80301-23-1; **5**, 80301-24-2; **6**, 80301-25-3; **6** triacetate, 80301-26-4; **7**, 80301-27-5; **8**, 80301-28-6; **9**, 80301-29-7; **10**, 80301-30-0; **11**, 80301-31-1; **14**, 80301-32-2; **15**, 80301-33-3; **16**, 80301-34-4; **17**, 80301-35-5; **18**, 80301-36-6; **20**, 80301-37-7; **21**, 80301-38-8; **23**, 80301-39-9; **24**, 80301-40-2; **25**, 80301-41-3; **28**, 80301-42-4; **29**, 80301-43-5; **30**, 80301-44-6; 1,5-cyclooctadiene, 111-78-4; 1,4-cyclohexadiene, 628-41-1; 1,3-cyclohexadiene, 592-57-4; *N*-methylnitrone, 54125-41-6; *N*-phenylnitrone, 4745-47-5.

Hydroboration. 59. Thexylchloroborane–Methyl Sulfide. A New Stable Monohydroborating Agent with Exceptional Regioselectivity

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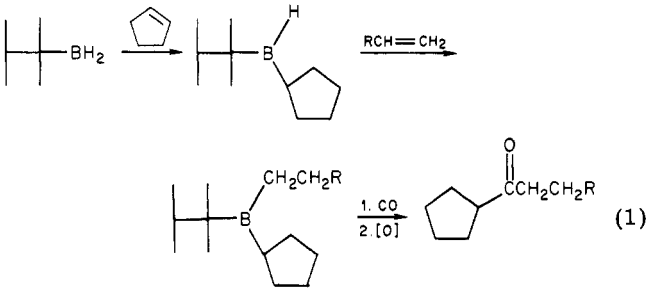
Under selected conditions, the hydroboration of 2,3-dimethyl-2-butene with 1 equiv of $BH_2Cl{\cdot}SMe_2$ proceeds cleanly in solution (CH_2Cl_2, $ClCH_2CH_2Cl$, Et_2O) or under neat conditions to give exclusively the monohydroboration product, thexylchloroborane–methyl sulfide (ThxBHCl·SMe_2). Stock solutions of ThxBHCl·SMe_2 in CH_2Cl_2 or Et_2O have unusual thermal stability at ambient temperatures or below. The hydroboration of reactive olefins, such as terminal or unhindered disubstituted alkenes, with ThxBHCl·SMe_2 proceeds quantitatively with high regiospecificity in CH_2Cl_2, $ClCH_2CH_2Cl$, Et_2O, and THF to produce isomerically pure thexylalkylchloroborane intermediates. Subsequent oxidation produces the desired alcohols in nearly quantitative yield with high regiospecificity. With less reactive olefins, such as 1-methylcyclopentene, cyclohexene, or α-pinene, ^{11}B NMR showed that the desired thexylalkylchloroborane products were contaminated with alkyldichloroborane species, indicating that a significant amount of product redistribution had occurred. This was reflected in a lower observed regioselectivity in the hydroboration of some less reactive alkenes with ThxBHCl·SMe_2.

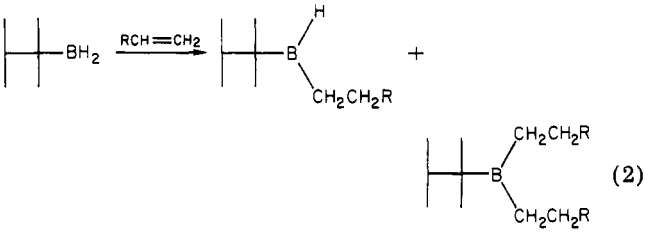
The thexyl (2,3-dimethyl-2-butyl, Thx) group is a particularly valuable blocking group in several reactions where coupling of two alkyl groups on boron is desired. For example, sequential hydroboration with thexylborane provides highly pure unsymmetrical trialkylboranes. Subsequent carbonylation or cyanidation produces the corresponding unsymmetrical ketones in high yield[2] (eq 1).



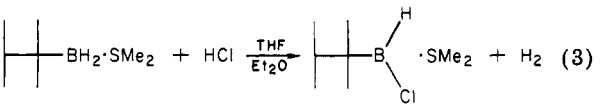
(1)

In this sequence, it is important to introduce first a relatively hindered alkene, such as cyclopentene or 2-methyl-1-butene, since treatment of thexylborane with unhindered terminal alkenes cannot be controlled to give exclusively monohydrboration[3] (eq 2). Consequently, this approach fails when one attempts to stitch together two different primary alkyl groups.

Two solutions to this problem utilizing thexylchloroborane (ThxBHCl) derivatives have recently been developed independently. Zweifel and Pearson have reported the successful synthesis of thexylchloroborane–methyl sulfide from thexylborane–methyl sulfide and hydrogen chloride[4] (eq 3). This reagent hydroborates terminal alkenes cleanly and quantitatively.



(2)



(3)

An alternative approach, developed in this laboratory, provides a direct route to this new reagent via hydroboration. The monohydroboration of 2,3-dimethyl-2-butene with various monochloroborane complexes has been examined in detail.[5] Whereas monomeric ThxBHCl·THF could be obtained cleanly from $BH_2Cl{\cdot}THF$, the product resulting from hydroboration of 2,3-dimethyl-2-butene with $BH_2Cl{\cdot}OEt_2$ was demonstrated to be a rapidly equilibrating mixture of $ThxBH_2$, $ThxBCl_2$, and $ThxBHCl{\cdot}OEt_2$. Treatment of either of these reagents with terminal alkenes led to complex mixtures in which the desired thexylalkylchloroborane was contaminated with significant amounts of trialkylborane and alkyldichloroborane species.

On the other hand, monohydroboration of 2,3-dimethyl-2-butene with $BH_2Cl{\cdot}SMe_2$ in methylene chloride proceeded cleanly to give pure thexylchloroborane–methyl

(1) (a) Graduate research assistant on temporary academic leave from Monsanto Agricultural Products Co. (b) Postdoctoral research associate, Purdue University. (c) Postdoctoral research associate on a grant from Albany International Chemicals Division.

(2) Brown, H. C.; Negishi, E. *J. Am. Chem. Soc.* **1967**, *89*, 5285–5287. Pelter, A.; Smith, K.; Hutchings, M. G.; Rowe, K. *J. Chem. Soc., Perkin Trans. 1* **1975**, 129–138. For a review of the synthetic applications of thexylborane, see: Negishi, E.; Brown, H. C. *Synthesis* **1974**, 77–89.

(3) Brown, H. C.; Negishi, E.; Katz, J.-J. *J. Am. Chem. Soc.* **1975**, *97*, 2791–2798.

(4) Zweifel, G.; Pearson, N. R. *J. Am. Chem. Soc.* **1980**, *102*, 5919–5920.

(5) Brown, H. C.; Sikorski, J. A. *Organometallics* **1982**, *1*, 28–37.

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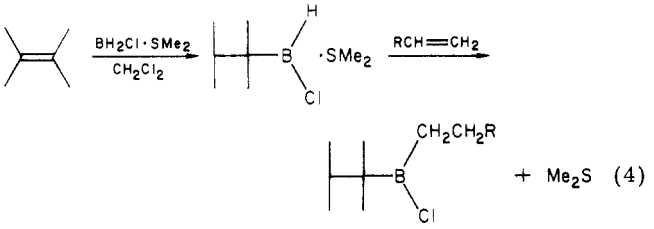
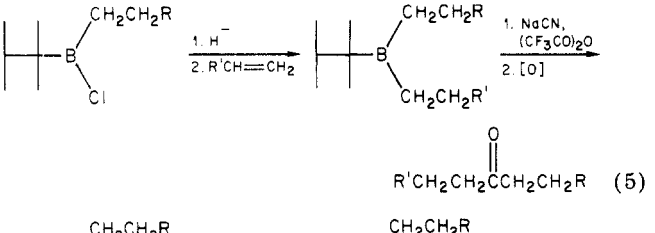
sulfide[5] (ThxBHCl·SMe_2). A preliminary investigation indicated that this reagent hydroborates representative olefins cleanly and quantitatively to give isomerically pure thexylalkylchloroboranes[5,6] (eq 4).



(4)

These intermediates have been successfully applied to the synthesis of unsymmetrical ketones[4,7] (eq 5) and a regioselectivie synthesis of trans alkenes[8] (eq 6). These preliminary results indicate that the thexylalkylchloroboranes are valuable intermediates for coupling two different primary alkyl groups attached to boron. As such, they represent a useful new class of reagents in organic synthesis. Consequently, we have undertaken a detailed study of the preparation, stability, and hydroboration properties of thexylchloroborane–methyl sulfide to establish the scope and utility of this new reagent.



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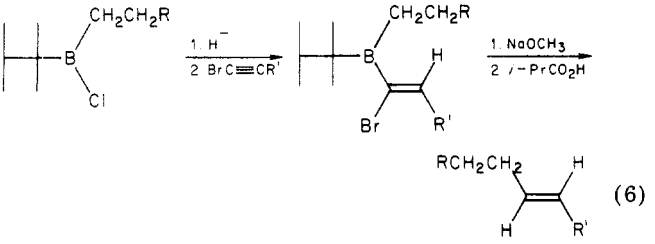


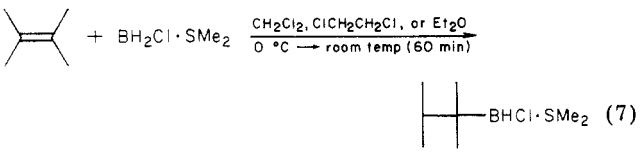
(6)

Results and Discussion

Effect of Solvent on the Monohydroboration of 2,3-Dimethyl-2-butene with BH_2Cl·SMe_2. A major advantage of the neat form of BH_2Cl·SMe_2[9] is that hydroborations can be conveniently carried out in either ethereal or nonethereal solvents. Consequently, a detailed study was undertaken to determine the effect of solvents on the monohydroboration of 2,3-dimethyl-2-butene with BH_2Cl·SMe_2. Four solvents were examined (CH_2Cl_2, $ClCH_2CH_2Cl$, Et_2O, THF) to determine the effect of increased solvent base strength on the reaction.

The rate of reaction of 2,3-dimethyl-2-butene (2.0 M) with BH_2Cl·SMe_2 (2.0 M) was measured in CH_2Cl_2 (Table I). At 25 °C, the reaction was essentially complete after 10 min. However, at this temperature, the reaction was sufficiently exothermic to reflux the CH_2Cl_2. To circumvent this problem, we initially mixed the reagents at 0 °C and then brought them to room temperature. Under these conditions, the reaction was 99% complete after 1 h. Essentially identical reaction times were observed by ^{11}B NMR for all four solvents. The resulting products were fully characterized by chemical and spectral analyses.

When CH_2Cl_2, $ClCH_2CH_2Cl$, or Et_2O were used as solvents, essentially identical products were observed. Chemical analysis for active hydride and chloride was consistent with the formation of a 1:1 adduct. Oxidation of 10 mmol of each of these solutions gave essentially quantitative yields (>95%) of 2,3-dimethyl-2-butanol by GLC. Methanolysis of 10 mmol of the CH_2Cl_2 reagent produced an essentially quantitative (9.7 mmol) yield of $ThxB(OMe)_2$ by ^1H NMR. ^{11}B NMR of this methanolysis product confirmed that $ThxB(OMe)_2$ was the only (>99%) boron species produced (δ 30.9). Similar results were observed with $ClCH_2CH_2Cl$ and Et_2O. In CH_2Cl_2, the infrared spectrum of this reagent exhibited a strong terminal B–H absorption at 2450 cm^{-1}. No bridged B–H species were observed by IR. These observations are consistent with the clean and quantitative formation of ThxBHCl·SMe_2 from the reaction of 2,3-dimethyl-2-butene with 1 equiv of BH_2Cl·SMe_2 in CH_2Cl_2, $ClCH_2CH_2Cl$, or Et_2O (eq 7).



(7)

The ^{11}B NMR spectral data observed for each of these ThxBHCl·SMe_2 solutions are summarized in Table II. In CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O essentially clean (>95%) doublets are observed. In each case a small signal (2.5%) was observed (δ 20.7, CH_2Cl_2; δ 21.5, $ClCH_2CH_2Cl$; δ 19.8, Et_2O), presumably due to the dimer or uncomplexed monomer of ThxBHCl. This value is in close agreement with

Table I. Rate of Reaction of 2,3-Dimethyl-2-butene with BH_2Cl·SMe_2 in CH_2Cl_2 (2.0 M)

BH_2Cl·SMe_2, mmol	2,3-dimethyl-2-butene, mmol	time, min	alkene reacted, mmol
10[a]	10	2	8.8
		6	9.0
		10	9.4
		30	9.6
10[b]	10	5	7.2
		10	8.2
		15	8.9
		30	9.6
		60	9.9
		90	9.9
10[b]	20	30	9.9
		60	9.9
		240	9.9
		1440	9.9

[a] At 25 °C. [b] The reagents were mixed at 0 °C, and then stirred at 25 °C.

Table II. Observed ^{11}B NMR Chemical Shifts for Thexylchloroborane–Methyl Sulfide

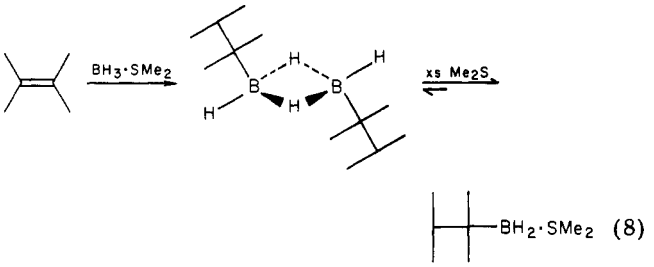
solvent	^{11}B NMR chemical shift, ppm	multiplicity	J_{BH}, Hz
neat	7.0	br d	61
CH_2Cl_2	6.9	d	128
$ClCH_2CH_2Cl$	7.3	d	129
Et_2O	7.0	d	131
THF[a]	13.0	d	136

[a] Contains 5% of $BHCl_2$·THF (δ 7.1) and BH_3·THF (δ -1.1).

(6) Brown, H. C.; Sikorski, J. A.; Kulkarni, S. U.; Lee, H. D. *J. Org. Chem.* **1980**, *45*, 4540–4542.
(7) (a) Kulkarni, S. U.; Lee, H. D.; Brown, H. C. *J. Org. Chem.* **1980**, *45*, 4542–4543. (b) Kulkarni, S. U.; Lee, H. D.; Brown, H. C., *Synthesis*, in press.
(8) Brown, H. C.; Lee, H. D.; Kulkarni, S. U., *Synthesis*, in press.
(9) Brown, H. C.; Ravindran, N.; Kulkarni, S. U. *J. Org. Chem.* **1979**, *44*, 2417–2422.

that observed previously for $ThxBHCl{\cdot}OEt_2$[5] (δ 17.7). Gradual addition of small amounts of excess methyl sulfide caused this signal to move toward the doublet. When 20% excess methyl sulfide was added, this small peak disappeared completely in each case. Consequently, stock solutions of $ThxBHCl{\cdot}SMe_2$ were routinely prepared with 20% excess methyl sulfide. These results confirm the earlier conclusion that this reaction proceeds cleanly to the 1:1 adduct in CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O (eq 7). The reaction proceeds cleanly to $ThxBHCl{\cdot}SMe_2$ in spite of the fact that the $BH_2Cl{\cdot}SMe_2$ starting material contains approximately 15% each of $BHCl_2{\cdot}SMe_2$ and $BH_3{\cdot}SMe_2$ by ^{11}B and ^{13}C NMR.[10] There is absolutely no evidence to indicate that either of these species is present to any significant extent in the $ThxBHCl{\cdot}SMe_2$ products or that these products contain any redistributed $ThxBCl_2$ (δ 65.0)[5] or $(ThxBH_2)_2$ (δ 24.0)[5] species.

These results are in contrast to those observed when thexyl-borane is prepared from $BH_3{\cdot}SMe_2$[11] (eq 8). In this



(8)

case, ^{11}B NMR indicates that >98% of the product is dimeric thexylborane (δ 24.2). Only trace amounts of the corresponding monomer complex, $ThxBH_2{\cdot}SMe_2$, are observed by ^{11}B NMR (triplet, δ −1.7, J_{BH} = 110 Hz). Gradual addition of excess methyl sulfide shifts the equilibrium toward the complex. However, even when neat thexylborane[11b] is dissolved in methyl sulfide at a concentration of 1.2 M, ^{11}B NMR indicates that the dimer still comprises 20% of the mixture. It is only at a concentration of 0.5 M (25 equiv) in methyl sulfide that the monomer complex is observed exclusively.[10]

In THF the reaction between 2,3-dimethyl-2-butene and 1 equiv of $BH_2Cl{\cdot}SMe_2$ is less clean. After 60 min at 25 °C at a concentration of 2.0 M, ^{11}B NMR (Table II) indicated that the desired $ThxBHCl{\cdot}SMe_2$ product had formed. However, this product was contaminated with significant amounts (>5%) of $BHCl_2{\cdot}THF$ (δ 7.1) and $BH_3{\cdot}THF$ (δ −1.1), indicating that all of the available hydride had not been utilized. This was reflected in a lower overall (80–85%) observed yield of 2,3-dimethyl-2-butanol by GLC after oxidation. In addition, after methanolysis, ^{11}B NMR indicated that a significant (10–15%) amount of $(MeO)_3B$ (δ 18.2) was produced along with the desired $ThxB(OMe)_2$ (δ 32.3). Longer reaction times of 3–5 h failed to improve these results. After only a few hours at 25 °C, ^{11}B NMR indicated that significant decomposition of this reagent had occurred.

Effect of Solvent on the Reaction of $ThxBHCl{\cdot}SMe_2$ with 1-Octene. Before undertaking a detailed study of the hydroboration properties of $ThxBHCl{\cdot}SMe_2$, we examined the effect of each of these solvents on the reaction of $ThxBHCl{\cdot}SMe_2$ with 1-octene. The hydroboration of 1-octene with $ThxBHCl{\cdot}SMe_2$ proceeded quantitatively with high regioselectivity in CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O.

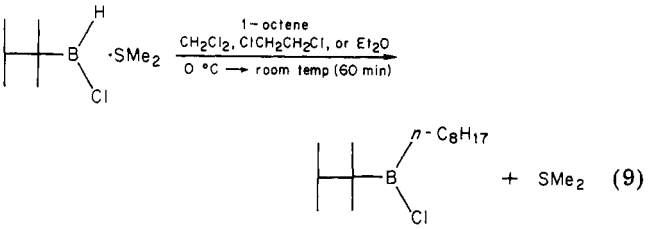
(10) Unpublished observation by H. C. Brown and J. A. Sikorski.
(11) (a) Schwier, J. R. Ph.D. Thesis, Purdue University, West Lafayette, IN, 1977. (b) Brown, H. C.; Mandal, A. K.; Kulkarni, S. U. *J. Org. Chem.* **1977**, *42*, 1392–1398.

Table III. Solvent Effects on the Regioselectivity of the Hydroboration of 1-Octene (2.0 M) with $ThxBHCl{\cdot}SMe_2$ (2.0 M)

	oxidation products, %		distribution of products, %	
solvent	ThxOH	octanols	1-octanol	2-octanol
CH_2Cl_2 [a]	90	97	99.5	0.5
$ClCH_2CH_2Cl$ [a]	99	100	99.4	0.6
Et_2O [a]	100	100	99.2	0.8
THF [a]	82	98	96.4	3.6
CH_2Cl_2 [b]	86	100	99.2	0.8
Et_2O [b]	86	100	99.0	1.0
THF [b]	86	100	99.1	0.9

[a] The $ThxBHCl{\cdot}SMe_2$ was prepared directly in the appropriate solvent at 2.0 M. [b] The $ThxBHCl{\cdot}SMe_2$ reagent was first prepared neat and then diluted to 2.0 M in the appropriate solvent.

Ten millimoles of cold $ThxBHCl{\cdot}SMe_2$ (2.1 M in CH_2Cl_2) was added to 10 mmol of 1-octene in sufficient CH_2Cl_2 at 0 °C to make the overall reactant concentration 1.0 M. After 5 min at 0 °C, the resulting solution was stirred at 25 °C. After 1 h, GLC analysis showed that all of the 1-octene had been consumed. ^{11}B NMR of the product solution indicated that all of the $ThxBHCl{\cdot}SMe_2$ starting material had disappeared with concomitant formation of a pure (>98%) dialkylchloroborane species (δ 79.2). After methanolysis, ^{11}B NMR showed a very clean (>95%) conversion of this product to a dialkylborinate species (δ 54.7). A small amount (2–3%) of $ThxB(OMe)_2$ (δ 30.5) was also observed along with a trace of $(MeO)_3B$ (δ 18.1). After oxidation with alkaline hydrogen peroxide, an essentially quantitative yield (9.7 mmol) of isomeric octanols was observed by GLC. 1-Octanol constituted >99% of the mixture. Similarly, clean conversions of 1-octene to 1-octanol were observed when either $ClCH_2CH_2Cl$ or Et_2O was substituted for CH_2Cl_2. The results are summarized in Table III. These results led us to conclude that isomerically pure thexylalkylchloroboranes could be conveniently prepared from the hydroboration of terminal olefins with $ThxBHCl{\cdot}SMe_2$ in CH_2Cl_2, $ClCH_2CH_2Cl$, or Et_2O (eq 9).



(9)

The hydroboration of 1-octene was less clean when $ThxBHCl{\cdot}SMe_2$ freshly prepared in THF was used as the hydroborating agent. Ten millimoles of neat 1-octene was added to 10 mmol of $ThxBHCl{\cdot}SMe_2$ (2.0 M) in sufficient THF at 0 °C to make the overall reactant concentration 1.0 M. After 5 min at 0 °C, the resulting solution was stirred at 25 °C. After 1 h, GLC analysis showed that all of the 1-octene had been consumed. ^{11}B NMR of the product solution, however, indicated that a highly complex mixture of products was obtained. After methanolysis, ^{11}B NMR indicated that the desired dialkylborinate product (δ 54.4) was contaminated with significant quantities of trialkylborane (δ 88) and alkylboronate (δ 31.3) species, indicating that redistribution had occurred.[5] After oxidation, GLC analysis showed that a low yield (8.2 mmol) of 2,3-dimethyl-2-butanol had been produced along with a quantitative yield (9.8 mmol) of isomeric octanols. In

this case, however, 2-octanol comprised almost 4% of the product mixture (Table III). Our previous study of the reaction of 2,3-dimethyl-2-butene with 1 equiv of $BH_2Cl{\cdot}SMe_2$ in THF indicated that the resulting $ThxBHCl{\cdot}SMe_2$ product contained at least two other hydride species, $BHCl_2{\cdot}THF$ and $BH_3{\cdot}THF$, because of incomplete reaction. Apparently, these hydride species catalyze the redistribution reaction, causing both the complex product mixture and the low regioselectivity.

THF was demonstrated to be an appropriate solvent for the hydroboration of 1-octene with pure $ThxBHCl{\cdot}SMe_2$ by the following experiments. Ten millimoles of cold $ThxBHCl{\cdot}SMe_2$ (2.1 M in CH_2Cl_2) was added to a solution of 1-octene (2.0 M) in THF at 0 °C. After 5 min at 0 °C, the resulting solution was stirred at 25 °C. After 1 h, ^{11}B NMR indicated that all of the $ThxBHCl{\cdot}SMe_2$ starting material had disappeared with concomitant formation of a fairly pure (>90%) dialkylchloroborane product (δ 79.4). After oxidation, GLC analysis showed the formation of 9.6 mmol of 2,3-dimethyl-2-butanol and 9.2 mmol of isomeric octanols. 2-Octanol comprised only 1.4% of the mixture.

Alternatively, a flask containing 10 mmol of freshly prepared $ThxBHCl{\cdot}SMe_2$ in CH_2Cl_2 was connected to a water aspirator to remove all of the CH_2Cl_2. A clear water–white oil (2.0 g, 10 mmol) of neat $ThxBHCl{\cdot}SMe_2$ resulted. This was dissolved in enough THF at 0 °C to make the reagent 1.0 M. When 10 mmol of neat 1-octene was added. After 5 min at 0 °C, the resulting solution was stirred at 25 °C for 1 h. ^{11}B NMR indicated that all of the $ThxBHCl{\cdot}SMe_2$ starting material had been consumed with fairly clean (>90%) conversion to a dialkylchloroborane product (δ 79.2). After oxidation, GLC analysis showed the formation of 9.2 mmol of 2,3-dimethyl-2-butanol and a quantitative yield (10.0 mmol) of isomeric octanols with 2-octanol comprising 2% of the mixture.

The preparation of $ThxBHCl{\cdot}SMe_2$ from monohydroboration of 2,3-dimethyl-2-butene with $BH_2Cl{\cdot}SMe_2$ proceeds cleanly in CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O. Subsequent reaction of these solutions with 1-octene leads to the clean, quantitative formation of isomerically pure thexylalkylchloroboranes. In THF, however, the reaction of $BH_2Cl{\cdot}SMe_2$ with 2,3-dimethyl-2-butene does not proceed to completion. Attempts to utilize this solution in the hydroboration of 1-octene leads to redistribution of the desired product. This approach to $ThxBHCl{\cdot}SMe_2$ is therefore complementary to that developed independently by Zweifel and Perason[4] (eq 3) where pure $ThxBHCl{\cdot}SMe_2$ can be prepared conveniently in THF and utilized for subsequent hydroborations.

Preparation of Neat $ThxBHCl{\cdot}SMe_2$. Since THF was found to be a problem only during the preparation of $ThxBHCl{\cdot}SMe_2$ and not during subsequent hydroboration reactions, it occurred to us that this problem might be circumvented by employing neat $ThxBHCl{\cdot}SMe_2$. Once the pure reagent is formed under neat conditions, it seemed likely that subsequent hydroborations could occur cleanly in any appropriate solvent. Consequently, we examined the synthesis of neat $ThxBHCl{\cdot}SMe_2$ from 2,3-dimethyl-2-butene and $BH_2Cl{\cdot}SMe_2$, using a modification of the procedure previously developed for the synthesis of neat thexylborane.[11b]

Accordingly, 20 mmol of neat $BH_2Cl{\cdot}SMe_2$ (8.6 M) was cooled to −10 °C in a flask immersed in an ice–salt bath. Then 20 mmol of cold neat 2,3-dimethyl-2-butene was added dropwise over a 10-min period. After 10 min at −10 °C, the ice–salt bath was replaced with an ice–water bath and the resulting solution was stirred at 0 °C for 2.5–3 h. ^{11}B NMR of the resulting clear, viscous liquid indicated clean formation of neat $ThxBHCl{\cdot}SMe_2$ as a broad doublet (δ 7.0, J_{BH} = 61 Hz). After methanolysis, ^{11}B NMR showed that $ThxB(OMe)_2$ (δ 31.0) was the only (>99%) boron species produced.

Table IV. Thermal Stability of 2.1 M $ThxBHCl{\cdot}SMe_2$ in CH_2Cl_2 or Et_2O at 20–25 °C

solvent	time, days	retention of hydride, %	distribution of 2,3-dimethylbutanol after oxidation: 2-ol, %	1-ol, %
CH_2Cl_2	0	100	99.4	0.6
	2	101	99.3	0.7
	4	100	99.2	0.8
	8	100	99.1	0.9
	15	101	98.9	1.1
	21	100	98.7	1.3
	30	101	98.8	1.2
	45	100	98.4	1.6
	60	100	98.4	1.6
Et_2O	0	100	99.3	0.7
	2	99	99.2	0.8
	4	99	99.2	0.8
	8	99	99.0	1.0
	15	98	99.0	1.0
	30	99	98.9	1.1
	60	99	98.1	1.9

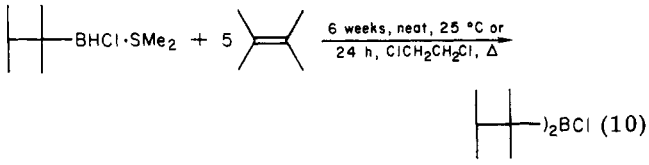
Twenty-millimole samples of freshly prepared neat $ThxBHCl{\cdot}SMe_2$ were dissolved in either CH_2Cl_2, Et_2O, or THF at 0 °C to a concentration of 2.0 M and were then treated with 20 mmol of neat 1-octene. After 5 min at 0 °C, the resulting solutions were stirred at room temperature. After 1 h, ^{11}B NMR indicated that all of the $ThxBHCl{\cdot}SMe_2$ starting material had been utilized when concomitant clean conversion (>95%) to a dialkylchloroborane product (δ 79.1, CH_2Cl_2; 79.2, Et_2O; 79.6, THF). After oxidation, GLC analysis showed the essentially quantitative formation of 2,3-dimethyl-2-butanol and 1-octanol (Table III) with high regiospecificity.

Thermal Stability of $ThxBHCl{\cdot}SMe_2$. Stock solutions of $ThxBHCl{\cdot}SMe_2$ in either CH_2Cl_2 or Et_2O are quite stable for prolonged periods at room temperature. No significant change is observed by ^{11}B NMR when these solutions were stored for 2 months at room temperature or for 7 months at 0 °C. As shown in Table IV, these solutions are much more stable with respect to isomerization of the thexyl group into the 2,3-dimethyl-1-butyl group than are solutions of thexylborane.[12] THF solutions of thexylborane undergo 9% isomerization after 16 days at 20–25 °C. However, with solutions of $ThxBHCl{\cdot}SMe_2$, less than 2% of such isomerization is observed after 60 days at 20–25 °C. At concentrations approaching 2%, this isomerization can be observed by ^{11}B NMR as a weak signal at δ 80, presumably due to a (2,3-dimethyl-1-butyl)thexylchloroborane species. For prolonged use in quantitative work, stock solutions of these reagents were routinely stored under nitrogen at 0 °C. Under these conditions, a sample of $ThxBHCl{\cdot}SMe_2$ (2.1 M in CH_2Cl_2) underwent only 2% isomerization of the thexyl group after 7 months at 0 °C.

Stability of $ThxBHCl{\cdot}SMe_2$ toward Excess 2,3-Dimethyl-2-butene. As shown in Table I, no additional uptake of 2,3-dimethyl-2-butene is observed when a twofold excess of this reagent is employed under the standard reaction conditions. The subsequent reaction of $ThxBHCl{\cdot}SMe_2$ with excess 2,3-dimethyl-2-butene to form $(Thx)_2BCl$ was observed to be an extremely slow reaction

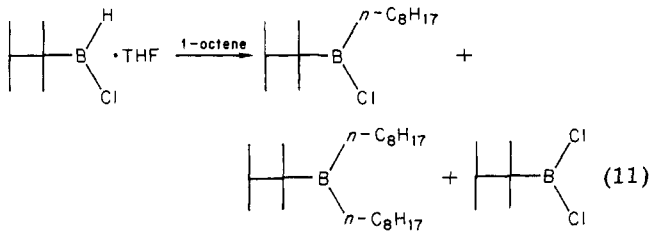
(12) Zwiefel, G.; Brown, H. C. *J. Am. Chem. Soc.* **1963**, *85*, 2066–2072.

in solution at 25 °C. Even when 5 equiv of neat 2,3-dimethyl-2-butene was added to ThxBHCl·SMe_2 (2.1 M) in CH_2Cl_2, only 50% reaction was observed by ^{11}B NMR after 7 days at 25 °C. Treatment of the neat ThxBHCl·SMe_2 with 5 equiv of 2,3-dimethyl-2-butene was also found to be a slow process at 25 °C. Several weeks were required under these conditions for the reaction to reach completion (eq 10). After oxidation, GLC analysis showed that an

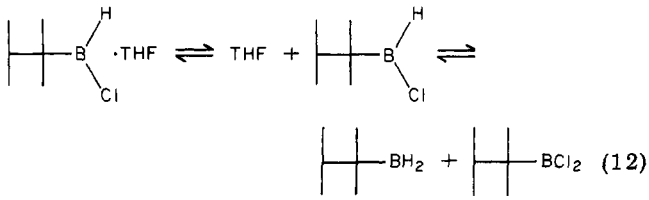


87% yield of 2,3-dimethyl-2-butanol was obtained along with 4% 2,3-dimethyl-1-butanol. By taking advantage of the higher boiling point of $ClCH_2CH_2Cl$, however, treatment of ThxBHCl·SMe_2 with 5 equiv of 2,3-dimethyl-2-butene proceeded cleanly to give a dialkylchloroborane product (δ 79.5) after 24 h at reflux. Oxidation, followed by GLC analysis, showed that an 82% yield of 2,3-dimethyl-2-butanol was obtained along with 14% of 2,3-dimethyl-1-butanol, indicating that more isomerization of the thexyl group had occurred under these conditions.

Hydroboration of Olefins with ThxBHCl·SMe_2. In previous approaches to a synthetically useful ThxBHCl reagent, problems associated with product redistribution occurred when these reagents were used to hydroborate terminal alkenes.[5] For example, treatment of 2,3-dimethyl-2-butene with 1 equiv of BH_2Cl·THF produced fairly clean ThxBHCl·THF. However, upon subsequent reaction with 1-octene, the desired dialkylchloroborane product contained significant quantities of trialkylborane and alkyldichloroborane species (eq 11). This mixture of



products presumably results from a preequilibration of the starting material (eq 12). Indeed, when ThxBHCl was prepared in the more weakly basic solvent, Et_2O, spectroscopic evidence indicated that the disproportion products described by eq 12 were the major products of the reaction.[5]



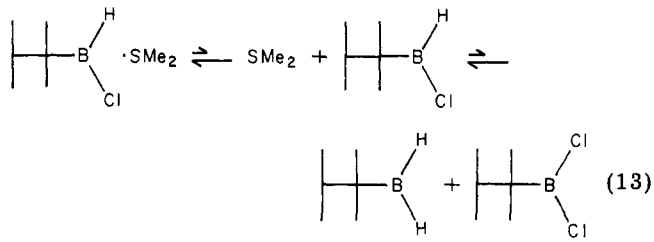
On the other hand, as discussed earlier, ThxBHCl·SMe_2 hydroborates 1-octene cleanly and quantitatively (>95%) to give the desired thexylalkylchloroborane derivative (eq 9). Any products due to preequilibration of the ThxBHCl·SMe_2 must comprise less than 5% of the total obtained from the reaction of ThxBHCl.·SMe_2 with 1-octene. Indeed, after methanolysis of this hydroboration product, ^{11}B NMR shows a small amount (2–3%) of $ThxB(OMe)_2$ which may arise from a $ThxBCl_2$ species. Apparently, in CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O, methyl

Table V. Hydroboration of Representative Alkenes with ThxBHCl·SMe_2 in CH_2Cl_2 at 25 °C[a]

alkene	reaction time,[b] h	oxidation products,[c] % ThxOH	ROH
1-decene	1.0	92	92
1-hexene	1.0	94	98
1-octene	1.0	90	96
cycloheptene	1.0	100	90
cyclooctene	1.0	98	98
2-methyl-1-butene	1.0	98	99
4-pentenyl acetate[d]	1.5		
2-methyl-2-butene	1.5	100	94
cis-2-pentene	2.0	90	91
cis-3-hexene	2.0	100	91
cis-4-methyl-2-pentene	2.0	98	89
cyclopentene	2.0	91	89
2-methyl-1-pentene	3.0	94	91
p-methoxystyrene	3.0	100	99
1-methylcyclopentene	5.0	98	89
styrene	6.0	92	94
norbornene	10.0	98	98
cis-4,4-dimethyl-2-pentene[e]	10.0	100	94
cyclohexene[e]	12.0	100	90
α-methylstyrene	13.0	97	97
1-methylcyclohexene[e]	36.0	95	94
α-pinene[e]	120	96	82

[a] Reactants were mixed at 0 °C and then brought to 25 °C. [b] Determined by ^{11}B NMR. [c] Determined by GLC, using a suitable internal standard. [d] Oxidation products not analyzed. [e] Reactants were mixed and stirred at 25 °C.

sulfide forms a relatively stable adduct with ThxBHCl, which does not undergo significant equilibration (eq 13).



In THF, however, the available ^{11}B NMR evidence (Table II) indicates that methyl sulfide has been displaced from the ThxBHCl complex by higher concentrations of the more basic ligand, THF. ^{11}B NMR, therefore, suggests that ThxBHCl·THF is the reactive species in this system. However, the hydroboration of 1-octene proceeds cleanly and quantitatively in THF when pure ThxBHCl·SMe_2 (neat or as Zweifel's reagent[4]) starting material is used in the reaction. The product mixture observed previously with ThxBHCl·THF[5] (eq 11) must therefore result from a redistribution of the product induced by trace amounts of BH_3·THF in the starting material. Such hydride induced redistribution reactions have been observed previously.[13] The low stability observed for the product resulting from the reaction of 2,3-dimethyl-2-butene with BH_2Cl·SMe_2 in THF suggests that such hyride-induced redistribution reactions may be occurring in this system.

We next examined the reaction of ThxBHCl·SMe_2 with alkenes of different structural types under standard conditions in CH_2Cl_2 to determine the time required for complete hydroboration and assess the effect of olefin structure and reactivity on the product purity. The results

(13) Brown, H. C.; Levy, A. B. *J. Organometal. Chem.* **1972**, 44, 233–236.

Table VI. Directive Effects in the Hydroboration of Representative Alkenes with ThxBHCl·SMe_2 in CH_2Cl_2

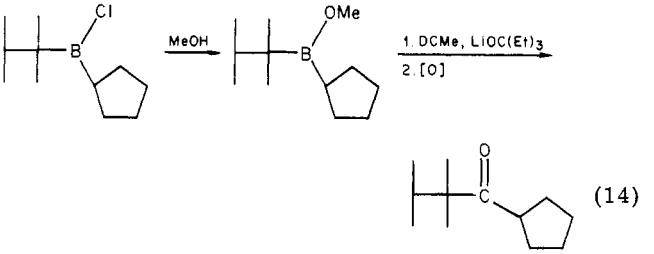
alkene	product	product distribution,[a] %				
		BH_3·THF[b]	$ThxBH_2$[c]	BH_2Cl·OEt_2[d]	9-BBN[e]	ThxBHCl·SMe_2
1-hexene	1-hexanol	94	94	>99.5	99.9	99.4
	2-hexanol	6	6	<0.5	<0.1	0.6
2-methyl-1-butene	2-methyl-1-butanol	99		>99.9	>99.8[g]	>99.9
	2-methyl-2-butanol	1		<0.1	<0.2	trace
2-methyl-2-butene	3-methyl-2-butanol	98		99.7	>99.8	99.6
	2-methyl-2-butanol	2		0.3	<0.2	0.4
cis-2-pentene	2-pentanol	55		58	66[h]	76
	3-pentanol	45		42	34	24
cis-4-methyl-2-pentene	4-methyl-2-pentanol	57[f]	66	60	99.8	97
	2-methyl-3-pentanol	43	34	40	0.2	3
cis-4,4-dimethyl-2-pentene	4,4-dimethyl-2-pentanol	58[f]		79	99.9	92
	2,2-dimethyl-3-pentanol	42		21	0.1	8
styrene	2-phenylethanol	80	94	96	98.5	>99.0
	1-phenylethanol	20	6	4	1.5	<1.0
p-methoxystyrene	2-(*p*-methoxyphenyl)ethanol	91				97.8
	1-(*p*-methoxyphenyl)ethanol	9				2.2
α-methylstyrene	2-phenylpropanol	100		100		99.4
	2-phenyl-2-propanol	trace		C		0.6
norbornene	*exo*-2-norbornanol	99.5		>99.8	99.5	>99.9
	endo-2-norbornanol	0.5		<0.2	0.5	<0.1
1-methylcyclopentene	*trans*-2-methylcyclopentanol	98.5		>99.8	>99.8	>99.0
	1-methylcyclopentanol	1.5		<0.2	trace	<1.0
1-methylcyclohexene	*trans*-2-methylcyclohexanol	97.2			>99.8	99.5
	1-methylcyclohexanol	1.5			<0.2	0.5

[a] Total yields 94 ± 5%. [b] Reference 18. [c] Reference 12. [d] Reference 16. [e] Reference 17. [f] Values obtained with trans alkene. [g] Values obtained with 2-methyl-1-pentene. [h] Reference 21.

are summarized in Table V. In all cases an essentially quantitative yield of 2,3-dimethyl-2-butanol was observed, indicating that the dehydroboration of the thexyl group was not a significant problem under these conditions. Careful examination of the product mixtures before oxidation indicated that no additional 2,3-dimethyl-2-butene was formed in these reactions. Essentially quantitative conversions of the alkenes to the corresponding alcohols were observed in every case, except for α-pinene.

In general, the hydroboration of terminal olefins was complete after 1 h at 25 °C. ^{11}B NMR indicated clean conversion (>98%) to the desired thexylalkylchloroborane (δ 79) products. After methanolysis, ^{11}B NMR showed a very clean conversion of these products to the corresponding dialkylborinates (δ 54–55). Only small amounts (2–3%) of $ThxB(OMe)_2$ were observed. However, when the reaction was performed with less reactive terminal alkenes, such as styrene, or simple internal olefins, ^{11}B NMR showed that a new species, presumably $ThBCl_2$·SMe_2 (δ 21–22) was formed in small amounts (3–5%) along with the thexylalkylchloroborane products. This resulted in a higher percentage of $ThxB(OMe)_2$ observed by ^{11}B NMR after methanolysis. The concentration of this species reached a maximum of approximately 10% of the product mixture when very unreactive alkenes, such as cyclohexene or trisubstituted olefins, were used in the reaction. With the very unreactive alkene, α-pinene, ^{11}B NMR indicated that the desired product was contaminated with several other boron species. Only an 82% yield of isopinocampheol was obtained after oxidation. These results indicate that, given enough time, equilibration of ThxBHCl·SMe_2 (eq 13) can occur. Only small amounts of redistributed product are observed with reactive olefins such as terminal alkenes or simple disubstituted olefins. Product redistribution only becomes a significant problem when very unreactive olefins are employed in the reaction.

Additional evidence for the formation of reasonably pure thexylalkylchloroborane derivatives is provided by examining the product produced after the usual replacement of boron by carbon[14] in the borane formed from reaction of ThxBHCl·SMe_2 with cyclopentene (eq 14). In this manner, isomerically pure thexylcyclopentyl ketone is produced in 82% yield by GLC.[15]



(14)

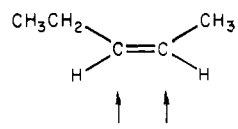
Directive Effects in the Hydroboration of Representative Alkenes with ThxBHCl·SMe_2. Previous workers have demonstrated that monohaloborane reagents (BH_2Cl·OEt_2, BH_2Cl·SMe_2) are more selective in the hydroboration of unsymmetrical olefins than are BH_3·THF and BH_3·SMe_2.[9,16] Since thexylborane exhibits approximately the same regioselectivity as borane itself,[12] one would expect ThxBHCl·SMe_2 to have approximately the same selectivity as the monohaloborane complexes. Indeed, as shown in Table VI, the regioselectivity of ThxBHCl·SMe_2 in CH_2Cl_2 equals and often exceeds that of BH_2Cl·OEt_2.[16] In many cases, the regioselectivity of ThxBHCl·SMe_2 matches that displayed by 9-borabicyclo[3.3.1]nonane (9-BBN), one of the most selective hydroborating agents known.[17] ThxBHCl·SMe_2, therefore, represents a new, stable, selective hydroborating agent. As shown in Table VII, slightly lower selectivities are observed

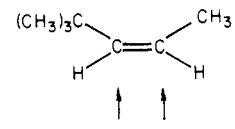
(14) Carlson, B. A.; Brown, H. C. *J. Am. Chem. Soc.* **1973**, *95*, 6876–6877.

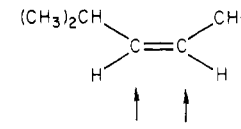
(15) In the DCME reaction involving secondary alkyl groups, up to 29% internal alkenes can be produced with the ketone (ref 14). In the present case, ~8% of a volatile impurity, probably such an olefin, was also formed.

(16) Brown, H. C.; Ravindran, N. *J. Am. Chem. Soc.* **1976**, *98*, 1785–1798.

(17) (a) Scouten, C. G.; Brown, H. C. *J. Org. Chem.* **1973**, *38*, 4092–4094. (b) Brown, H. C.; Knights, E. F.; Scouten, C. G. *J. Am. Chem. Soc.* **1974**, *96*, 7765–7770.







BH_3·THF	45:55	43:57	42:58
BH_2Cl·OEt_2	42:58	40:60	21:79
ThxBHCl·SMe_2	24:76	3:97	8:92

Table VII. A Comparison of the Directive Effects Observed with ThxBHCl·SMe_2 in CH_2Cl_2 and Et_2O

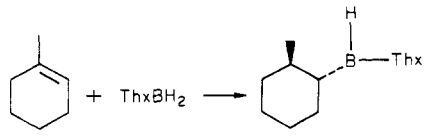
alkene	product	product distribution,[a] % CH_2Cl_2	Et_2O
1-octene	1-octanol	99.5	99.2
	2-octanol	0.5	0.8
styrene	2-phenylethanol	>99.0	98.5
	1-phenylethanol	<1.0	1.5
cis-4,4-dimethyl-2-pentene	4,4-dimethyl-2-pentanol	92	90
	2,2-dimethyl-3-pentanol	8	10

[a] Total yields were 94 ± 5%.

when the hydroboration of a few select alkenes were performed in Et_2O.

The data in Table VI also provide us with a quantitative measure of the amount of product redistribution that occurs in the hydroboration of less reactive olefins with ThxBHCl·SMe_2. The hydroborations of both *cis*-2-pentene and *cis*-4-methyl-2-pentene occur at approximately the same rate.[19] There is a dramatic increase in regioselectivity observed in the hydroboration of *cis*-4-methyl-2-pentene with that observed with *cis*-2-pentene. By introducing a second methyl group at the 4-position in 2-pentene, one would expect the regioselectivity of the hydroboration reaction to increase. In fact, a decrease in the overall regioselectivity of the hydroboration of *cis*-4,4-dimethyl-2-pentene is observed with ThxBHCl.SMe_2 in CH_2Cl_2 compared to that observed with *cis*-4-methyl-2-pentene. We believe that the 8% of 2,2-dimethyl-3-pentanol observed in this reaction arises from monohydroboration of this olefin with $(ThxBH_2)_2$. This value correlates quite well with the amount of $ThxBCl_2$·SMe_2 observed by ^{11}B NMR in the crude reaction product. Thus in this case, ~8% of the product arises from equilibration of ThxBHCl·SMe_2 (eq 13).

The lower reactivity of hindered olefins requires a longer reaction time. Under these conditions, redistribution of the ThxBHCl·SMe_2 reagent can take place, producing $ThxBH_2$·SMe_2 and $ThxBCl_2$·SMe_2. (Similar redistributions have been observed in the hydroboration of olefins with RBHCl·THF reagents.[16]) However, in the present reaction the thexylborane produced in situ should not undergo any significant dihydroboration with the hindered olefins present. Only monohydroboration should occur[3] (eq 15). Consequently, no trialkylborane species would



(15)

(18) (a) Brown, H. C.; Zweifel, G. *J. Am. Chem. Soc.* **1960**, *82*, 4708–4712. (b) Brown, H. C. "Hydroboration"; The Benjamin/Cummings Publishing Co., Inc.: Reading, MA, 1980.

(19) For a detailed study of the relative reactivities of representative olefins with ThxBHCl·SMe_2, see: Sikorski, J. A.; Brown, H. C., following paper in this issue.

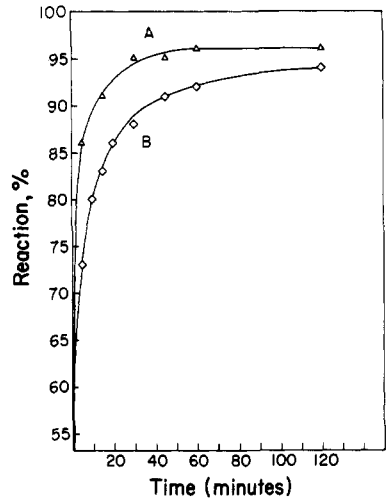


Figure 1. Effect of added excess methyl sulfide on the rate of reaction of ThxBHCl·SMe_2 with 1-decene at 0 °C. (A) No added Me_2S. (B) One equivalent excess Me_2S.

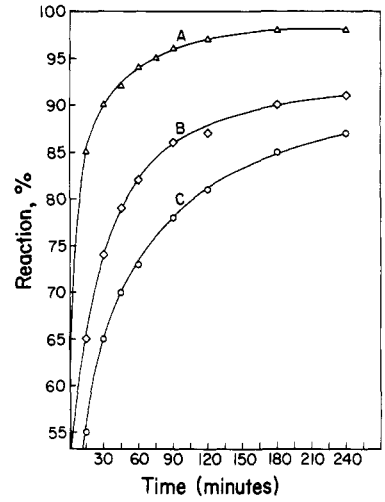


Figure 2. Effect of added excess methyl sulfide on the rate of reaction of ThxBHCl·SMe_2 with cyclohexene at 25 °C. (A) No added Me_2S. (B) One equivalent of excess Me_2S. (C) Two equivalents of excess Me_2S.

be observed following methanolysis. Instead, a small amount of unreacted olefin should be present in the reaction mixture, even though ^{11}B NMR shows complete consumption of ThxBHCl·SMe_2. These considerations account for the slightly lower overall yield observed for the corresponding alcohols (Table V) when hindered olefins are used.

Effect of Added Methyl Sulfide on the Rate of Reaction of ThxBHCl·SMe_2 with Alkenes. If dissociation of the ThxBHCl·SMe_2 complex is a necessary precondition for the hydroboration of alkenes, one would expect that the addition of excess methyl sulfide would cause a dramatic decrease in the observed rate of hydroboration. Accordingly, we examined the rate of hydroboration of a reactive substrate, 1-decene, at 0 °C. As shown in Figure 1, there was a dramatic decrease in the

rate of reaction when 1 equiv of excess methyl sulfide was added to the reaction. Similar results were observed when the less reactive substrate, cyclohexene, was hydroborated with ThxBHCl·SMe_2 at 25 °C (Figure 2). Again, a dramatic decrease in the rate of olefin uptake was observed when either 1 or 2 equiv of excess methyl sulfide was added to the medium. These results suggest that predissociation of the ThxBHCl·SMe_2 complex is occurring before hydroboration (eq 16).

$$\text{ThxBHCl}\cdot\text{SMe}_2 \underset{\text{slow}}{\overset{\rightarrow}{\leftarrow}} \text{SMe}_2 + \text{ThxBHCl} \xrightarrow[\text{fast}]{\text{alkene}} \text{ThxBRCl} \quad (16)$$

Conclusions

This study has shown that ThxBHCl·SMe_2, readily available from the monohydroboration of 2,3-dimethyl-2-butene with BH_2Cl·SMe_2, is a new, stable hydroborating agent with exceptional regioselectivity. With reactive alkenes (terminal or simple disubstituted olefins), this reagent results in the clean and essentially quantitative formation of isomerically pure thexylalkylchloroboranes. With less reactive olefins, redistribution of the product occurs at a significant level, due to preequilibration of the reagent. The reagent is therefore limited to the preparation of thexylalkylchloroborane derivatives containing primary or unhindered secondary alkyl groups. A detailed study to determine the synthetic potential of these new borane intermediates is in progress.

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 prepurified nitrogen (Airco). Syringes were assembled and fitted with needles while hot and then cooled. All reactions were carried out under a static pressure of nitrogen in flasks fitted with septum-covered sidearms, using standard techniques for handling air-sensitive materials.[20]

Materials. Commercial grade THF was distilled from excess lithium aluminum hydride and stored under nitrogen prior to use. Reagent grade methyl sulfide was distilled under nitrogen from a small quantity of 9-BBN (Aldrich). Reagent grade ethyl ether was degassed and stored under nitrogen over type 5Å molecular sieves. Spectroquality methylene chloride and 1,2-dichloroethane were degassed and stored under nitrogen over anhydrous potassium carbonate. Spectroquality, anhydrous methanol was degassed and stored under nitrogen over type 3Å molecular sieves. The hydrocarbons employed as internal standards for GLC analyses were obtained from Phillips Petroleum Co. and were labeled >99% pure. 2,3-Dimethyl-2-butene, cycloheptene, cyclooctene, norbornene, styrene, α-methylstyrene, and p-methoxystyrene were obtained from the Aldrich Chemical Co. The styrene derivatives were distilled from $LiAlH_4$ and stored under nitrogen at 0 °C. The remaining alkenes, except norbornene, were distilled from $LiAlH_4$ and stored under nitrogen at ambient temperatures. The other alkenes employed in this study were used as received from the Chemical Samples Division of Albany International after their refractive indices and ^1H NMR spectral characteristics were checked. BH_2Cl·SMe_2 was prepared via literature procedures.[9]

GLC Analyses. GLC analyses were carried out with a Varian Model 1200 FID chromatograph. When residual alkenes were analyzed, the injection port was lined with a 6 in. × 0.25 in. column of 10% THEED on 80/100 mesh Supelcoport. Residual 2,3-dimethyl-2-butene was analyzed on a 6 ft × 0.125 in. column of 30% adiponitrile on 60/80 mesh Firebrick. Residual 1-octene was analyzed on a 6 ft × 0.125 in. column of 10% SE-30 on 100/120 mesh Supelcoport. Alcohols were analyzed on a 6 ft × 0.125 in. column of 10% OV-225 on 100/120 mesh Supelcoport or a 12 ft × 0.125 in. column of 5% Carbowax on 100/120 mesh Supelcort. All GLC yields were determined with a suitable internal standard and authentic synthetic mixtures.

Spectra. Spectra were obtained under inert atmosphere with apparatus and techniques described elsewhere.[20] Infrared spectra were obtained with a Perkin-Elmer Model 700 spectrometer using sealed liquid cells and the two-syringe technique.[20] ^{11}B NMR spectra were recorded on a Varian FT-80A spectrometer equipped with a broad-band probe and a Hewlett-Packard 3335A frequency synthesizer. All ^{11}B NMR chemical shifts are reported relative to BF_3·OEt_2 (δ 0) with the chemical shifts downfield from BF_3·OEt_2 assigned as positive. ^1H NMR spectra were obtained with a Varian T-60 (60 MHz) spectrometer. All ^1H NMR chemical shifts are reported relative to tetramethylsilane (δ 0).

Rate of Reaction of 2,3-Dimethyl-2-butene with BH_2Cl·SMe_2 in CH_2Cl_2. A 25-mL round-bttom flask equipped with magnetic stirring bar, septum-covered sidearm, and connector tube leading to a mercury bubbler was charged at 25 °C with 1.16 mL of 8.6 M neat BH_2Cl·SMe_2 (10 mmol), 0.89 mL of n-nonane (4.66 mmol, internal standard), and 1.75 mL of CH_2Cl_2. The resulting clear solution was stirred at 25 °C for 30 min, and then 1.20 mL of neat 2,3-dimethyl-2-butene (10 mmol) was added via syringe. The overall initial concentration of reactants was 2.0 M. Addition of the alkene caused an exothermic reaction sufficient to reflux the solution. Aliquots of 0.25 mL were withdrawn at specific intervals, quenched by injection into 3 mL of acetone at −78 °C, and then analyzed for residual olefin by GLC. The amount of alkene consumed was calculated for each interval from the amount of residual olefin obtained. The results are summarized in Table I.

To avoid the exotherm problem, we repeated the experiment by adding the neat 2,3-dimethyl-2-butene (10 mmol) to a CH_2Cl_2 solution of BH_2Cl·SMe_2 (10 mmol) and n-nonane maintained at 0 °C. When the olefin addition was complete, the ice–water bath was replaced by a tap water bath, and the reaction mixture was stirred at room temperature. Aliquots were removed and analyzed as described above (Table I). Similarly, the reaction was repeated under these conditions by adding 2.40 mL of neat 2,3-dimethyl-2-butene (20 mmol) to a cold CH_2Cl_2 solution of BH_2Cl·SMe_2 (10 mmol) and n-nonane. After 5 min at 0 °C, the resulting clear solution was stirred at 25 °C. Aliquots were removed and analyzed as above (Table I).

Standard Procedure for the Preparation of ThxBHCl·SMe_2 in CH_2Cl_2, $ClCH_2CH_2Cl$, or Et_2O. Stock solutions of 2.1 M ThxBHCl·SMe_2 were prepared in CH_2Cl_2, $ClCH_2CH_2Cl$, or Et_2O as follows. A 500-mL round-bottom flask equipped with magnetic stirring bar, septum-covered sidearm, and connector tube leading to a mercury bubbler was charged at 0 °C with 69.0 mL of 8.7 M neat BH_2Cl·SMe_2 (600 mmol), 8.8 mL of methyl sulfide (120 mmol), and 144 mL of the desired solvent. The resulting solution was stirred at 0 °C for 30 min. Then, 79.0 mL of neat 2,3-dimethyl-2-butene (660 mmol) was added dropwise over a 1-h period. The resulting clear solution was stirred at 0 °C for 30 min and 25 °C for 3 h and then was stored under nitrogen at 0 °C. The usual analysis for active hydride and chloride[20] showed this solution to be 2.1 M in ThxBHCl·SMe_2.

Standard Procedure for the Hydroboration of Alkenes with ThxBHCl·SMe_2 in CH_2Cl_2, $ClCH_2CH_2Cl$, and Et_2O. The following procedures for the hydroboration of 1-octene in CH_2Cl_2 is representative. A 100-mL round-bottom flask equpped with magnetic stirring bar, septum-covered sidearm, and reflux condenser topped by a connector tube leading to a mercury bubbler was charged at 0 °C with 2.6 mL of CH_2Cl_2, 1.00 mL of n-dodecane (0.763 g, 4.48 mmol, internal standard), and 1.60 mL of 1-octene (1.140 g, 10.2 mmol). The resulting solution was stirred at 0 °C for 30 min. Then 4.8 mL of cold 2.1 M ThxBHCl·SMe_2 (10.0 mmol) in CH_2Cl_2 was added via syringe. After 5 min at 0 °C, the ice bath was replaced with a tap water bath, and the reaction was stirred at 25 °C. Periodically, 0.5-mL aliquots were withdrawn and monitored by ^{11}B NMR for consumption of ThxBHCl·SMe_2. After 60 min at 25 °C, ^{11}B NMR indicated that all of the ThxBHCl·SMe_2 had been consumed with concomitant clean (>98%) formation of a dialkylchloroborane species (δ 79.2). After methanolysis, ^{11}B NMR showed that clean conversion (>95%) of this product to a dialkylborinate species (δ 54.7) had occurred

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along with a small amount (2–3%) of $ThxB(OMe)_2$ (δ 30.5) and a trace of $(MeO)_3B$ (δ 18.1). So the reaction was cooled to 0 °C and oxidized by successively adding 15 mL of 3 N NaOH (45 mmol), 10 mL of absolute ethanol, and 8 mL of 30% aqueous hydrogen peroxide (80 mmol). The resulting heterogeneous mixture was stirred at 0 °C for 1 h and 25 °C for 1 h and then heated to 55 °C overnight. After the mixture was cooled to room temperature, 10 mL of Et_2O was added and the aqueous layer was saturated with K_2CO_3. The Et_2O layer was then analyzed by GLC on a 6 ft × 0.125 in. column of 10% OV-225 over 100/120 mesh Varaport 30. The results are summarized in Tables III and V. With more hindered olefins such as 1-methylcyclohexene and α-pinene, it is recommended that 20–30 mL of absolute ethanol be used as cosolvent for the oxidation.

Preparation of Neat ThxBHCl·SMe_2. A 50-mL round-bottom flask equipped with magnetic stirring bar, septum-covered sidearm, and connector tube leading to a mercury bubbler was cooled to −10 °C in an ice–salt bath and charged with 2.32 mL of 8.6 M neat $BH_2Cl·SMe_2$ (20 mmol). Then 2.40 mL of cold, neat 2,3-dimethyl-2-butene (20 mmol) was added dropwise over a 10-min period. After 10 min at −10 °C, the ice–salt bath was replaced with an ice–water bath, and the resulting viscous solution was stirred vigorously for 2.5–3 h. ^{11}B NMR of this viscous liquid indicated the clean formation of neat ThxBHCl·SMe_2 (Table II). Then 2.00 mL of absolute methanol (50 mmol) was added at 0 °C. After 30 min at 0 °C, ^{11}B NMR showed that $ThxB(OMe)_2$ (δ 31.0) was the only species produced (>99%).

Standard Procedure for Studying the Effect of Solvent on the Hydroboration of 1-Octene with Neat ThxBHCl·SMe_2. A 20-mmol sample of neat ThxBHCl·SMe_2 was prepared fresh via the standard procedure in a 100-mL round-bottom flask equipped with magnetic stirring bar, septum-covered sidearm, and reflux condenser topped by a connector tube leading to a mercury bubbler. Then 6.8 mL of the desired solvent (CH_2Cl_2, Et_2O, THF) and 2.0 mL of *n*-dodecane (8.6 mmol, internal standard) were added at 0 °C. The resulting solution was stirred at 0 °C. Then 3.2 mL of 1-octene (20 mmol) was added via syringe. After 5 min at 0 °C, the ice–water bath was replaced with a tap water bath and the resulting solution was stirred at 25 °C for 1 h. ^{11}B NMR of the crude product indicated very clean (>98%) formation of a dialkylchloroborane species (δ 79.6). After methanolysis, ^{11}B NMR showed the clean conversion (>95%) of this product to a dialkylborinate species (δ 53.9) along with a small amount (2–3%) of $ThxB(OMe)_2$ (δ 30.1) and a trace of $(MeO)_3B$ (δ 18.3). So the reaction mixture was cooled to 0 °C and oxidized by the successive addition of 20.0 mL of 3 N NaOH (60 mmol), 10.0 mL of absolute ethanol, and 8.0 mL of 30% aqueous hydrogen peroxide (80 mmol). The resulting heterogeneous mixture was stirred at 0 °C for 1 h and 25 °C for 1 h and then was heated at 55 °C overnight. After the mixture was cooled to room temperature, 10 mL of ether was added, the aqueous layer was saturated with K_2CO_3, and then the ether layer was analyzed by GLC. The results are summarized in Table III.

Thermal Stability of ThxBHCl·SMe_2 in CH_2Cl_2 and Et_2O. Stock solutions of 2.1 M ThxBHCl·SMe_2 (300 mmol) were prepared in CH_2Cl_2 and Et_2O according to the standard procedure and were stored on a benchtop under nitrogen at room temperature (20–25 °C). The residual hydride activity was followed with time by periodically measuring the amount of hydrogen evolved when 2.0-mL aliquots were injected into 1:1:1 (by volume) THF/H_2O/glycerine.[20]

The isomerization of the thexyl group into the 2,3-dimethyl-1-butyl group was followed with time by oxidizing 2.4-mL (5.0 mmol) aliquots at 0 °C successively adding 8.0 mL of 3 N NaOH (24 mmol), 3.0 mL of absolute ethanol, and 4.0 mL of 30% aqueous hydrogen peroxide (40 mmol). The resulting heterogeneous mixtures were stirred at 0 °C for 1 h and 25 °C for 1 h and then were heated at 55 °C overnight. After the mixtures were cooled to room temperature, 10 mL of Et_2O was added and the aqueous layer was saturated with potassium carbonate. The ether layer was then analyzed by GLC on a 6 ft × 0.125 in. column of 10% OV-225 on 100/120 mesh Varaport 30 to determine the ratio of 2,3-dimethyl-1-butanol to 2,3-dimethyl-2-butanol. The results are summarized in Table IV.

Preparation of Thexylcyclopentyl Ketone. A 0.97-mL sample of neat cyclopentene (11 mmol) was added dropwise to 5.0 mL of 2.0 M ThxBHCl·SMe_2 (10 mmol) in CH_2Cl_2 at 0 °C. The resulting solution was stirred at room temperature for 4 h. Then 3.0 mL of absolute MeOH (74 mmol) was carefully added. The solution was stirred at room temperature for 30 min and then reduced to a clear liquid on a water aspirator. The residue was dissolved in 10 mL of THF at 0 °C and then 1.1 mL of dichloromethyl methyl ether was added dropwise via syringe followed by the slow addition of 10 mL of 1.8 M lithium triethylcarboxide (18 mmol). The reaction was stirred for 1 h at 0 °C and 1 h at 25 °C. Then 1.3 mL of *n*-tetradecane (5.0 mmol, internal standard) was added. Oxidation was carried out by the successive addition of 0.4 g NaOH (10 mmol), 5 mL of absolute ethanol, 2 mL of H_2O, and 3 mL of 30% aqueous H_2O_2. The reaction mixture was stirred at 25 °C for 1 h and then heated to 60 °C for 2 h. After the mixture was cooled to room temperature, the aqueous layer was saturated with solid NaCl. The organic layer was then separated, dried over anhydrous K_2CO_3, and analyzed by GLC. Thexyl cyclopentyl ketone (8.2 mmol, 82%) was obtained by GLC along with ~8% of a volatile alkene impurity.

Rate of Reaction of ThxBHCl·SMe_2 with 1-Decene at 0 °C: Effect of Excess Methyl Sulfide. A stock solution of 2.1 M ThxBHCl·SMe_2 was prepared fresh in CH_2Cl_2 *without* the usual 20% excess of methyl sulfide and stored under nitrogen at 0 °C for use in this series of experiments. A 50-mL round-bottom flask equipped with magnetic stirring bar, septum-covered sidearm, and connector tube leading to a mercury bubbler was charged at 0 °C with 12.4 mL of CH_2Cl_2, 1.00 mL of *n*-nonane (0.726 g, 5.66 mmol, internal standard), and 1.9 mL of 1-decene (1.402 g, 10.0 mmol). The resulting solution was stirred at 0 °C for 30 min. Then 4.72 mL of the cold ThxBHCl·SMe_2 (10.0 mmol) solution, prepared as above in CH_2Cl_2, was quickly added via syringe. A timer was started, 0.5-mL aliquots were withdrawn at specified intervals, quenched by injection into 1.0 mL of 6 N NaOH in a septum-covered vial at 0 °C, and then were analyzed for residual 1-decene by GLC. The percent reaction was then calculated for each interval. The reaction was analyzed at 5 (86%), 15 (91%), 30 (95%), 45 (95%), 60 (96%), and 120 min (96%), as shown in Figure 1.

The procedure was then repeated in the presence of 1 equiv of methyl sulfide as follows. A 50-mL round-bottom flask was charged at 0 °C with 5.85 mL of CH_2Cl_2, 0.50 mL of *n*-nonane (0.373 g, 2.91 mmol, internal standard), 0.95 mL of 1-decene (0.712 g, 5.08 mmol), and 0.37 mL of methyl sulfide (0.318 g, 5.12 mmol). The resulting solution was stirred at 0 °C for 30 min. Then 2.35 mL of the cold ThxBHCl·SMe_2 (10.0 mmol) solution, prepared as above in CH_2Cl_2, was quickly added via syringe. Aliquots of 0.5 mL were withdrawn at specific intervals and analyzed as described above. The reaction was analyzed at 5 (73%), 10 (80%), 15 (83%), 20 (86%), 30 (88%), 45 (91%), 60 (92%), and 120 min (94%), as shown in Figure 1.

Rates of Reaction of ThxBHCl·SMe_2 with Cyclohexene at 25.0 °C: Effect of Excess Methyl Sulfide. A stock solution of 2.1 M ThxBHCl·SMe_2 was prepared fresh in CH_2Cl_2 *without* the usual 20% excess methyl sulfide and was stored under nitrogen at 0 °C for use in this series of experiments. A 50-mL round-bottom flask equipped with magnetic stirring bar, septum-covered sidearm, and connector tube leading to a mercury bubbler was charged at 25 °C with 3.26 mL of CH_2Cl_2, 1.00 mL of *n*-octane (0.697 g, 6.10 mmol, internal standard), and 1.01 mL of cyclohexene (0.870 g, 10.6 mmol). The resulting clear solution was then equilibrated in a constant temperature bath at 25.0 ± 0.05 °C. Then 4.72 mL of the cold ThxBHCl·SMe_2 (10.0 mmol) solution, prepared as above in CH_2Cl_2, was quickly added via syringe. A timer was started. Aliquots of 0.5 mL were withdrawn at specific intervals, quenched by injection into 1.0 mL of 6 N NaOH in a septum-covered vial at 0 °C, and then were analyzed for residual cyclohexene by GLC. The percent reaction was then calculated for each interval. As shown in Figure 2, the reaction was analyzed at 15 (85%), 30 (90%), 45 (92%), 60 (94%), 75 (95%), 90 (96%), 120 (97%), 180 (98%), and 240 min (98%).

The procedure was then repeated in the presence of 1 equiv of methyl sulfide as follows. A 50-mL flask was charged at 25 °C with 2.52 mL of CH_2Cl_2, 1.00 mL of *n*-octane (0.702 g, 6.14 mmol, internal standard), 1.01 mL of cyclohexene (0.822 g, 10.0 mmol), and 0.74 mL of methyl sulfide (0.623 g, 10.0 mmol). The resulting clear solution was then equilibrated at 25.0 ± 0.05 °C

and 4.72 mL of the cold ThxBHCl·SMe_2 (10.0 mmol) solution in CH_2Cl_2 was added quickly via syringe. A 0.5-mL sample was analyzed with time, as described above. As shown in Figure 2, the reaction was analyzed at 15 (65%), 30 (74%), 45 (79%), 60 (82%), 90 (86%), 120 (87%), 180 (90%), 240 (91%), and 630 min (95%).

This procedure was then repeated with 2 equiv of methyl sulfide as follows. A 50-mL flask was charged at 25 °C with 1.80 mL of CH_2Cl_2, 1.00 mL of *n*-octane (0.663 g, 5.80 mmol, internal standard), 1.01 mL of cyclohexene (0.820 g, 10.0 mmol), and 1.48 mL of methyl sulfide (1.265 g, 20.7 mmol). The resulting clear solution was then equilibrated at 25.0 ± 0.05 °C and 4.72 mL of the cold ThxBHCl·SMe_2 (10.0 mmol) solution in CH_2Cl_2 was added quickly via syringe. Aliquots of 0.5 mL were analyzed with time, as described above. As shown in Figure 2, the reaction was analyzed at 15 (55%), 30 (65%), 45 (70%), 60 (73%), 90 (78%), 120 (81%), 180 (85%), 240 (87%) and 600 min (93%).

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Registry No. $BH_2Cl·SMe_2$, 63348-81-2; ThxBHCl·SMe_2, 75067-06-0; thexylcyclopentyl ketone, 80375-46-8; 1-decene, 872-05-9; 1-hexene, 592-41-6; 1-octene, 111-66-0; cycloheptene, 628-92-2; cyclooctene, 931-88-4; 2-methyl-1-butene, 563-46-2; 4-pentenyl acetate, 1576-85-8; 2-methyl-2-butene, 513-35-9; *cis*-2-pentene, 627-20-3; *cis*-3-hexene, 7642-09-3; *cis*-4-methyl-2-pentene, 691-38-3; cyclopentene, 142-29-0; 2-methyl-1-pentene, 763-29-1; *p*-methoxystyrene, 637-69-4; 1-methylcyclopentene, 693-89-0; styrene, 100-42-5; norbornene, 498-66-8; *cis*-4,4-dimethyl-2-pentene, 762-63-0; cyclohexene, 110-83-8; α-methylstyrene, 98-83-9; 1-methylcyclohexene, 591-49-1; α-pinene, 80-56-8.

Hydroboration. 60. Effect of Structure on the Relative Reactivity of Representative Olefins toward Hydroboration by Thexylchloroborane–Methyl Sulfide

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The relative reactivities of 24 alkenes of different structural types toward hydroboration by thexylchloroborane–methyl sulfide (ThxBHCl·SMe_2) were determined in CH_2Cl_2 at 25 °C. The data for these reactions are presented to show how structural variations in the olefins are reflected in their relative reactivities. Whenever possible, the selectivity observed with ThxBHCl·SMe_2 is compared and contrasted with that observed previously for 9-borabicyclo[3.3.1]nonane (9-BBN), disiamylborane (Sia_2BH), and dibromoborane–methyl sulfide ($HBBr_2·SMe_2$). Like Sia_2BH and 9-BBN, ThxBHCl·SMe_2 has large steric requirements, reacting preferentially with the least hindered carbon atom of the double bond. However, ThxBHCl·SMe_2 is much more sensitive to electronic factors than either Sia_2BH or 9-BBN. This is attributed to the higher Lewis acidity of the ThxBHCl·SMe_2 reagent. The reagent exhibits a far higher reactivity toward cis alkenes relative to trans than any hydroborating reagent hitherto examined, giving cis/trans reactivity ratios of the order of 100/1.

Thexylchloroborane–methyl sulfide[2,3] (ThxBHCl·SMe_2) is a new, stable reagent for the selective hydroboration of alkenes of different structural types. For most olefins, hydroboration with ThxBHCl·SMe_2 proceeds cleanly with high regio- and stereospecificity.[2] This reagent reacts with simple terminal or disubstituted alkenes to produce isomerically pure thexylalkylchloroboranes. These versatile intermediates have been used effectively to couple two different primary alkyl groups on boron, providing new syntheses of unsymmetrical ketones,[3,4] alkynes,[5] and trans olefins.[6] As a prelude to incorporating unsaturated substrates in these synthetic procedures, we undertook a relative rate study of olefin hydroboration utilizing ThxBHCl·SMe_2 in CH_2Cl_2 at room temperature to determine the potential of this new reagent for selective hydroborations.

Results and Discussion

Competitive Hydroboration of Alkenes with ThxBHCl·SMe_2. The time required to achieve essentially complete hydroboration of different types of oelfins with ThxBHCl·SMe_2 in CH_2Cl_2 was established in an earlier study.[2] In general, longer reaction times were required as the steric requirements of the double bond increased. It seemed likely that the selective hydroboration of terminal alkenes in the presence of highly hindered double bonds could be achieved. For comparison of the reactivities of more structurally similar olefins, the relative reactivities were determined under competitive conditions. A solution containing equimolar quantities of two olefins (0.50 M in CH_2Cl_2) and a suitable inert hydrocarbon as an internal standard for GLC analysis was treated with only 1 equiv of ThxBHCl·SMe_2 (0.50 M in CH_2Cl_2). The resulting solution was stirred at 25.0 °C for sufficient time to allow complete consumption of the ThxBHCl·SMe_2. After the reaction was quenched at 0 °C, the ratios of unreacted substrates to the internal standard were determined by GLC. The relative reactivity of each olefin pair was then calculated by using the Ingold and Shaw expression (see the Experimental Section).[7] Each olefin pair was carefully

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