$C_{17}H_{16}$ m/e 220.1252, found m/e 220.1252.

***cis*-1,1-Dimethyl-2,5-diphenylsilacyclopent-3-ene:**[1] IR (neat) 3078, 3059, 3020, 2954, 2895, 2850, 1599, 1495, 1250, 1061, 858, 802, 746, 698 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.00–7.30 (m, 10 H), 6.11 (s, 2 H), 3.27 (s, 2 H), 0.39 (s, 3 H), –0.67 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 143.4, 135.0, 128.3, 126.4, 124.3, 39.9, –2.8, –6.8.

1,1-Diphenyl-3,4-dimethylsilacyclopent-3-ene[26] (89% GC yield): IR (neat) 3066, 3049, 2976, 2906, 2871, 1427, 1174, 1117, 773, 731, 698 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.27–7.62 (m, 10 H), 1.87 (s, 4 H), 1.77 (s, 6 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 136.4, 134.7, 130.7, 129.3, 127.8, 24.2, 19.3.

1-Methyl-1-(2-propenyl)cyclopentane[1] (94% GC yield): IR (neat) 2958, 2871, 1639, 1452, 1369, 889 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 4.65–4.73 (m, 2 H), 1.76 (dd, J = 1.3, 0.7 Hz, 3 H), 1.35–1.73 (m, 8 H), 1.05 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 153.3, 107.6, 48.0, 37.7, 26.0, 23.7, 20.2.

1-Methyl-1-(2-propenyl)cyclohexane[1] (54% GC yield): ^1H NMR (200 MHz, $CDCl_3$) δ 4.72–4.82 (m, 2 H), 1.71 (dd, J = 1.4, 0.7 Hz, 3 H), 1.20–1.75 (m, 10 H), 0.98 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 152.6, 109.1, 38.8, 36.4, 27.1, 26.4, 22.6, 19.5.

1,2-Epoxy-3,6-diphenylcyclohexane. 3,6-Diphenylcyclohexene (50 mg, 0.21 mmol), *m*-chloroperbenzoic acid (55%, 200 mg, 0.64 mmol), and K_2CO_3 (150 mg, 1.09 mmol) were stirred in CH_2Cl_2 (10 mL) for 24 h. The reaction mixture was filtered and washed with CH_2Cl_2 (40 mL). The filtrate and aqueous $Na_2S_2O_3$ solution (10%, 10 mL) were stirred for 2 h. The organic phase was washed with saturated $NaHCO_3$ solution and H_2O and dried over anhydrous magnesium sulfate. Preparative thin-layer chromatography (silica gel, 2 mm, developed with 10:1 hexane-/EtOAc) gave 1,2-epoxy-3,6-diphenylcyclohexane (32 mg, 60% yield) as a colorless oil along with recovery of starting material (10 mg, 20%). 1,2-Epoxy-3,6-diphenylcyclohexane:[25] ^1H NMR (200 MHz, $CDCl_3$) δ 7.20–7.45 (m, 10 H), 3.45 (s, 2 H), 3.37 (t, J = 6.4 Hz, 2 H), 1.67–1.88 (m, 2 H), 1.37–1.58 (m, 2 H); ^{13}C NMR (50 MHz) δ 143.2, 128.6, 128.0, 126.5, 56.2, 39.9, 25.0.

3,6-Diphenylcyclohexane-1,2-diol. 1,2-Epoxy-3,6-diphenylcyclohexane (32 mg, 0.13 mmol) was dissolved in acetone (10 mL). $HClO_4$ (6%, 10 mL) was added, and the mixture was stirred at room temperature for 24 h. The reaction solution was neutralized with Na_2CO_3, and the reaction mixture was reduced to approximately half volume under reduced pressure. Extraction with CH_2Cl_2 and removal of the solvent yielded crude product (93% yield) as a white solid. Based upon the analyses of NMR spectra of crude and recrystallized product, reaction gave a single product. Recrystallization from hexane/CH_2Cl_2 gave pure product as a white crystalline solid: mp 134–135 °C; IR (KBr) 3303, 3086, 3059, 3026, 2935, 2858, 1603, 1495, 1454, 1041, 760, 698 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 7.20–7.60 (m, 10 H), 4.08 (t, J = 9.8 Hz, 1 H), 3.95 (dd, J = 9.5, 5.5 Hz, 1 H), 3.56 (m, 1 H), 2.67 (ddd, J = 11.7, 9.9, 4.3 Hz, 1 H), 1.65–2.39 (m, 6 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 142.3, 140.8, 129.7, 128.8, 128.4, 127.8, 126.9, 126.5, 76.8, 74.6, 50.6, 44.7, 29.9, 29.2; MS (EI) m/e (relative intensity) 268 (M^+, 61.9), 250 (12.9), 237 (11.5), 219 (7.3), 146 (30.1), 131 (94.9), 117 (55.4), 104 (100.0), 91 (73.6), 77 (15.3); HRMS calcd for $C_{18}H_{20}O_2$ m/e 268.1463, found m/e 268.1464.

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Hydroboration. 87. Controlled and Sequential Hydroboration of Simple Representative Alkenes with Methylborane in Tetrahydrofuran. An Examination of the Directive Effects in the First and Second Stages of Hydroboration

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Methylborane ($MeBH_2$), the simplest of the monoalkylboranes, possesses extraordinary hydroborating characteristics in tetrahydrofuran. In this solvent $MeBH_2$ selectively hydroborates all important classes of alkenes, hindered and nonhindered, to yield the methylalkylboranes MeRBH. These dialkylboranes are readily converted into and isolated as their borinic esters, MeRBOR′, which in turn can be transformed into methyl ketones, thus providing a simple and highly regio- and stereoselective synthesis of the latter. The addition of a second equivalent of another alkene to the methyalkylborane gives a sequential hydroboration product, MeR^AR^BB. This mixed trialkylborane is readily converted into the corresponding tertiary alcohol via carbonylation–oxidation. The ability to hydroborate an alkene in consecutive stages enables the regioselectivity of the first and second stages of hydroboration to be determined. Thus, the first hydroboration of 1-hexene gives a C-1/C-2 ratio of 98.5:1.5, similar to values obtained with 9-BBN and Sia_2BH. The second hydroboration of *cis*-4-methyl-2-pentene occurs with complete regioselectivity, i.e., 100:0, surpassing the values obtained with the two aforementioned hydroborating agents. $MeBH_2$ is the first example of a sterically nonhindered monoalkylborane capable of stepwise hydroborations of all classes of alkenes.

Investigation of the chemical properties of methylborane ($MeBH_2$) the simplest of the monoalkylboranes has been hampered by lack of suitable synthetic methodology. The method of preparing this compound has changed little over the years, employing the redistribution of trimethylborane—a highly pyrophoric gas—with diborane.[2] These routes are experimentally tedious, difficult to carry out on large-scale preparations, and give a mixture of products that must be carefully fractionated at low temperatures.

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(2) (a) Schlesinger, H. I.; Walker, A. O. *J. Am. Chem. Soc.* **1935**, *57*, 621. (b) Schlesinger, H. I.; Flodin, N. W.; Burg, A. B. *Ibid.* **1939**, *61*, 1078.

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These factors have also hindered the application of $MeBH_2$ as a means of preparing substituted methylboranes via hydroboration and conversion of the methylboranes into other valuable products.

Recently we reported a simple procedure for the preparation of $MeBH_2$.[3] The reaction of lithium aluminum hydride $(LiAlH)_4$ with alkylboronic acids or esters yields the lithium monoalkylborohydrides.[4] Thus, the reaction of $LiAlH_4$ with methylboronic acid or ester affords cleanly and in high yield lithium methylborohydride (eq 1).

$$MeB(OR)_2 + LiAlH_4 \rightarrow LiMeBH_3 + HAl(OR)_2\downarrow \quad (1)$$

The borohydride is readily isolated in pure form from the relatively insoluble dialkoxyalane by filtration. Treatment of lithium methylborohydride with, inter alia, ethereal hydrogen chloride[5] cleanly liberates $MeBH_2$ (eq 2).

$$2LiMeBH_3 + 2HCl \rightarrow (MeBH_2)_2 + 2H_2 + 2LiCl\downarrow \quad (2)$$

With the synthetic methodology solved, we turned our attention to the investigation of the chemistry of $MeBH_2$.[6] Solutions of $MeBH_2$ in tetrahydrofuran (THF) or diethyl ether (EE) are remarkably stable for a nonhindered monoalkylborane. Little redistribution is observed at room temperature over the course of 2–3 h by ^{11}B NMR spectroscopy. Encouraged by these results, we initiated studies into the hydroboration characteristics of $MeBH_2$ with simple representative alkenes.[6] In the course of these studies, we made two important observations. First, in order to obtain cleanly methyldialkylboranes MeR_2B unaccompanied by products of redistribution, it is necessary to conduct the hydroborations in THF. Using this procedure, we developed a convenient synthesis of methyldialkylboranes MeR_2B (eq 3).

$$(MeBH_2)_2 + 4\text{alkene} \xrightarrow{THF} 2MeR_2B \quad (3)$$

In contrast, in EE a mixture of redistributed products is obtained (eq 4).

$$(MeBH_2)_2 + \text{alkene} \xrightarrow{EE} Me_3B + Me_2BR + MeBR_2 + BR_3 \quad (4)$$

Second, methylborane in THF hydroborates quickly the first equivalent of alkene, forming a methylalkylborane at a rate essentially independent of the alkene. The rate of the second hydroboration is slower than the first and is more dependent on the steric requirements of the alkene (eq 5).

$$(MeBH_2)_2 + 2\text{alkene} \xrightarrow{THF} (MeRBH)_2 \xrightarrow{\text{alkene}} 2MeBR_2 \quad (5)$$

The above observations suggested that it should in principle be possible to stop the hydroboration with $MeBH_2$ at successive stages and thus allow the simple preparation of methylalkylboranes MeRBH or alkylmethylborinic esters MeRBOR′ and totally mixed methyldialkylboranes MeR^AR^BB free of redistributed materials. The present report details the results of our investigations into controlled and sequential hydroborations of simple representative alkenes with methylborane in THF. In addition, an examination of the regioselectivity obtained in the first and second stages of hydroboration is described.

Table I. Product Distribution in the Hydroboration/Oxidation of Representative Alkenes with $MeBH_2$ in THF in a 1:1 Molar Ratio

alkene	reactn time (min)	reactn temp (°C)	product distribution,[a] % $MeB(OR)_2$	MeRBOR	Me_2RB
1-hexene	5	−25	5	95	0
styrene	60	0	5	95	0
2-methyl-1-pentene	5	0	6	88	6
	1	−25	4	96	0
cis-4-methyl-2-pentene	5	0	2	98	0
trans-4-methyl-2-pentene	5	0	2	98	0
2-methyl-2-butene	5	0	2	98	0
trans-2-hexene	5	0	4	96	0
2,3-dimethyl-2-butene	10	0	2	98	0
cyclopentene	5	0	2	98	0
1-methylcyclopentene	5	0	2	98	0
1-phenylcyclopentene	90	0	4	96	0
1-methylcyclohexene	10	0	2	98	0
norbornene	5	0	5	90	5
	5	−25	3	97	0
(+)-α-pinene	10	0	2	98	0

[a] Determined by ^{11}B NMR spectroscopy.

Results and Discussion

Controlled Hydroboration of Representative Alkenes with $MeBH_2$ in THF in a 1:1 Molar Ratio. A solution of $MeBH_2$ in THF cooled to 0 °C was generated in situ from a standard solution of $LiMeBH_3$ by reaction with 1 equiv of ethereal hydrogen chloride (eq 2). The alkene, 1.1 equiv, was added and the reaction mixture stirred at 0 °C or −25 °C, as warranted, for the specific period of time. Since these sterically nonhindered dialkylboranes are frequently unstable and readily prone to redistribution, the initial products of hydroboration were converted into oxygenated boranes by the reaction of the borane with methanol or 2-propanol at the reaction temperature (eqs 6 and 7).

$$(MeRBH)_2 + 2MeOH \rightarrow 2MeRBOMe + 2H_2\uparrow \quad (6)$$

$$(MeRBH)_2 + 2i\text{-}PrOH \rightarrow 2MeRB(O\text{-}i\text{-}Pr)_2 + 2H_2\uparrow \quad (7)$$

An aliquot was removed for analysis by ^{11}B NMR spectroscopy for the various alkylated boranes. The percentage of trialkylboranes, starting material, and product borinic ester was estimated by using peak heights. This method of analysis gives good mass balance, ±5%, for compounds with similar peak shapes.[7,8] We find this procedure to be convenient and quick. It compares favorably with gas chromatography and is the method of choice for analysis of nonvolatile boranes, which can easily undergo disproportionation at the high temperatures required for GC analysis. The results of the hydroboration of a series of representative alkenes with methylborane in THF are given in Table I.

To our gratification we could indeed stop the reaction of $MeBH_2$ with an alkene at the first stage of hydroboration. Monohydroboration with $MeBH_2$ in THF is very fast. Most alkenes are hydroborated within 5–10 min at 0 °C. Even sterically hindered alkenes such as α-pinene,

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(7) Brown, H. C.; Cole, T. E.; Srebnik, M. *Organometallics* **1985**, *4*, 1788.
(8) Brown, H. C.; Cole, T. E. *Organometallics* **1985**, *4*, 1316. In the presence of trialkylboranes, more accurate results are obtained by the integration of peak areas.

Table II. Preparation of Esters of Alkylmethylborinic Acids from the Reaction of Representative Alkenes with $MeBH_2$ in THF, Followed by Methanolysis

alkene	borane	^{11}B NMR δ (ppm)	bp, °C (mmHg)	yield (%) isol
2-methyl-1-pentene	methyl(2-methyl-1-pentyl)isopropoxyborane	52.4	86–88 (25)	75
cyclopentene	methylcyclopentylmethoxyborane	54.5	60–62 (40)	80
1-methylcyclohexene	methyl(*trans*-2-methylcyclohexyl)methoxyborane	54.4	68–70 (14)	81
(+)-α-pinene	methylisopinocampheylmethoxyborane	54.0	100–102 (12)	79

1-methylcyclohexene, and 2,3-dimethyl-2-butene react completely within 10 min. The much slower hydroborating alkenes, such as styrene and phenylcyclopentene, require 60 min and 90 min, respectively, at 0 °C. As can be seen from Table I, the major classes of alkenes furnish the monoalkylated products with only residual amounts of starting material present. Even the reaction of $MeBH_2$ with very reactive alkenes, i.e., 1-hexene, 2-methyl-1-pentene, and norbornene, gives predominantly the desired methylmonoalkylboranes at 0 °C accompanied by some trialkylborane. However, lowering the temperature to −25 °C furnishes the desired methylmonoalkylborane products cleanly, even with these highly reactive alkenes. Indeed, the clean monohydroboration of 1-hexene occurs at −45 °C, as evidenced by quenching the mixture with pyridine and examining the products by ^{11}B NMR. It should be pointed out that controlled monohydroboration of such terminal alkenes had been previously achieved only by highly hindered hydroborating agents, such as thexylborane ($ThxBH_2$) and monoisopinocampheylborane ($IpcBH_2$), with relatively hindered alkenes. Even $ThxBH_2$, the most successful monoorganylborane to date for such monohydroborations, gives mixtures of mono- and dihydroborated products with monosubstituted terminal alkenes.

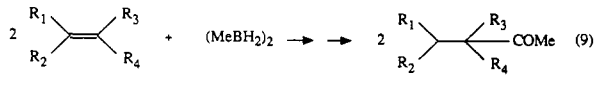
The methylalkylboranes were isolated and characterized as their borinic esters. Isolation was readily accomplished by removal of volatiles in vacuo, followed by treatment with pentane to precipitate LiCl; filtration and distillation then furnished the esters of the methylalkylborinic acids in good yields (Table II). Proton NMR confirmed the proposed structures, which were further corroborated by chemical ionization mass spectroscopy (CIMS). In most cases examined, the protonated molecular ion was readily observable. Equally important was the fact that no higher weight molecular species were detectable, indicating that no redistribution reactions had occurred during hydroboration.

Additional confirmation of the purity of these borinic esters and therefore of the methylalkylboranes was obtained by conversion to the corresponding methyl ketones by the reaction with α,α-dichloromethyl methyl ether (DCME)[9] in the presence of base, followed by oxidation and analysis by GC (eq 8).

$$MeRBOR' + HCCl_2OCH_3 \xrightarrow{\text{base,[O]}} MeCOR \quad (8)$$

The results are summarized in Table III.

In all cases examined, we obtained the expected methyl ketones cleanly and in excellent yield. There was no indication of redistribution products, firmly establishing that no redistribution had occurred during hydroboration. This development now provides, in the highly regio- and stereoselective manner typical of hydroboration, a general synthesis of methyl ketones from $MeBH_2$ and an appropriate alkene (eq 9).



(9)

(9) Carlson, B. A.; Brown, H. C. *J. Am. Chem. Soc.* **1973**, *95*, 6876.

Table III. Preparation of Methyl Ketones from the Hydroboration of Representative Alkenes with Methylborane in THF, Followed by the DCME Reaction

alkene	methyl ketone	yield[a] (%)
1-hexene	2-octanone	96
1-phenylcyclopentene	(±)-*trans*-2-phenylcyclopentyl methyl ketone[b]	89
norbornene	(±)-2-*exo*-norbornyl methyl ketone[b]	96
(+)-α-pinene	isopinocampheyl methyl ketone[b]	82

[a] GC yield calculated in the presence of an internal standard. [b] See ref 25.

Reaction of Methylmonoalkylboranes with Representative Alkenes in THF in a 1:1 Molar Ratio. The ability to control and stop hydroboration at the first stage suggests that the addition of another alkene to the newly formed methylalkylborane should give mixed methyldialkylboranes MeR^AR^BB (eq 10).

$$(MeR^ABH)_2 + 2\text{alkene B} \rightarrow 2MeR^AR^BB \quad (10)$$

We therefore next investigated the reaction of an appropriate alkene with an equimolar quantity of methylalkylborane in THF at 0 °C. Each of these methylmonoalkylboranes was prepared as described above (alkene A) with an equimolar quantity of methylborane in THF at the appropriate temperature. The methylmonoalkylborane thus obtained was allowed to react with an equimolar quantity of a second alkene (B) at 0 °C, and the reaction mixture was stirred for the required period of time. Examination by ^{11}B NMR spectroscopy of an aliquot indicated the clean formation of a trialkylborane ($\delta \sim 84$ ppm), but, owing to the intrinsic insensitivity of ^{11}B NMR to structurally similar compounds, the ^{11}B NMR spectrum does not establish whether this is the desired mixed methyldialkylborane (eq 10) or the various redistributed trialkylboranes (eq 11).

$$(MeBH_2)_2 \xrightarrow[\text{2. alkene B}]{\text{1. alkene A}}$$
$$Me_3B + Me_2BR^A + Me_2BR^B + MeBr^A_2 + MeBr^B_2 + MeBR^AR^B + BR^A_2R^B + BR^AR^B_2 + BR^A_3 + BR^B_3 \quad (11)$$

In order to examine the purity of the trialkylboranes produced, it is necessary to convert these labile boron compounds into more stable carbon compounds that reflect the structure of the trialkylborane. It has been demonstrated that all three groups migrate from boron to carbon via carbonylation,[10] cyanidation,[11] and reaction with DCME,[12] forming the corresponding tertiary alcohol after oxidation. Examination of the isomeric tertiary alcohols obtained reflects the isomeric purity of the trialkylborane. Inasmuch as we had previously observed incomplete transfer of methyl groups in the cyanidation or DCME reactions of methylalkylborane derivatives[5] but complete

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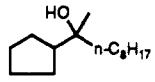
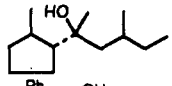
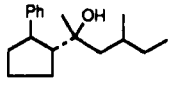
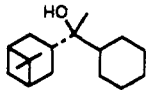
Table IV. Preparation of Tertiary Alcohols from Sequential Hydroboration of Alkenes with $MeBH_2$ in THF, Followed by Carbonylation[a]

alkene A	alkene B	tertiary alcohol	isol yield (%)
1-octene	cyclopentene		71
2-methyl-1-pentene	1-phenylcyclopentene		84[b]
2-methyl-1-butene	1-phenylcyclopentene		77[b]
cyclohexene	α-pinene		75[b]

[a] For reaction conditions, see Experimental Section. [b] Mixture of diastereomers.

transfer in carbonylation, we selected the latter reaction for the conversion of the trialkylboranes to the tertiary alcohols. In addition, in previous work it has been proven that redistribution does not occur in the course of the carbonylation reaction with trialkylboranes.[13] Therefore, the product(s) of hydroboration of alkene A and alkene B with methylborane was carbonylated (700 psi CO, 150 °C, 24 h) and oxidized (H_2O_2, OH^-) to yield the tertiary alcohols (eq 12).

$$MeR^AR^BB \xrightarrow[2.\ H_2O_2,\ OH^-]{1.\ CO} MeR^AR^BCOH \qquad (12)$$

These were purified by bulb-to-bulb distillation and/or column chromatography. Analysis by capillary GC (methylsilicone, 50 m) showed clean formation of the desired tertiary alcohols, indicating clean formation of the parent methyldialkylboranes. The results are summarized in Table IV. No products attributable to redistribution were detected. The proposed structures were corroborated by CIMS and, where applicable, by ^{13}C NMR spectroscopy (see Experimental Section). Importantly, no higher molecular weight species were observed. Thus, we have demonstrated that $MeBH_2$ in THF can indeed hydroborate alkenes sequentially without redistribution to yield the mixed methyldialkylboranes. However little selectivity is observed in the migratory aptitude of the various alkyl groups during carbonylation.[14] This may be due to the high temperatures (150 °C) and long reaction times (24 h) required for the reaction. But, in practice, it means that the *tertiary* alcohols are obtained as mixtures of diastereomers (Table IV, entries 2–4), except in the case where the compound contains one stereogenic carbon (Table IV, entry 1). It is of interest to note that even in the case where an optically active substituent is part of the trialkylborane undergoing carbonylation (Table IV, entry 4), low selectivity is observed, as might be expected, and an approximately 1:2 mixture of diastereomers is obtained. Thus while carbonylation/oxidation serves admirably to determine the isomeric purity of the triorganylboranes, the present reaction sequence is limited to the synthesis of *tertiary* alcohols with at most one stereogenic center. Finally, it should be pointed out that in the sequential addition of alkenes to $MeBH_2$, the most reactive alkene should be added first, followed by the less reactive alkene. The reverse addition would obviously lead to mixtures of various trialkylboranes.

In a recent evaluation of our initial studies with methylborane and various alkenes, it was suggested that a limiting factor in subsequent hydroborations of hindered alkenes with hindered methylalkylboranes might be a very sluggish hydroboration or no hydroboration at all.[15] Fortunately, this does not appear to be the case. Thus, hydroboration of (+)-α-pinene with the dialkylborane obtained from hydroboration of cyclohexene with methylborane furnished the relatively hindered trialkylborane in good yield, Table IV. Presumably, even more hindred examples should be possible.

We have to await a more diastereoselective reaction sequence to utilize these mixed trialkylboranes fully in selective carbon–carbon bond-forming reactions.

Mechanistic Aspects. Although the overall rate of hydroboration in EE or THF is essentially the same, in THF the methylalkylborane MeRBH is selectively formed from $MeBH_2$, while in EE, mono- and dihydroborated products are formed competitively. The relative lack of sensitivity to the steric demands of the alkene (Table I) seems to indicate that the rate-determining step is a fast equilibrium formation of the $MeBH_2$·THF adduct, followed by a more rapid monohydroboration, while the second hydroboration is relatively slow, similar to the behavior of 9-BBN in the hydroboration of reactive alkenes. On the other hand, the slowness of the second hydroboration must be attributed either to slow formation of RMeBH monomer or to a relatively slow reaction of this monomer with alkenes, or to both (eq 13).[16]

$$(MeBH_2)_2 \underset{THF}{\overset{fast}{\rightleftharpoons}} 2MeBH_2{\cdot}THF \xrightarrow[alkene]{very\ fast} (MeRBH)_2 \xrightarrow[alkene]{slow} 2MeR_2B \qquad (13)$$

Indeed, in EE, $MeBH_2$ exists solely as the dimer (δ +21.9), whereas in THF, a more powerful coordinating solvent, a small amount of $MeBH_2$·THF adduct (δ + 15) can be detected by ^{11}B NMR spectroscopy. As has been pointed out above, THF is critical in achieving controlled hydroboration with $MeBH_2$. Mixtures of EE and THF—up to 85:15—fail to achieve selective hydroboration. However, a 1:1 solution of EE and THF behaves essentially the same as THF. Methyl sulfide, a strong coordinating reagent (up to 10 equiv) in EE, does not appreciably enhance monohydroboration. These observations suggest that in addition to the rapid monomer, THF adduct formation, other subtle factors are involved in the process of achieving selective hydroborations with $MeBH_2$·THF. We hope to study and elucidate these factors in the future.

Regioselectivity in the First and Second Stages of Hydroborations of Representative Alkenes with Methylborane in THF. Having demonstrated that hydroboration of alkenes with $MeBH_2$ in THF can be controlled to yield either the methylalkylborane or methyldialkylborane selectively, it was of interest to examine the regioselectivity achieved in both stages of hydroboration. Previously, data were available only for the overall regioselectivity observed for mono- and dialkylboranes of much greater steric requirements, such as $ThxBH_2$,[17] disiamylborane,[18] Sia_2BH, 9-borabicyclo[3.3.1]nonane,[19] 9-

(13) (a) Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* **1971**, *93*, 1818, 4062. (c) Brown, H. C.; Negishi, E.; Gupta, S. K. *J. Am. Chem. Soc.* **1970**, *92*, 6648. (d) Negishi, E.; Brown, H. C. *Synthesis* **1972**, 197.

(14) We have also observed little selectivity in the DCME reaction.

(15) Hansen, M. M.; Heathcock, C. L. *Chemtracts* **1988**, *1*, 159.

(16) Wang, K. K.; Brown, H. C. *J. Am. Chem. Soc.* **1982**, *104*, 7148.

(17) (a) Zweifel, G.; Brown, H. C. *J. Am. Chem. Soc.* **1963**, *85*, 2066. (b) Brown, H. C.; Negishi, E.; Katz, J.-J. *J. Am. Chem. Soc.* **1975**, *97*, 2791.

(18) Brown, H. C.; Zweifel, G. *J. Am. Chem. Soc.* **1961**, *83*, 1241.

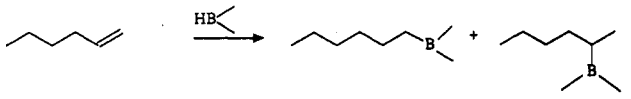
(19) Brown, H. C.; Knights, E. F.; Scouten, C. G. *J. Am. Chem. Soc.* **1974**, *96*, 7765.

Table V. Product Distribution from the Hydroboration–Oxidation of Representative Alkenes with $MeBH_2$ in THF at 0 °C in 1:1 and 1:2 Molar Ratios

alkene	alcohol	product distribution[a] MeRBH	product distribution[a] MeR_2B	estimated regioselectivity of second hydroboration
1-hexene[b]	1-hexanol	98.5	99.5	(100)
	2-hexanol	1.5	0.5	(0)
styrene	1-phenylethanol	83	85	(87)
	2-phenylethanol	17	15	(13)
trans-2-hexene	2-hexanol	53	63	(73)
	3-hexanol	47	37	(27)
cis-4-methyl-2-pentene	4-methyl-2-pentanol	56	78	(100)
	4-methyl-3-pentanol	44	22	(0)
trans-4-methyl-2-pentene	4-methyl-2-pentanol	55	76	(97)
	4-methyl-3-pentanol	45	24	(3)
2-methyl-2-butene	2-methyl-3-butanol	99.8	99.9	(100)
	2-methyl-2-butanol	0.2	0.1	(0)
1-methylcyclopentene	*trans*-2-methylcyclopentanol	99.7	99.9	(100)
	1-methylcyclopentanol	0.2	0.1	(0)

[a] Chemical yields of alcohols in selected runs is ≳95% as determined by GC in the presence of an internal standard. [b] First hydroboration with 1-hexene was run at −25 °C.

Scheme I



BH_3	94	6
$MeBH_2$	98.5	1.5
$ThxBH_2$	94	6
$BH_2Cl{\cdot}EE$	> 99.5	< 0.5
$BH_2Br{\cdot}SMe_2$	99.6	0.4

BBN, and the monohaloboranes,[20] XBH_2·ligand.

In this study, a representative series of alkenes was hydroborated for the appropriate period of time in THF. After the first stage of hydroboration, the methylalkylborane was methanolyzed, the reaction mixture was oxidized by alkaline H_2O_2, and the alcohols produced were analyzed by capillary GC (methylsilicone, 50 m). After the second stage of hydroboration, the trialkylborane was directly oxidized with alkane H_2O_2 and similarly examined. The results are summarized in Table V. The second stage of hydroboration was estimated by the relation, $2A - B$, where A represents the selectivity in percent obtained in the overall hydroboration and B represents the selectivity achieved in the first hydroboration.

In the first stage of hydroboration with 1 equiv of styrene, *trans*-2-hexene, or *cis*- or *trans*-4-methyl-2-pentene, low selectivity is obtained. The results are comparable to borane (Table V). High selectivity, as expected, is obtained in the first hydroboration of trisubstituted alkenes.

However, in one case, there is an unexpected result. $MeBH_2$ gives a C-1/C-2 distribution of boron in the first hydroboration of 1-hexene of 98.5:1.5. This is comparable to the averaged distributions realized in the hydroborations with chloroborane and bromoborane but very different from the averaged distribution obtained with $ThxBH_2$,[21] 94:6, as well as borane itself, 94:6 (Scheme I).

The regioselectivity of the second hydroboration is more profoundly influenced by the newly formed methylalkylborane. Being more sterically demanding, the regioselectivity of this hydroboration step should be much greater.

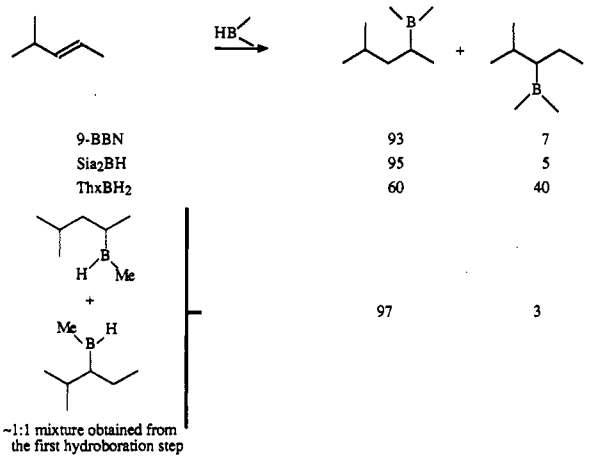
Indeed, in the second hydroboration of *trans*-4-methyl-2-pentene with the mixture of methylalkylboranes obtained in the first hydroboration, a 97:3 ratio is obtained (Scheme II). With *cis*-4-methyl-2-pentene, the second hydroboration occurs with complete regioselectivity, approaching 100:0 (Table V).

In these systems the MeRBH surpasses even 9-BBN and Sia_2BH in the high degree of regioselectivity achieved. This has some interesting possible ramifications. In the future these and other new methylalkylboranes could be tailor-made with an appropriate alkene to achieve high degrees of regioselectivity.

The second stage of hydroboration of 1-hexene and the trisubstituted alkenes proceeds with high C-1/C-2 selectivity (Table V).

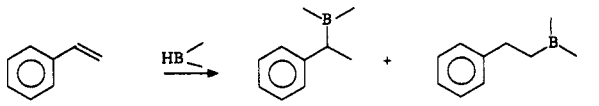
Styrene, however, behaves anomalously (Scheme III). Little improvement in selectivity is observed in the second

Scheme II



9-BBN	93	7
Sia_2BH	95	5
$ThxBH_2$	60	40
~1:1 mixture obtained from the first hydroboration step	97	3

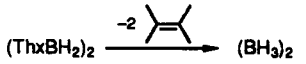
Scheme III



BH_3	19	81
Sia_2BH	2	98
9-BBN	1.5	98.5
$MeBH_2$	13	87

(20) Brown, H. C.; Ravindran, N.; Kulkarni, S. U. *J. Org. Chem.* **1979**, *44*, 2417.

(21) It is possible that the results obtained in the early studies with $ThxBH_2$ conducted at 0 °C did not fully take into account the extent of dehydroboration to give diborane. This phenomenon, discovered later (ref 17b), could account for the observed similarities in the results for $ThxBH_2$ and diborane.



hydroboration. The distribution achieved in this case approaches the low regioselectivity exhibited by diborane itself and not the high selectivities observed with other mono- and dialkylboranes (Table V). The reasons for this are presently not clear.

Conclusion

We have discovered that $MeBH_2$ in THF hydroborates simple alkenes in a 1:1 molar ratio cleanly to give methylalkylboranes MeRBH. These boranes are highly useful organoborane intermediates. They can be converted via their borinates into methyl ketones that retain the high regio- and stereoselectivity typical of the hydroboration reaction. On the other hand, these newly formed methylalkylboranes can hydroborate another equivalent of the same alkene to give MeR_2B or hydroborate a different alkene to give MeR^AR^BB. These trialkylboranes can be converted into tertiary alcohols via carbonylation–oxidation sequence. Thus, methylborane, though sterically nonhindered, is capable of providing controlled hydroboration in THF to a degree previously achieved only by the much more sterically demanding $ThxBH_2$. Controlled hydroboration enables the positional selectivity of the first and second stages to be accurately determined.

Clearly $MeBH_2$ possesses highly interesting hydroboration properties. It will be of interest to examine this reagent and derivatized reagents, i.e., MeBHCl·ligand, as regards selective reduction, cyclic hydroboration of dienes, hydroboration of acetylenes, and the synthesis of cyclic ketones, to name but a few possible applications. It is reasonable to assume that $MeBH_2$ should display equally intriguing properties in these types of reaction.

Experimental Section

All glassware, syringes and needles were oven-dried at 150 °C prior to use. The glassware was assembled while hot and then cooled under a flow of nitrogen. A small positive pressure of nitrogen was maintained by using a mercury bubbler as a pressure relief valve. Syringes were fitted with needles while hot and then cooled under nitrogen. ^{11}B NMR spectra were obtained at 25.517 MHz relative to BF_3·EE. ^1H NMR spectra were obtained at 60 MHz relative to TMS. ^{13}C NMR spectra were obtained at 20.000 MHz relative to TMS. ^{27}Al NMR spectra were obtained at 20.725 MHz. GC analysis of alcohols were carried out on a 50-m methylsilcone capillary column.

Anhydrous diethyl ether (Mallinckrodt) and pentane (Phillips) were stored over 4A molecular sieves under nitrogen and used without further purification. THF was distilled from sodium ketyl and stored under nitrogen in an ampule. The alkenes were obtained from commercial sources (Aldrich Chemical Company or Wiley Organics) and were distilled from $LiAlH_4$ or used as received. Anhydrous ethereal hydrogen chloride (3 M) was prepared by using a Brown apparatus from hydrochloric acid and sulfuric acid.[22] The solutions were standardized by hydrolyzing an aliquot with water and titrating it with a standard solution of sodium hydroxide in the presence of phenolphthalein. Techniques for handling air-sensitive compounds have been previously described.[23]

Procedures for Establishing the Identity of the Products. Owing to the relative lability of the boron–hydrogen and boron–carbon bonds, procedures for establishing isomeric purity of boranes involve a major difficulty. The desired compound, $R^1R^2R^3B$, can readily redistribute to give ten different species: $(R^1)_3B$, $(R^2)_3B$, $(R^3)_3B$, $(R^1)_2R^2B$, $(R^1)_2R^3B$, $(R^2)_2R^1B$, $(R^2)_2R^3B$, $(R^3)_2R^1B$, $(R^3)_2R^2B$, $R^1R^2R^3B$. Oxidation gives a quantitative conversion into the three alcohols, R^1OH, R^2OH, and R^3OH, in a 1:1:1 ratio. But this does not establish the homogeneity of the organoborane products, which are the main objective of this research. The most convincing procedure that we have adopted for many years is the quantitative conversion of dialkylboranes R^1R^2BH into R^1R^2BOMe and then into the ketone R^1R^2CO buy the DCME reaction. Similarly, $R^1R^2R^3B$ is converted into the tertiary alcohol $R^1R^2R^3COH$ by the carbonylation reaction. Therefore, the following procedures developed over the years have been found adequate in assessing the isomeric purity of boranes.

Monohydroboration of Alkenes with Monoalkylboranes. The products of monohydroboration of alkenes with monoalkylboranes are dialkylboranes. The reaction may be conveniently followed by disappearance of the alkene by GC methods and for hydride incorporation by evolution of hydrogen upon treatment of the reaction mixture with acid. We have utilized these methods for determining mass balance. However, while these methods can quantify the extent of the reaction, they cannot determine the isomeric purity of the dialkylboranes as mentioned above. These contain a boron–hydrogen bond and generally exist in solution as dimeric bridged structures, with redistribution always a possible consequence (see eq 11). To ascertain the extent, if any, of redistribution, it is advisable to convert these labile dialkylboranes to more stabile compounds. The procedure we have adopted for determining the isomeric purity of dialkylboranes involves initial conversion to a borinic ester, which is then transformed to the corresponding ketone by the DCME reaction.[9] The R groups of the ketone(s) reflect the substituents around the corresponding borane. In this way the extent and degree of redistribution, if any, of the dialkylboranes can be quantified. To our satisfaction, mass balance indicated essentially quantitative uptake of 1 equiv of alkene, and conversion of the dialkylboranes to ketones followed by GC analysis indicated that no significant redistribution of the dialkylboranes had occurred.

Hydroboration of Alkenes with Dialkylboranes. The dialkylboranes obtained in the aforementioned step were reacted with a different alkene to give mixed trialkylborane. Since in the course of the reaction both dialkyl- and trialkylboranes exist in solution, redistribution by bridged species is also possible. Again although quantitative uptake of the second alkene was observed by GC analysis and ^{11}B NMR spectroscopy, the isomeric purity of the trialkylboranes could not be determined directly. Instead, as in the previous examples, these were converted into more stable and readily analyzable compounds, namely, carbinols, by carbonylation–oxidation of the trialkylboranes. The carbinols were then analyzed by GC. Again, to our satisfaction no significant products attributable to redistribution were detected.

In addition to the above methods, the narrow boiling range we obtained is indicative of a single major product. A mixture of organoboranes would lead to wide boiling fractions. GC analysis of the oxygenated derivatives likewise proves the formation of a single product (as diastereomeric mixtures). Finally, GC–mass spectra of the corresponding ketones and carbinols also confirms the existence of a single borane species.

Preparation of Lithium Methylborohydride in THF. This is a modified version of the literature preparation.[6] A 500-mL round-bottom flask fitted with a side arm and stirring bar was charged with 2-methyl-1,3,2-dioxaborinane (15.0 g, 150 mmol) and pentane (150 mL). The solution was cooled to 0 °C and $LiAlH_4$ in EE (150 mL of 1 M, 150 mmol) was added. During the addition, a heavy white precipitate was formed. The reaction mixture was stirred an additional 15 min at 0 °C, then allowed to warm to room temperature, and filtered through a filter chamber under nitrogen pressure. The white precipitate was washed with EE (3 × 150 m). ^{11}B NMR spectroscopy indicated the clean formation of $LiMeBH_3$. ^{27}Al NMR spectra showed that a small amount of aluminum salts were present, which are removed as follows. All volatiles were removed, first at aspirator pressure (12 mmHg) and then at high vacuum (0.1 mmHg). The white solid was treated with pentane (150 mL) and EE (15 mL). The residual aluminum salts were allowed to settle, and the clear supernatant solution transferred to a calibrated ampule. The volatiles were removed in vacuo as before. The solid was cooled to 0 °C and THF (~150 mL) was slowly added. (The addition of THF is exothermic! Care should be taken.) The solution of $LiMeBH_3$ in THF was standardized by hydrolyzing an aliquot and measuring the amount of hydrogen liberated.[24] Yield: 85–90%.

(22) Brown, H. C.; Rei, M.-H. *J. Org. Chem.* **1966**, *31*, 1090.
(23) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. *Organic Synthesis via Boranes*; Wiley-Interscience: New York, 1975.
(24) Reference 23, p 241.

Reaction of Alkenes with $MeBH_2$ in THF in a Molar Ratio of 1:1. $LiMeBH_3$ in THF (5 mL, 5 mmol) was added to a 50-mL centrifuge tube capped with a rubber septum and containing a stirring bar. The solution was cooled to 0 °C and ethereal HCl (1.46 mL, 5 mmol) was added. The reaction mixture was then maintained at the appropriate temperature (Table I) and the alkene (5.5 mmol) was added neat via syringe. After stirring the requisite time (Table I), either methanol or 2-propanol was added in excess, and the reaction mixture was maintained at the reaction temperature until all evolution of hydrogen had ceased (~15–20 min). The reaction mixture was allowed to warm to room temperature, during which time LiCl precipitated. This was either allowed to settle or centrifuged to obtain a clear supernatant. An aliquot was examined by ^{11}B NMR spectroscopy to determine product distribution by peak heights (see text).

Isolation of Borinic Esters Obtained from the Reaction of Alkenes with $MeBH_2$ in THF in a Molar Ratio of 1:1. The preparation of (±)-methyl(2-methylpentyl)isopropoxyborane is typical. $LiMeBH_3$ in THF (13.7 mL, 12.2 mmol) was cooled to 0 °C, and ethereal HCl (3.6 mL, 12.2 mmol) was added. After the evolution of H_2 ceased, the reaction mixture was cooled to −25 °C and 2-methyl-1-pentene (1.6 mL, 13.4 mmol) was added via syringe. The reaction was stirred for 1 min, quenched with 2-propanol (1.84 mL, 24.4 mmol), and stirred at −25 °C for an additional 20 min until the evolution of H_2 ceased. The reaction was warmed to 0 °C, and the THF was removed at diminished pressure (12 mmHg). Pentane (2 × 20 mL) was added. After the LiCl settled, the clear supernatant was transferred to a distillation apparatus. The pentane was removed at 0 °C (12 mmHg) and the product distilled. Yield: 1.55 g (9.2 mmol, 75%). Bp: 86–88 °C (25 mmHg). n^{20}_D 1.4044. Mass spectrum (chemical ionization, isobutene) m/z: 171 ($M^+ + H$, 100), 129 ($M^+ - C_3H_6$, 25). ^{11}B NMR (neat): 52.4 ppm (s). ^1H NMR ($CDCl_3$): δ 4.13 (septet, J = 18 Hz, 1 H), 0.87 ($OCH(CH_3)_2$, J = 18 Hz), 0.53 ($CHCH_3$, J = 15 Hz), 0.05 (bs, 3 H). IR: ν_{max} (neat) cm^{-1} 1332 (B–O). A criterion for purity of this borinic ester and the others was conversion into the known ketones[25] by the DCME reaction, vide infra.

Preparation of Methylcyclopentylmethoxyborane. This reaction was run as described above using $LiMeBH_3$ (16.12 mL, 15 mmol). Ethereal HCl (4.82 mL, 15 mmol) was added at 0 °C, followed by cyclopentene (1.45 mL, 16.5 mmol). The reaction was quenched with methanol (2 mL). Yield: 1.38 g (11 mmol, 73%). Bp: 62 °C (40 mmHg). n^{20}_D 1.4326. Mass spectrum (chemical ionization, isobutene) m/z: 127 ($M^+ + H$, 100). ^{11}B NMR (neat): δ 54.5 (s). ^1H NMR ($CDCl_3$): δ 3.70 (s, 3 H), 1.50 (m, 9 H), 0.33 (s, 3 H). IR: ν_{max} (neat) cm^{-1} 1342 (B–O).

Preparation of (±)-Methyl(*trans*-2-methylcyclohexyl)methoxyborane. The reaction was conducted by the above procedure, using $LiMeBH_3$ in THF (16.12 mL, 15 mmol), ethereal HCl (4.82 mL, 15 mmol), and 1-methylcyclohexene (2 mL, 16.5 mmol) at 0 °C. After the addition of the alkene, the reaction mixture was raised to room temperature and stirred for 15 min when the reaction was complete, as evidenced by ^{11}B NMR spectroscopy after quenching an aliquot with methanol. The reaction was quenched with methanol (2 mL). Yield: 1.85 g (12.03 mmol, 80%). Bp: 68–70 °C (14 mmHg). n^{21}_D 1.4376. Mass spectrum (chemical ionization, isobutene): m/z 155 ($M^+ + H$, 43.18), 97 [$M^+ + H - HB(Me)(OMe)$, 100]. ^{11}B NMR (neat): δ 54.4 (s). ^1H NMR ($CDCl_3$): δ 3.5 (s, 3 H), 1.1–1.18 (m, 11 H), 0.7 (d, J = 6 Hz, 3 H), 0.33 (s, 3 H). IR ν_{max} (neat) cm^{-1} 1342 (B–O).

Preparation of Methylisopinocampheylmethoxyborane. The reaction was carried out as above, using $LiMeBH_3$ in THF (16.12 mL, 15 mmol), ethereal HCl (4.82 mL, 15 mmol), and α-pinene (2.44 mL, 16.5 mmol) at 0 °C. After stirring at 0 °C for 10 min, the reaction was quenched with methanol (2 mL). Yield: 2.3 g (11.88 mmol), 79%). Bp 100–102 °C (12 mmHg). The fact that the product is obtained in 79% yield after removal of volatiles under aspirator pressure and the fact that the material boils in a narrow range are clean evidence that significant redistribution has not occurred. n^{21}_D 1.4627. Mass spectrum (chemical ionization, isobutene): m/z 195 ($M^+ + H$, 34.74), 137 [$(M^+ + H) - HB(Me)(OMe)$, 100]. ^{11}B NMR (neat): δ 54.0 (s). ^1H NMR ($CDCl_3$): δ 3.7 (s, 3 H), 0.42 (s, 3 H). IR ν_{max} (neat) 1331 (B–O).

Conversion of the Esters of Methylborinic Acids into Ketones via the DCME Reaction. Methylborane (1.28 mmol) was prepared as described above. The alkene (1.41 mmol) was added at the appropriate temperature, and the solution was stirred and quenched with 2-propanol. A hydrocarbon is added as an internal standard. The reaction mixture was maintained at 0 °C and DCME was added (0.23 mL, 2.56 mmol), followed by lithium *tert*-butoxide (0.9 mL, 2.56 mmol) in hexane. The reaction was stirred at 0 °C for 15 min and allowed to warm to room temperature. ^{11}B NMR spectroscopy indicated the clean formation of the borate (δ ~ 28 ppm). Aqueous sodium hydroxide was added (0.43 mL, 1.28 mmol), followed by excess H_2O_2. The reaction was allowed to stir at room temperature for 3 h and then analyzed by GC on a SP-2100 column. The yields are listed in Table III.

Carbonylation–Oxidation of the Products Obtained from the Sequential Addition of Alkene A and Alkene B to a Solution of $MeBH_2$ in THF. The preparation of (±)-2-(*trans*-2-methylcyclopentyl)-4-methylheptan-2-ol is typical. In a 100-mL flask equipped with a septum-covered side arm, magnetic stirring bar, and gas inlet adaptor was added $LiMeBH_3$ in THF (15.5 mL, 14 mmol). The reaction was cooled to 0 °C and treated with ethereal HCl (4.1 mL, 14 mmol). 1-Methylcyclopentene (1.62 mL, 15.4 mmol) was added, and the reaction was stirred for 5 min, followed by addition of 2-methyl-1-pentene (1.73 mL, 14 mmol). The reaction was stirred for 30 min. ^{11}B NMR spectroscopy at this point showed a single peak at δ +86. The lithium chloride was allowed to settle and the clear supernatant decanted via a double-ended needle into the nitrogen-flushed Paar "mini" reactor. The remaining solid LiCl was washed with THF (2 × 3 mL) and added to the pressure reactor along with ethylene glycol (1.25 mL, 22.5 mmol). The Paar reactor was sealed and pressurized to ~700 psi with carbon monoxide and heated to 150 °C for 24 h. After cooling and carefully venting the reactor, the contents were transferred to a 100-mL flask fitted with a septum-capped side arm, magnetic stirring bar, and reflux condenser. The ^{11}B NMR spectrum showed a single peak at δ +34, indicating clean formation of the boronic ester. Ethanol (5 mL) was added as co-solvent, and then sodium hydroxide (5.5 mL, 33 mmol) was added, followed by careful dropwise addition of 30% H_2O_2 (5.5 mL). The reaction mixture was heated to 50–60 °C for at least 2 h to ensure complete oxidation. Potassium carbonate was added to the aqueous fraction to near saturation (complete saturation caused formation of an emulsion which was difficult to break), and the organic layer was separated. The aqueous portion was extracted with a hydrocarbon solvent (pentane, hexane, or petroleum ether, 3 × 20 mL). The combined organic fractions were washed with a solution of potassium carbonate (2 × 10 mL) and then dried over anhydrous $MgSO_4$. The volatiles were removed under reduced pressure (12 mmHg) to obtain the crude tertiary alcohol. Yield: 2.48 g (84%) of the tertiary alcohol as a mixture of diastereomers. Bp: 165–170 °C (12 mmHg). Mass spectrum (chemical ionization, isobutene) m/z: 213 ($M^+ + H$, 5.57), 195 ($M^+ + H - H_2O$, 40.58), 111 (100). Mass spectrum (electron impact) m/z: 197 ($M^+ - CH_3$, <1), 83 ($C_6H_{11}^+$, 56.5), 71 ($C_5H_{11}^+$, 37), 55 ($C_4H_7^+$, 38). IR: ν_{max} cm^{-1} (neat) 3455 (O–H).

Preparation of (±)-2-Cyclopentyldecan-2-ol. The reaction was carried out by using a procedure similar to that above. $MeBH_2$ was liberated from $LiMeBH_3$ in THF (16.12 mL, 15 mmol) by using ethereal HCl (4.9 mL, 15 mmol) at 0 °C and was used to hydroborate cyclopentene (1.32 mL, 15 mmol). After stirring for 10 min at 0 °C, 1-octene (2.35 mL, 15 mmol) was added at 0 °C, and the solution was stirred for another 20 min. The ^{11}B NMR spectrum at this stage showed a singlet at δ 84 corresponding to a trialkylborane. The trialkylborane was transferred to a Paar "mini" reactor by using a double-ended needle. Ethylene glycol (1.25 mL, 22.5 mmol) was then added to the reactor, which was pressurized with CO to ~700 psi and heated at 150 °C for 24 h. The reaction was worked up as above. Yield (crude): 3.05 g (13.4 mmol, 90%). Normally, we distill such products. However, high boiling tertiary alcohols readily dehydrate. In order to preclude this possibility, we avoided such distillation. The achievement of a 90% yield indicates that there cannot be significant amounts of volatile material. Since redistribution requires that the material

(25) For a previous preparation of these and related ketones, see: Brown, H. C.; Srebnik, M.; Bakshi, R. K.; Cole, T. E. *J. Am. Chem. Soc.* **1987**, *109*, 5420.

of low volatility should be comparable to material of much higher volatility, it appears safe to conclude that redistribution is insignificant. This material was purified by column chromatography (silica gel, Davidson grade 62, 60–200 mesh, 50 g) and eluted with a mixture of hexane/EE (98:2). Yield: 2.37 g (10.4 mmol, 70%). This material is pure by capillary GC (methylsilicone, 50 m, 200 °C). ^{13}C NMR ($CDCl_3$): δ 74.14, 49.60, 41.91, 32.14, 30.62, 29.88, 29.53, 27.34, 26.75, 26.11, 24.83, 24.14, 22.84, 14.28. Mass spectrum (chemical ionization, isobutene) m/z: 225 ($M^+ + H - H_2$, <1), 209 ($M^+ + H - H_2O$, 100). Mass spectrum (electron impact) m/z: 211 ($M^+ + CH_3$, 2), 157 (M^+ – cyclopentyl, 49), 113 ($C_8H_{17}^+$, 100). IR: ν_{max} (neat) cm^{-1} 3457.

Preparation of (±)-2-(*trans*-2-Phenylcyclopentyl)-4-methylheptan-2-ol. This compound was prepared in the same proportions as described above, except that after the addition of phenylcyclopentene (2.38 g, 16.5 mmol), the reaction was stirred at 0 °C for 2 h, then 2-methyl-1-pentene was added (1.85 mL, 15 mmol), and the stirring was continued for an additional hour. Yield (crude): 3.82 g. The product was purified by column chromatography on silica gel as above and eluted with a mixture of hexane/EE (90:10) to give two diastereomeric fractions. Yield: 3.2 g (11.6 mmol, 77%). The fractions were analyzed by capillary GC (methylsilicone, 50 m, 200 °C). Each fraction consisted of a mixture of three diastereomeric alcohols in the ratio of 1:2.1:3.1 and 8.6:2.9:1, respectively, which exhibited identical mass spectra. See above example for a statement on purity and distillation. Mass spectra (chemical ionization, isobutene) m/z: 257 ($M^+ + H - H_2O$, 100). IR: ν_{max} cm^{-1} (neat) 3475 (O–H).

Preparation of 1-(2-Isopinocampheyl)-1-cyclohexylethanol. This compound was prepared as described above in the typical procedure, except that α-pinene (2.4 mL, 15 mmol) was used, followed by cyclohexene (1.62 mL, 15 mmol). The reaction was stirred for 40 min at 0 °C after the second addition. Yield (crude): 3.48 g. The compound was purified on silica gel (hexane/EE, 98:2) to yield 2.97 g (11.25 mmol, 75%). Analysis by capillary GC (methylsilicone, 50 m, 190 °C) showed this to be a 1:2 mixture of diastereomers, which gave identical mass spectra. Mass spectrum (chemical ionization, isobutene) m/z: 263 ($M^+ + H - H_2$ <1), 247 ($M^+ + H - H_2O$, 67), 137 ($C_{10}H_{17}^+$, 100). Mass spectrum (electron impact) m/z: 246 ($M^+ - H_2O$, <1), 181 ($M^+ - C_6H_{11}$, 14), 127 ($M^+ - C_{10}H_{17}$, 100), 83 ($C_6H_{11}^+$, 63), 55 ($C_4H_7^+$, 52), 43 ($C_3H_7^+$, 64). IR: ν_{max} cm^{-1} (neat) 3474 (O–H).

General Procedure for the Determination of Regioselectivity in the Hydroboration of Representative Alkenes by $MeBH_2$ in Molar Ratios of 1:1 and 1:2. The hydroboration in a 1:1 molar ratio was conducted as described under "Reaction of Alkenes with ...", except that an internal standard was added prior to the addition of the alcohol. To the borinic ester was added sodium hydroxide (4.5 mL, 7.5 mmol), and the reaction was cooled to 0 °C and 30% H_2O_2 (1.7 mL) was slowly added. The reaction mixture was heated at 50–60 °C for at least 2 h, potassium carbonate was added to the aqueous phase to near saturation, and the ether layer was separated and dried over $MgSO_4$. This was analyzed for alcohols by capillary GC (methylsilicone, 50 m). For determination of the regioselectivity in a molar ratio of 1:2, the hydroboration–oxidation procedure was identical, except that in the hydroboration step, 2 equiv of alkene was utilized. The results are summarized in Table II. In all cases, the combined alcohols for each run were obtained in >95% yield based on the internal standard.

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Asymmetric Hetero-Diels–Alder Reaction of α-Alkoxy Aldehydes with Activated Dienes. The Scope of Lewis Acid Chelation-Controlled Cycloadditions

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The cycloaddition reactions of various α-alkoxy aldehydes with 1,3-dimethoxy-1-[(trimethylsilyl)oxy]-1,3-butadiene (Brassard's diene, **2**) were performed under the Lewis acid catalysis of $Eu(hfc)_3$, magnesium dibromide, or diethylaluminum chloride. Moderate to high diastereoselectivities were observed with $Eu(hfc)_3$ and magnesium dibromide. Evidence from reactions of $Eu(hfc)_3$ and magnesium dibromide catalysis indicated a possible "chelation-control" pathway. Lewis acid catalysis from diethylaluminum chloride provided products with moderate to high diastereoselectivity. The mechanistic pathway with catalysis by diethylaluminum chloride was less clear. A possible mechanism based upon a "Cram" addition is considered.

Introduction

The utility of the Diels–Alder reaction has been greatly expanded and the synthesis of heterocycles and complex natural products facilitated by the incorporation of hetero atoms in both the diene and dienophile. The applications of the hetero-Diels–Alder reaction has been recently reviewed.[1]

The use of carbonyl groups as the π group in the dienophile has been successfully employed with highly reactive carbonyl compounds[2] and by employing high pressure techniques.[3] Danishefsky found that aldehydes would undergo cycloaddition reactions with activated dienes under the influence of Lewis acid catalysts.[4] The reactions were performed by using activated dienes such as 1-methoxy-3-[(trimethylsilyl)oxy]-1,3-butadiene (Danishefsky's diene, Figure 1). The potential for stereocontrol in

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