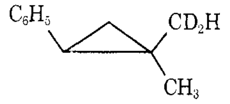
this ratio at various conversions and extrapolating back to zero conversion. The formation of **6** and **7** is also subject to primary and secondary isotope effects and knowledge of these values is necessary to make the data applicable to compound **1**. If we define π as the primary, α and β as secondary type I and type II isotope effects, respectively, and x as the fraction migration from the *cis*-methyl group, an expression relating the corrected m/e 91/92 (H/D) to the **6**:**7** ratio can be written; *i.e.*, hydrogen migration to give **6** occurs from the cis side (x) and is subject to three secondary type II effects (β^3), while **7** results *via* trans migration ($1 - x$) and is subject to a primary (π) and a pair of secondary type I effects (α^2) (eq 1).

$$\mathrm{H/D} = \frac{x/\beta^3}{(1-x)/\pi\alpha^2} = \frac{x\pi\alpha^2}{(1-x)\beta^3} \qquad (1)$$

Similarly for systems **8** → **11** + **12** equations 2–5 can be written. These equations allow a solution for

$$\mathrm{H/D} = \frac{\pi\beta^2x + (1-x)3\pi\alpha^2}{2x\alpha\beta^2} \quad \text{for} \qquad (2)$$



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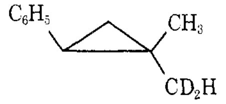
$$\mathrm{H/D} = \frac{3x\pi\alpha^2 + (1-x)\pi\beta^2}{2\alpha\beta^2(1-x)} \quad \text{for} \qquad (3)$$



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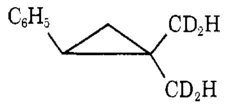
$$\mathrm{H/D} = \frac{\pi}{2\alpha} \quad \text{for} \qquad (4)$$



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$$\mathrm{H/D} = \pi\alpha^2\beta^3 \quad \text{for} \qquad (5)$$

+

x, π, α, and β[17] and substitution of the experimental H/D values (Table I) affords isotope effect values: $\pi = 1.96 \pm 0.22$; $\alpha = 1.10 \pm 0.05$; $\beta = 1.04 \pm 0.09$.[18,19]

The calculated value of x is 0.373 ± 0.054; *i.e.*, there is a distinct preference for migration from the methyl group trans to the benzene ring. The 63:37 ratio of trans to cis migration is significant and clearly rules out **2** as a viable intermediate. In addition, processes which proceed with exclusive disrotatory or conrotatory opening to an intermediate such as **3** are also excluded by these results.

TABLE I

System	4	8	9	10	11 + 12
H/D[a]	1.23 ± 0.12	5.68 ± 0.97	2.49 ± 0.25	0.893 ± 0.089	2.67 ± 0.27

[a] Corrected m/e 91/92 intensity ratio.

The data are consistent with mechanisms which either result from a mixture of disrotatory and conrotatory openings to **3** followed by hydrogen migration or a reaction which proceeds *via* a $[_\sigma2_s + {}_\sigma2_s]$ transition state, or its equivalent,[20] subject to a slight steric discrimination.

It is inviting to attempt to interpret the isotope effects determined. Whereas the secondary effects are of the expected magnitude and direction for the hybridization changes involved,[21] the primary effect is low. In fact the magnitude of this effect is in the range predicted for a four-centered transition[22] state like that which would be involved in a $[_\sigma2_s + {}_\sigma2_s]$ process. However, the lack of appropriate models for isotope effects in photochemical systems would make mechanistic interpretation of these data dangerous. Experiments on the stereochemistry at the migration terminus further elucidate the mechanism of this reaction.[23]

Acknowledgment.—We wish to thank the Research Corporation and the Center of Materials Research of the University of Maryland for partial support of this work.

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[17] S-H. Dai and W. R. Dolbier, Jr., *J. Amer. Chem. Soc.*, **94**, 3953 (1972). These authors use a similar method to calculate isotope effects.

[18] The validity of the use of eq 5 can be questioned; *i.e.*, these are intermolecular isotope effects as opposed to intramolecular effects in the other cases. In the case of **11** + **12** we could be seeing an effect which arises on formation of the reactive excited state. The use of five equations for the four unknowns allows a solution for x independent of eq 5. Furthermore the fact that the calculated values constitute a solution, well within experimental error, of eq 1–4 suggests that there is little, if any, isotope effect on formation of the reactive excited state.

[19] The inclusion of the secondary type 2 effect is actually mechanistically prejudicial suggesting that C_1–C_2 bond cleavage occurs in the rate-determining step in the reaction. We have no evidence on this point. Inclusion of a value $\beta = 1.00$ results in little change in the calculated values for π and α ($\pi = 2.11$, $\alpha = 1.05$) and the value for x is unchanged.

[20] We cannot at present differentiate a $[_\sigma2_s + {}_\sigma2_s]$ process from one in which 1,2 bond cleavage has occurred *via* simple expansion of the C_1–C_3–C_2 bond angle followed by hydrogen migration.

[21] A. Streitwieser, R. Jagow, R. Fahey, and S. Suzuki, *J. Amer. Chem. Soc.*, **80**, 2326 (1958).

[22] R. A. More O'Ferrall, *J. Chem. Soc. B*, 785 (1970).

[23] P. H. Mazzocchi and R. S. Lustig, *J. Amer. Chem. Soc.*, **95**, 7178 (1973).

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Exceptionally High Regioselectivity in the Hydroboration of Representative Olefins with 9-Borabicyclo[3.3.1]nonane in a Simplified Rapid Procedure

Summary: Hydroboration–oxidation of olefins with stoichiometric amounts of 9-borabicyclo[3.3.1]nonane in refluxing tetrahydrofuran proceeds rapidly and gives the anti-Markovnikov alcohols in high isomeric purity, often >99.5%. The regioselectivity obtained surpasses that obtained with other hydroborating agents, especially in the case of internal olefins.

Sir: The hydroboration of even highly substituted olefins with stoichiometric quantities of 9-borabicyclo-

TABLE I

PRODUCT DISTRIBUTION IN THE HYDROBORATION-OXIDATION OF REPRESENTATIVE OLEFINS WITH 9-BBN, BH_3, AND Sia_2BH IN THF AND WITH $ClBH_2$-OEt_2

		Product distribution, %[a]			
Olefin	Product	9-BBN-THF	BH_3-THF[b]	Sia_2BH-THF[c]	H_2BCl-OEt_2[d]
1-Hexene	1-Hexanol	99.9	94	99	>99.5
	2-Hexanol	<0.1	6	1	<0.5
3,3-Dimethyl-1-butene	3,3-Dimethyl-1-butanol	99.7	94		
	3,3-Dimethyl-2-butanol	<0.3	6		
2-Methyl-1-pentene	2-Methyl-1-pentanol	99.8			
	2-Methyl-2-pentanol	<0.2			
Styrene	2-Phenylethanol	98.5	81[e]	98	96
	1-Phenylethanol	1.5	19[e]	2	4
cis-4-Methyl-2-pentene	4-Methyl-2-pentanol	99.8	57[f]	97	60
	2-Methyl-3-pentanol	0.2	43[f]	3	40
cis-4,4-Dimethyl-2-pentene	4,4-Dimethyl-2-pentanol	99.9	58[f]		79
	2,2-Dimethyl-3-pentanol	0.1	42[f]		21
2-Methyl-2-butene	3-Methyl-2-butanol	>99.8	98		99.7
	2-Methyl-2-butanol	<0.2	2		0.3
1-Methylcyclopentene	*trans*-2-Methylcyclopentanol	>99.8	98.5		>99.8
	1-Methylcyclopentanol	Trace	1.5		<0.2
Norbornene	*exo*-2-Norbornanol	99.5	99.5		>99.8
	endo-2-Norbornanol	0.5	0.5		0.2

[a] Total yields were 95 ± 5%. [b] Reference 2a,b. [c] Reference 4. [d] Reference 3. [e] Reference 2c. [f] Trans olefin.

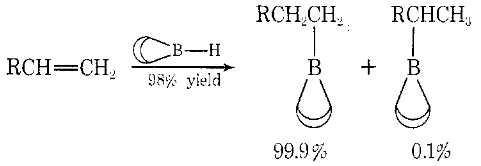
[3.3.1]nonane[1] (9-BBN) proceeds rapidly in refluxing tetrahydrofuran (THF). Oxidation of the intermediate *B*-R-9-BBN derivatives establishes that the regioselectivity realized with 9-BBN under these conditions is exceptionally high, both for terminal and for internal olefins. Moreover, 9-BBN is thermally stable and can be stored at room temperature almost indefinitely, either as the solid or as the THF solution. Consequently, hydroboration with 9-BBN using this procedure offers convenience and major improvements in product purities, both for the synthesis of the *B*-R-9-BBN derivatives and for the anti-Markovnikov hydration of carbon-carbon double bonds.

The use of hydroboration-oxidation with BH_3-THF for the anti-Markovnikov hydration of olefins[2] suffers from the formation of significant amounts of the minor isomer in the hydroboration stage. The use of monochloroborane-ethyl etherate (H_2BCl-OEt_2) was recently found to give very pure (>99.5%) primary alcohols from terminal olefins.[3] However, little regioselectivity was obtained with internal olefins. Hydroboration with disiamylborane (Sia_2BH) offers higher regioselectivity, but the reagent reacts only very sluggishly with internal and cyclic olefins.[4]

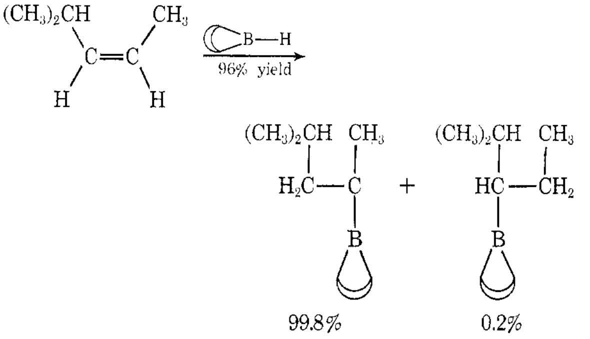
It appeared that 9-BBN might overcome these difficulties. Unfortunately, the rate of reaction of 9-BBN with olefins, especially the more substituted compounds, is relatively slow. Consequently, the procedure adopted used a large excess (100%) of 9-BBN to facilitate the reaction.[1] The presence of such an excess was especially undesirable for hydroborations in which it was desired to use the *B*-R-9-BBN derivatives for further syntheses.[5]

We have now established that it is possible to achieve the hydroboration of even highly substituted olefins with the stoichiometric quantity of 9-BBN in refluxing THF. First, the reaction time is relatively short. Unexpectedly, under these conditions isomerization of the *B*-R-9-BBN derivatives is not significant.[6] Finally, the regioselectivity observed is remarkably high, much higher than that noted previously.[1]

For example, 1-hexene undergoes hydroboration to give only 0.1% minor isomer (eq 1). Even more remarkable, internal olefins, such as *cis*-4-methyl-2-pentene, reveal a remarkable preference for placing the boron adjacent to the less bulky substituent (eq 2).



(1)



(2)

The following procedure for the hydroboration-oxidation of *cis*-4-methyl-2-pentene with 9-BBN is representative.[7]

A dry, nitrogen-flushed, 50-ml flask with an injection port was charged with 5.0 mmol of 9-BBN[8] (0.61 g) in a

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[1] E. F. Knights and H. C. Brown, *J. Amer. Chem. Soc.*, **90**, 5280 (1968).

[2] (a) H. C. Brown and G. Zweifel, *J. Amer. Chem. Soc.*, **82**, 4708 (1960); (b) H. C. Brown, "Hydroboration," W. A. Benjamin, New York, N. Y., 1962; (c) H. C. Brown and R. L. Sharp, *J. Amer. Chem. Soc.*, **88**, 5851 (1966); (d) G. Zweifel, N. R. Ayyangar, and H. C. Brown, *ibid.*, **85**, 2072 (1963).

[3] H. C. Brown and N. Ravindran, *J. Org. Chem.*, **38**, 182 (1973).

[4] H. C. Brown and G. Zweifel, *J. Amer. Chem. Soc.*, **83**, 1241 (1961).

[5] (a) H. C. Brown and M. M. Rogić, *J. Amer. Chem. Soc.*, **91**, 2146 (1969); (b) H. C. Brown and R. A. Coleman, *ibid.*, **91**, 4606 (1969).

[6] A detailed study of the isomerization of *B*-R-9-BBN derivatives is underway with Hiroaki Taniguchi.

[7] For an excellent discussion of applicable technique, see D. F. Shriver, "The Manipulation of Air-Sensitive Compounds," McGraw-Hill, New York, N. Y., 1969, Chapter 7.

[8] 9-BBN is now available from the Aldrich Chemical Co., Milwaukee, Wis.

nitrogen-filled glove bag. Dry THF (10 ml) was then added *via* syringe. The solution was heated to reflux and the reaction initiated by adding 2.5 ml of 2 *M cis*-4-methyl-2-pentene in THF (5.0 mmol). The mixture was stirred under reflux for 1 hr[9] and then cooled to room temperature. The intermediate organoboranes were oxidized by adding, successively, 3 ml of ethanol, 1 ml of 6 *N* NaOH, and 2 ml of 30% H_2O_2. Complete oxidation was ensured by maintaining the reaction mixture at 50° for 1 hr. The aqueous phase was saturated with potassium carbonate to give a dry THF solution of the product. The absolute and relative product yields were determined by glpc using dodecane as an internal standard. (The reliability of the instrument in determining the minor component was checked by analyzing known synthetic mixtures of the two products in the proportions expected from the reaction.) 4-Methyl-2-pentanol was obtained in 96% yield, together with 0.2% 2-methyl-3-pentanol.

The results are summarized in Table I together with comparable data for hydroborations with BH_3–THF, H_2BCl–OEt_2, and Sia_2BH.

The origin of the exceptionally high regioselectivity obtained with 9-BBN is not clear. The facile reaction of 9-BBN with highly substituted olefins seems to indicate that the reagent is sterically less demanding than Sia_2BH. However, the bicyclic structure of 9-BBN is rigid and steric crowding in the transition state cannot be relieved by internal rotation in the borane moiety. Thus 9-BBN may be more sensitive to subtle differences in steric environment than the acyclic dialkylborane, Sia_2BH.

In any case, it is clear that hydroboration with 9-BBN furnishes a convenient route to the synthetically useful *B*-alkyl-9-BBN derivatives, as well as furnishing the anti-Markovnikov alkylborane moiety in extremely high isomeric purity. This development, together with the stability and commercial availability of the reagent,[8] greatly simplifies the synthesis of regiospecifically and stereochemically pure derivatives.

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[9] One hour in refluxing THF proved adequate for all olefins examined except the most sluggish, such as 1-methylcyclohexene and 2,3-dimethyl-2-butene. In these cases, 8 hr under reflux proved adequate to complete the hydroboration.

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