine structure.

Of the possible structures, only 2,4,4-trimethyl-1,5-pentanol was compatible both with the infrared and nmr spectra.

Equilibration–Cyclization of the Trialkylborane from 2,4,4-Trimethyl-1-pentene. In the usual manner 22.4 g, 200 mmoles, of 2,4,4-trimethyl-1-pentene was hydroborated externally in 60 ml of diglyme by the action of diborane generated by the addition of 60 ml of 1.00 *M* sodium borohydride (20% excess) to boron trifluoride diglymate. The reaction mixture was heated to 75° and 20 more mmoles of diborane was passed into the stirred solution over a

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[14] P. D. Bartlett, F. E. Condon, and A. Schneider, *J. Am. Chem. Soc.*, **66**, 1531 (1944).

[15] H. B. Hass, E. T. McBee, and P. Weber, *Ind. Eng. Chem.*, **27**, 1190 (1935); **28**, 333 (1936).

[16] H. C. Brown, K. J. Murray, L. T. Murray, J. A. Snover, and G. Zwiefel, *J. Am. Chem. Soc.*, **82**, 4233 (1960).

period of 100 min. After 1 additional hr, the temperature was raised to 160° and maintained there for 8 hr. There was evolved 104 mmoles of hydrogen. Addition of 1 ml of water liberated an additional 13 mmoles of hydrogen. (In the acetone trap was found a total of 3 mmoles of boric acid.) Oxidation was carried out as described above. The gas chromatographic analysis showed 118 mmoles of 2,4,4-trimethyl-1-pentanol and 70 mmoles of the -1,5-diol. Distillation yielded 9.47 g, 65 mmoles, of 2,4,4-trimethyl-1,5-pentanediol, bp 132–133° (8.5 mm), $n^{22}D$ 1.4565.

Equilibration–Cyclization for the Trialkylboranes from 1-Pentene and 1-Hexene. The procedure for the hydroboration and equilibration was as described above. However, hydrogen evolution was slow so cyclization was carried on for 24 hr. Because of the greater water solubility of the diols, borax was precipitated and removed. The remaining mixture then was distilled. From 1-pentene there was obtained 3.43 g, 33 mmoles, of pentanediols, bp 223–241° (743 mm), $n^{20}D$ 1.4435 and 1.4457.

Anal. Calcd for $C_5H_{12}O_2$: C, 57.66; H, 11.61. Found: C, 57.82; H, 11.49.

From 1-hexene there was obtained 3.75 g, 31.8 mmoles, of hexanediols, bp 226–242° (744 mm), $n^{22}D$ 1.4425.

Anal. Calcd for $C_6H_{12}O_2$: C, 60.97; H, 11.98. Found: C, 61.06; H, 12.22.

The results are summarized in Table II.

Equilibration–Cyclization under Neat Conditions. The olefin, 200 mmoles, was mixed with 50 ml of a 1.0 *M* solution of diborane in tetrahydrofuran at 0°. The solution then was maintained at 60° for 2 hr to achieve equilibration. The tetrahydrofuran was removed under vacuum and the clear liquid organoborane residue was heated at 200° for 2 hr (nitrogen atmosphere). The gas evolution was noted. Tetrahydrofuran (50 ml) was added to facilitate the oxidation. The work-up then was similar to the above. The results are summarized in Table II.

Cyclization of Monoalkylthexylborane. The apparatus consisted of a three-neck flask equipped with a thermometer, a rubber cap through which the olefin could be added to the solution of diborane in tetrahydrofuran and which could later be replaced by a glass stopper for the cyclization phase, and a short Vigreux column. The thexylborane was synthesized *in situ* by adding 8.4 g (100 mmoles) of 2,3-dimethyl-2-butene to 50 ml of 1.00 *M* solution of diborane in tetrahydrofuran, cooled to approximately 5°. After 0.5 hr, 100 mmoles of the olefin was added slowly to the solution of the thexylborane, the temperature of the solution being maintained at 5° until the addition of the olefin was over (approximately 10 min). After another hour, the solvent was taken off though the short Vigreux column, and the reaction mixture then was slowly taken up to 200°. (In the case of thexyl-*n*-pentylborane, the most volatile derivative used, it was desirable to provide additional cooling capacity by inserting a small reflux condenser on the top of the Vigreux.) At the end of the reaction, usually 10 hr, the receiver usually contained small quantities (5 to 10 mmoles) of 2,3-dimethyl-1-butene and -2-butene and about 3 mmoles of a borane. The contents of the flask was allowed to cool, 50 ml of tetrahydrofuran was added to facilitate the oxidation, and the product was treated with 30 ml of 3 *N* sodium hydroxide, followed by 36 ml of 30% hydrogen peroxide. The oxidation was carried out at 50 to 60° to ensure complete conversion of the less reactive heterocycle. The yields were determined by gas chomatography on a 6-ft column filled with 10% Carbowax 20M, A/W Chromosorb W-DMCS 70–80. The results are summarized in Table III.

Trifluoroacetic Acid as a Medium for Electrophilic Substitution Reactions. Rates and Isomer Distributions for the Bromination, Nitration, and Mercuration of Benzene and Toluene in Trifluoroacetic Acid[1-3]

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Abstract: The applicability of trifluoroacetic acid as a reaction medium for electrophilic substitution reactions was investigated as a means of circumventing some of the difficulties encountered with acetic acid itself. In contrast to the complex kinetics observed in acetic acid, bromination in trifluoroacetic acid exhibits simple second-order kinetics. The rate constants at 0, 25, and 35° for the bromination of toluene yield $\Delta H^* = 11.3$ kcal mole^{-1} and $\Delta S^* = -33.2$ eu. The observed rate constants for benzene and toluene at 25°, 7.62×10^{-7} and 1.97×10^{-3} l. mole^{-1} sec^{-1}, respectively, and the isomer distribution in toluene, 17.6% *ortho* and 82.4% *para*, yield the partial rate factors o_f 1360 and p_f 12,700. Thus bromination in trifluoroacetic acid is the most selective of the known reactions. The relative rate, toluene to benzene, for nitration in trifluoroacetic acid at 25.0° is 28. Combined with the isomer distribution, 61.6% *o*-, 2.6% *m*-, and 35.8% *p*-nitrotoluene, the data yield values for the partial rate factors o_f 51.7, m_f 2.18, and p_f 60.1. The reaction of mercuric trifluoroacetate with benzene and toluene in trifluoroacetic acid yielded second-order rate constants at 25° of 2.85×10^{-2} and 2.82×10^{-1} l. mole^{-1} sec^{-1}, respectively, and an isomer distribution in toluene of 12.2% *o*-, 8.6% *m*-, and 79.2% *p*-tolylmercuric trifluoroacetate, resulting in partial rate factors o_f 3.62, m_f 2.55, and p_f 46.9. Mercuration in trifluoroacetic acid proceeds at a rate 690,000 times faster than mercuration by mercuric acetate in acetic acid. The results for the three reactions are correlated satisfactorily by the Selectivity Relationship. In contrast to acetic acid, the mercuration of relatively inert aromatics proceeds without interference by the solvent. Consequently, trifluoroacetic acid promises to be a useful medium for extending study of the Selectivity Relationship to the less reactive aromatic derivatives.

The utilization of acetic acid as a medium for electrophilic substitution reactions suffers from several serious disadvantages. Thus bromination in acetic acid exhibits complex kinetics, approximating third order[6,7] (second order in bromine), but complicated by

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(4) National Science Foundation Summer Fellow at Purdue University, 1959.

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