Hydroboration. 97. Synthesis of New Exceptional Chloroborane−Lewis Base Adducts for Hydroboration. Dioxane−Monochloroborane as a Superior Reagent for the Selective Hydroboration of Terminal Alkenes[†]

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Several less volatile oxygen-containing Lewis bases, such as *tert*-butyl methyl ether, dioxane, anisole, ethyl acetate, β-chloroethyl ether, and monoglyme, were examined as prospective mono- and dichloroborane carriers. Dioxane, ethyl acetate, and β-chloroethyl ether form relatively stable boron trichloride adducts, but the boron trichloride adduct of monoglyme is not very stable and must be used immediately. On the other hand, *tert*-butyl methyl ether and anisole fail to form stable boron trichloride adducts and the corresponding ether-cleaved products are obtained. Among the selected oxygen-containing Lewis bases, only dioxane forms stable and reactive mono- and dichloroborane adducts. Monoglyme and β-chloroethyl ether give stable dichloroborane adducts requiring excess of diborane. Convenient methods for the preparation of mono- and dichloroborane adducts of dioxane from dioxane−BCl_3 and $NaBH_4$ in the presence of catalytic amounts of tri- or tetraglyme were developed. The dioxane−monochloroborane adduct hydroborates representative olefins cleanly and rapidly. The corresponding alcohols were obtained in quantitative yields after oxidation. Also, the hydroboration of several terminal olefins with dioxane−monochloroborane were highly regioselective and the primary alcohols were obtained almost exclusively (>99.5%), after oxidation. Accordingly, dioxane−monochloroborane should serve as a reagent of choice for such hydroborations. The dioxane−dichloroborane adduct showed remarkable selectivity toward 2-substituted terminal olefins, such as 2-methyl-1-butene and β-pinene, when compared to simple terminal and hindered olefins, giving a unique tool for selective hydroborations. Dichloroborane adducts of monoglyme and β-chloroethyl ether also showed high reactivity, even at room temperature, toward simple unhindered olefins. However, hydroboration of hindered olefins is slow and requires either higher temperatures or the addition of 1 equiv of boron trichloride to liberate free dichloroborane, as in the case of the previously known dichloroborane adducts of methyl sulfide and diethyl ether.

Hydroboration of less hindered alkenes using monochloroborane provides anti-Markovnikov hydroboration products in >99.5% isomeric purity,[1] unlike the simple borane reagents, such as BH_3:THF and BMS, which give a mixture of regioisomers.[2] The products obtained after the hydroboration of various olefins with mono- and dichloroboranes provide valuable synthetic intermediates, which can be converted further to a variety of compounds.[2b,3] For example, dicyclohexylchloroborane has been used as an enolizing agent for aldol-type reactions,[4] while (+)- or (−)-Ipc₂BCl and Eap₂BCl reveal promising character-

istics as chiral reducing agents.[5] Also, the product dialkylchloroboranes can be converted to amines, ketones, dienes, and many more functional groups.[3] Similarly, alkyl- and alkenyldichloroboranes obtained after the hydroboration of alkenes and alkynes using dichloroborane reagents are finding increased applications in organic synthesis, including the synthesis of many natural products. The important application of alkenyl boronic acids, obtained after the hydrolysis of alkenyl dichloroboranes, in Suzuki−Miyaura-type couplings is worth mentioning, in addition to their many other applications.[6] The current monochloroborane adducts, such as dimethyl sulfide−monochloroborane and diethyl ether−monochloroborane, serve major needs in these applications. However, these reagents do suffer from significant disadvan-

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(2) (a) Brown, H. C.; Subba Rao, B. C. *J. Am. Chem. Soc.* **1959**, *81*, 6428. (b) Brown, H. C.; Zweifel, G. *J. Am. Chem. Soc.* **1960**, *82*, 4708. (c) Brown, H. C. *Organic Syntheses via Boranes*; Aldrich Chemical Co., Inc.: Milwaukee, 1997; Vol. 1.

(3) References are too numerous to list here. For an exclusive compilation of various applications with experimental procedures with individual references see: Brown, H. C.; Zaidlewicz, M. *Organic Syntheses via Boranes, Vol. 2. Recent Developments*; Aldrich Chemical Co., Inc.: Milwaukee, 2001.

(4) Brown, H. C.; Dhar, R. K.; Ganesan, K.; Singaram, B. *J. Org. Chem.* **1992**, *57*, 499.

(5) (a) Brown, H. C.; Chandrasekharan, J.; Ramachandran, P. V. *J. Am. Chem. Soc.* **1988**, *110*, 1539. DIP Chloride is a trademark of Aldrich Chemical Co., WI. (b) Brown, H. C.; Ramachandran, P. V.; Teodorovic, A. V.; Swaminathan, S. *Tetrahedron Lett.* **1991**, *32*, 6691. (c) Ramachandran, P. V.; Brown, H. C. In *Reductions in Organic Synthesis*; Abdel-Magid, A. F., Ed.; American Chemical Society: Washington, DC, 1996; Chapter 5.

(6) (a) Suzuki, A. *Acc. Chem. Res.* **1982**, *15*, 178. (b) Miyaura, N. *Adv. Met.-Org. Chem.* **1998**, 6, 187. (c) Ishiyama; Miyaura, N. In *Advances in Boron Chemistry*; Siebert, W., Ed.; The Royal Society of Chemistry: Cambridge, 1997; p 92; Suzuki, A. *Ibid.* p 163.

Table 1.   Preparation of Trichloro-, Dichloro-, and Monochloroborane Adducts of Various Oxygen-Containing Lewis Bases

s no.	Lewis base	LB:BCl$_3$	LB:BHCl$_2$	LB:BH$_2$Cl
1	dioxane	99% pure (stable for several hours at 0 °C)	99% pure (stable for several months)	97% pure (stable indefinitely, 2% BHCl$_2$ adduct)
2	*t*-BuOMe	cleaved product obtained even at −75 °C	cleaved product obtained	cleaved product obtained
3	PhOCH$_3$	cleaved product obtained even at −75 °C	not prepared (may be prepared by exchange reaction)	not prepared (may be prepared by exchange reaction)
4	CH$_3$COOC$_2$H$_5$	99% pure (stable for several hours at 0 °C)	cleaved product obtained	cleaved product obtained
5	monoglyme	99% (unstable, must be used immediately)	98% (requires excess diborane)	80% (20% BHCl$_2$ adduct, even after using excess diborane)
6	(ClCH$_2$CH$_2$)$_2$O	99% pure (stable for several hours at 0 °C)	97% pure (requires excess diborane)	not formed even after excess diborane addition

tages. The dimethyl sulfide−BH$_2$Cl is a stable reactive adduct but exists in equilibrium with dimethyl sulfide−BH$_3$ (12.5%) and dimethyl sulfide−BHCl$_2$ (12.5%). Also, the unpleasant odor of dimethyl sulfide poses significant environmental problems in large-scale operations. Very recently, we have also synthesized various dialkyl sulfides as borane and chloroborane carriers. During this study, we were able to find a nonodoriferous, highly reactive dialkyl sulfide−borane adduct in the diisoamyl sulfide−borane adduct. However, the chloroborane adduct exists only as an equilibrium mixture, as in the case of dimethyl sulfide.[7] The diethyl ether−BH$_2$Cl adduct is free from these problems, but can be obtained only in approximately 90% purity. Moreover, this reagent is unstable and must be freshly prepared before utilization. The adduct, tetrahydrofuran−BH$_2$Cl, can be obtained in 98% purity; however, its slow reactivity and relatively rapid ring opening limits its applications.[8]

The increasing use of these monochloroborane reagents and the diverse applications of the product dialkyl chloroboranes in organic synthesis prompted us to investigate the possibilities of providing a more desirable reagent for these applications. Accordingly, we undertook a detailed investigation for the synthesis of new, highly pure, reactive monochloroborane and dichloroborane adducts, which could substitute for the older hydroborating agents BH$_3$:THF and BMS, without their disadvantages.

As mentioned above, the monochloroborane adduct of diethyl ether can be obtained in approximately 90% purity, and it is highly reactive toward representative olefins. However, this reagent is unstable and can be prepared only in dilute solutions. Also, the high volatility of diethyl ether results in some practical problems. Accordingly, for the current study we selected several less volatile ethers, such as *tert*-butyl methyl ether, dioxane, anisole, ethyl acetate, β-chloroethyl ether, and monoglyme, as prospective Lewis bases. All these compounds, except ethyl acetate, dissolve considerable diborane, but fail to form strong complexes with borane, and thus may be good candidates for complexation with the mono- and dichloroborane intermediates.

Preparation of Tri-, Di-, Monochloroborane Adducts of Various Oxygen Containing Lewis Bases.
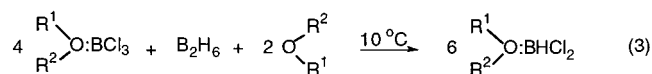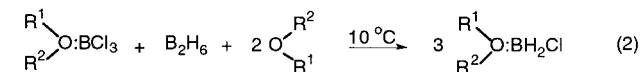
(7) Zaidlewicz, M.; Kanth, J. V. B.; Brown, H. C. *J. Org. Chem.* **2000**, *65*, 6697.

(8) Brown, H. C.; Zaidlewicz, M. *Polish J. Appl. Chem.* **1983**, *26*, 155.

The boron trichloride adducts were prepared by passing boron trichloride gas slowly into the ether at −78 to 0 °C.

$$\underset{R^2}{\overset{R^1}{}}\!\!O \; + \; BCl_3 \; \xrightarrow{\text{-78 - 0°C}} \; \underset{R^2}{\overset{R^1}{}}\!\!O{:}BCl_3 \qquad (1)$$
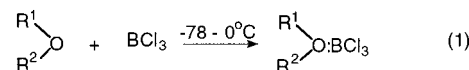
Following this procedure, dioxane, ethyl acetate, and β-chloroethyl ether formed stable (for several hours at 0° C, somewhat less at room temperature) boron trichloride adducts. The boron trichloride adduct of monoglyme, although obtained cleanly, is very unstable and hence must be used immediately after preparation for further transformations. On the other hand, boron trichloride adducts of *tert*-butyl methyl ether and anisole could not be prepared, as they react vigorously with the boron trichloride, giving ether-cleaved products rapidly. The mono- and dichloroborane adducts were prepared by passing an appropriate amount of diborane gas into the corresponding ether solutions of the boron trichloride adduct according to the following equations.

$$\underset{R^2}{\overset{R^1}{}}\!\!O{:}BCl_3 \; + \; B_2H_6 \; + \; 2 \, \underset{R^1}{\overset{R^2}{}}\!\!O \; \xrightarrow{10\,°C} \; 3 \, \underset{R^2}{\overset{R^1}{}}\!\!O{:}BH_2Cl \qquad (2)$$

$$4 \, \underset{R^2}{\overset{R^1}{}}\!\!O{:}BCl_3 \; + \; B_2H_6 \; + \; 2 \, \underset{R^1}{\overset{R^2}{}}\!\!O \; \xrightarrow{10\,°C} \; 6 \, \underset{R^2}{\overset{R^1}{}}\!\!O{:}BHCl_2 \qquad (3)$$

Among all the ethers examined, only dioxane gave pure mono- and dichloroborane adducts. Monoglyme required an excess of diborane for the preparation of monoglyme−BH$_2$Cl, and the adduct was obtained only in 80% pure form (by ^{11}B NMR). On the other hand, even by passing in excess diborane failed to give the desired β-chloroethyl ether−BH$_2$Cl, whereas ethyl acetate−BCl$_3$ reacted with diborane to give the reduced products. However, both monoglyme and β-chloroethyl ether gave quite pure dichloroborane adducts with excess of diborane. These results are summarized in Table 1.

It is clearly evident from these experiments that only dioxane formed the clean monochloroborane adduct. The dioxane−BH$_2$Cl adduct thus obtained was 97% pure by ^{11}B NMR (+7.9, triplet). The adduct is a liquid, 6.2 M in BH$_2$Cl, with a hydrogen-to-chlorine ratio of 2.00:1.00. The stability of this adduct at 0 °C and room temperature (25 °C) was monitored using ^{11}B NMR examination of a sealed sample (2 M dioxane−BH$_2$Cl in dioxane) in an
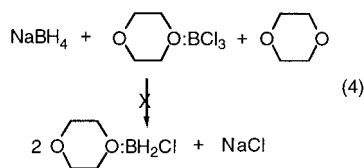
Table 2. Hydroboration of Representative Olefins Using Dioxane−BH₂Cl in Dioxane and Dichloromethane at Room Temperature[a]

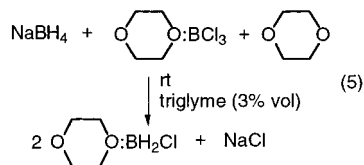| s no.	olefin	reaction time (h) in dioxane	hydrides used[b]	reaction time (h) in dichloromethane	hydrides used[b]
1	1-decene	0.25	2.00	0.25	2.00
2	2-methyl-1-butene	0.25	2.00	0.25	2.00
3	*cis*-4-methyl-2-pentene	0.25	2.00	0.25	2.00
4	2-methyl-2-butene	0.5	2.00	0.5	2.00
5	β-pinene	0.25	2.00	0.25	2.00
6	cyclohexene	0.5	2.00	0.5	2.00
7	3-carene	0.5	2.00	1.0	2.00
8	α-pinene	0.5	1.92	0.5	1.82
		1.0	2.00	1.5	2.00
9	2-methyl-1-phenyl-1-propene	0.25	1.00	0.5	1.00
		4.0	1.82	4.0	1.76
10	2,3-dimethyl-2-butene	0.25	1.18	0.5	1.18
		48.0	1.76	48.0	1.68
11	1,2-dimethylcyclopentene	0.5	1.00	0.5	1.00
		48.0	1.62	48.0	1.54

[a] All reactions were carried out in solutions of dioxane or dichloromethane which is 1 M in an olefin and 0.5 M in BH₂Cl (olefin was taken in 5% excess). [b] Hydride analyses were carried out by hydrolyzing an aliquot with glycerol/water (1:1) mixture and measuring the hydrogen evolved.

NMR tube, recording the ¹¹B NMR at intervals. It was also checked using active hydride analysis. Both of these studies did not show any detectable change over a period of one year.

To make the synthesis more convenient for large-scale preparations, the possibility was explored of synthesizing the dioxane−BH₂Cl complex using NaBH₄ and dioxane−BCl₃. However, the formation of dioxane−BH₂Cl was not achieved, as indicated by ¹¹B NMR, even after 3 days of stirring at room temperature (eq 4).

$$\text{NaBH}_4 \;+\; \text{O} \!\!\bigcirc\!\! \text{O:BCl}_3 \;+\; \text{O} \!\!\bigcirc\!\! \text{O}$$

(4)

$$2\;\text{O} \!\!\bigcirc\!\! \text{O:BH}_2\text{Cl} \;+\; \text{NaCl}$$

Fortunately, addition of small catalytic amounts of triglyme changed the course of the reaction dramatically, so that dioxane−BH₂Cl was conveniently prepared by taking appropriate amounts of NaBH₄ (10% excess), dioxane, dioxane−BCl₃, and 3 mol % of triglyme (eq 5).[9]

$$\text{NaBH}_4 \;+\; \text{O} \!\!\bigcirc\!\! \text{O:BCl}_3 \;+\; \text{O} \!\!\bigcirc\!\! \text{O}$$

rt
triglyme (3% vol)   (5)

$$2\;\text{O} \!\!\bigcirc\!\! \text{O:BH}_2\text{Cl} \;+\; \text{NaCl}$$

Decantation of the clear supernatant layer provided dioxane−BH₂Cl of 98% purity. Interestingly, the ¹H NMR spectrum in CDCl₃ of dioxane−BH₂Cl thus obtained did not show the presence of triglyme. It is apparently absorbed by the precipitated sodium chloride. The adduct thus obtained is 6.3 M in BH₂Cl and is stable indefinitely, both at 0 °C as well as at room temperature.

Hydroboration of Representative Olefins with Dioxane−BH₂Cl. To examine the reactivity of this new adduct toward representative olefins, hydroboration studies using dioxane−BH₂Cl were carried out in dioxane and in dichloromethane solvents. The hydroborations were carried out by the addition of an olefin in dioxane or

dichloromethane to dioxane−BH₂Cl at 0 °C, followed by further stirring as the reaction mixture was brought to room temperature. The final solution was 0.5 M in BH₂Cl and 1 M in the olefin. Representative olefins such as 1-decene, 2-methyl-1-pentene, *cis*-4-methyl-2-pentene, 2-methyl-2-butene, β-pinene, cyclohexene, α-pinene, 3-carene, 1-phenyl-2-methyl-1-propene, 2,3-dimethyl-2-butene, and 1,2-dimethylcyclopentene were utilized. The progress of these hydroboration reactions were monitored both by ¹¹B NMR and by hydride analysis of the residual active hydride present achieved by removing aliquots at intervals and measuring the hydrogen evolved by injecting them into a glycerol−water mixture. The mono-, di-, and some trisubstituted olefins were hydroborated rapidly to the corresponding dialkylchloroborane stage within 0.5 h. The more hindered olefins were rapidly hydroborated to the monoalkyl stage, with further hydroboration proceeding slowly. The results are summarized in Table 2.

In the hydroboration of less hindered olefins using dioxane−BH₂Cl, only the corresponding dialkylchloroboranes were obtained, as observed by ¹¹B NMR (∼+75 ppm). Methanolysis of these products gave *B*-methoxydialkylboranes cleanly (∼+54 ppm). However, in the hydroboration of hindered olefins, such as 2,3-dimethyl-2-butene and 1,2-dimethylcyclopentene, considerable amounts of the monoalkylchloroboranes were also formed.

Regioselectivity Studies in the Hydroboration of Representative Olefins Using Dioxane−Monochloroborane. In continuation of the hydroboration studies with dioxane−BH₂Cl, regioselectivity studies in hydroboration of some representative olefins were carried out. Hydroborations were carried out using dioxane−BH₂Cl (3 mmol) and an olefin (6 mmol) in dioxane. The olefin was added at 0 °C and the reaction mixture further stirred at room temperature. At the reaction time indicated (Table 2), the reaction mixture was oxidized using alkaline hydrogen peroxide. The ratio of the product alcohols was established by GC analysis using a Carbowax column with an internal standard. The hydroboration of terminal olefins with dioxane−monochloroborane was highly regioselective, and the primary alcohols were obtained almost exclusively (>99.5%), after oxidation. Generally, the hydroboration of 1-alkenes with BH₃:THF or BMS gives a mixture of primary and secondary

(9) For a preliminary communication, see: Kanth, J. V. B.; Brown, H. C. *Org. Lett.* **1999**, *1*, 315.

Table 3. Products from Hydroboration−Oxidation of Representative Olefins with BH₂Cl in Dioxane
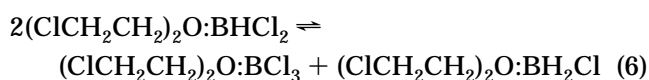
s no.	olefin	products	relative yield of the products with dioxane−BH₂Cl[a]
1	1-octene	1-octanol	100
		2-octanol	0
2	1-decene	1-decanol	100
		2-decanol	0
3	2-methyl-1-butene	2-methyl-1-butanol	99.5
		2-methyl-2-butanol	0.5
4	2-methyl-2-butene	3-methyl-2-butanol	99.1
		2-methyl-2-butanol	0.9
5	styrene	2-phenylethanol	95
		1-phenylethanol	5
6	α-methylstyrene	2-phenyl-1-propanol	99.6
		2-phenyl-2-propanol	0.4
7	*cis*-4-methyl-2-pentene	4-methyl-2-pentanol	59
		2-methyl-3-pentanol	41

[a] Relative yields of the product alcohols were obtained by GC (Varian) analysis using a Carbowax column with an internal standard.

Table 4. Hydroboration of Representative Olefins Using (ClCH₂CH₂)₂O:BHCl₂ in Dichloromethane at Room Temperature[a]

s no.	olefin	amount (in %) of RBCl₂[b]	amount (in %) of BCl₃[b]	amount (in %) of R₂BCl[b]
1	1-octene	90	8	2
2	1-decene	89	9	2
3	2-methyl-1-butene	91	5	4
4	β-pinene	95	2	3
5	*cis*−4-methyl-2-pentene	80	9	11
6	methylidinecyclopentane	75	12	13
7	cyclohexene	21	50	28
8	2-carene	37	45	18
9	α-pinene	58	37	5
10	2,3-dimethyl-2-butene	18	50	32
11	1,2-dimethylcyclopentene	19	49	32

[a] Hydroborations were carried out by the addition of an olefin to (ClCH₂CH₂)₂O:BHCl₂ in dichloromethane at 0 °C and further stirred at room temperature. The final solution is 1 M in an olefin and 1 M in BHCl₂. [b] Amounts obtained from ¹¹B NMR analysis of the methanolized product.

Scheme 1

alcohols in the ratio 94:6, after oxidation. Along similar lines, the hydroboration−oxidation of styrene with BH₃: THF or BMS gives a mixture of 1- and 2-phenylethanols in the ratio 80:20, due to the influence of the phenyl group. However, the hydroboration with dioxane−monochloroborane gives the 2-phenylethanol in 95% (1-phenylethanol, 5%). On the other hand, when both the carbon atoms of an olefin are substituted, the regioselectivity is lost. Thus, hydroboration of *cis*-4-methyl-2-pentene gives mixture of 4-methyl-2-pentanol and 2-methyl-3-pentanol in the ratio 59:41. In general, the regioselectivities achieved with dioxane−BH₂Cl are comparable to that reported for dimethyl sulfide−BH₂Cl, disiamylborane (Sia₂BH), 9-BBN, etc.[2c,3] However, the rate of hydroboration achieved with dioxane−BH₂Cl is much faster than those achieved by these reagents. Accordingly, dioxane−monochloroborane would serve as a reagent of choice for the hydroboration of terminal olefins to obtain primary alcohols after oxidation. Table 3 summarizes the results.
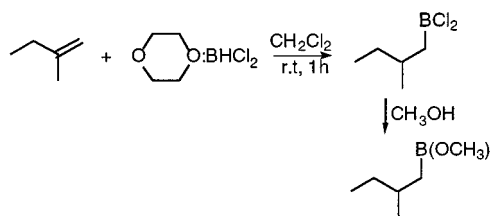
Hydroborations Using Other Chloroborane Adducts. Although the other ethers selected failed to form stable monochloroborane adduct, both β-chloroethyl ether and monoglyme form a stable reactive dichloroborane adduct. Accordingly, hydroboration studies using β-chloroethyl ether−BHCl₂ toward representative olefins were carried out. Hydroboration of simple unhindered olefins such as 1-octene, 1-decene, 2-methyl-1-butene, and β-pinene was very fast and complete within 30 min. The ¹¹B NMR analysis of the reaction mixture showed the nearly exclusive formation of RBCl₂ along with trace amounts of (ClCH₂CH₂)₂O:BCl₃ and R₂BCl.

Hydroboration of moderately hindered olefins, such as *cis*-4-methyl-2-pentene cyclohexene and methylenecyclopentane, were also very fast and complete in 30 min. However, ¹¹B NMR examination of the reaction mixture showed the formation of considerable amounts of (ClCH₂CH₂)₂O:BCl₃ and R₂BCl in addition to RBCl₂. The formation of the BCl₃ adduct may be due to the disproportionation of the BHCl₂ adduct in the presence of an olefin.

$$2(ClCH_2CH_2)_2O:BHCl_2 \rightleftharpoons$$
$$(ClCH_2CH_2)_2O:BCl_3 + (ClCH_2CH_2)_2O:BH_2Cl \quad (6)$$

Hydroboration of hindered olefins, such as 2-carene, α-pinene, 2,3-dimethyl-2-butene, and 1,2-dimethylcyclopentene, were slow. The ¹¹B NMR examination showed the formation of major amounts of (ClCH₂CH₂)₂O:BCl₃ (in 45% by ¹¹B NMR) and the corresponding monoalkyl and dialkylchloroboranes were obtained in only minor quantities. Table 4 summarizes the hydroboration study results. Monoglyme-BHCl₂ adduct also showed similar reactivities, and thus, it was not studied in detail. In these cases, where the hydroboration is either very slow or does not take place, the rate of reaction can be improved either by performing the hydroborations at higher temperature or by the addition of 1 equiv of BCl₃ to the reaction mixture.

Hydroboration Studies Using Dioxane−BHCl₂. Hydroboration studies of dioxane−BHCl₂ toward representative olefins were carried out in dichloromethane. The hydroborations were carried out using dioxane−BHCl₂ (1 mL, 5 M, 5 mmol) in dichloromethane and an olefin (5 mmol) at 0 °C. The solvent dichloromethane is taken in such a way that the final solution is 1 M in BHCl₂ and 1 M in the olefin. The progress of hydroboration was simultaneously followed by ¹¹B NMR and by hydride analysis of an aliquot using glycerol−water mixture, measuring the hydrogen evolved to know the amount of active hydride utilized.

Hydroboration of simple unhindered olefins such as 1-octene, 1-decene, 2-methyl-1-butene, β-pinene and methylenecyclopentane were complete. Interestingly, the hydroboration of 2-substituted terminal olefins such as 2-methyl-1-butene was very fast and complete within 1 h at room temperature (Scheme 1).

The ¹¹B NMR analysis of the reaction mixture showed the exclusive formation of RBCl₂, whereas relatively less-hindered olefins, such as 1-octene and 1-decene, took a longer time (12 h). Also, the hydroboration of 1-octene

and 1-decene resulted in disproportionation with the formation of considerable amounts of R_2BCl and BCl_3.

To examine the generality of this observation, several other 2-substituted terminal olefins, such as β-pinene and methylenecyclopentane, were also hydroborated with dioxane$-BHCl_2$ in dichloromethane. In all these cases, the hydroborations are very fast and complete within 1 h at room temperature. The ^{11}B NMR analysis of the reaction mixtures showed the exclusive formation of $RBCl_2$ (>90%). This unusual reactivity toward 2-substituted terminal olefins makes it easy to achieve the selective hydroboration of such olefins in the presence of simple terminal olefins (eq 7).


$$\text{(7)}$$
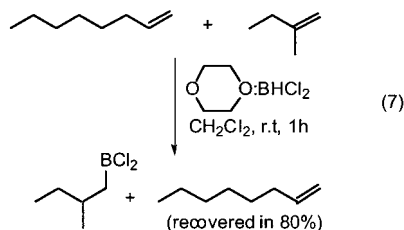
Though we do not have any other experimental data to explain this unusual selectivity, it may be due to the combination of electronic and steric effects (electronic effect slightly more influencing over steric effect in the case of 2-substituted terminal olefins, when compared to terminal olefins). The hydroboration of moderately hindered olefins, such as *cis*-4-methyl-2-pentene and cyclohexene, were very slow and incomplete, even after 4 days. Also, the hydroboration proceeded with disproportionation. Thus, ^{11}B NMR examination of the reaction mixture showed the formation of major amounts of dioxane$-BCl_3$ and R_2BCl in addition to minor amounts of $RBCl_2$. The formation of the BCl_3 adduct may be due to the disproportionation of the $BHCl_2$ adduct in the presence of an olefin, as observed in the case of β-chloroethyl ether-$BHCl_2$.

Hydroboration of hindered olefins, such as 2-carene, α-pinene, 2,3-dimethyl-2-butene, and 1,2-dimethylcyclopentene, were also very slow and incomplete even after 7 days. Attempts to accelerate the reaction using BF_3: OEt_2 were not successful. The ^{11}B NMR analysis of the reaction mixtures showed the formation of new signals around +4 ppm (singlet), in addition to the BF_3 signal at +0.2 ppm, but no signals due to $RBCl_2$ were noted. The nonreactivity of the dioxane-$BHCl_2$ adduct toward hindered olefins and its ready reactivity toward 2-substituted terminal olefins was made use of in the selective hydroboration of terminal olefins in the presence of internal olefins.

Thus, the hydroboration of limonene (1 equiv) with dioxane$-BHCl_2$ (1 equiv) in dioxane or dichloromethane was complete in 1 h as observed by ^{11}B NMR, and no signal corresponding to dioxane$-BHCl_2$ was noted (Scheme 2). Methanolysis of the reaction mixture gave a single peak at +32 ppm in ^{11}B NMR. Oxidation of the reaction mixture using $NaOH/H_2O_2$ and GC analysis of the product showed the presence of only one alcohol corresponding to the terminal olefin hydroboration product (compared with a sample obtained from hydroboration using BH_3:THF, which gave a diol). The ^{1}H NMR examination showed no traces of terminal olefin and the internal olefin was found to be intact.

Scheme 2
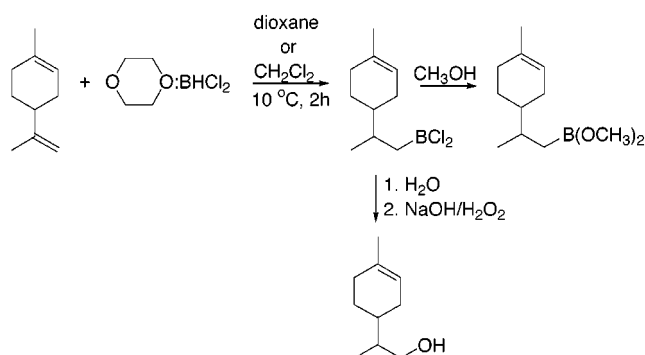
In conclusion, the present study clearly demonstrates that the new dioxane$-BH_2Cl$ adduct is free of the problems that are associated with the reagents currently used. The hydroboration of various representative olefins with dioxane-monochloroborane were rapid and quantitative. Also, the hydroboration of several terminal olefins with dioxane$-$monochloroborane were highly regioselective and the primary alcohols were obtained exclusively (>99.5%), after oxidation. Accordingly, dioxane$-$monochloroborane should serve as a reagent of choice for such hydroborations. This study also provided highly reactive dichloroborane adducts, namely dioxane$-BHCl_2$, monoglyme$-BHCl_2$, and β-chloroethyl ether$-BHCl_2$. Convenient procedures for the preparation of these chloroborane adducts were developed. These dichloroborane reagents hydroborate less hindered olefins readily at room temperature. It is worth noting that to achieve hydroborations with earlier dichloroborane reagents either required refluxing conditions or 1 equiv of boron trichloride. However, in the case of hindered olefins, these chloroborane reagents also need either refluxing conditions or one equivalent of boron trichloride for clean hydroborations. Also, the unusual reactivity of dioxane-$BHCl_2$ toward 2-substituted olefins in the presence of terminal and other internal olefins should find useful synthetic application.

Experimental Section

General Methods. All glassware was oven-dried for several hours at 120 °C, assembled while hot, and cooled in a stream of dry nitrogen gas. Syringes were assembled and fitted with needles while hot and cooled under nitrogen gas. Techniques for handling air-sensitive compounds described elsewhere were followed.[2c] All manipulations and reactions with air-sensitive compounds were carried out under nitrogen atmosphere. ^{1}H, ^{13}C, and ^{11}B NMR spectra were recorded on a 300 MHz multinuclear instrument. The [11]B chemical shifts are in δ relative to boron trifluoride$-$diethyl etherate. The hydride analysis studies were carried out, by hydrolyzing the reaction mixture and measuring the hydrogen evolved using a gasimeter.[2c] GC analyses were carried out on a chromatograph equipped with FID and CI-100A integrator. The following columns were used, 12 ft × 0.125 in column packed with 10% Carbowax 20M, SE-30 on Chromosorb W (100$-$120 mesh).

Materials. Dioxane, *tert*-butyl methyl ether, ethyl acetate, β-chloroethyl ether, and monoglyme are commercial products. They were further purified by distillation and stored under nitrogen. Dioxane and monoglyme were distilled over sodium/benzophenone, and *tert*-butyl methyl ether, ethyl acetate, and β-chloroethyl ether were distilled over a small amount of calcium hydride. Boron trichloride gas was used as obtained.

All the olefins were also commercial products. Diborane was generated using the reported procedure.[10]

Preparation of the Boron Trichloride Adducts. The procedure followed for all of the Lewis bases is same and procedure used for dioxane is representative. Two procedures were followed for the preparation of these boron trichloride adducts.

(a) By the Reaction of BCl₃ Gas with Dioxane. An oven-dried marked centrifuge tube having a septum inlet was cooled to −75 °C under nitrogen, and boron trichloride gas (11.72 g, 100 mmol) was condensed into this. An oven-dried 100 mL round-bottom flask provided with stirring bar, septum inlet, gas inlet, and a condenser whose end was connected to a mercury bubbler was cooled to 10 °C under nitrogen. The flask was charged with dioxane (8.81 g, 100 mmol) and boron trichloride gas, earlier condensed into a marked centrifuge tube was slowly passed in. (Caution! Exothermic reaction and rapid passing can result in the formation of charred compounds). The reaction of boron trichloride with the selected Lewis bases is instantaneous, and the boron trichloride adduct is formed as soon as the addition is complete. The reaction of boron trichloride with dioxane results in the quantitative formation of the dioxane−BCl₃ adduct, melting point 35−38 °C with decomposition. The purity was confirmed using ¹¹B NMR examination. ¹¹B NMR (in dichloromethane): +11.3 ppm (singlet).

(b) By the Reaction of BCl₃ in Dichloromethane with Dioxane. An oven-dried marked centrifuge tube provided with a septum inlet was cooled to −75 °C under nitrogen. Boron trichloride gas (11.72 g, 100 mmol) was condensed into the tube and dry dichloromethane (20 mL) was added. To this solution dioxane (8.81 g, 100 mmol) was added slowly during 30 min, and the contents were slowly brought to 0 °C. Pumping-off the volatile dichloromethane at that temperature provided a white solid of dioxane−BCl₃.

The dioxane−BCl₃ thus obtained is stable for several hours at 0 °C. The stability details for other boron trichloride adducts are listed in Table 1. However, it was observed that it is desirable to prepare the BCl₃ adducts and to use them immediately for further reactions.

Preparation of Monochloroborane Adducts. The procedure followed for dioxane, monoglyme, ethyl acetate, and β-chloroethyl ether is similar, and the procedure used for dioxane is representative.

An oven-dried 100 mL round-bottom flask provided with stirring bar, septum inlet, gas inlet, a condenser whose end was connected to a mercury bubbler was cooled to 10 °C under dry nitrogen. The flask was charged with dioxane−BCl₃ (21.33 g, 100 mmol) in dioxane (19.38 g, 220 mmol). The diborane gas (110 mmol) was bubbled slowly into the dioxane−BCl₃ and dioxane through a sintered tip gas bubbler during 3 h (a rate at which most of the diborane gas is absorbed). The contents were further stirred at 10 °C for another 1 h, by which time the ¹¹B NMR examination of the reaction mixture showed clean formation of dioxane−BH₂Cl (+7.9, triplet, 97%) and disappearance of the peak due to dioxane−BCl₃ (+11.8, singlet).

Among the other Lewis bases selected, only monoglyme gave reasonably pure (80%) monochloroborane adduct (containing 20% dichloroborane adduct). The results are listed in Table 1.

Preparation of Dichloroborane Adducts. The procedure followed for dioxane, monoglyme, ethyl acetate, and β-chloroethyl ether is similar, and the procedure used for dioxane is representative.

An oven-dried 100 mL round-bottom flask provided with stirring bar, septum inlet, gas inlet, and a condenser, whose end was connected to a mercury bubbler, was cooled to 10 °C under dry nitrogen. The flask was charged with dioxane−BCl₃ (42.67 g, 200 mmol) in dioxane (9.67 g, 110 mmol). The diborane gas (55 mmol) was bubbled slowly into dioxane−BCl₃ and dioxane through a sintered tip gas bubbler during 2 h (a rate at which most of the diborane gas is absorbed). The

contents were further stirred at 10 °C for another 1 h, by which time the ¹¹B NMR examination of the reaction mixture showed the clean formation of dioxane−BHCl₂ (+8.2, doublet, >98%) and the disappearance of the peak due to dioxane−BCl₃ (+11.7, singlet).

Among the other Lewis bases selected, monoglyme and β-chloroethyl ether gave pure (>97%) dichloroborane adducts. However, they required excess diborane gas to shift the equilibrium in favor of the dichloroborane adduct. The results are listed in Table 1.

Preparation of Dioxane−BH₂Cl, by the Reaction of Sodium Borohydride with Dioxane−BCl₃. An oven-dried 100 mL round-bottom flask provided with stirring bar and septum inlet was cooled to 10 °C under dry nitrogen. The flask was charged with sodium borohydride (7.92 g, 220 mmol). To this was added dioxane−BCl₃ (42.67 g, 200 mmol) in dioxane (19.38 g, 220 mmol), and the contents were stirred for 10 min. Triglyme (1.5 mL, 9 mmol, 3% volume) was added to the reaction mixture, and the contents were further stirred at room temperature for 36 h. The contents were allowed to settle (can be centrifuged for quantitative precipitation of the sodium chloride formed) and the clear supernatant solution decanted under nitrogen. The ¹¹B NMR examination showed clean formation of dioxane−BH₂Cl (+7.8, triplet, 97%).

Preparation of Dioxane−BHCl₂, by the Reaction of Sodium Borohydride with Dioxane−BCl₃. An oven-dried 100 mL round-bottom flask provided with stirring bar and septum inlet was cooled to 10 °C under dry nitrogen. The flask was charged with dioxane−BCl₃ (64.00 g, 300 mmol) in dioxane (9.69 g, 110 mmol). To this was added sodium borohydride (3.96 g, 110 mmol), and the contents were stirred for 10 min. Triglyme (1.5 mL, 9 mmol, 3% volume) was added to the reaction mixture, and the contents were further stirred at room temperature for 36 h. The contents were allowed to settle (can be centrifuged for quantitative precipitation of the sodium chloride formed) and the clear supernatant solution decanted under nitrogen. The ¹¹B NMR examination showed the clean formation of dioxane−BHCl₂ (+8.2, doublet, >98%).

Hydroboration of Representative Olefins Using Dioxane−BH₂Cl. Hydroboration of representative olefins, such as 1-octene, 1-decene, styrene, α-methylstyrene, 2-methyl-1-pentene, *cis*-4-methyl-2-pentene, 2-methyl-2-butene, β-pinene, cyclohexene, α-pinene, 3-carene, 1-phenyl-2-methyl-1-propene, 2,3-dimethyl-2-butene, and 1,2-dimethylcyclopentene, with dioxane−BH₂Cl was carried out in dioxane and dichloromethane solvents. The procedure followed for all the olefins in both the solvents are same. The procedure followed for 1-decene in dichloromethane is representative.

An oven-dried 50 mL round-bottom flask provided with a septum inlet and stirring bar was cooled to 0 °C under nitrogen. The flask was charged with dioxane−BH₂Cl in dichloromethane (8.7 mL, 5 mmol). To this was added 1-decene (1.4 g, 10 mmol). The final solution is 0.5 M in BH₂Cl and 1.0 M in 1-decene. The contents were further stirred at room temperature. The course of reaction was followed by ¹¹B NMR and hydride analysis of residual active hydride. Both of these studies showed the completion of the reaction after 15 min. ¹¹B NMR after 15 min: +75 (broad singlet), +52 (singlet, after methanolysis) and hydride analysis showed no active hydride after 15 min.

The reaction mixture was treated with slow addition of water followed by the addition of sodium hydroxide (7.0 mL, 3 M, 21 mmol). Methanol (3.0 mL) was added followed by the slow addition of hydrogen peroxide (6 mmol), and the contents were further stirred at room temperature (3 h) and 40 °C (1 h) to ensure complete oxidation. The organic compound was extracted into diethyl ether. Drying and evaporation of the solvent provided essentially pure 1-decanol in 98% (by GC): isolated 1.48 g, 95% yield. The GC analysis did not show the presence of 2-decanol. These results are summarized in Table 3.

Hydroboration of Representative Olefins Using Dioxane−BHCl₂. Hydroboration studies of representative olefins such as 1-octene, 1-decene, 2-methyl-1-butene, β-pinene, methylenecyclopentane, *cis*-4-methyl-2-pentene, cyclohexene,

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(10) Kanth, J. V. B.; Brown, H. C. *Inorg. Chem.* **2000**, *39*, 1795.

Table 5. Hydroboration of Representative Olefins Using Dioxane−BHCl$_2$ in Dichloromethane at Room Temperature[a]

s no.	olefin	amount (in %) of RBCl$_2$[b]	amount (in %) of BCl$_3$[b]	amount (in %) of R$_2$BCl[b]
1	1-octene	30	60	10
2	1-decene	28	60	12
3	2-methyl-1-butene	95	2	3
4	methylenecyclopentane	92	4	3
5	β-pinene	94	4	2
6	*cis*−4-methyl-2-pentene	very slow reaction		
7	cyclohexene	very slow reaction		
8	2-carene	no significant hydroboration		
9	α-pinene	no significant hydroboration		
10	2,3-dimethyl-2-butene	no significant hydroboration		
11	1,2-dimethyl-cyclopentene	no significant hydroboration		

[a] Hydroborations were carried out by the addition of an olefin to dioxane−BHCl$_2$ in dichloromethane at 0 °C and further stirred at room temperature. The final solution is 1 M in an olefin and 1 M in BHCl$_2$. [b] Amounts obtained from ^{11}B NMR analysis of the methanolized product.

2-carene, α-pinene, 2,3-dimethyl-2-butene, and 1,2-dimethyl-cyclopentene using dioxane−BHCl$_2$ were carried out in dichloromethane. The hydroborations are rapid and complete only for 2-substituted-1-enes, such as 2-methyl-1-butene, 2-methyl-1-octene, β-pinene, and methylenecyclopentane. These results are summarized in Tables 4 and 5. The hydroboration of other olefins is sluggish at room temperature. The procedure followed for β-pinene is representative.

An oven-dried 50 mL round-bottom flask provided with a septum inlet and stirring bar was cooled to 0 °C under nitrogen gas. The flask was charged with dioxane−BHCl$_2$ in dichloro-methane (7.5 mL, 10 mmol). To this was added β-pinene (1.37 g, 10 mmol). The final solution is 1.0 M in BHCl$_2$ and 1.0 M in β-pinene. The contents were further stirred at room temperature. The progress of the reaction was monitored by the hydrolysis of an aliquot with glycerin−water mixture and measuring the hydrogen evolved. It was also followed using ^{11}B NMR analysis. Both of these studies showed completion of the reaction after 1.5 h. ^{11}B NMR after 1.5 h: +16.9 (broad singlet), +31.5 (singlet, after methanolysis)

Selective Hydroboration of Limonene Using Dioxane−BHCl$_2$. An oven-dried 50 mL round-bottom flask provided with a septum inlet and stirring bar was cooled to 0 °C under nitrogen gas. The flask was charged with dioxane−BHCl$_2$ in dichloromethane (7.5 mL, 10 mmol). To this was added limonene (1.36 g, 10 mmol). The final solution is 1.0 M in BHCl$_2$ and 1.0 M in limonene. The contents were further stirred at room temperature. The course of the reaction was followed by the hydrolysis of an aliquot with glycerin−water mixture and measuring the hydrogen evolved. It was also followed using ^{11}B NMR analysis. Both of these studies showed completion of the reaction after 2 h. ^{11}B NMR after 2 h: +17.3 (broad singlet), +31.5 (singlet, after methanolysis). Hydride analysis reveals no presence, after 2 h.

The reaction mixture was treated with slow addition of water followed by the addition of sodium hydroxide (10.0 mL, 3 M, 30 mmol). Methanol (3.0 mL) was added followed by the slow addition of hydrogen peroxide (12 mmol), and the contents were further stirred at room temperature (3 h) and 40 °C (1 h) to ensure complete oxidation. The organic compound was extracted into diethyl ether. Drying and evaporation of the solvent provided essentially pure *p*-menth-1-en-9-ol in 90.5 yield (1.35 g). The GC analysis did not show any signal corresponding to the diol. The spectral data matched with the commercial sample.