^{1}H NMR δ 7.41 (m, 5 H), 5.81 (dt, J = 15.5, 6.4 Hz, 1 H), 5.65 (d, J = 15.5 Hz, 1 H), 5.15 (m, 1 H), 3.63 (d, J = 6.4 Hz, 2 H), 2.5-1.0 (m, 14 H); ^{13}C NMR δ 140.35, 135.69, 131.76, 130.27, 128.69, 126.25, 124.22, 122.81, 72.80, 42.16, 36.19, 27.99, 25.63, 22.66, 17.66; exact mass calcd for $C_{17}H_{24}OS$ 276.1547, found 276.1543.

Ethyl (*E*)-2,3-Dimethyl-5-hydroxy-3-pentenoate. To a slurry of Sm powder (0.160 g, 1.05 mmol) in THF (5 mL) at room temperature was added a solution of 1,2-diiodoethane (0.280 g, 1.00 mmol) in THF (5 mL). The resultant slurry was stirred at ambient temperature for 1 h, after which the slurry of SmI_2 formed was cooled to -90 °C and treated with a solution of ethyl (E)-4,5-epoxy-3-methyl-2-pentenoate, (0.075 g, 0.48 mmol), and iodomethane (0.5 mL) in THF (5 mL). The resultant mixture was stirred for 10 min at -90 °C, allowed to warm to room temperature, stirred for an additional 30 min at ambient temperature, and then quenched with pH 8 buffer. The aqueous phase was extracted with Et_2O, and the combined extracts were dried (Na_2SO_4) and then concentrated to provide 0.032 g (39%) of ethyl (*E*)-2,3-dimethyl-5-hydroxy-3-pentenoate after flash chromatography (50% ethyl acetate in hexanes): IR (neat) 3400, 1720 cm^{-1}; ^{1}H NMR δ 5.53 (m, 1 H), 4.10 (m, 4 H), 3.10 (q, J = 7.2 Hz, 1 H), 1.81 (br s, 1 H), 1.67 (narrow m, 3 H), 1.25 (m, 6 H); ^{13}C NMR δ 174.28, 137.35, 126.04, 60.56, 59.22, 48.15, 44.83, 15.66, 14.21 ppm; exact mass calcd for $C_9H_{16}O_3$ 172.1099, found 172.1091.

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Selective Reductions. 38. Reaction of Thexylchloroborane-Methyl Sulfide Complex in Methylene Chloride with Selected Organic Compounds Containing Representative Functional Groups. Comparison of the Reducing Characteristics of Thexylchloroborane, Thexylborane, and Diborane

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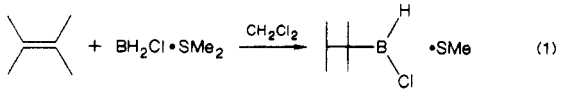
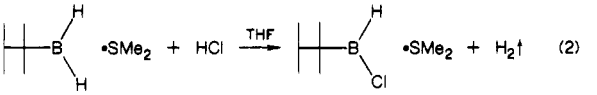
The approximate rate and stoichiometry of the reaction of excess thexylchloroborane-methyl sulfide complex, ThxBHCl·SMe_2, with 56 selected organic compounds containing representative functional groups under standard conditions (methylene chloride, 0 °C) were determined in order to define the characteristics of the reagent for selective reductions. The selectivity of the reagent was also compared to the selectivities of thexylborane and diborane. Alcohols and phenol react with the reagent at a fast rate to evolve an equivalent of hydrogen without any further reduction. Amines and aliphatic thiols do not form any hydrogen, while benzenethiol shows partial hydrogen formation. Aldehydes and ketones are reduced rapidly and quantitatively to give the corresponding alcohols. Unlike thexylborane and diborane, the reagent shows good stereoselectivity toward cyclic ketones. For example, 2-methylcyclohexanone is reduced to the less stable isomer, *cis*-2-methylcyclohexanol, in a high ratio (99.9% cis isomer at -78 °C). Cinnamaldehyde is reduced rapidly to cinnamyl alcohol, and any further reduction of the double bond is very slow under these conditions. *p*-Benzoquinone reacts only partially with the reagent while anthraquinone is totally unreactive. Carboxylic acids liberate 1 equiv of hydrogen rapidly and are further reduced to the corresponding aldehydes in good yields and purity. Acid chlorides react sluggishly with the reagent to use 2 equiv of hydride, while acetic anhydride utilizes 3 equiv of hydride to yield acetaldehyde and ethanol. On the other hand, cyclic anhydrides, such as succinic anhydride and phthalic anhydride, react very slowly with the reagent. Esters are almost inert toward thexylchloroborane. γ-Butyrolactone and phthalide are only partially reduced under the reaction conditions. Isopropenyl acetate utilizes 3 equiv of hydride to yield the corresponding acetaldehyde and presumably the hydroboration product of propylene. Only a partial reduction of epoxides can be observed. Primary amides like caproamide and benzamide evolve 1 equiv of hydrogen, but further reaction is very slow. Tertiary amides are almost inert under these conditions. Capronitrile reacts with the reagent to use 2 equiv of hydride in less than 24 h, while the reaction between benzonitrile and thexylchloroborane is sluggish. Nitrobenzene and 1-nitropropane do not react with the reagent, while azobenzene reacts only partially. Azoxybenzene consumes 2 equiv of hydride in 48 h. Only a sluggish reaction between thexylchloroborane and cyclohexanone oxime or phenyl isocyanate can be observed. Pyridine does not react, while pyridine *N*-oxide utilizes 3 equiv of hydride. Of the sulfur compounds tested, only dimethyl sulfoxide is reduced by the reagent to form the corresponding sulfide, while other sulfur compounds, such as disulfide, sulfide, and sulfone, are inert under these conditions. Although sulfonic acids evolve hydrogen, no further reduction is observed.

Thexylchloroborane can be prepared from the addition of 2,3-dimethyl-2-butene to monochloroborane-methyl sulfide in methylene chloride (eq 1). Preparation of



(1)

thexylchloroborane from thexylborane and hydrogen chloride has also been reported (eq 2).[2]



(2)

The reagent, ThxBHCl·SMe_2, in methylene chloride is very stable[3] and no disproportionation or loss of hydride is observed while the reagent is kept at 0 °C, at least for

(1) (a) Postdoctoral research associate on Grant ARO DAAG-29-79-C-0027 supported by the United States Army Research Office. (b) Graduate research assistant on temporary academic leave from Monsanto Agricultural Products Co.

(2) Zweifel, G.; Pearson, N. R. *J. Am. Chem. Soc.* **1980**, *102*, 5919.
(3) Brown, H. C.; Sikorski, J. A. *Organometallics* **1982**, *1*, 28.

0022-3263/86/1951-5264$01.50/0

a period of 2 months. The reagent has been studied extensively.[4] For example, the use of ThxBHCl·SMe_2 for the preparation of unsymmetrical ketones[5] and for hydroboration[6] and the effect of structure on the relative reactivity of the reagent toward olefins[7] have been reported recently. Because a full investigation of the reagent as a reducing agent was not available, we undertook to study the approximate rate and stoichiometry for the reaction of excess thexylchloroborane–methyl sulfide in methylene chloride with 56 compounds containing representative functional groups under standardized conditions (methylene chloride, 0 °C).

Results and Discussion

Procedure for Rate and Stoichiometry Studies. Thexylchloroborane–methyl sulfide was prepared by adding 2,3-dimethyl-2-butene (tetramethylethylene) to a solution of monochloroborane methyl sulfide in methylene chloride. The reagent was stable at 0 °C; no change in hydride concentration or in the ^{11}B NMR spectra of the reagent was observed after 2 months. The procedure used in this study involved preparation of a reaction mixture of thexylchloroborane–methyl sulfide (1.0 M, 1.0 M in hydride) and the compound (0.25 M) under study in methylene chloride at 0 °C. Hydrogen evolution, following addition of the compound to the reagent, was measured. A blank reaction was run under identical conditions, but without addition of the compound. From time to time, aliquots were taken from the reaction mixture and analyzed for residual hydride by hydrolysis.[8] From the difference in yields of hydrogen in the two cases, the hydride used by the compound for reduction was calculated. In this way it was possible to calculate a value for the number of moles of the hydride used by the compound to evolve hydrogen and the number of moles of hydride utilized for the reduction process.[8,9]

Alcohols, Phenols, Amines, and Thiols (Active Hydrogen Compounds). Of those active hydrogen compounds studied, alcohols evolved 1 equiv of hydrogen rapidly and quantitatively. Primary, secondary, and tertiary alcohols all evolved 1 equiv of hydrogen in less than 1 h. Surprisingly, phenol also reacted with ThxBHCl·SMe_2 at a fast rate and 1 equiv of hydrogen was evolved in a short time. *n*-Hexylamine did not react with ThxBHCl·SMe_2 while benzenethiol liberated 1 equiv of hydrogen slowly. 1-Hexanethiol did not evolve any hydrogen under these conditions. These results are summarized in Table I.[9b]

Aldehydes and Ketones. All of the saturated and unsaturated aldehydes and ketones studied use 1 equiv of hydride rapidly. Hence, in these cases, the reduction goes cleanly to the corresponding alcohol stage. Thexylchloroborane is a stronger reducing agent toward carbonyl compounds than thexylborane. For example, benzophenone is reduced with ThxBHCl·SMe_2 in less than 12 h, while under similar conditions, the reaction between benzophenone and $ThxBH_2$ required more than 48 h for completion. Cinnamaldehyde consumes one hydride rapidly, while the rate of the second hydride uptake is very slow. These results are summarized in Table II.[9b]

Table III. Reaction of Thexylchloroborate–Methyl Sulfide with Different Cyclic Ketones in Tetrahydrofuran[a]

compound	reaction temp, °C	less stable isomer,[b] %
2-methylcyclohexanone	0	94.5
	−25	96.5
	−78	99.9
3-methylcyclohexanone	0	68.5
	−25	69.5
	−78	77
4-methylcyclohexanone	0	56.5
	−25	58
	−78	60
4-*tert*-butylcyclohexanone	0	65.5
	−78	66
3,3,5-trimethylcyclohexanone	0	98.5
	−25	99.5
	−78	99.7
norcamphor	0	98.5
	−25	>99.9
	−78	>99.9

[a] A 2:1 ratio for ThxBHCl–ketone was used. [b] The yields of alcohols were quantitative.

The stereoselectivity of the reagent toward cyclic ketones was studied also. Unlike thexylborane and diborane, thexylchloroborane–methyl sulfide shows good selectivity toward cyclic ketones. For example, 2-methylcyclohexanone is reduced to the correspondingly less stable isomer (cis alcohol) in a high ratio of 99.9% at −78 °C. These results are summarized in Table III.

Quinones. While *p*-benzoquinone reacts with thexylchloroborane–methylsulfide very slowly, no reaction between anthraquinone and ThxBHCl·SMe_2 under these conditions was observed. These results are summarized in Table IV.[9b]

Carboxylic Acids and Acyl Derivatives. Both caproic and benzoic acids react with thexylchloroborane to evolve 1 equiv of hydrogen rapidly and quantitatively. Caproic acid reacts further to consume one more equivalent of hydride to yield the corresponding aldehyde. Caproaldehyde is formed in almost quantitative yields in less than 0.5 h. The reaction of benzoic acid with ThxBHCl·SMe_2 is also relatively fast and consumes only 1 equiv of hydride for reduction, suggesting the formation of benzaldehyde. However, only a 50% yield of benzaldehyde is obtained after 24 h by analysis with 2,4-dinitrophenylhydrazine.

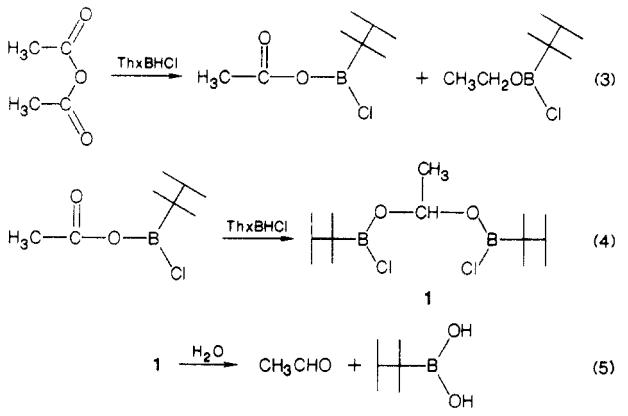
There are very few reagents capable of reducing carboxylic acids to the corresponding aldehydes.[10] Consequently, this appeared to be a promising development and further investigations to improve the procedure and the method of isolation were undertaken. The results for this interestingly direct reduction of carboxylic acids to the corresponding aldehydes have been communicated.[11]

Acetic anhydride consumes almost 3 equiv of hydride in less than 3 h. Apparently, like carboxylic acids, acetic anhydride can also be reduced to the corresponding aldehyde and presumably to the corresponding alcohol segment. The formation of acetaldehyde was confirmed by the preparation of the 2,4-dinitrophenylhydrazone

(4) Sikorski, J. A. Ph.D. Thesis, Purdue University, 1981.
(5) (a) Kulkarni, S. U.; Lee, H. D. Brown, H. C. *J. Org. Chem.* **1980**, *45*, 4542. (b) Brown, H. C.; Sikorski, J. A.; Nazer, B.; Kulkarni, S. U.; Lee, H. D., manuscript in preparation.
(6) Brown, H. C.; Sikorski, J. A.; Kulkarni, S. U.; Lee, H. D. *J. Org. Chem.* **1982**, *47*, 863.
(7) Sikorski, J. A.; Brown, H. C. *J. Org. Chem.* **1982**, *47*, 872.
(8) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. *Organic Syntheses via Boranes*; Wiley-Interscience: New York, 1975.
(9) (a) When the reaction stopped and no further hydride uptake was observed, the sample was analyzed for tetramethylethylene in order to make certain there was no displacement. (b) Tables I, II, IV, V, VI, VII, VIII, IX, X, and XI are available as Supplementary Material. See note at end of publication.
(10) (a) Brown, H. C.; Heim, P.; Yoon, N. M. *J. Org. Chem.* **1972**, *37*, 2942. (b) Fujisawa, T.; Mori, T.; Tsuge, S.; Sato, T. *Tetrahedron Lett.* **1983**, *24*, 1543 and references cited therein.
(11) Brown, H. C.; Cha, J. S.; Nazer, B.; Yoon, N. M. *J. Am. Chem. Soc.* **1984**, *106*, 8001.

derivative. More study is needed to clear up this interesting reduction process.

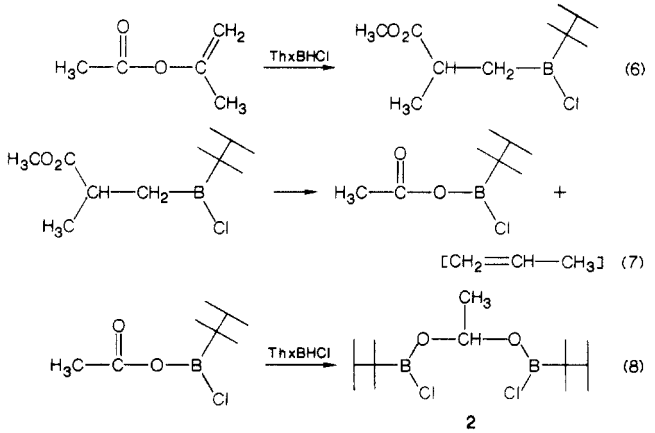
A possible route for this reaction can be postulated as follows. First, a thexylacetoxychloroborane moiety is formed. Then a hydride is transferred to the thexylacetoxychloroborane moiety intermolecularly to give (intermediate) 1. This, upon hydrolysis, generates the corresponding acetaldehyde (eq 3–5). The reaction process



probably goes through a reaction path similar to that in the reduction of carboxylic acids to the corresponding aldehydes.[10a]

Succinic anhydride and phthalic anhydride react at a slow rate with thexylchloroborane under these conditions. The reaction of ThxBHCl·SMe_2 with caproyl chloride and benzoyl chloride is very sluggish; however, both acid chlorides consume 2 equiv of hydride after a long period of time, corresponding to reduction to the alcohols. These results are summarized in Table V.[9b]

Esters and Lactones. Esters, such as ethyl caproate and ethyl benzoate, do not react with thexylchloroborane–methyl sulfide and are considered to be inert toward ThxBHCl·SMe_2 under these conditions. γ-Butyrolactone reacts rather sluggishly with the reagent. The reaction of phthalide is very slow at 0 °C. Isopropenyl acetate utilizes 2 equiv of hydride slowly, and unlike the case of thexylborane, a third hydride uptake in the reduction process is observed. Apparently the reaction involves an initial hydroboration, followed by elimination, to yield propylene, which in turn undergoes a second hydroboration. The reaction intermediate, thexylchloroacetoxyborane, is reduced further to form (intermediate) **2**, which, like the previous cases (carboxylic acids and acetic anhydride), did not react with the excess hydride present under these conditions (eq 6–8).



The corresponding acetaldehyde is detected as the 2,4-dinitrophenylhydrazone derivative. These results are summarized in Table VI.[9b]

Epoxides. Thexylchloroborane shows very little reactivity toward different epoxides. The results are summarized in Table VII.[9b]

Amides and Nitriles. Primary amides undergo a slow reaction with thexylchloroborane. Both caproamide and benzamide evolve hydrogen slowly, and the subsequent reduction is sluggish. Of the tertiary amides studied, none showed a significant reactivity toward ThxBHCl·SMe_2. This was unexpected because under similar conditions thexylborane and disiamylborane react with tertiary amides to yield the corresponding aldehydes.[12]

On the other hand, capronitrile reacts with ThxBHCl·SMe_2 rapidly and 2 equiv of hydride are utilized. Apparently, capronitrile can be reduced to the corresponding amine. Benzonitrile was not as reactive as capronitrile, and only a slow reaction with ThxBHCl·SMe_2 is observed. These results are summarized in Table VIII.[9b]

Nitro Compounds and Their Derivatives. Both nitrobenzene and 1-nitropropane are inert toward thexylchloroborane. Azobenzene does not show any reactivity toward the reagent, while a slow reaction between azoxybenzene and ThxBHCl·SMe_2 is observed. These results are summarized in Table IX.[9b]

Other Nitrogen Compounds. Cyclohexanone oxime undergoes partial hydrogen evolution, accompanied by a slow reduction. Phenyl isocyanate is slowly reduced, but the reduction does not go to completion under these conditions. Pyridine does not show any reactivity toward the reagent, while pyridine *N*-oxide consumes 3 equiv of hydride in 24 h. This reactivity of thexylchloroborane toward nitrogen compounds is very similar to that which has been reported for thexylborane and diborane. These results are summarized in Table X.[9b]

Sulfur Compounds. Of the sulfur compounds studied, only dimethyl sulfoxide reacts with thexylchloroborane under these reaction conditions. All of the other organosulfur compounds, such as disulfides, sulfone, and sulfide, are inert toward the reagent. One and three equivalents of hydrogen, respectively, are evolved when methanesulfonic acid and *p*-toluenesulfonic acid monohydrate are added to the reagent. No reduction of these two sulfonic acids is observed. Cyclohexyl tosylate is inert toward the reagent.

Unlike thexylborane, thexylchloroborane–methyl sulfide reacts with representatives of sulfoxides very quickly and the corresponding sulfides are isolated in high yields and purity. Further research in this area is underway, and the results will be reported shortly. The results of the reaction between thexylchloroborane and sulfur compounds are summarized in Table XI.[9b]

Comparison of the Reducing Characteristics of Diborane, Thexylborane, and Thexylchloroborane. The characteristics of diborane as a reducing agent for organic functional groups were first published some 44 years ago.[13] Since then, data for other valuable borane-substituted reagents, such as thexylborane,[10a] disiamylborane,[12] 9-BBN,[14] and chloroborane,[15] have been reported. In general, borane and borane-substituted compounds have been shown to be acid-type (electrophilic) reducing agents exhibiting a variety of selectivities and strengths.[16]

(12) Brown, H. C.; Bigley, D. B.; Arora, S. K.; Yoon, N. M. *J. Am. Chem. Soc.* **1970**, *92*, 7161.
(13) Brown, H. C.; Schlesinger, H. I.; Burg, A. B. *J. Am. Chem. Soc.* **1939**, *61*, 673.
(14) (a) Brown, H. C.; Krishnamurthy, S.; Yoon, N. M. *J. Org. Chem.* **1976**, *41*, 1778. (b) Krishnamurthy, S.; Brown, H. C. *J. Org. Chem.* **1975**, *40*, 1864.
(15) (a) Ravindran, N. Ph.D. Thesis, Purdue University, 1972. (b) Brown, H. C.; Ravindran, N. *Synthesis* **1972**, 42.
(16) Brown, H. C.; Krishnamurthy, S. *Tetrahedron* **1979**, *35*, 567.

At this point, it would be beneficial to compare the selectivity and reactivity of the new reagent, thexylchloroborane–methyl sulfide, to diborane and thexylborane. Some caution must be exercised in making these comparison dues to the fact that the diborane and thexylborane studies were carried out in THF, while the present reagent, ThxBHCl·SMe_2, was investigated in methylene chloride as the preferred solvent. (The reagent is less stable in THF.)

I. Active Hydrogen Compounds. Thexylchloroborane reacts with alcohols, including tertiary ones, such as 3-ethyl-3-pentanol, very rapidly. A quantitative hydrogen evolution for all of the reactions (with alcohols) is observed in a short period of time. In this respect, thexylchloroborane was much more reactive than either diborane or thexylborane. Phenol also reacts with thexylchloroborane faster than diborane or thexylborane. All of the reagents, ThxBHCl, $ThxBH_2$, and BH_3, are unreactive with respect to hydrogen evolution toward *n*-hexylamine. Diborane exhibits greater reactivity toward both aliphatic and aromatic thiols than do ThxBHCl or $ThxBH_2$. Only a partial reaction involving hydrogen evolution between benzenethiol and ThxBHCl or $ThxBH_2$ is observed, while 1-hexanethiol is unreactive toward both ThxBHCl and $ThxBH_2$ under the experimental conditions.

II. Aldehydes and Ketones. All of the aldehydes and ketones studied react with ThxBHCl, $ThxBH_2$, and BH_3, and quantitative yields of the corresponding alcohols are obtained. Benzophenone is reduced with ThxBHCl in less than 12 h, while a minimum of 24 h and 48 h is required for the corresponding reduction with BH_3 and $ThxBH_2$, respectively.

Cinnamaldehyde reacts with ThxBHCl at a faster rate than is the case for $ThxBH_2$ and BH_3, yielding the corresponding cinnamyl alcohol. It would appear that ThxBHCl might have potential application as a selective reagent to prepare α,β-unsaturated alcohols by reduction of the corresponding α,β-unsaturated aldehydes and ketones, while under very similar conditions, BH_3 and $ThxBH_2$ are much more reactive toward the double bond, yielding the saturated alcohols.

Thexylchloroborane is a more stereoselective reducing agent toward cyclic ketones than is BH_3 or $ThxBH_2$. For example, 2-methylcyclohexanone is reduced to 99.9% cis isomer at −78 °C. However, the reagent ThxBHCl is not as selective toward all of the cyclic ketones, such as has been observed for the hindered trialkylborohydrides.[16,17]

III. Quinones. The reaction between *p*-benzoquinone and BH_3 is rapid and results in the formation of hydroquinone. On the other hand, both ThxBHCl and $ThxBH_2$ are not very reactive toward the quinones studied (*p*-benzoquinone and anthraquinone).

IV. Carboxylic Acids and Acyl Derivatives. Both caproic and benzoic acids react with ThxBHCl to evolve 1 equiv of hydrogen with reduction to the corresponding aldehydes. The reactivity of ThxBHCl toward carboxylic acids differs considerably from that of BH_3 and $ThxBH_2$. Diborane reacts with both acids to evolve 1 equiv of hydrogen with rapid reduction to the corresponding alcohols. Thexylborane is reactive toward aliphatic acids such as caproic acid, with the reduction process usually stopping at the aldehyde stage. On the other hand, the reaction with aromatic acids is very sluggish. The use of ThxBHCl promises to overcome this problem associated with $ThxBH_2$, providing a new, effective method for the reduction of both aliphatic and aromatic carboxylic acids to the corresponding aldehydes in high yields and purity.

Acetic anhydride reacts with ThxBHCl to consume 3 equiv of hydride. This characteristic of ThxBHCl is in contrast to results realized in reactions with BH_3 and $ThxBH_2$. In the reaction between acetic anhydride and BH_3, almost 4 equiv of hydride are consumed. $ThxBH_2$ consumes 2 equiv of hydride very slowly; however, in the reduction of acetic anhydride with ThxBHCl, acetaldehyde is detected as its 2,4-DNP derivative. This is a promising new development, and it is under detailed study.

Acid chlorides are reduced with ThxBHCl very slowly, as had been noted for both BH_3 and $ThxBH_2$.

V. Esters and Lactones. Esters, such as ethyl caproate and ethyl benzoate, are only partially reactive toward BH_3 and $ThxBH_2$ and exhibit almost no reactivity toward ThxBHCl under these experimental conditions. In general, the reactivity of the reagents toward esters follows the order $BH_3 > ThxBH_2 \gg$ ThxBHCl. BH_3 is much more reactive toward γ-butyrolactone than $ThxBH_2$ or ThxBHCl.

Isopropenyl acetate reacts much more quickly with ThxBHCl than is the case for $ThxBH_2$. Almost 3 equiv of hydride are consumed in the case of ThxBHCl, with production of the corresponding acetaldehyde, as identified by its 2,4-DNP derivative. On the other hand, the reactivity of ThxBHCl toward cyclic anhydrides lies between that of BH_3 and $ThxBH_2$.

VI. Epoxides. A slow reaction between 1,2-butylene oxide and BH_3 is observed, while $ThxBH_2$ and ThxBHCl show an even lower reactivity than BH_3 toward epoxides. Styrene oxide exhibits very little reactivity toward ThxBHCl but is reduced by BH_3 and $ThxBH_2$.

VII. Amides and Nitriles. BH_3 and $ThxBH_2$ react with primary and tertiary amides to yield the corresponding amines,[18] while under very similar conditions, only partial reduction of the amides (both primary and tertiary) with ThxBHCl is observed.

Nitriles, with the exception of some aromatic nitriles, are unreactive toward $ThxBH_2$, but ThxBHCl shows an exceptional reactivity toward aliphatic nitriles. Apparently, aliphatic nitriles can be readily reduced to the corresponding amines with ThxBHCl. This reactivity of ThxBHCl toward aliphatic nitriles is very similar to that observed previously for BH_3.

VIII. Nitro Compounds and Derivatives. 1-Nitropropane is not reduced with any of the reagents studied. However, nitrobenzene is partially reduced with $ThxBH_2$, but not reactivity is evident toward BH_3 and ThxBHCl. Azobenzene reacts with diborane to give aniline, but only a sluggish reaction with $ThxBH_2$ and ThxBHCl is observed. Azoxybenzene is reduced with ThxBHCl slowly in 24 h, while BH_3 and $ThxBH_2$ are unreactive toward azoxybenzene.

IX. Other Nitrogen Compounds. Cyclohexanone oxime is reduced slowly with BH_3, while a sluggish reaction was observed with $ThxBH_2$ and ThxBHCl. Phenyl isocyanate reacts with BH_3 and $ThxBH_2$ to an intermediate state; however, a lower reactivity is observed for ThxBHCl. Pyridine does not react with any of the reagents; however, pyridine *N*-oxide consumes 3 equiv of hydride without hydrogen evolution.

X. Sulfur Compounds. All three reagents show very similar reactivity toward sulfur groups. ThxBHCl reacts with different sulfoxides at a much faster rate than $ThxBH_2$ and BH_3.

(17) (a) Brown, H. C.; Krishnamurthy, S. *J. Am. Chem. Soc.* **1972**, *94*, 7159. (b) Krishnamurthy, S.; Brown, H. C. *J. Am. Chem. Soc.* **1976**, *98*, 3383.

(18) Brown, H. C.; Heim, P. *J. Am. Chem. Soc.* **1964**, *86*, 3566.

These results and the comparison study between ThxBHCl, $ThxBH_2$, and BH_3 are summarized in Table XII. In this table, "hydrogen evolution" and "hydride used for reduction" correspond to the ratios of moles of hydrogen evolved and the hydride used per mole of the compound under investigation. In cases where no significant reduction is observed, the values reported are for the longest period for which the observation was made. Where reaction occurs, the data are for the shortest period when essentially constant values of hydrogen evolution and hydride uptake are observed. Thus, the values do not necessarily give the maximum evolution of hydrogen nor the maximum possible utilization of hydride. They merely define the point where further reduction either does not occur or proceeds so slowly as to provide a convenient stopping place for the reduction.

Experimental Section

The reaction flasks and other glassware required for the experiments were predried at 140 °C for several hours, assembled hot, and cooled under a stream of nitrogen. Syringes were assembled and fitted with needles while hot, and then they were cooled. All reactions were carried out under a static pressure of nitrogen in flasks fitted with septum-covered sidearms with use of standard techniques for handling air-sensitive materials.[8]

Material. The compounds examined were the same collection used in the earlier studies.[19] Spectro-quality methylene chloride was degassed and stored under nitrogen over anhydrous potassium carbonate. 2,3-Dimethyl-2-butene was distilled from lithium aluminum hydride and stored under nitrogen. Pentane (99%) was purchased from Phillips and dried over molecular sieves (4 Å) and deoxygenated prior to use. Methyl sulfide (Aldrich) was distilled from a small quantity of 9-BBN prior to use.

GC Analysis. GC analyses were carried out on a Varian Model 1400 FID chromatograph equipped with a Hewlett-Packard 3390A integrator/plotter. Alcohol products were analyzed with use of a 12 ft × 0.125 in. column of 15% THEED (tetrakis(hydroxyethyl)ethylenediamine) on a 100–120-mesh Supelcoport or of 10% Carbowax 20M on 100–120-mesh Supelcoport. Other compounds were analyzed with use of a 12 ft × 0.125 in. column of 10% SP 2100 on a 100–120-mesh Supelcoport. All GC yields were determined with use of a suitable internal standard and authentic mixtures.

Preparation of Trichloroborane–Methyl Sulfate (BCl_3·SMe_2). To a tared, oven-dried, 2-L, three-necked flask equipped with a nitrogen inlet, a magnetic stirring bar, and a condenser tube with stopcock leading to a mercury bubbler was added ~1.5 L of 99% pentane. The flask was cooled to −20 °C in a dry ice–water–ethylene glycol bath. The gaseous BCl_3 was condensed in a graduated cylinder that was placed in a −78 °C bath (170.0 mL, 2 mol).[8] The condensed BCl_3 was added to the pentane solution via a double-ended needle. To this was added 200 mL of methyl sulfide. The addition was very exothermic and should be done dropwise.[20] A white precipitate, presumably BCl_3·SMe_2, was formed. After addition of methyl sulfide was complete, the mixture was stirred for an extra 1 h and then brought to room temperature. The excess pentane was removed via reverse flow through a gas dispersion tube. The precipitate was washed three times with 500 mL of fresh pentane, and the excess pentane was then removed as described above. The slurry of BCl_3·SMe_2 was first dried by using a water aspirator and then dried further under vacuum. Trichloroborane–methyl sulfide was obtained as an off-white solid weighing 359 g (2 mol). No further purification was performed, and the material was used to prepare monochloroborane–methyl sulfide complex.[21]

Preparation of Monochloroborane–Methyl Sulfide Complex in Methylene Chloride (BH_2Cl·SMe_2). Assuming that trichloroborane–methyl sulfide (previous section) is only about 80% pure (to avoid addition of excess BH_3·SMe_2), 320 mL of 10 M BH_3·SMe_2 (3.2 mol) was added to the neat BCl_3·SMe_2 (359 g, 2 mol). The precipitate dissolved in ~20 min, and after 0.5 h, the yellowish color of the solution disappeared. The solution was stirred at room temperature for 6 h, followed by heating at 55 °C for 6 h. ^{11}B NMR spectra of the solution showed it to be an equilibrium mixture of $BHCl_2$·SMe_2 (31.9%), BH_2Cl·SMe_2 (53.8%), and BH_3·SMe_2 (14.3%). The remaining 73 mL of BH_3·SMe_2 was added in four portions. After addition of each portion, the solution was heated at 55 °C for 2 h. The final solution, when examined by ^{11}B NMR, was found to be an equilibrium mixture of $BHCl_2$·SMe_2 (14.3%), BH_2Cl·SMe_2 (71.4%), and BH_3·SMe_2 (14.3%). For the entire reaction, 393 mL of 10 M BH_3·SMe_2 (3.93 mol) was utilized. This corresponds to a 98.13% pure trichloroborane–methyl sulfide complex (BCl_3·SMe_2).

Preparation of Thexylchloroborane–Methyl Sulfide Complex in Methylene Chloride.[22] An oven-dried, 500-mL, round-bottom flask with sidearm, equipped with a magnetic stirring bar and an adaptor, was attached to a mercury bubbler. The flask was flushed with dry nitrogen and then maintained under a static pressure of nitrogen. To this flask was added 71.60 g (0.65 mol) of monochloroborane–methyl sulfide (previous section). The temperature of the mixture was lowered to 0 °C by using an ice–water bath. To this was added 140 mL of methylene chloride and ~8 mL of methyl sulfide. 2,3-Dimethyl-2-butene (61.38 g, 0.73 mol) was added dropwise to the BH_2Cl·SMe_2 solution over a period of 1 h via a double-ended needle. The solution was stirred at 0 °C for 2 h, followed by stirring at room temperature for 5 h. The resulting thexylchloroborane–methyl sulfide was 2 M in hydride content. The ^{11}B NMR spectra showed a doublet at δ 7.43 (relative to BF_3·OEt_2) (J_{B-H} = 128.3 Hz).[3]

General Procedure for Determination of Rate and Stoichiometry. To a 100-mL flask fitted with a sidearm and capped by a rubber septum was added 25 mL of a solution of ThxBHCl (2 M) in methylene chloride (50 mmol in hydride). The flask was immersed in an ice bath. The reaction mixture was diluted with 25 mL of methylene chloride containing 12.5 mmol of the compound to be reduced. This makes the mixture 1 M in hydride and 0.25 M in the compound under investigation. At different time intervals, 4 mL of sample were withdrawn and quenched in a THF–glycerin–2 N HCl hydrolyzing mixture. The hydrogen evolved was measured volumetrically. The reaction was stopped when two or more analyses indicated that no more hydride was taken up. Solutions were transferred by means of a hypodermic syringe. For the reaction of compounds with active hydrogen, the reaction flask was attached to a gas meter to measure the evolved hydrogen.

The reaction of 2-heptanone is described as an example. A 100-mL oven-dried, round-bottom flask, equipped with sidearm and reflux condenser, was connected to a gas meter via a dry ice–acetone trap.[8] The flask was placed in an ice–water bath and cooled down under dry nitrogen. To this flask was added 25 mL of 2 M ThxBHCl. A sample of 2-heptanone (1.43 g, 12.5 mmol) in 25 mL of methylene chloride was prepared and then added to the ThxBHCl solution. This made the mixture 1 M in hydride and 0.25 M in 2-heptanone. No hydrogen evolution was observed. After 0.5 h of reaction time at 0 °C, hydrolysis of a 4-mL aliquot

(19) Previous work is given in the following references. (a) Diborane: Brown, H. C.; Heim, P.; Yoon, N. M. *J. Am. Chem. Soc.* **1970**, *92*, 1637. (b) Thexylborane: ref 10a. (c) Disiamylborane: ref 12. (d) 9-BBN: ref 14. (e) $LiEt_3BH$: Brown, H. C.; Kim, S. C. Krishnamurthy, S. *J. Org. Chem.* **1980**, *45*, 1. (f) $LiAlH_4$: Brown, H. C.; Weissman, P. M. Yoon, N. M. *J. Am. Chem. Soc.* **1966**, *88*, 1458. (g) AH_3: Brown, H. C.; Yoon, N. M. *J. Am. Chem. Soc.* **1966**, *88*, 1464. (h) Li-(*t*-BuO)$_3$AlH: Brown, H. C.; Weissman, P. M. *Israel J. Chem.* **1963**, *1*, 430. (i) Li(MeO)$_3$AlH: Brown, H. C.; Weissman, P. M. *J. Am. Chem. Soc.* **1965**, *87*, 5614. (j) Yoon, N. M.; Cha, J. S. *Taehan Hwahakhoe Chi* **1977**, *21*, 108.

(20) CAUTION: The addition of methyl sulfide to trichloroborane (BCl_3) is an exothermic reaction. The needle might become clogged during the formation of BCl_3·SMe_2; hence, a periodical inspection is recommended.

(21) The best result was obtained when the entire procedure was carried out in one day and the solid BCl_3·SMe_2 was further used immediately to prepare the required BH_2Cl·SMe_2. See also: Brown, H. C.; Ravindran, N. *J. Org. Chem.* **1977**, *42*, 2533.

(22) Although the starting material, monochloroborane–methyl sulfide, is an equilibrium mixture of $BHCl_2$·SMe_2 (minor), BH_2Cl·SMe_2 (major), and BH_3·SMe_2 (minor) during the preparation of thexylchloroborane–methyl sulfide, an equilibrium between thexyldichloroborane ($ThxBCl_2$) and thexylborane ($ThxBH_2$) shifts toward the formation of pure thexylchloroborane–methyl sulfide.[3]

Table XII. Reaction of Representative Organic Derivatives with Excess Diborane, Thexylborane, and Thexylchloroborane at 0 °C

compound[a]	diborane[b] time, h	diborane[b] H_2 evoln	diborane[b] hydride used for redn	thexylborane[c] time, h	thexylborane[c] H_2 evoln	thexylborane[c] hydride used for redn	thexylchloroborane[d] time, h	thexylchloroborane[d] H_2 evoln	thexylchloroborane[d] hydride used for redn
I. Active Hydrogen Compounds									
1-hexanol	0.5	1.00	0.00	0.5	1.00	0.00	0.25	1.00	0.00
benzyl alcohol	0.5	0.98	0.00	0.5	1.00	0.00	0.25	1.00	0.00
3-hexanol	1.0	0.98	0.00	0.5	1.00	0.00	0.25	1.00	0.00
3-ethyl-3-pentanol	12.0	1.00	0.00	0.5	1.00	0.00	0.25	1.00	0.00
phenol	12.0	1.00	0.00	6.0	1.00	0.00	0.5	1.00	0.00
n-hexylamine	20.0	0.13	0.00	14.0	0.00	0.00	24.0	0.00	0.00
1-hexanethiol	12.0	1.00	0.00	10.0	0.00	0.00	12.0	0.00	0.00
benzenethiol	1.0	1.00	0.00	24.0	0.92	0.00	24.0	1.06	0.00
II. Aldehydes and Ketones									
caproaldehyde	2.0	0.00	1.00	0.5	0.00	0.99	0.25	0.00	0.99
benzaldehyde	0.5	0.00	1.00	0.5	0.00	1.05	0.5	0.00	1.01
2-heptanone	1.0	0.00	1.00	6.0	0.00	1.05	3.0	0.00	1.02
norcamphor	1.0	0.03	0.96	3.0	0.03	0.99	3.0	0.00	1.06
acetophenone	2.0	0.00	1.00	3.0	0.00	0.97	1.0	0.00	1.02
benzophenone	24.0	0.00	1.00	48.0	0.00	0.96	12.0	0.00	1.01
cinnamaldehyde	1.0	0.00	2.10	6.0	0.00	2.00	3.0	0.00	1.02
III. Quinones									
p-benzoquinone	6.0	0.90	1.05	12.0	0.46	0.66	24.0	0.04	0.10
anthraquinone	1680	0.00	0.95	72.0	0.00	0.32	24.0	0.00	0.00
IV. Carboxylic Acids and Acyl Derivatives									
caproic acid	0.5	1.00	1.96	12.0	1.00	1.40	3.0	1.02	1.20
benzoic acid	24.0	1.00	2.00	48.0	1.00	0.08	48.0	1.03	1.02
acetic anhydride	24.0	0.00	3.82	0.5	0.00	2.00	3.0	0.00	2.95
succinic anhydride	48.0	0.00	1.32	48.0	0.00	0.75	24.0	0.00	1.30
phthalic anhydride	48.0	0.00	0.87	48.0	0.00	0.52	48.0	0.02	0.52
caproyl chloride	48.0	0.00	1.13	48.0	0.00	0.20	60.0	0.00	0.95
benzoyl chloride	48.0	0.00	0.98	48.0	0.00	0.55	24.0	0.00	0.56
V. Esters and Lactones									
ethyl caproate	24.0	0.00	2.00	48.0	0.00	0.65	12.0	0.00	0.00
ethyl benzoate	24.0	0.00	0.18	48.0	0.00	0.34	24.0	0.00	0.04
phenyl acetate	24.0	0.00	1.67	48.0	0.00	0.25	24.0	0.00	0.04
γ-butyrolactone	24.0	0.00	2.00	24.0	0.00	1.50	48.0	0.11	1.67
phthalide	24.0	0.00	0.13	48.0	0.00	0.34	24.0	0.00	0.15
isopropenyl acetate	24.0	0.00	3.95	1.0	0.00	2.02	72.0	0.00	2.98
VI. Epoxides									
1,2-butylene oxide	72.0	0.04	0.99	48.0	0.00	0.55	36.0	0.00	0.09
styrene oxide	24.0	0.04	1.85	24.0	0.00	1.68	48.0	0.00	0.17
cyclohexene oxide	48.0[e]	0.00	0.94	48.0	0.00	0.41	24.0	0.00	0.07
1-methyl-1,2-cyclohexene oxide	24.0[e]	0.96	0.96	12.0	0.97	1.04	24.0	0.04	0.12
VII. Amides and Nitriles									
caproamide	48.0	1.10	1.00	24.0	0.00	1.62	48.0	0.93	0.43
benzamide	48.0	1.38	1.20	24.0	0.90	1.68	24.0	1.39	0.41
N,N-dimethylcaproamide	12.0	0.00	2.00	72.0	0.00	1.92	48.0	0.00	0.52
N,N-dimethylbenzamide	24.0	0.00	2.00	48.0	0.00	1.99	48.0	0.00	0.16
capronitrile	120.0	0.00	1.94	24.0	0.00	0.42	24.0	0.00	2.01
benzonitrile	80.0	0.00	1.97	24.0	0.00	0.32	24.0	0.00	0.67
VIII. Nitro Compounds and Their Derivatives									
1-nitropropane	96.0	0.00	0.00	40.0	0.00	0.00	48.0	0.00	0.00
nitrobenzene	20.0	0.00	0.00	48.0	0.00	1.95	48.0	0.00	0.00
azobenzene	48.0	0.00	2.00	48.0	0.00	0.25	24.0	0.00	0.09
azoxybenzene	24.0	0.00	0.05	24.0	0.00	0.89	48.0	0.00	2.02
IX. Other Nitrogen Compounds									
cyclohexanone oxime	48.0	0.56	1.22	144.0	0.44	0.98	24.0	0.33	0.88
phenyl isocyanate	24.0	0.00	2.05	48.0	0.00	2.03	48.0	0.00	1.76
pyridine	48.0	0.00	0.00	6.0	0.00	0.04	48.0	0.00	0.00
pyridine *N*-oxide	48.0	0.00	2.76	24.0	0.00	2.90	24.0	0.00	2.99
X. Sulfur Compounds									
di-*n*-butyl disulfide	24.0	0.00	0.00	20.0	0.00	0.00	12.0	0.00	0.00
diphenyl disulfide	72.0	0.00	0.00	20.0	0.00	0.00	12.0	0.00	0.00
methyl *n*-propyl sulfide	40.0	0.00	0.00	24.0	0.00	0.00	12.0[f]	0.00	0.00
dimethyl sulfoxide	48.0	0.83	0.77	6.0	1.00	1.00	0.5	1.00	1.02
diphenyl sulfone	24.0	0.00	0.00	40.0	0.00	0.00	12.0	0.00	0.00
methanesulfonic acid	0.5	1.00	0.00	0.5	1.00	0.00	0.25	1.00	0.00
p-toluenesulfonic acid monohydrate	3.0	2.97	0.00	0.5	3.00	0.00	0.5	3.00	0.00
cyclohexyl tosylate	40.0	0.00	0.00	24.0	0.00	0.00	12.0	0.00	0.00

[a] Hydride to compound ratio: 4:1. [b] 0.33 M BH_3 (1.00 M hydride). [c] 0.50 M RBH_2 (1.00 M hydride). [d] 1.00 M RBHCl (1.00 M hydride); methyl sulfide complex. [e] At 25 °C. [f] Di-*n*-butyl sulfide was used.

of the reaction mixture indicated 3.38 mmol of residual hydride, which means that 0.62 mmol of hydride per millimole of 2-heptanone had been consumed. After 3 h, the analysis showed 2.98 mmol of residual hydride, which indicated that 1.02 mmol of hydride per millimole of the compound had been consumed. These results are summarized in Table II.[9b]

General Procedure for Stereoselectivity Study. The reduction of 2-methylcyclohexanone is described here as representative. To a 100-mL round-bottom flask fitted with a sidearm and capped by a rubber septum was added 2 mL of a solution of ThxBHCl in methylene chloride (4 mmol in hydride). The flask was kept at -78 °C with the aid of a dry ice-acetone bath. To this was added 2 mL of a 1 M 2-methylcyclohexanone solution in methylene chloride (at -78 °C). The reaction mixture was kept at -78 °C for 12 h. It was then hydrolyzed by the addition of 1 mL of 3 N NaOH and 0.5 mL of 30% H_2O_2. The aqueous layer was saturated with anhydrous potassium carbonate, and the organic layer was analyzed by means of GC. The results are summarized in Table III.

Supplementary Material Available: Tables I, II, IV, V, VI, VII, VIII, IX, X, and XI, giving the rate and stoichiometry data (10 pages). Ordering information is given on any current masthead page.

Vinylic Organoboranes. 6. A General Synthesis of (*E*)-Disubstituted Alkenes or Ketones via the (*E*)-(1-Substituted-1-alkenyl)boronic Esters[1]

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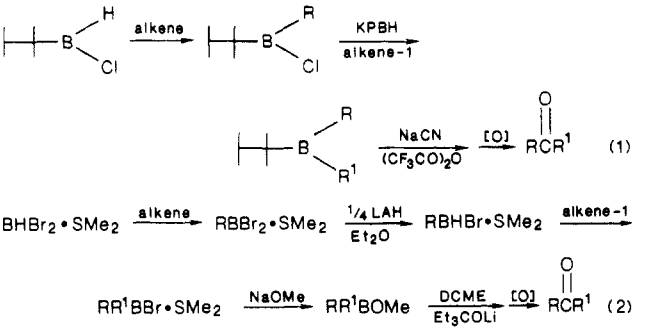
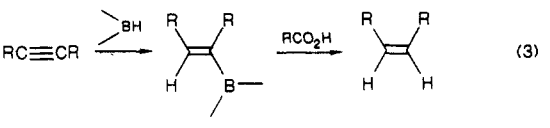
Development of a general stereospecific synthesis of (*E*)-disubstituted alkenes utilizing a variety of hydroborating agents such as monohaloborane, thexylborane, thexylchloroborane, and dibromoborane is discussed. Hydroboration of 1-halo-1-alkynes with dialkylboranes (R_2BH, **1**), thexylmonoalkylborane (ThxBHR, **6**), or alkylbromoborane (RBHBr·SMe_2, **10**) provides the corresponding *B*-(*cis*-1-halo-1-alkenyl)alkylborane derivatives (**2**, **7**, **11**), respectively. Treatment of *B*-(*cis*-1-halo-1-alkenyl)dialkylborane (**2**) with sodium methoxide results in the intramolecular displacement of bromine by one of the alkyl groups on boron to produce *B*-(*trans*-1-alkyl-1-alkenyl)alkylborinate esters **3**. Protonolysis of **3** provides *trans*-alkenes **4** in high yields and in >99% isomeric purities. Similarly, the intermediates **8** and **12** afford the *trans*-disubstituted alkenes in excellent yields and in >99% isomeric purities. Alternatively, oxidation of these vinylboron derivatives, **3**, **8**, and **12**, with alkaline hydrogen peroxide provides the corresponding ketones in excellent yields.

Recent developments in organic synthesis demand greater regio- and stereoselectivities in organic synthesis. Stereospecific synthesis of (*Z*)- and (*E*)-disubstituted alkenes has attracted considerable attention in recent years because most of the insect pheromones belong to this class of compounds with hydroxy or acetate functionality.[3] Since the presence of geometric isomers inhibits the activity of the pheromones,[4] the isomeric purity is a highly important factor in preparing the insect sex attractants.

Another valuable group of organic compounds are the carbonyl derivatives. A number of methods have been developed for the synthesis of ketones using organoboranes via carbonylation, cyanidation, or carbenoidation.[5] All of these reactions involve the conversion of two alkenes into the corresponding ketone. Recently thexylchloroborane[6] (eq 1) and dibromoborane[7] (eq 2) have been found to be the best reagents for this elegant conversion of two alkenes into the corresponding ketones.



The hydroboration reaction readily converts alkenes and alkynes into the corresponding organoboranes that can be conveniently transformed into a variety of organic functional derivatives.[8,9] Monohydroboration of internal alkynes provides the vinylboranes (eq 3). Protonolysis



of these vinylboranes proceeds with retention of configuration, thus providing a stereospecific synthesis of (*Z*)-alkenes in excellent yields.[8] Oxidation of these vinylborane intermediates affords ketones in excellent yields, thus

(1) For preliminary results, see: (a) Brown, H. C.; Basavaiah, D. *J. Org. Chem.* **1982**, *47*, 754. (b) Negishi, E.; Katz, J.-J.; Brown, H. C. *Synthesis* **1972**, 555. (c) Brown, H. C.; Lee, H. D.; Kulkarni, S. U. *Ibid.* **1982**, 195. (d) Brown, H. C.; Basavaiah, D.; Kulkarni, S. U. *J. Org. Chem.* **1982**, *47*, 3808. (e) Kulkarni, S. U.; Lee, H. D.; Brown, H. C. *Synthesis* **1982**, 193.

(2) (a) Postdoctoral research associate on Grant GM 10937 from the National Institutes of Health. (b) Postdoctoral research associate (1978-1982) Purdue University. (c) Postdoctoral research associate (1979-1982) on a grant from Albany International Chemical Division. (d) Graduate student, Purdue University (1971-1974), on grant GM 10937 from the National Institutes of Health.

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