Molecular Addition Compounds. 16. New, Highly Reactive Borane Adducts with *N,N*-Dialkyl-*tert*-alkylamines for Hydroboration

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Several *N,N*-diethyl-*tert*-alkylamines, such as *N,N*-diethyl-2-methyl-2-butylamine (**1**, *t*-PentNEt$_2$), *N,N*-diethyl-2,3-dimethyl-2-butylamine (**2**, *t*-HexNEt$_2$), *N,N*-diethyl-2,3,3-trimethyl-2-butylamine (**3**, *t*-HeptNEt$_2$), and *N,N*-diethyl-1,1,3,3-tetramethylbutylamine (**4**, *t*-OctNEt$_2$) with varying steric bulk around nitrogen (by changing the *tert*-alkyl group) have been prepared and examined as borane carriers. The complexing ability of these *N,N*-diethyl-*tert*-alkylamines with borane decreases in the order: *t*-BuNEt$_2$ > *t*-PentNEt$_2$ > *t*-HeptNEt$_2$ > *t*-HexNEt$_2$ ≥ *t*-OctNEt$_2$. From these preliminary studies, the more promising *tert*-octyldialkylamines were selected for detailed studies. The optimum steric bulk around the nitrogen atom was established by comparing various *tert*-octyldialkylamines containing variable steric requirements for both the alkyl groups. The complexing ability of these amines with borane decreases in the order shown: *t*-OctNMe$_2$ (**5**) > *t*-OctNEtMe (**6**) > *t*-OctN(CH$_2$CH$_2$)$_2$O (**7**) > *t*-OctNEt$_2$ (**4**) > *t*-OctNBu^{i}Me (**8**) > *t*-OctNPr$^n_2$ (**9**). The reactivity of the corresponding borane adducts toward 1-octene increases in the reverse order. Among the various *tert*-octyldialkylamine-boranes prepared and examined, only *t*-OctNEt$_2$ (**4**) forms a highly reactive liquid borane adduct, which hydroborates 1-octene in tetrahydrofuran rapidly at room temperature. Accordingly, detailed hydroboration studies with this new, highly reactive amine-borane adduct, *t*-OctEt$_2$N:BH$_3$ (**10**) and representative mono-, di-, tri-, and tetra-substituted olefins were carried out at room temperature (22 ± 3 °C) in selected solvents, tetrahydrofuran, dioxane, *tert*-butyl methyl ether, *n*-pentane and dichloromethane. Simple unhindered olefins were hydroborated to the trialkylborane stage, whereas hindered olefins were partially hydroborated to the mono or dialkylborane stage. The hydroborations can be carried out conveniently in a variety of solvents. The amine-borane adduct showed enhanced reactivity in dioxane but low reactivity in dichloromethane. The alkylboranes obtained after hydroboration were oxidized with hydrogen peroxide/sodium hydroxide and the product alcohols were obtained in quantitative yields, as established by GC analysis. The carrier amine was recovered by simple acid−base manipulations in good yield and can be readily recycled back to the borane adduct.

Borane−amine adducts are important reducing agents with a multitude of applications in organic synthesis and industrial processes.[3] They have a wide range of reactivities, are soluble in various solvents including hydrocarbons, and often show low sensitivity to moisture and air. In contrast, their use as hydroborating agents is of limited scope due to the formation of strong borane complexes, rendering the reactivity toward olefins lower than that of the adducts with ethers and sulfides. On the other hand, the growing importance of diborane for the synthesis of pharmaceuticals and other compounds[3] and certain inconveniences of well-established reagents, e.g., the low concentration and stability of borane-tetrahydrofuran (BH$_3$·THF), and the high volatility, flammability and unpleasant odor of dimethyl sulfide from borane-dimethyl sulfide (BMS) create a need for easy-to-handle, stable and environmentally benign hydroborating agents.

Accordingly, we have undertaken an extensive study in the hope of developing some highly reactive amine-borane adducts for hydroboration and reduction. In the preceding papers of this series, we reported highly reactive borane adducts with *N,N*-dialkylanilines, alkyldiisopropylamines and *tert*-butyldialkylamines as demonstrated by their success in hydroborating 1-octene in tetrahydrofuran at room temperature in less than 1 h.[4] Recently it was shown that borane adducts of *N*-silylamines also show similar high reactivity in hydroborations.[5] All these studies show for the first time that aliphatic amines are useful borane carriers for hydrobo-

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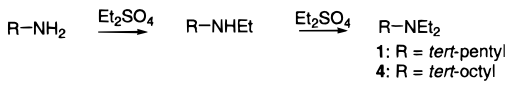
ration. Their potential advantages over traditional carriers, such as tetrahydrofuran or dimethyl sulfide for large-scale applications have been pointed out. We, in our several earlier papers, demonstrated that borane complexation depends strongly on the steric requirements of the amine.[4] The results obtained with alkylisopropylamines and *tert*-butyldialkylamines prompted us to examine *N,N*-dialkyl-*tert*-alkylamines, with the objective of developing useful borane adducts meeting the following requirements: (1) hydroboration of 1-octene in tetrahydrofuran at room temperature in less than 1 h; (2) liquid adduct (for easy transfer, miscibility and convenience in neat reactions) of high borane concentration, stable at room temperature, soluble in various solvents.

Results and Discussion

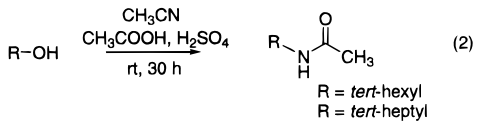
In our earlier studies with various *N,N*-dialkyl derivatives of *tert*-butylamine, the corresponding *N,N*-diethyl derivative takes 85% of borane from BMS and its adduct is relatively unreactive in hydroboration and requires 6 h for the hydroboration of 1-octene.[4f] However, the corresponding *N*-methyl-*N*-isopropyl or *N*-ethyl-*N*-isobutyl derivatives form stable, highly reactive borane adducts and the hydroboration of 1-octene is complete within 30 min. On the other hand, *tert*-butyl-*N*-ethyl-*N*-isopropylamine forms an unstable borane adduct and *N,N*-diisobutyl-*tert*-butylamine completely fails to complex with borane. These observations clearly show the dramatic effect of steric bulk around nitrogen on its complexing abilities with borane. Though our earlier studies provided highly reactive trialkylamine-boranes for hydroboration, the synthesis of amines containing three different alkyl groups is not an economical process. Accordingly, the introduction of two identical alkyl groups on a primary amine is more practical. It was therefore decided to prepare various *tert*-alkyl derivatives keeping the *N,N*-diethyl groups common, to obtain a better understanding of the steric effect, leading to the development of a new generation of hydroborating agents. Consequently, the syntheses of the following *N,N*-diethyl-2-methyl-2-butylamine (**1**, *t*-PentNEt$_2$), *N,N*-diethyl-2,3-dimethyl-2-butylamine (**2**, *t*-HexNEt$_2$), *N,N*-diethyl-2,3,3-trimethyl-2-butylamine (**3**, *t*-HeptNEt$_2$) and *N,N*-diethyl-1,1,3,3-tetramethylbutylamine (**4**, *t*-OctNEt$_2$) were undertaken.

Synthesis of Amines and the Corresponding Borane Adducts. The *tert*-pentyl-*N,N*-diethylamine and *tert*-octyl-*N,N*-diethylamine were prepared from the commercially available *tert*-pentylamine and *tert*-octylamines, respectively. The diethyl derivatives were prepared by treatment of the amines with diethyl sulfate, following the procedure reported for *tert*-butylamine.[4f]



(1)

Unlike *tert*-pentylamine, the corresponding *tert*-hexyl and heptylamines are not commercially available. Out of several possible syntheses,[6,7] the preparation from the corresponding *tert*-alcohols was thought to be one that could be used conveniently for large-scale synthesis. The *N*-acetyl derivatives were prepared following the reported procedure.[7b]



(2)

Reduction of the *N*-acetyl derivative with BMS provides the corresponding *N*-ethyl derivative in very good yields. *N,N*-Diethyl-*tert*-alkylamines can be prepared by treatment with diethyl sulfate. However, in the case of the *tert*-hexylamine, the diethyl derivative carried some sulfur derivative contamination even after the purification, interfering with the preparation of the borane adduct. Fortunately, preparation of the acetyl derivative of the secondary amine followed by the reduction gave a highly pure sample (Scheme 1).

The complexing ability of these amines toward borane was tested by the exchange with BMS and BH$_3$·THF mixed in 1:1 molar ratio. The amount of borane taken by the amine in the equilibrium was determined by ^{11}B NMR and is shown in Table 1. As expected, *tert*-pentyl-*N,N*-diethylamine shows reactivities similar to those of the corresponding *tert*-butyl derivative, with only marginal improvement of the rate. Also, the *tert*-heptyl-*N,N*-diethylamine forms a relatively strong borane adduct and the hydroboration of 1-octene takes 2.5 h. However, the *tert*-hexyl-*N,N*-diethylamine (**2**) and *tert*-octyl-*N,N*-diethylamine (**4**) show much improved reactivity. The *tert*-hexyl derivative (**2**) takes 87% borane from BH$_3$·THF and 40% from BMS (Table 1) and its hydroboration of 1-octene is complete within 30 min. Similarly, the *tert*-octyl-*N,N*-diethylamine takes up only 38% of the borane from BMS and 88% from BH$_3$·THF and its borane adduct hydroborates 1-octene within 20 min (Table 1).

It is quite evident from these preliminary studies that the amines **2** and **4** show the qualities of a good hydroborating agent. However, the starting material for the preparation of **4**, namely *tert*-octylamine is commercially

Scheme 1

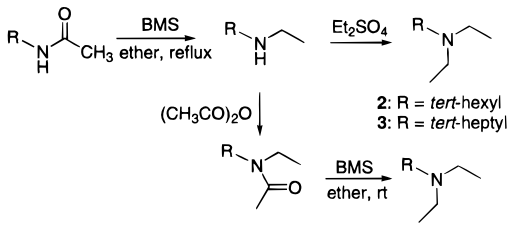


Table 1. Borane Adducts with *N,N*-Diethyl Derivatives of *tert*-Alkylamines

amine	exchange,[a] % BH$_3$·THF	exchange,[a] % BMS	^{11}B NMR[b]	hydroboration of 1-octene[c,d]
t-BuNEt$_2$[e]	100	85	−14.89	6 h
t-PentNEt$_2$ (**1**)	100	83	−14.86	4 h
t-HexNEt$_2$ (**2**)	87	40	−19.23	30 min
t-HeptNEt$_2$ (**3**)	100	80	−16.77	3.5 h
t-OctNEt$_2$ (**4**)	88	38	−15.14	20 min

[a] Amine mixed with BH$_3$·THF or BH$_3$·SMe$_2$ in 1:1 molar ratio at room temperature and analyzed by ^{11}B NMR at equilibrium. [b] From the exchange with BH$_3$·SMe$_2$. [c] 5% excess of 1-octene, room temperature in THF. [d] 3 M solution of 1-octene and 1 M in BH$_3$. [e] Values taken from ref 4f.

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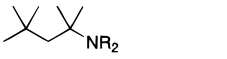
Table 2. Borane Adducts with *t*-OctNR$_2$ and *t*-OctNR^{1}R^2

	exchange,[a] %		amine·BH$_3$			hydroboration of 1-octene[e]	
amine	BH$_3$·SMe$_2$	BH$_3$·THF	state[b] (mp, °C)	[BH$_3$][c] M	^{11}B NMR[d] (δ)	in THF[f]	neat
t-OctNMe$_2$ **5**	85	94			−11.40	no	
t-OctNEtMe **6**	77	100			−15.60	24 h	
t-OctN(CH$_2$CH$_2$)$_2$O **7**	50	87	96−97		−16.42		20 min
t-OctNEt$_2$ **4**	38	88	liquid	4.0	−15.14	20 min	3 h
t-OctNBu^{i}Me, **8**	35	88	48−50		−14.29	1.5 h	
t-OctNPr$^n_2$ **9**	25	81	43−45		−14.32	20 min	

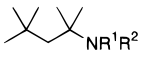
[a] Amine mixed with BH$_3$:SMe$_2$ or 1 *M* BH$_3$:THF in 1:1 molar ratio at room temperature and analyzed by ^{11}B NMR at equilibrium. [b] At 0 °C. [c] Estimated by hydrolysis in 2 *M* HCl-glycerol-water (2:1:1) and measuring the hydrogen evolved. [d] From the exchange with BH$_3$:SMe$_2$. [e] 5% excess of 1-octene, room temperature. [f] 3 *M* solution of 1-octene and 1 *M* in BH$_3$.

available and is less expensive. Accordingly we selected this derivative for our detailed studies.

To make sure that we were not sacrificing the possibility of obtaining an even better hydroborating agent by confining ourselves to *N*,*N*-diethyl groups on *tert*-octylamine, it was decided to examine more fully the steric factors around the nitrogen atom. Accordingly, we prepared several *N*,*N*-dialkyl substituted *tert*-octylamines (**4**−**9**), with increasing steric bulk of the alkyl groups within the series keeping the *tert*-octyl group common.

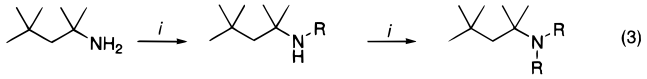


5 R = Me
7 R = -CH$_2$CH$_2$OCH$_2$CH$_2$-
4 R = Et
9 R = Pr^n



6 R^1 = Et; R^2 = Me
8 R^1 = Bu^i; R^2 = Me

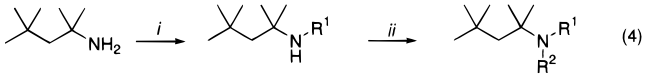
The amines **4**, **5**, **7**, and **9** having two primary unbranched alkyl groups, were prepared by the repetitive alkylation of *tert*-octylamine, following routine procedures (eq 3).



(3)

7: *i* = (ClCH$_2$CH$_2$)$_2$O; **4**: *i* = Et$_2$SO$_4$;
9: *i* = Pr^{n}I; **5**: *i* = HCHO/HCOOH

Slow addition of diethyl sulfate at controlled temperature and subsequent methylation gave **6** in a good yield, while **8** was obtained by routine alkylation with isobutyl bromide and methylation, according to eq 4.

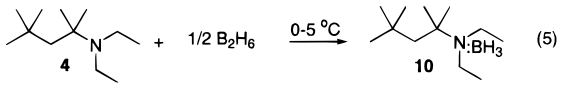


(4)

6: R^1 = Et, R^2 = Me, *i* = Et$_2$SO$_4$; *ii* = HCHO/HCOOH
8: R^1 = Bu^i, R^2 = Me, *i* = Bu^{i}Br; *ii* = HCHO/HCOOH

The complexing ability of these amines toward borane was tested by the exchange with BMS (borane−methyl sulfide) and BH$_3$·THF (borane−tetrahydrofuran) mixed in 1:1 molar ratio. The amount of borane taken by an amine in the equilibrium was determined by ^{11}B NMR and is shown in Table 2. Values for the exchange with BH$_3$·THF, a 1 M solution, should be considered qualitative since THF is in considerable excess. As revealed by the exchange experiments, the dimethyl derivative, **5**, takes 85% of borane from BMS and its adduct is unreactive in hydroboration. In contrast, **4** takes up only 38% of the borane and the reactivity of its adduct is dramatically increased (Table 2). It is a liquid, 4.0 M, in borane, stable at room temperature. The borane adducts of **7** and **9** are both solids of similar reactivity in THF. In general, the adducts of **4**, **7**, **8**, and **9** are more reactive, however, the adduct **4** meets our requirements to be a good hydroborating agent, liquid at room temperature, high borane concentration and hydroborates 1-octene rapidly at room temperature. Accordingly, the borane adduct of this amine was selected for detailed hydroboration studies.

Hydroboration Studies Using *tert*-Octyldiethylamine−Borane. The borane adduct of *tert*-octyldiethylamine (**4**) was prepared by passing a slight excess of diborane gas into the neat amine at 0−5 °C (eq 5). The concentration of the adsorbed borane was established to be 4.0 M by hydrolysis of an aliquot, using a 2 M HCl−glycerol−water mixture, measuring the hydrogen evolved.



(5)

The adduct thus obtained, maintained under nitrogen, is stable at room-temperature indefinitely. The ^{11}B NMR examination reveals a peak at −14.9 (q, CCl$_4$). The stability of this adduct in THF was also studied. Thus a solution of the adduct in THF (2.0 M in BH$_3$) was sealed in an NMR tube and monitored over several months using ^{11}B NMR at appropriate intervals. No new peaks in the ^{11}B NMR spectra other than that given by the adduct appeared during the 6 months of observation.

Hydroboration of Olefins in Tetrahydrofuran. Hydroboration of representative mono-, di-, tri-, and tetrasubstituted olefins with **10** was conducted in THF at room temperature. To establish the rate and stoichiometry, the reactions were carried out in solutions that were 0.5 M in BH$_3$ and 1.5 M in an olefin. The procedure followed was to add the THF solution of the olefin (3 equiv) to the amine−borane (1 equiv) in THF at 0 °C, stirring the mixture further at room temperature (22 ± 3 °C). The progress of the hydroboration was conveniently followed by taking out aliquots at intervals, hydrolyzing with 3 M HCl−glycerol−THF (2:1:0.2), and measuring the hydrogen evolved.[9] The reactions were also followed by ^{11}B NMR, monitoring a decreasing amine-borane signal and an increasing alkylborane signal.

Under the conditions indicated, the hydroboration of 1-hexene by *tert*-octyldiethylamine−borane (**10**) in THF is complete in 2 h, forming the trihexylborane. Hydrolysis

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(9) ref 8, p 241.

Table 3. Hydroboration of Representative Olefins With 10 in Various Solvents at Room Temperature[a]

	dioxane		THF		*tert*-butyl methyl ether		*n*-pentane		dichloromethane	
olefin	time, h	hydrides utilized	time, h	hydrides utilized	time, h	hydrides utilized	time, h	hydrides utilized	time, h	hydrides utilized
1-hexene	2.0	3.00	2.0	3.00	4.0	3.00	3.0	3.00	48	2.50
	1.0	2.76	1.0	2.88	1.0	2.66	1.0	2.05		
styrene	3.0	3.00	4.0	3.00	4.0	3.00	4.0	3.00	48	2.51
	1.0	2.73	1.0	2.52	1.0	2.66	1.0	2.02		
β-pinene	3.0	3.00	4.0	3.00	4.0	3.00	4.0	3.00	48	2.61
	1.0	2.73	1.0	2.66	1.0	2.66	1.0	2.02		
cyclopentene	3.0	3.00	4.0	3.00	4.0	3.00	4.0	3.00	48	2.80
	1.0	2.54	1.0	2.40	1.0	2.40	1.0	2.12		
norbornene	3.0	3.00	4.0	3.00	4.0	3.00	4.0	3.00	48	2.88
	1.0	2.64	1.0	2.36	1.0	2.53	1.0	2.95		
cyclohexene	24	2.95	24	2.81	24	2.90	24	2.92	48	2.76
	0.91	2.00	0.91	2.00	0.91	2.00	3.0	2.00		
2-methyl-2-butene	24	2.95	24	2.85	24	2.90	24	2.90	48	2.85
	1.66	2.00	2.16	2.00	1.66	2.00	6.0	2.00		
α-pinene	24	2.00	24	1.90	24	1.85	24	1.70	48	1.64
	0.33	1.00	0.50	1.00	0.66	1.00	0.50	1.00		
2,3-dimethyl-2-butene	24	1.76	24	1.71	24	1.67	24	1.66	48	1.69
	0.40	1.00	0.33	1.00	0.75	1.00	0.66	1.00		

[a] Reactions were carried out using amine−borane **10** (5 mmol) and an olefin (15 mmol) in a total volume of 10 mL solution.

of the reaction mixture does not evolve any hydrogen, indicating the complete utilization of borane. Disubstituted olefins, such as β-pinene and cyclopentene, are hydroborated to the trialkylborane stage in 4 h. Moderately hindered 2-methyl-2-butene gave disiamylborane after 2 h (^{11}B NMR, δ ppm +31.5), with further hydroboration proceeding more slowly. Cyclohexene forms dicyclohexylborane rapidly in 1 h (^{11}B NMR, δ ppm, +51.2 after methanolysis), and 2.81 hydride equivalents are utilized in 24 h (^{11}B NMR, δ ppm, +81.3 after methanolysis corresponding to the formation of tricyclohexylborane). However, the more hindered α-pinene consumes one hydride rapidly in 30 min and then the reaction continues slowly, with the hydride utilization increasing to 1.9 in 24 h at room temperature, indicating incomplete formation of Ipc_2BH. This is also confirmed by ^{11}B NMR, which reveals two peaks after methanolysis, at +31.5 (minor, due to $IpcB(OMe)_2$) and +52.6 (major, due to Ipc_2BOMe). Further substitution on the olefin, i.e., the tetrasubstituted 2,3-dimethyl-2-butene, results in a further lowering of the hydride uptake. Here also, the addition of the first hydride is very fast, giving thexylborane (^{11}B NMR, δ ppm +24.6) with the olefin/BH_3 ratio then rising to 1.71 after 24 h (^{11}B NMR, δ ppm +23.9 and +80.8, after methanolysis +31.1 and +52.9).

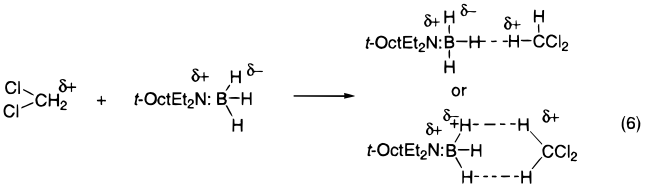
Hydroboration of Olefins in Other Solvents. Hydroborations with **10** were also conducted in solvents such as dioxane, *tert*-butyl methyl ether, *n*-pentane, and dichloromethane. In dioxane, **10** show an enhanced reactivity when compared to solutions of **10** in tetrahydrofuran. Thus, in dioxane, **10** hydroborates unhindered mono- and disubstituted olefins to the corresponding trialkylborane stage within 3 h (Table 3). Enhanced reactivity is also observed for hindered olefins. For example, α-pinene is cleanly hydroborated to the Ipc_2BH stage. This is also confirmed by ^{11}B NMR observation, which reveals the exclusive presence of Ipc_2BOMe after methanolysis (δ ppm +53).

In *n*-pentane, the hydroborations are comparable to that in THF requiring only 4 h to reach the trialkylborane stage with simple unhindered olefins. However, the hydroboration of moderately hindered olefins, such as cyclohexene and 2-methyl-2-butene, does not give trialkylboranes cleanly, even after 24 h. In the case of cyclohexene, 2.92 equivalents of hydride were consumed after 24 h, whereas it is 2.9 for 2-methyl-2-butene. More hindered α-pinene and 2,3-dimethyl-2-butene were rapidly hydroborated to the monoalkyl stage within 30 min, with further hydroboration proceeding slowly, consuming only 1.7 and 1.66 hydride equivalents, respectively, after 24 h (see Table 3)

In *tert*-butyl methyl ether also the reactivity of the borane-amine adduct **10** is very similar to that observed in THF and *n*-pentane. However, in dichloromethane unusual rate retardation in hydroboration was observed. Thus, the hydroboration of simple unhindered olefins, such as 1-hexene, is incomplete even after 48 h at room temperature, consuming only 2.5 equivalents of hydride out of the 3.00 available. ^{11}B NMR analysis of the reaction mixture showed the presence of unreacted amine-borane (**10**) (~15%). The hydride uptake is higher for moderately hindered cyclohexene and 2-methyl-2-butene, 2.76 and 2.85, respectively. Also, ^{11}B NMR analysis of the reaction mixture after 48 h did not show the presence of any starting amine-borane. A similar reactivity was also observed for the more hindered α-pinene and 2,3-dimethyl-2-butene. This unusual reactivity is may be due to the solvent interference in the reaction.

It is well established from our earlier studies[4,8] that, the rate-determining step in the hydroboration of olefins with BH_3:LB, is the formation of free "BH_3". However, such dissociation is not observed when the borane adduct **10**, was taken in dichloromethane. The ^{11}B NMR examination of the amine−borane in dichloromethane over a period of time showed only signals due to the amine-borane and no gas evolution was noted in gasimeter studies (diborane, after dimerization of dissociated "BH_3"). Whereas, in coordinating solvents such as THF, small amounts (2%) of BH_3:THF (^{11}B NMR, 0.9 ppm, q) were noted. Also, the amine−borane may be stabilized by the hydrogen in dichloromethane carrying a positive charge (eq 6). This could be the reason for initial slower reactivity of olefins toward the borane adduct **10** in dichloromethane.

In the case of less bulkier olefins, the RBH_2 formed after first hydroboration may coordinate with the carrier amine **4** to form $RBH_2{\cdot}NR_3$, leading to slower further hydroboration. This is confirmed with 1-hexene by ^{11}B

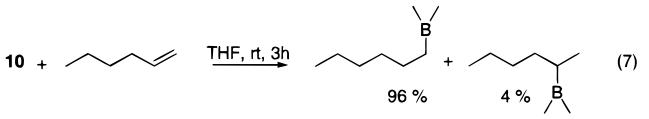


(6)

NMR analysis, which showed the formation of major amounts of $RB(OCH_3)_2$ after methanolysis of the reaction mixture at 24 h. However, such coordination is minimum or absent in the case of hindered olefins, due to the more bulky alkyl groups, leading to relatively faster hydroborations with the second and third equivalents of olefin.

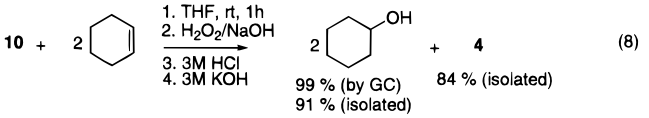
Summarizing the data for all the solvents, the following order of reactivity with solvent in the hydroboration of representative olefins with **10** was noted: dioxane > tetrahydrofuran > *n*-pentane ≥ *tert*-butyl methyl ether ≫ dichloromethane. Table 3 summarizes the results in various solvents.

Hydroboration−Oxidation of Olefins. To further establish the synthetic applicability of this new highly reactive amine-borane adduct, the hydroboration-oxidation of representative olefins was also studied. Hydroboration-oxidation of 1-hexene in THF gave a mixture of 1,2-hexanols in quantitative yield, as observed by GC analysis with an internal standard. The ratio of the boron addition to the internal vs the terminal positions in 1-hexene was established as 4:96 from the relative ratios of the corresponding alcohols after oxidation. These selectivities are similar to that reported for $THF{\cdot}BH_3$ or BMS.[8]



(7)

Hydroboration−oxidation of cyclohexene with **10** in THF gave cyclohexanol in quantitative yields (~99% by GC, 91% isolated, eq 8). The recovered amine, using acid−base manipulations, can be used again for the preparation of borane adducts.



(8)

Hydroboration−oxidation studies of various representative olefins listed in Table 3 and the adduct **10** in THF were also carried out. The results obtained are similar to that reported for $BH_3{\cdot}THF$ and no interference of carrier amine was noted. However, since the basic amine **4** was present in the reaction mixture after hydroboration, oxidation of the organoborane with hydrogen peroxide was also examined without the usual addition of sodium hydroxide. The oxidation was instantaneous, however the yield of cyclohexanol was slightly lower (~91% by GC). In the case of 1-hexene, the yield of 1- and 2-hexanols was even less (80% by GC) and the isomeric ratio was 89:11. Apparently, the oxidation is not complete. The complete oxidation can be achieved by the addition of 20 mol % of carrier amine to the reaction mixture before oxidation. Also, these preparative scale experiments can be carried out in other solvents such as dioxane, *tert*-butyl methyl ether and *n*-pentane. When the hydroborations are carried out in water-immiscible solvents, such as *tert*-butyl methyl ether and *n*-pentane, addition of small amounts of methanol or ethanol is essential to ensure complete oxidation using $NaOH/H_2O_2$.

Conclusions

This study has demonstrated that *N*,*N*-dialkyl-*tert*-alkylamines are convenient borane carriers for hydroboration. The complexing ability of amines can be varied in a predictable manner by a proper choice of alkyl groups. Among the various *tert*-alkyl-*N*,*N*-dialkylamineboranes prepared, the amine **4** formed a stable, highly reactive liquid adduct. Simple procedures for the synthesis of the majority of amines examined have been worked out. As a result of this and other previous studies,[4,5] a group of new, highly reactive borane−amine adducts has become available for the first time. The present study also demonstrates the synthetic potential of the new, highly reactive amine-borane adduct *tert*-octyldiethylamine−borane (**10**). Simple unhindered olefins can be hydroborated to the trialkylborane stage, whereas hindered olefins can be partially hydroborated to the mono or dialkylborane stage. The hydroborations can be carried out conveniently in a variety of solvents. The amine−borane adduct shows enhanced reactivity in dioxane but low reactivity in dichloromethane. This unusual reactivity in dichloromethane may be used for selective hydroborations. The hydroboration products were oxidized using hydrogen peroxide/sodium hydroxide to give the corresponding alcohols in quantitative yields, without any interference by the amine. As the carrier amine is basic, oxidation in the absence of sodium hydroxide can also be carried out. However, under these conditions, the oxidation is incomplete. It can be made complete by the addition of 20 mol % of the carrier amine to the reaction mixture before the oxidation. The borane carrier amine **4** can be readily recovered from the hydroboration products by simple acid−base manipulations, distillation, or column chromatography, and can be easily recycled for the preparation of the borane adduct.

Experimental Section

Manipulations and reactions with air-sensitive compounds were carried out under a nitrogen atmosphere. Glassware was oven-dried for several hours, assembled while hot and cooled in a stream of dry nitrogen gas. Techniques for handling air-sensitive compounds, described elsewhere were followed.[8] ^1H, ^{13}C and ^{11}B NMR spectra were recorded on a 300 MHz multinuclear instrument. The ^{11}B NMR chemical shifts are in δ relative to $BF_3{:}Et_2O$. Mass spectra were obtained on a mass spectrometer in both CI and EI modes. GC analyses were carried out either on a chromatograph equipped with capillary column (0.25 μm × 30 m) or with a chromatograph provided with FID and a CI-100A integrator. The following columns were used, 6 ft × 0.125 in, 15% Carbowax 20M on Chromosorb W, 9 ft × 0.125 in, 3% OV-17 on Chromosorb-G and 3 ft × 0.125 in, 10% SE 30 on Chromosorb W. Optical rotations were measured on a polarimeter. The hydride analysis studies were carried out using the gasimeter.[9] Microanalyses were performed at the Microanalytical Laboratory, Purdue University.

Materials. *tert*-Hexylamine,[7] *tert*-heptylamine[7] *N*-*tert*-octylmorpholine,[10] **1c**, and diisopropyl sulfate[11] were prepared

(10) Olin, S. M.; Brit. Pat. 742, 298 **1955**; *Chem. Abstr.* **1957**, *51*, 4936.

(11) Kranzfelder, A. L.; Sowa, F. J. *J. Am. Chem. Soc.* **1937**, *59*, 1491.

according to the literature. *tert*-Octylamine and *tert*-pentylamine were commercial products. All solvents were purified according to literature procedures and stored under nitrogen. Tetrahydrofuran and dioxane were freshly distilled from benzophenone ketyl before use. All olefins were distilled from a small amount of lithium aluminum hydride and stored under nitrogen. (+)-α-Pinene, $[\alpha]^{22}_D$ +45.2° (87.3% ee) was used.

***tert*-Alkyldiethylamines.** The procedures followed for *tert*-pentyl-, -hexyl-, -heptyl-, and -octyldiethylamine are the same. The procedure followed for *tert*-octyldiethylamine (**4**) is representative.

***tert*-Octyldiethylamine 4.** The diethyl sulfate (18.50 g, 0.12 mol) was added to *tert*-octylamine (12.93 g, 0.1 mol) at room temperature. The reaction was exothermic and the temperature rose to 120 °C. After cooling to 50 °C, aqueous 8 *M* potassium hydroxide (40 mL, 0.32 mol) was added, the organic layer was separated when warm, and then dried over anhydrous magnesium sulfate. This crude product was treated with diethyl sulfate (18.50 g, 0.12 mol) and heated with stirring at 100−150 °C for 15 min. After the same workup as described above, the organic layer was separated, dried over anhydrous magnesium sulfate and heated at 120 °C for 30 min. Basic workup and distillation gave the product, *tert*-octyldiethylamine: 16.66 g (90%); bp 88−89 °C/17 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.99 (*s*, 9H, CH_3), 1.02 (*t*, J = 7.0, 6H, CH_3), 1.13 (*s*, 6H, CH_3), 1.40 (*s*, 2H, CH_2), 2.53 (*q*, J = 7.0, 4H, CH_2); ^{13}C NMR ($CDCl_3$) δ 17.00 (CH_3), 27.56 (CH_3), 31. 41 (C), 31.99 (CH_3), 43.06 (CH_2), 50.04 (CH_2), 58.75 (CN); MS (70 eV EI CI) 185 (M^+), 114 (100), 58 (14). Anal. Calcd for $C_{12}H_{27}N$: C, 77.76; H, 14.68; N, 7.56. Found: C, 77.47; H, 14.71; N, 7.93.

***tert*-Pentyldiethylamine 1:**[7a] yield 70%; bp 129−131 °C/760 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.83 (t, J = 7.3, 3H), 0.88 (s, 6H), 0.98 (t, J = 7.3, 6H), 1.82 (m, 1H), 2.49 (t, J = 7.1, 4H); ^{13}C NMR ($CDCl_3$) δ 17.02 (CH_3), 17.42 (CH_3), 20.01 (CH_3), 34.49 (CH), 35.54 (C), 42.70 (CH_2).

***tert*-Heptyldiethylamine 3:**[7b] yield 62%; bp 58−60 °C/20 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.91 (s, 9H), 1.02 (s, 6H), 1.21 (t, J = 7.0, 6H), 3.47 (t, J = 7.05, 4H); ^{13}C NMR ($CDCl_3$) δ 16.35 (CH_3), 21.07 (CH_3), 25.42 (CH_3), 36.74 (C), 46.23 (CH_2), 56.69 (C).

***tert*-Hexyldiethylamine 2.**[7c] **Method A.** Initially this amine was prepared by the reaction of diethyl sulfate with *tert*-hexylamine following the procedure used for *tert*-octyldiethylamine: yield 75%; bp 156−160 °C/760 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.83 (t, J = 7.5, 3H), 0.98 (s, 6H), 1.01 (t, J = 7.1, 6H), 1.41 (q, J = 7.4, 2H), 2.51 (q, J = 7.08, 4H); ^{13}C NMR ($CDCl_3$) δ 8.74 (CH_3), 16.77 (CH_3), 24.20 (CH_3), 32.74 (CH_2), 42.63 (CH_2), 57.13 (C).

Method B. To a diethyl ether (50 mL) solution of *N*-acetyl-*tert*-hexylamine[7b] (21.50 g, 150 mmol), borane−dimethyl sulfide (30 mL, 10 M, 300 mmol) was added slowly (caution! hydrogen evolution) during 30 min. After the gas evolution ceased, the reaction mixture was refluxed for 24 h. The reaction was quenched with careful addition of water and 6 N HCl was added. The diethyl ether was removed by rotary evaporation and the residue was made basic by the addition of KOH pellets. The amine later was separated and dried over anhydrous magnesium sulfate. Filtration and simple distillation provided essentially pure *N*-ethyl-*tert*-hexylamine in 92.2% yield (17.49 g): bp 98−100 °C/760 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.86 (d, J = 6.0, 6H), 0.98 (s, 6H), 1.07 (t, J = 7.1, 3H), 1.75 (m, 1H), 2.1 (bs, 1H), 2.54 (q, J = 7.1, 2H); ^{13}C NMR ($CDCl_3$) δ 16.01 (CH_3), 17.30 (CH_3), 23.53 (CH_3), 34.51 (CH), 35.41 (CH_2), 54.52 (C).

Treatment of *N*-ethyl-*tert*-hexylamine with acetic anhydride provided the corresponding *N*-acetyl derivative, which was again reduced using borane-dimethyl sulfide complex to the corresponding *tert*-hexyldiethylamine following the above-mentioned procedure in 83% yield.

***tert*-Octyldimethylamine 5.** Formic acid, 88% (20.92 g, 0.4 mol) was added to *tert*-octylamine (12.93 g, 0.1 mol), followed by a 37% formaldehyde solution (17.83 g, 0.22 mol) at 0 °C. The mixture was warmed to 50−55 °C and kept at this temperature for 2 h. Aqueous 8 *M* potassium hydroxide (65 mL, 0.52 mol) was added and the mixture was extracted with *n*-pentane. The pentane solution was dried over anhydrous magnesium sulfate and the product, *tert*-octyldimethylamine, was isolated by distillation: 12.24 g (77%); bp 62−63 °C/17 mmHg (lit.[12] bp 174−175 °C); ^{1}H NMR ($CDCl_3$) δ 1.00 (*s*, 9H, CH_3), 1.11 (*s*, 6H, CH_3), 1.39 (*s*, 2H, CH_2), 2.21 (*s*, 6H, CH_3).

***tert*-Octylethylmethylamine 6.** Diethyl sulfate (33.92 g, 0.22 mol) was slowly added to *tert*-octylamine (25.86 g, 0.2 mol) keeping the reaction mixture at 60−65 °C and then it was stirred for 15 min. Aqueous 8 M potassium hydroxide (40 mL, 0.32 mol) was added to the warm mixture. The organic layer was separated, dried over anhydrous magnesium sulfate and then again heated at 80 °C for 0.5 h. The two layers formed were separated. The upper amine layer was dried over anhydrous magnesium sulfate and the product, *tert*-octylethylamine, was isolated by distillation: 28 g (89%); bp 64−66 °C/20 mmHg.

A 37% solution of formaldehyde (7.93 g, 109 mmol) was added to a mixture of *tert*-octylethylamine (17.3 g, 100 mmol) and 88% formic acid (8.31 g, 181 mmol) at 0 °C. The reaction mixture was kept at 80 °C for 3 h. Aqueous 8 M potassium hydroxide (33 mL, 211 mmol) was added, the organic layer was separated and aqueous layer was extracted with *n*-pentane. The organic solutions were combined, dried over anhydrous magnesium sulfate and the product, *tert*-octylethylmethylamine, was isolated by distillation: 14.5 g (85%); bp 78−80 °C/20 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.99 (*s*, 9H, CH_3), 1.02 (*t*, 3H, J = 6.1, CH_3), 1.10 (*s*, 6H, CH_3), 1.39 (*s*, 2H, CH_2), 2.16 (*s*, 3H, CH_3), 2.41 (*q*, 2H, J = 6.1, CH_2); ^{13}C NMR ($CDCl_3$) δ 14.80 (CH_3), 26.21 (CH_3), 31.42 (C), 31.96 (CH_3), 33.93 (CH_2), 44.16 (CH_3), 49.20 (CH_2), 57.83 (CN); MS (70 eV EI CI) 171 (M^+), 100 (100). Anal. Calcd for $C_{11}H_{25}N$: C, 77.11; H, 14.70; N, 8.17. Found: C, 76.80; H, 14.63; N, 8.55.

***tert*-Octylisobutylmethylamine 8.** A mixture of *tert*-octylamine (25.86 g, 0.2 mol) and 2-methyl-1-bromopropane (13.70 g, 0.1 mol) was heated at 130 °C for 28 h. Aqueous 8 *M* potassium hydroxide (40 mL, 0.32 mol) was added. The organic layer was separated and dried with anhydrous magnesium sulfate. The organic layer, after distillation gave a pure fraction of *tert*-octylisobutylamine, 10.37 g, (56%), bp 92−94 °C/23 mmHg.

A 37% solution of formaldehyde (4.22 g, 58 mmol) was added to a mixture of *tert*-octylisobutylamine (10 g, 53 mmol) and 88% formic acid (9.41 g, 96 mmol) at 0 °C. The reaction mixture was kept at 50−55 °C for 10 h. Aqueous 8 *M* potassium hydroxide (17 mL, 143 mmol) was added, the organic layer was separated and the aqueous layer was extracted with *n*-pentane. The organic solutions were combined, dried over anhydrous magnesium sulfate and the product, *tert*-octylisobutylmethylamine, was isolated by distillation: 9.08 g (86%); bp 104−106 °C/20 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.86 (*d*, 6H, J = 6.6, CH_3), 0.99 (*s*, 9H, CH_3), 1.07 (*s*, 6H, CH_3), 1.37 (*s*, 2H, CH_2), 1.64 (*nonet*, 1H, J = 6.6, CH), 2.09 (*d*, 2H, J = 6.6, CH_2), 2.12 (*s*, 3H, CH_3); ^{13}C NMR ($CDCl_3$) δ 21.03 (CH_3), 26.54 (CH_3), 27.12 (CH), 31.41 (C), 31.98 (CH_3), 35.58 (CH_2), 49.31 (CH_2), 57.41 (C), 59.06 (CH_2); MS (70 eV EI CI), 200 (M^+ + 1), 128-(100), 72(39), 57(27). Anal. Calcd for $C_{13}H_{29}N$: C, 78.31; H, 14.66; N, 7.02. Found: C, 78.21; H, 14.72; N, 7.41.

***tert*-Octyldi-*n*-propylamine 9.** A mixture of *tert*-octylamine (25.86 g, 0.2 mol), 1-iodopropane (25.50 g, 0.15 mol) and glycerol (7.13 g, 77 mmol) was refluxed for 2 h. Aqueous 8 *M* potassium hydroxide (40 mL, 0.32 mol) was added, the organic layer was separated and dried with anhydrous magnesium sulfate. It was treated with 1-iodopropane (25.50 g, 0.15 mol) and refluxed for 6 h. Basic workup as described above and distillation gave the product, *tert*-octyldi-*n*-propylamine: 9.90 g (31%); bp 112−113 °C/17 mmHg; ^{1}H NMR ($CDCl_3$) δ 0.82 (*t*, J = 7.0, 6H, CH_3), 0.88 (*s*, 9H, CH_3), 1.12 (*s*, 6H, CH_3), 1.39 (*s*, 2H, CH_2), 1.41 (*sextet*, J = 7.0, 4H, CH_2), 2.37 (*m*, 4H, CH_2); ^{13}C NMR ($CDCl_3$) δ 11.85 (CH_3), 25.07 (CH_2), 27.78 (CH_3), 31.28 (C), 31.99 (CH_3), 49.45 (CH_2), 52.79 (N−CH_3), 58.46 (C);

(12) Bortnick, N. M.; Luskin, L. S.; Hurwitz, M. D.; Craig, W. E.; Exner, L. J.; Mizra, J. *J. Am. Chem. Soc.* **1956**, *78*, 4039.

MS (70 eV El Cl) 213 (M^+), 142 (100), 72 (18), 58 (10), 57 (16). Anal. Calcd for $C_{14}H_{31}N$: C, 78.79; H, 14.64; N, 6.56. Found: C, 78.80; H, 14.49; N, 6.81.

Borane−Amine Adducts. General Procedure. Diborane generated as described elsewhere[13,14] was passed into a neat amine (50 mmol) at 0 °C, placed in a bubbler provided with a sintered glass tip and a magnetic stirring bar. Excess of diborane not absorbed by the amine was absorbed in a next bubbler containing tetrahydrofuran over mercury and cooled in ice water. A mercury bubbler was connected to the exit. Diborane was passed into the amine until the concentration of borane in THF was ~1 M. The borane-amine adduct was stirred overnight at room temperature prior to disconnecting the bubblers and then analyzed for active hydride by a standard procedure,[9] using a 2 M hydrochloric acid-glycerol-water (2:1:1) hydrolysis solution.

Hydroboration of Representative Olefins with 10. General Procedure. An oven-dried, 50 mL RB flask, provided with a septum inlet to introduce and remove compounds, a stirring bar and a stopper, was cooled to 0 °C under nitrogen. The flask was charged with an amine-borane adduct **10** (5.0 mmol) and a solvent. A solution of an olefin (15.0 mmol, 6.0 M, 2.5 mL) was added at 0 °C and the contents were further stirred at room temperature (19−25 °C). The contents of the reactions were always maintained in the temperature range. Aliquots (1.0 mL) were taken out at intervals and hydrolyzed using 3.0 M HCl−glycerol−THF (2:1:0.2) as the hydrolysis solvent. The hydrogen evolved was measured using a gasimeter to establish the presence of active hydride. The reactions were simultaneously followed by ^{11}B NMR, observing the relative ratio of an amine−borane signal and the signals due to the hydroboration product.

Hydroboration−Oxidation of 1-Hexene with 10 in Tetrahydrofuran. An oven-dried RB flask was cooled to 0 °C under a stream of nitrogen gas. In the flask was placed **10** (1.1 mL, 4.5 M, 5.0 mmol) in freshly distilled THF (7.4 mL) and undecane (7.5 mmol, GC standard). 1-Hexene (15.0 mmol, 1.26 g) was added slowly during 5 min. at 0 °C. The contents were further stirred for 2 h at room temperature. The reaction was quenched with careful addition of water. The reaction mixture was cooled to 10 °C and 3.0 mL of 3.0 N NaOH was added, followed by the slow addition of 2.0 mL 30% hydrogen peroxide during 10 min. The contents were further stirred at 50 °C for 2 h to ensure completion of oxidation. The reaction mixture was cooled to room temperature and the organic layer was separated. The aqueous layer was saturated with potassium carbonate and extracted with ether, the combined organic extract was washed with brine and dried over anhydrous magnesium sulfate. The combined yield of 1- and 2-hexanols was 98% (by GC using OV-17 column). The ratio of 1-hexanol/2-hexanol is 96:4

Hydroboration−Oxidation of Cyclohexene with 10 in Tetrahydrofuran. An oven-dried hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. In the flask was placed **10** (1.1 mL, 4.5 M, 5.0 mmol) in freshly distilled THF (7.4 mL). Cyclohexene (10.0 mmol, 0.82 g) was added slowly during 5 min at 0 °C. The contents were further stirred for 1 h at room temperature. The reaction was quenched with careful addition of water. The reaction mixture was cooled to 10 °C and 3.0 mL of 3.0 N NaOH was added followed by the slow addition of 1.0 mL 30% hydrogen peroxide. The contents were further stirred at 50 °C for 2 h. The reaction mixture was cooled to room temperature and the organic layer was separated. The aqueous layer was saturated with potassium carbonate and extracted with ether. The combined organic layer was washed with 3.0 *N* HCl, then with brine, and dried over anhydrous magnesium sulfate. Evaporation of the solvent gave essentially pure cyclohexanol, which was further purified by passing through a small silica gel pad, providing a yield of 1.07 g (90.3%).

The aqueous layer was neutralized with 3.0 N KOH solution and extracted with ether. The combined organic extract was washed with brine and dried over anhydrous magnesium sulfate. GC analysis of the crude showed the presence of cyclohexanol (2%) in addition to **4** (98%). Amine was recovered in pure form by column chromatography using hexane/ethyl acetate (95:5) as eluent in 86% (0.68 g) yield.

Acknowledgment. Financial support of this study by the Borane Research Fund and Aldrich Chemical Co. is gratefully acknowledged.

JO0002745

(13) ref 8, p 18.

(14) For improved methods for the generation of diborane, see: Kanth, J. V. B.; Brown, H. C. *Inorg. Chem*. **2000**, *39*, 1795.