Molecular Addition Compounds. 13. *N,N*-Diisopropyl-*N*-isobutylamine−Borane: The First Highly Reactive Trialkylamine−Borane Reagent for Hydroborations

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N,N-Diisopropyl-*N*-isobutylamine (**1**) forms a stable liquid borane adduct (4.7 M in BH_3), when diborane is bubbled into the neat amine. The adduct thus formed is stable indefinitely at room temperature under an inert atmosphere. Hydroboration studies with this new, highly reactive amine−borane adduct, $H_3B{:}NPr^i{}_2Bu^i$ (**2**) and representative olefins, such as 1-hexene, styrene, *β*-pinene, cyclopentene, norbornene, cyclohexene, 2-methyl-2-butene, α-pinene, and 2,3-dimethyl-2-butene, were carried out at room temperature (22 ± 3 °C) in selected solvents, tetrahydrofuran, dioxane, *tert*-butyl methyl ether, *n*-pentane, and dichloromethane. The reactions are faster in dioxane and *n*-pentane, requiring ∼2 h for the hydroboration of simple, unhindered olefins to the trialkylborane stage. Moderately hindered olefins, such as cyclohexene and 2-methyl-2-butene, give the corresponding dialkylboranes rapidly, with further hydroboration to the trialkylborane stage slower. However, the hindered α-pinene and 2,3-dimethyl-2-butene structures give stable monoalkylboranes very rapidly, with further hydroboration proceeding relatively slowly. The hydroborations also proceed readily in other solvents, such as THF and *tert*-butyl methyl ether. However, a dramatic rate retardation in dichloromethane is observed. The hydroboration of less hindered olefins is not complete even after 48 h at room temperature, and starting amine−borane still persisted as observed by ^{11}B NMR analysis of the reaction mixture. Surprisingly, more hindered olefins, such as α-pinene and 2,3-dimethyl-2-butene, underwent hydroboration relatively rapidly with no detectable starting amine−borane in ^{11}B NMR analysis of the reaction mixture. 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 to make the borane adduct. This new amine−borane adduct was also very efficient for the synthesis of important dialkylborane reagents. Various dialkylboranes, such as disiamylborane, $^{d}Ipc_2BH$, 2-$^{d}Icr_2BH$, 9-BBN, and Chx_2BH, were conveniently prepared in dioxane and THF. In the case of solid dialkylborane products, the amine can usually be separated by simple filtration. When the product is a liquid dialkylborane, such as disiamylborane, the presence of amine in the reaction medium usually does not interfere with further reactions.

Diborane is a versatile reagent with a multitude of applications in organic and inorganic syntheses.[2−7] Since it is a pyrophoric gas, it is preferably handled in the form of liquid borane complexes with suitable Lewis base carriers. Among the various borane−Lewis base complexes that have been explored, borane−tetrahydrofuran (BH_3:THF) and borane−dimethyl sulfide (BMS) are the reagents of choice for most hydroborations and reductions.[2,3] However, these important reagents are not free from certain disadvantages. For example, the low concentration of borane in commercial BH_3:THF limits its applications to only one solvent, THF. Unfortunately, the complex is not stable over long periods. Although BMS does not possess these disadvantages, the volatility, flammability, and unpleasant odor of the dimethyl sulfide create problems from the environmental viewpoint. Amines as borane carriers are free of these problems.[4] However, the amine−borane

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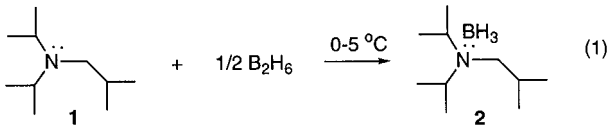
adducts previously described are much less reactive than BH_3:THF and BMS.[8−10]

In the hope of developing new, highly reactive amine−boranes for hydroborations and reductions, we recently initiated an extensive study in this area. We synthesized many new amines and amine−boranes with varying electronic and steric factors around nitrogen.[11,12] Although *N*,*N*-diisopropyl-*N*-ethylamine has been commercially available for some time, the corresponding borane adduct is unreactive and the hydroboration of 1-octene is incomplete, even after 24 h at room temperature. Accordingly, we synthesized several *N*,*N*-diisopropyl-*N*-alkylamines and their borane adducts.[13] Among the various amine−borane adducts prepared, the most promising, *N*,*N*-diisopropyl-*N*-isobutylamine−borane, was selected for a detailed study, and the results are herein described.

Results and Discussion

Preparation and Stability. The borane adduct of *N*,*N*-diisopropyl-*N*-isobutylamine **(1)** was prepared by passing a slight excess of diborane gas into the neat amine at 0−5 °C (eq 1). The concentration of the adsorbed borane was established to be 4.7 M by hydrolysis of an aliquot, using a 2 M HCl−glycerol−water mixture, measuring the hydrogen evolved.



(1)

The adduct thus obtained, maintained under nitrogen, is stable at room temperature indefinitely. ^{11}B NMR reveals a peak at −13.2 (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 first three months of observation. However, after four months there appeared a small additional peak at 18.3 (3−5%), probably arising from a slow cleavage of THF by borane.

Hydroboration of Olefins in Tetrahydrofuran. Hydroboration of representative mono-, di-, tri-, and tetrasubstituted olefins with **2** 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 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. 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 *N*,*N*-diiisopropyl-*N*-isobutylamine−borane **(2)** in THF is complete in 4 h, forming the trihexylborane. Hydrolysis of the reaction mixture does not evolve any hydrogen, indicating complete utilization of borane. Disubstituted olefins, such as *β*-pinene and cyclopentene, are also hydroborated to the trialkylborane stage in 4 h. The moderately hindered 2-methyl-2-butene gave disiamylborane after 2 h (^{11}B NMR, *δ* ppm, +30.8), with further hydroboration proceeding more slowly. Cyclohexene forms dicyclohexylborane rapidly in 30 min (^{11}B NMR, *δ* ppm, +51.2 after methanolysis), and 2.88 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 40 min, and then the reaction continues slowly, with the hydride utilization increasing to 1.76 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 1.45 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 **2** were also conducted in solvents such as dioxane, *tert*-butyl methyl ether, *n*-pentane, and dichloromethane. In dioxane, **2** shows an enhanced reactivity when compared to solutions of **2** in tetrahydrofuran. Thus, in dioxane **2** hydroborates unhindered mono- and disubstituted olefins to the corresponding trialkylborane stage within 2 h. 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). Figure 1 illustrates the plots of hydroboration of hindered olefins with time in dioxane at room temperature.

In *n*-pentane also, the hydroborations are faster than in THF, requiring only 2 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, 2.88 equiv of hydride was consumed after 24 h, whereas it is 2.95 for 2-methyl-2-butene. More hindered α-pinene and 2,3-dimethyl-2-butene were rapidly hydroborated to the monoalkyl stage within 40 min, with further hydroboration proceeding slowly, consuming only 1.91 and 1.76 hydride equivalents, respectively, after 24 h (see Table 1)

In *tert*-butyl methyl ether the reactivity of the bo-

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Table 1. Hydroboration of Representative Olefins Using 2 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	3.00	4	3.00	4	3.00	2	3.00	48	1.76
	1	2.78	1	2.45	1	2.57	1	2.29		
styrene	2	3.00	4	3.00	4	3.00	2	3.00	48	1.92
	1	2.80	1	2.14	1	2.52	1	2.29		
β-pinene	2	3.00	4	3.00	4	3.00	2	3.00	48	2.03
	1	2.78	1	2.40	1	2.52	1	2.31		
cyclopentene	2	3.00	4	2.93	4	3.00	2.5	3.00	48	2.11
	1	2.80	1	2.52	1	2.40	1	2.36		
norbornene	2	3.00	4	2.95	4	3.00	2.5	3.00	48	2.14
	1	2.80	1	2.36	1	2.37	1	2.40		
cyclohexene	24	2.95	24	2.88	24	2.95	24	2.88	48	2.79
	0.83	2.00	0.83	2.00	1	2.00	0.66	2.00		
2-methyl-2-butene	24	2.95	24	2.94	24	2.90	24	2.95	48	2.75
	1.83	2.00	2.16	2.00	1.16	2.00	2.66	2.00		
α-pinene	24	2.00	24	1.76	24	1.81	24	1.91	48	1.54
	0.33	1.00	0.66	1.00	0.66	1.00	0.66	1.00		
2,3-dimethyl-2-butene	24	1.71	24	1.45	24	1.69	24	1.76	48	1.64
	0.66	1.00	0.91	1.00	0.91	1.00	0.50	1.00		

[a] Reactions were carried out using amine−borane **2** (5.0 mmol) and an olefin (15.0 mmol) in a total volume of 10.0 mL of solution.

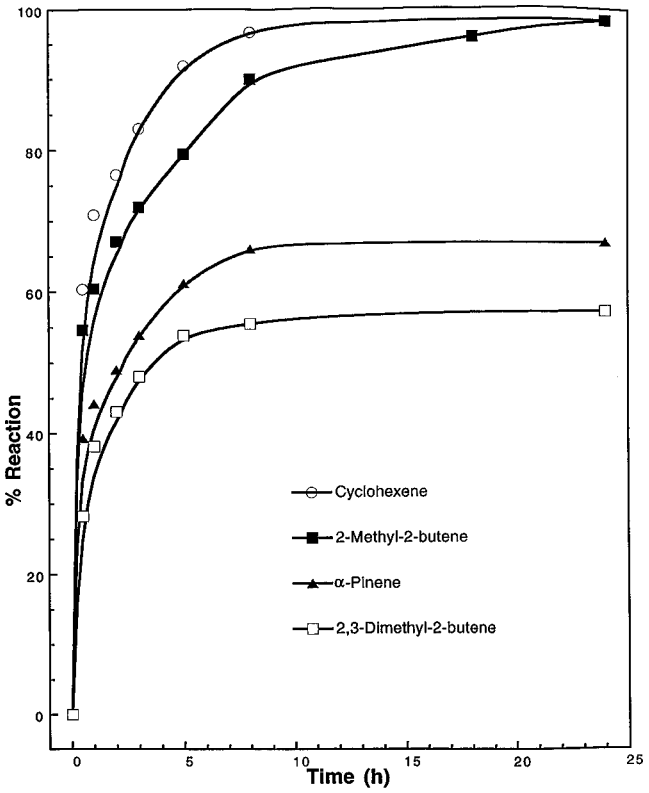
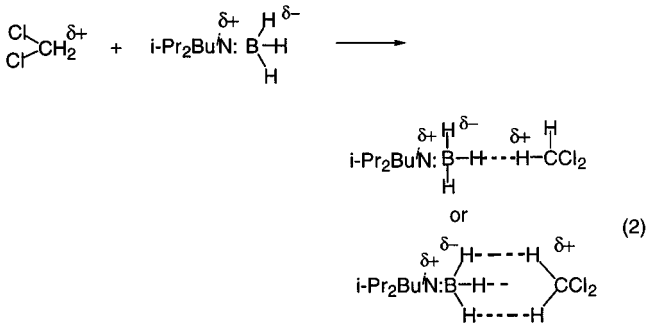


Figure 1. Hydroboration of hindered olefins using **2** in dioxane at room temperature.

rane−amine adduct **2** is very similar to that observed in THF. However, in dichloromethane an 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 1.76 equiv of hydride out of the 3.00 available. ^{11}B NMR analysis of the reaction mixture showed the presence of unreacted amine−borane (**2**) (~40%). The hydride uptake is higher for moderately hindered cyclohexene and 2-methyl-2-butene, 2.79 and 2.75, 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 may be due to the following.

It is well established from our earlier studies[2,3] 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 borane adduct **2** 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 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. This could be the reason for initial slower reactivity of olefins toward the borane adduct **2** in dichloromethane.



In the case of less bulkier olefins, the RBH_2 formed after first hydroboration may coordinate with the carrier amine **1** to form RBH_2:NR_3, leading to slower further hydroboration. This is confirmed with 1-hexene by ^{11}B 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 minimal or absent in the case of hindered olefins, due to the more bulky alkyl groups, leading to relatively faster hydroborations with second and third equivalents of olefin. Figure 2 illustrates plots of hydroboration of hindered olefins with time in dichloromethane at room temperature.

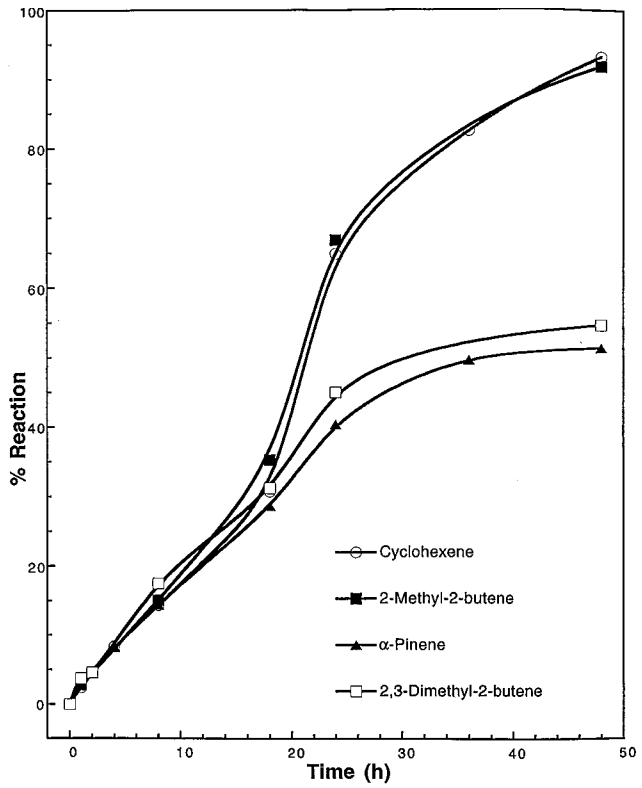
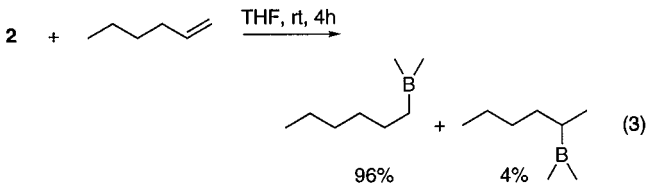


Figure 2. Hydroboration of hindered olefins using **2** in dichloromethane at room temperature.

Summarizing the data for all the solvents, the following order of reactivity with solvent in the hydroboration of representative olefins with **2** was noted: dioxane > *n*-pentane > tetrahydrofuran > *tert*-butyl methyl ether ≫ dichloromethane. Table 1 summarizes the results in various solvents.

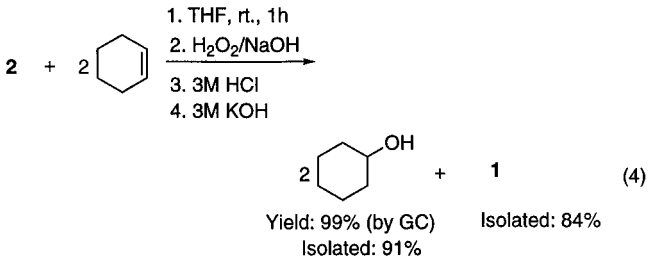
Hydroboration−Oxidation of Olefins. To further establish the synthetic applicability of this new highly reactive amine−borane adduct, the hydroboration−oxidation of representative olefins was also studied. Hydroboration−oxidation of 1-hexene in THF gave mixture of 1-, 2-hexanols in quantitative yield, as observed by GC analysis with an internal standard. The ratio of the boron addition to internal vs 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 $THF:BH_3$ or BMS.[2]



(3)

Hydroboration−oxidation of cyclohexene with **2** in THF gave cyclohexanol in quantitative yields (~99% by GC, 91% isolated, eq 4). The recovered amine using acid−base manipulations can be used again for the preparation of borane adducts.

Since the basic amine **1** 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

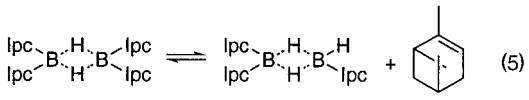


(4)

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 hydroboraions 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 $NaOH/H_2O_2$.

Convenient Preparations of Representative Dialkylborane Reagents Using 2. The hydroboration of certain moderately hindered olefins with **2** proceeds relatively rapidly to the mono- or dialkylborane stage, with further reaction being slow. Consequently, we undertook a study of the preparation of several well-established dialkylboranes,[14] such as diisopinocampheylborane, (1*S*)-2-diisocaranylborane, 9-borabicyclo[3,3,1]-nonane, disiamylborane, and dicyclohexylborane, using the new environmentally benign amine−borane reagent (**2**).

Preparation of Diisopinocampheylborane, ^{d}Ipc$_2$-BH. The reaction of borane with α-pinene, not optically pure, was originally studied in diglyme and THF.[15] Asymmetric hydroboration of *cis*-2-butene with Ipc_2BH thus formed and not isolated yielded 2-butanol in 87% and 78% ee, respectively. The lower ee in THF compared to that in diglyme was attributed to greater solubility of tetraisopinocampheyldiborane in THF and hence to more dissociation of the reagent to triisopinocampheyldiborane and α-pinene (eq 5).



(5)

In recent years, it has been demonstrated that Ipc_2-BH approaching almost 100% ee can be prepared by hydroboration of α-pinene with borane−tetrahydrofuran or BMS. Several procedures[16,17] have been developed; the most convenient one starting with (+)-α-pinene of 91% ee gives Ipc_2BH of >99% ee in 91% yield.[18] The

(14) All these partially substituted boranes exist mainly as diborane dimers, but the monomeric forms are shown for the sake of convenience.

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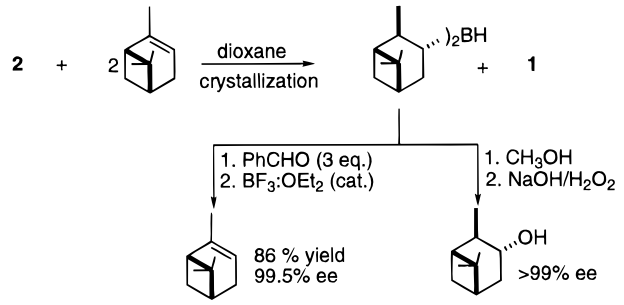
Scheme 1



reagent hydroborates *cis*-2-butene to afford after oxidation 2-butanol in 97.2% ee. Hence, it was interesting to use the new amine−borane for the preparation of this remarkable reagent.

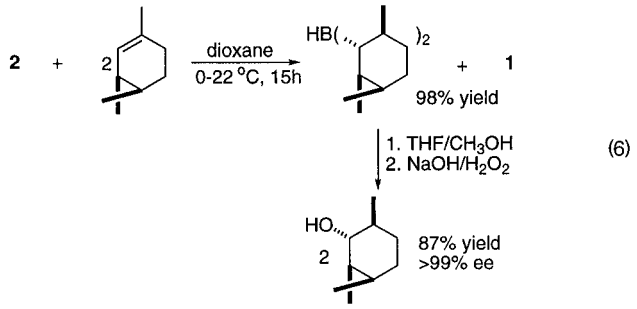
A considerable increase in the yield of $^{d}Ipc_2BH$ was observed when the hydroboration of (+)-α-pinene with **2** was carried out in dioxane. Thus, when (+)-α-pinene (87.3% ee) in 25% excess was added to **2** in dioxane (1.25 M in borane) at 0 °C and the reaction mixture was left at room temperature for 15 h, a white crystalline $^{d}Ipc_2BH$ was obtained in almost quantitative yields (98−99%). The supernatant solution did not show the presence of active hydride. The (+)-α-pinene was liberated from the product by the addition of benzaldehyde in the presence of catalytic amounts of boron trifluoride-etherate.[18] It was obtained in 86% yield and 99.5% ee, indicating effective upgradation during the crystallization of $^{d}Ipc_2BH$ (eq 4). Further confirmation was obtained by recovering (+)-α-pinene of 78% ee from the supernatant dioxane solution. $^{d}Ipc_2BH$ thus obtained was free from amine. See Scheme 1.

In tetrahydrofuran, the adduct **2** also gave $^{d}Ipc_2BH$ of >99% ee. However, the yield was lower (89−90%), similar to that reported for borane−tetrahydrofuran and BMS.

Preparation of (1*S*)-2-Diisocaranylborane, 2-$^{d}Icr_2$-BH. Recently, it was reported that 2-$^{d}Icr_2BH$ hydroborates prochiral cis-disubstituted olefins, giving the corresponding alcohols in high enantiomeric excess.[19] Its B-allyl derivative proved to be a highly enantioselective allylborating reagent for aldehydes.[20] Accordingly, the synthesis of this important chiral auxiliary using the new amine−borane **2** was examined.

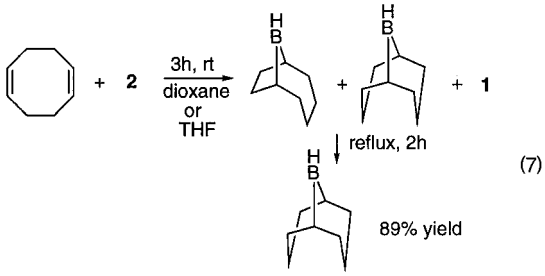
It was prepared by the addition of (+)-2-carene, 98% ee (10% excess), to a dioxane solution of **2** at 0 °C and keeping the mixture undisturbed at room temperature for 15 h. The 2-$^{d}Icr_2BH$ started crystallizing out from the dioxane solution in the form of needles, 20 min after mixing the reagents. The crystals can be conveniently washed with pentane, and the carrier amine can be removed by decantation. Thus, amine-free 2-$^{d}Icr_2BH$ was obtained in excellent yields (99%). Enantiomeric purity of the product was checked by oxidation, which gave (−)-2-isocaranol of >99% ee (eq 6). In tetrahydrofuran, 2-$^{d}Icr_2BH$ was obtained in lower yields (85−86%).

Preparation of 9-Borabicyclo[3,3,1]nonane, 9-BBN. The hydroboration of 1,5-cyclooctadiene with **2** in dioxane and tetrahydrofuran was carried out at room



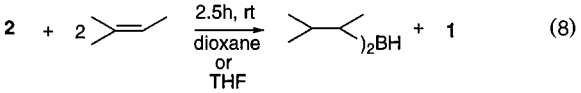
(6)

temperature. The reaction was complete in 3 h, as revealed by estimation of residual hydride. Oxidation of an aliquot with alkaline hydrogen peroxide gave 1,4- and 1,5-cyclooctanediol (29% and 71%), corresponding to borabicyclo[4.2.1]nonane and -[3,3,1]nonane, respectively (eq 7). Thermal isomerization of the mixture of organoboranes in refluxing solvents was complete in 2 h. After cooling, 9-BBN was obtained as a crystalline solid, free from amine, in 70% yield, with the mother liquor containing about 20% 9-BBN in dissolved form. Alternatively, after the thermal isomerization, the amine and the solvent dioxane or THF can be pumped off, and recrystallization of the residue from monoglyme or diglyme provides crystalline 9-BBN in 89% yield.



(7)

Preparation of Disiamylborane, Sia$_2$BH. The reaction of 2-methyl-2-butene with **2** in dioxane and tetrahydrofuran was complete within 2.5 h at room temperature (eq 8). The formation of disiamylborane was confirmed by ^{11}B NMR, from the disappearance of a peak at δ −13.2 corresponding to **2** and the appearance of absorption at δ +31.1. The reagent thus prepared can be utilized for hydroborations or can be converted by methanolysis to methyl disiamylborinate, which is valuable for the synthesis of unsymmetrical diynes.[21] Oxidation of the reaction mixture gave 3-methyl-2-butanol in quantitative yields.



(8)

Application of Disiamylborane for Regiospecific Hydroboration of Styrene. The reagent prepared as described above was reacted with styrene at room temperature. The reaction was complete in 1 h both in dioxane and in THF (eq 9). Oxidation of the product with alkaline hydrogen peroxide gave 2-phenylethanol (99%) and 1-phenylethanol (1%).

Clearly, the amine present in the reagents does not interfere in the subsequent hydroborations. The amines

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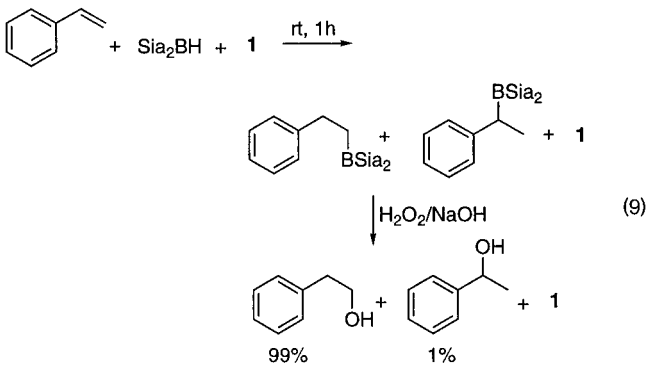
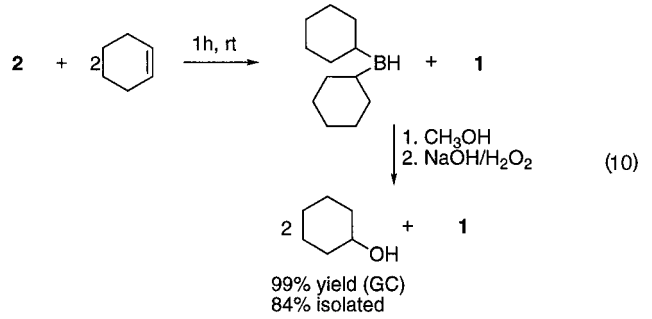
(21) Sinclair, J. A.; Brown, H. C. *J. Org. Chem.* **1976**, *41*, 1078.



(9)

can be readily separated from the product alcohol by simple acid−base manipulations.

Preparation of Dicyclohexylborane. The hydroborations of cyclohexene with **2** in 2:1 ratio were complete within 1 h at room temperature in both dioxane and tetrahydrofuran (eq 10). Dicyclohexylborane precipitated from the solution and was isolated in 89% yield.



(10)

Oxidation of the methanolized solution in THF using alkaline hydrogen peroxide afforded cyclohexanol in quantitative yields (99% by GC), which was also isolated, free of amine by simple acid−base manipulations, in 84% yield.

Conclusions

The present study demonstrates the synthetic potential of the new, highly reactive amine−borane adduct *N,N*-diisopropyl-*N*-isobutylamine−borane **(2).** 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 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 **1** 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.

The present study also demonstrates the usefulness of this new amine−borane adduct for the preparation of well-established dialkylborane reagents. In certain cases the adduct showed advantages over borane−tetrahydrofuran and BMS; for example, $^{d}Ipc_2BH$ and 2-$^{d}Icr_2BH$ were prepared in higher yields and excellent optical purity. Other partially substituted boranes, such as disiamylborane, dicyclohexylborane, and 9-BBN, can also be prepared conveniently. Crystalline dialkylborane products are readily isolated free of amines by simple filtration. The liquid dialkylborane products can be used for further applications, such as selective hydroborations, in the presence of carrier amine. However, additional studies are needed to establish the scope of such applications. It should be pointed out that we now have for the first time a highly reactive trialkylamine−borane adduct, **2**, for hydroborations, which can serve as an eco-friendly substitute for the currently popular hydroborating agents, such as borane−dimethyl sulfide and borane−tetrahydrofuran.

Experimental Section

Methods. All manipulations and reactions with air-sensitive compounds were carried out in an atmosphere of dry nitrogen. The special techniques employed in handling air-sensitive materials are described elsewhere.[2] The glassware was oven-dried for several hours, assembled while hot, and cooled in a stream of dry nitrogen gas. ^{1}H, ^{13}C, and ^{11}B NMR spectra were recorded on a 200 MHz multinuclear instrument. The ^{11}B NMR chemical shifts δ are in ppm relative to BF_3:OEt_2. GC analyses were carried out either on a chromatograph equipped with a SPB-5 (0.25 μm × 30 m) capillary column or with a chromatograph provided with a 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.[2]

Materials. *N,N*-Diisopropyl-*N*-isobutylamine and its borane adduct were prepared following the procedure reported in preceding paper.[13] 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), and (+)-2-carene, $[\alpha]^{22}_D$ +92.0°(Camphor and Allied Products, Bombay), were used.

Hydroboration of Representative Olefins with 2, General Procedure. An oven-dried, 50 mL hydroboration 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 (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 2 in Tetrahydrofuran. An oven-dried hydroboration flask was cooled

to 0 °C under a stream of nitrogen gas. In the flask was placed **2** (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 of 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, and 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 an OV-17 column). The ratio of 1-hexanol:2-hexanol is 96:4.

Hydroboration−Oxidation of Cyclohexene with 2 in Tetrahydrofuran. An oven-dried hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. In the flask was placed **2** (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 of 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 **1** (98%). Amine was recovered in pure form by column chromatography using hexane:ethyl acetate (95:5) as eluent in 86% (0.68 g) yield.

Preparation of Diisopinocampheylborane, ^{d}Ipc$_2$BH. An oven-dried hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. (+)-α-Pinene (8.52 g, 62.5 mmol, 87.3% ee) was added with stirring to a solution of **2** (5.55 mL, 25 mmol) in dioxane (4.45 mL) over 5 min at 0 °C. The ice bath was removed, and the solution was left undisturbed. After 30 min crystals started separating out. The mixture was left for 15 h at room temperature, and the supernatant solution was decanted using a double-ended needle. The crystalline mass was broken, washed with pentane, and kept under reduced pressure to remove the remaining solvent, and solid Ipc$_2$BH, 6.91 g, 98% yield, was obtained.

Methanol (1.0 mL) was slowly added to a mixture of ^{d}Ipc$_2$-BH (5.72 g, 20.0 mmol) in tetrahydrofuran. The hydrogen evolved was vented out, and 3.0 M sodium hydroxide (6.8 mL, 20.0 mmol) was added followed slowly by hydrogen peroxide (4.0 mL, 30%, 40.0 mmol) at 10−20 °C. The mixture was stirred at room temperature for 1 h at 45 °C. It was cooled to room temperature, saturated with potassium carbonate, and extracted with ether. The combined organic extracts were dried over anhydrous magnesium sulfate. GC analysis did not show the presence of **1**. Evaporation of the solvent afforded (−)-isopinocampheol, which was further purified by column chromatography on silica gel using hexane/ethyl acetate (8:2) as an eluant, 5.29 g, 86% yield, $[\alpha]^{22}_{D}$ −34° (*c* 20, EtOH), >99% ee (lit.[16c] $[\alpha]^{22}_{D}$ −34° (*c* 20, EtOH)).

Liberation of (+)-α-Pinene from ^{d}Ipc$_2$BH. Benzaldehyde (7.6 mL, 75.0 mmol) was cautiously added (caution! exothermic reaction) to ^{d}Ipc$_2$BH (6.91 g, 24 mmol) keeping the reaction temperature about 50 °C. Once the initial reaction subsided, the mixture was slowly heated to 100 °C (bath temperature), boron trifluoride−etherate (0.06 mL, 0.5 mmol) was added, and the mixture was stirred for 1 h at 100 °C. The liberated α-pinene was distilled off at reduced pressure. Redistillation from lithium aluminum hydride gave (+)-α-pinene: 5.40 g, 83% yield, bp 50−51 °C/17 mmHg, $[\alpha]^{22}_{D}$ +51.34° (neat), 99.5% ee, lit.[22] $[\alpha]^{22}_{D}$ +51.4° (neat).

Preparation of [1*S*]-Diisocaranylborane, 2-^{d}Icr$_2$BH. A 50 mL round-bottomed flask provided with a septum inlet and magnetic stirring bar was charged with **2** (3.3 mL, 15.0 mmol) in dioxane (6.5 mL). To this was added (+)-2-carene (5.2 mL, 33.0 mmol) during 5 min. The ice bath was removed, and the reaction mixture was kept at room temperature undisturbed for 15 h. Crystalline needles of Icr$_2$BH started separating out after 20 min. The supernatant solution was decanted using a double-ended needle. The crystalline mass was broken, washed with *n*-pentane, and kept under reduced pressure to remove solvent, yielding pure 2-^{d}Icr$_2$BH, 4.23 g, 98.6% yield. The solid thus obtained was suspended in 15 mL of THF, and 0.8 mL (20.0 mmol) of methanol was added slowly at 0 °C. After the evolution of hydrogen ceased the liberated hydrogen was vented out, and the mixture was oxidized by using 5.0 mL of 3.0 M NaOH solution and 3.0 mL of 30% hydrogen peroxide at 30 °C for 3 h and at 50 °C for 1 h. The mixture was cooled to room temperature, saturated with potassium carbonate, and extracted with ether. The combined organic extract was washed with brine and dried over anhydrous magnesium sulfate. (−)-2-Isocaranol was isolated by distillation: bp 60−62 °C/2 mmHg, 3.87 g (85.5%), $[\alpha]^{22}_{D}$ −31.2° (neat) [lit.[19] bp 50−52 °C/0.05 mm, $[\alpha]^{22}_{D}$ −31.5° (neat)].

Preparation of 9-BBN. An oven-dried hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. The flask was charged with **2** (2.2 mL, 10.0 mmol) in 1.6 mL of dioxane at room temperature, and 1,5-cyclooctadiene (1.08 g, 10.0 mmol) was added dropwise to a well-stirred solution. The mixture was further stirred for 3 h. The reaction was complete within that period, as indicated by active hydride estimation.

An aliquot was taken out and oxidized with aqueous alkaline hydrogen peroxide in THF. A few drops (0.3 mL) of this THF solution was taken in a vial and dried with magnesium sulfate. The 0.3 mL of dry pyridine and 0.3 mL of *N*,*O*-bis(trimethylsilyl)acetamide (BSA) were added. The mixture was heated for 10−15 min while shaking. The product was analyzed on GC using an SE 30 column. The isomeric distribution of 1,4- and 1,5-cyclooctanediols (29:71) was determined from the integration of peaks, assuming the same response factor for both diols.

The dioxane solution was refluxed and the progress of isomerization was controlled by GC analysis of the oxidized product as described above. After 2 h, the isomerization was complete, as indicated by the exclusive presence of 1,5-cyclooctanediol in the oxidation product.

Isolation of 9-BBN. In a preweighted 50 mL flask equipped with a reflux condenser and a magnetic stirring bar was placed **2** (2.2 mL, 10.0 mmol) in 1.6 mL of dioxane under nitrogen. The flask was placed in a water bath (20 °C), and 1,5-cyclooctadiene (1.08 g, 10.0 mmol) was added slowly with stirring. The stirring continued for another 3 h at room temperature and 2 h under reflux. After cooling the reaction mixture to room temperature, the 9-BBN crystallized out. The supernatant liquid was decanted using a double-ended needle; the crystals were washed with ice cold *n*-pentane and left under reduced pressure: yield 0.92 g (70%), recrystallized from THF, mp 152 °C [lit.[23] mp 153 °C].

(22) Based on the maximum rotation reported for (+)-α-pinene, $[\alpha]^{22}_{D}$ +51.6°: Johnson, W. S.; Frei, B.; Gopalan, A. S. *J. Org. Chem.* **1981**, *46*, 1512.

(23) Brown, H. C.; Mandal, A. K. *J. Org. Chem.* **1992**, *57*, 4970.

Preparation of Disiamylborane. An oven-dried hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. The flask was charged with **2** (2.2 mL, 10.0 mmol) in dioxane (5.7 mL) at 0 °C, and 2-methyl-2-butene (2.1 mL, 20.0 mmol) was slowly added to this solution. The reaction mixture was further stirred at room temperature. The reaction was complete within 1 h as indicated by active hydride analysis and the presence of one peak at δ +31.1 in the ^{11}B NMR spectrum. The reaction mixture was oxidized using 3.0 M NaOH (4.0 mL) and 30% hydrogen peroxide (4.0 mL). The GC analysis of the oxidation product using an OV-17 column revealed the quantitative formation of 3-methyl-2-butanol.

Application of Disiamylborane in Regioselective Hydroboration of Styrene. To a solution of disiamylborane (10.0 mmol) in dioxane prepared as described above was added styrene (1.04 g, 10.0 mmol) at room temperature, and stirring was continued at room temperature for 1 h, by which time the hydroboration was complete. The mixture was oxidized by alkaline hydrogen peroxide, and GC analysis of the oxidized product revealed the formation of 2-phenylethanol (99%) and 1-phenylethanol (1%).

Preparation of Dicyclohexylborane. An oven-dried 50 mL hydroboration flask was cooled to 0 °C under a stream of nitrogen gas. The flask was charged with **2** (2.2 mL, 10.0 mmol) in dioxane (5.0 mL) and *n*-nonane (1.78 mL, GC standard). Cyclohexene (0.82 g, 20.0 mmol) was added slowly at 0 °C during 5 min, and the mixture was stirred at room temperature. The reaction was complete within 1 h, as indicated by active hydride estimation. The reaction mixture was oxidized using alkaline hydrogen peroxide. The aqueous layer was saturated with potassium carbonate, and GC analysis of the organic layer using a Carbowax 20M column revealed a 99% yield of cyclohexanol.

Isolation of Dicyclohexylborane. Hydroboration of cyclohexene was carried out with **2** in 10 mmol scale in dioxane as described above in a preweighted centrifuge flask. After the hydroboration was complete, the reaction mixture was centrifuged and the supernatant liquid was decanted using a double-ended needle. The precipitate was washed with cold *n*-pentane and kept under reduced pressure to yield 1.52 g of dicyclohexylborane: 85% yield, free from amine, mp 102−3 °C (lit.[23] mp 103−4 °C, after sublimation).

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