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Borenium Ion Catalyzed Hydroboration of Alkenes with N-Heterocyclic Carbene Boranes

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Abstract

Treatment of alkenes such as 3-hexene, 3-octene, and 1-cyclohexyl-1-butene with the N-heterocyclic carbene-derived borane **2** and catalytic $HNTf_2$ effects hydroboration at room temperature. With 3-hexene, surprisingly facile migration of the boron atom from C3 of the hexyl group to C2 was observed over a time scale of minutes to hours. Oxidative workup gave a mixture of alcohols containing 2-hexanol as the major product. A similar preference for the C(2) alcohol was observed after oxidative workup of the 3-octene, and 1-cyclohexyl-1-butene hydroborations. NHC-borenium cations (or functional equivalents) are postulated as the species that accomplish the hydroborations, and the C(2) selective migrations are attributed to the 4-center inter-conversion of borenium cations with cationic NHC-borane olefin π-complexes.

Introduction

N-Heterocyclic carbene boranes (NHC-boranes) are formally Lewis complexes between an *N*-heterocyclic carbene (NHC) and borane (BH_3) or a substituted borane.[1] Still emerging, the chemistry of NHC-boranes is already rich and varied.[2] These compounds donate hydrogen atoms in radical reactions,[3] transfer hydrides in ionic reactions,[4] and are valuable coinitiators for photopolymerizations.[5] New compositions of matter including NHC-complexed boryllithiums,[6] diborenes[7] and NHC-boryl radicals[8] have been characterized. Exotic NHC-borylenes (4-electron boron analogs of carbenes) have been suggested as reactive intermediates.[9]

The quintessential reaction of Lewis base complexes of boranes is hydroboration (HB).[10] Exchange of a Lewis base such as an ether or a sulfide with an alkene, for example, provides a short-lived alkene-borane complex that quickly transforms to an alkylborane by hydroboration (Figure 1a). So the relatively labile borane-Lewis base complexes of THF, dimethyl sulfide, or hindered amines are often thought of as synthetic equivalents of “free borane”, a species that generally does not exist in condensed phase.

NHC-boranes and phosphine-boranes[11] are remarkable compared to most other Lewis base complexes of boranes because of their stability. They resist decomplexation and are therefore unusual in that they are essentially inert to hydroboration reactions, even under heating (Figure 1b). Rather than somehow forcing the carbene of an NHC-borane to leave,

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Supporting Information. Contains complete experimental details and additional copies of spectra for time course migration experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

we hypothesized that hydroborations of NHC-boranes could be induced instead by removal of hydride to vacate a coordination site on boron. In a formal sense, this gives an NHC-borenium ion **1**, which is isoelectronic with free borane (Figure 1b).

Because the NHC-borenium **1** is cationic, it might be a super Lewis acid and could exhibit hydroboration chemistry different from the usual borane chemistry. Cationic Lewis acids with a trivalent boron atom are popular reagents, but most acquire their positive charge by quaternization of a nitrogen atom.[12] However, borenium ions with the formal positive charge residing in a **π**-system are known,12b,13 and a handful of NHC-borenium ions bearing either large or electron donating substituents (or both) have been characterized recently.[9c,14]

Like free borane, a free NHC-borenium ion **1** with a BH_2 group may not exist in solution unless it is stabilized by electronic or steric factors.[13,15] But boronium cations (Lewis base adducts of borenium cations) having the general structure $[NHC–BH_2–LB]^+$ **1a** might behave as borenium equivalents if the Lewis base (LB) is a weak donor.[13b] Furthermore, even the neutral carbene boranes NHC–BH_2–LG **1b** bearing outstanding leaving groups (LG = bistriflimidate, triflate, etc.) can be regarded as borenium equivalents.[6] They might express borenium ion reactivity by exchanging with another Lewis base like an alkene (Figure 1c). Covalent molecules **1b** are easily made by reactions of NHC-boranes with strong acids or electrophiles.[4c]

Electrophilic activations of amine-boranes indeed induce hydroborations in the presence of alkenes.[16a–d] Unlike the thermal reactions of amine-boranes, these reactions generally do not exhibit free borane chemistry and do not depend on B-N dissociation. Instead tricoordinate amine borenium equivalents (H_2B-N^+) initiate p-complex formation and hydroboration.

Here we report that the hydroboration of alkenes by NHC-boranes is catalyzed by NHC-borenium ions (or equivalents thereof). Unusual characteristics such as penchants for bis-hydroboration and rearrangement show that the transformations do not occur by borane release from the complexes. We first describe in detail experiments on the borenium-catalyzed hydroborations of 1-, 2- and 3-hexene. Mechanistic insight is gleaned by identifying key intermediates. The work is then expanded to other alkenes to flesh out the scope of the new reaction.

Results and Discussion

Hydroboration of 1-, 2- and 3-hexene

Reactions were first probed between *E*-3-hexene and 1,3-dimethylimidazol-2-ylidene **2**. This reagent is a stable solid that is convenient to handle. As expected from the amine-[16b,16c] and NHC-borane[2] analogies, no hydroboration (HB) occurred at room temperature without activation by added electrophiles.[17]

Table 1 shows results of selected preliminary experiments, which were conducted in a glove box to ensure the absence of moisture. Briefly, an activator (5 mol%) was added to **2** in CH_2Cl_2, then excess *E*-3-hexene was added. Conventional oxidative workup with NaOH/H_2O_2 in aqueous methanol was slow, but eventually gave full conversion after 16 h at rt. The yields of alcohol products were determined by ^1H NMR analysis with an internal standard ($PhCH_3$).

Activation of **2** with 5% trifluoromethanesulfonimide ($(CF_3SO_2)_2NH$ or Tf_2NH) in DCM generated a reactive intermediate that converted *E*-3-hexene to hydroboration products over 1.5 h at room temperature (entry 2). To our surprise, the major product after oxidation was

not 3-hexanol, but the isomeric 2-hexanol (about 15:1 ratio, C(2)OH:C(3)OH). A trace of 1-hexanol was also detected. A similar experiment was quenched after 20 min at rt and gave a very different product ratio (1:10, C(2)OH:C(3)OH) after oxidative workup (entry 1). On the other hand, an experiment conducted at 50 °C revealed increasing conversion to 1-hexanol (entry 3). Evidently, a kinetically formed intermediate isomerizes over time.

Activation of **2** was also achieved at room temperature by using 5% of the electrophilic trityl cation source $TrB[C_6F_5]_4$ as the hydride acceptor,[18] resulting in nearly the same conversion and product ratio (14:1 C(2)OH:C(3)OH) as with the Tf_2NH activation (compare entry 4 to entry 2). However, the Tf_2NH activation gave cleaner product mixtures in preliminary studies, and was used in most of the subsequent experiments.

Based on these observations, we inferred that the catalytic cycle in the hydroborations with **2** and Tf_2NH resembles that previously postulated for reactions with DMAP•BH_3 and iodine.[16c] Scheme 1 shows the sequence of events (not including migration steps), which has at least three key stages: (1) electrophilic activation of **2** by the strongly acidic Tf_2NH (pKa–12[19]) to generate dihydrogen and the reactive intermediate **3**; (2) reaction of **3** with a two-fold excess 3-hexene to afford the HB adducts **4** and **5**; and (3) formation of product **6** via hydride transfer from **2** to **5** (H/Tf_2N exchange).

An intermediate fourth stage involving hydride transfer between **4** and **2** may occur to provide **7**, but this pathway is invisible if the reaction is rapidly reversible. The monohydroboration product **7** will not accumulate and the excess hexene will drive it on to the dihydroboration product **5**.

If the mechanism of Scheme 1 is followed, then HB is feasible only if boron contains both a hydride (for hydroboration) and a triflimidate (for activation). Thus like **2**, **7** cannot react directly with hexene without activation to regenerate **4**. And even though precursor **2** has three B–H bonds, a third hydroboration cannot occur because activated intermediate **5** derived from dihydroboration lacks a B–H bond.

The product-forming stage (3) regenerates the activated borane complex **3** as well as forming **6**. This critical event completes the catalytic cycle in an HB pathway wherein the NHC–B bond remains intact in all the intermediate borane complexes. This mechanism resembles that suggested for hydroboration by electrophilic activation of amine and pyridine boranes,[16c] but the facile formation of rearranged products has a surprising new twist—the migration of boron stops before the end of the chain is reached.

Alkylborane intermediates are well known from Brown's classic studies[20a–c] to undergo migration of an internal C–B bond at very high temperatures (typically ≫ 100 °C). Adducts from electron poor reagents like the Piers borane ($HB(C_6F_5)_2$) might be better models for borenium ions and indeed they rearrange at lower temperatures.[20d] But such migrations inevitably proceed to the thermodyanic product, usually a primary alkylborane. In contrast, in the reaction between **2** and (*E*)-3-hexene, the boron atom migrates from C(3) to C(2) even though the two carbons are both secondary.[21] We assume that the primary alkylborane resulting from migration to C(1) is the most stable isomer, so there must be a higher barrier for migration from C(2) to C(1) than from C(3) to C(2).

To understand the initial activation stage (1), we studied the direct reaction of NHC-BH_3 **2** with triflimide (Tf_2NH) under conditions of *in situ* monitoring by NMR spectroscopy. Addition of 1 equiv of Tf_2NH to **2** in an NMR tube resulted in a rapid, exothermic reaction with gas evolution to form a single new species assigned as the boryl triflimide **3** (Scheme 2). At δ −16.9 ppm, the observed ^{11}B chemical shift indicates that **3** is tetracoordinate and

boron binds the triflimidate with either a B–N or B–O bond.[13] So **3** is not an ion pair consisting of a tricoordinate borenium cation and a triflimide anion. Under argon, **3** is stable in solution at ambient temperature for at least one week.

Reactions of NHC-boranes with triflic acid can produce stable ditriflates [NHC-$BH(OTf)_2$],[14a] but a reaction of **2** with 2 equiv of triflimide again gave an ^{11}B NMR spectrum showing **3**. Apparently a ditriflimide [NHC-$BH(NTf_2)_2$] is not easily formed. For the catalytic hydroborations, however, the relevant stoichiometry is to have **2** present is excess. Addition of less than 1 equiv of triflimide to **2** gave a new resonance at δ −21.6 ppm which we assign to the H-bridged dimer **8**.[15,18] The same species can be generated by mixing equimolar amounts of NHC-BH_3 **2** and separately generated NHC-BH_2NTf_2 **3** (see Supporting Information).

Thus, **8** rather than **3** is the borenium ion equivalent that is present at the start of hydroboration reactions with **2** and catalytic amounts of Tf_2NH. Likewise, the idea that mono- and dialkyl triflimides **4** and **5** are the actual borenium equivalents might be too simple. Bridged dimers analogous to **8** or even free borenium ions could be involved.

To understand the NHC-borane transformations at the level of the C–B bond forming events (stages (2)–(4)), we followed several hydroborations by ^{11}B NMR spectroscopy. From the mechanism in Scheme 1, we supposed that bis-hydroboration would dominate to give *B,B*-dihexylborane adducts **6**. To assign signals in HB-derived product mixtures prior to oxidative workup, we prepared authentic samples of two bis-hydroboration products by direct complexation as shown in Scheme 3.

Hydroboration of 1-hexene (2 equiv) with bromoborane dimethyl•sulfide ($BH_2Br•SMe_2$, 1 equiv) followed by reduction with $LiAlH_4$ provided a solution of bis(1-hexyl)borane [$(C_6H_{13})_2BH$].[22] Next, the N-heterocyclic carbene **9** was generated *in situ* by deprotonation of the corresponding imidazolium iodide with NaHDMS, and the borane was then added to **9**. This resulted in the immediate formation of a doublet in the ^{11}B NMR spectrum at δ −19.0 ppm, J_{BH} = 77 Hz, which we assigned to the linear NHC-$BH(C_6H_{13})_2$ (1,1)-**6**. No signals of complexes isomeric with (1,1)-**6** were detected, and indeed none were expected because the ratio of 1-hexyl/2-hexyl products in the hydroboration with $BH_2Br•SMe_2$ is reported to be 99.6/0.4.[22]

Attempts to isolate (1,1)-**6** by flash chromatography were not successful. NHC-boranes bearing a BH_3 group can generally be purified by chromatography, as can some mono-alkyl and arylborane complexes.[6a] In contrast, complexes of Et_3B[23] do not survive chromatography. Even though (1,1)-**6** could not be purified, it is stable in solution and readily identifiable.

In a similar sequence, *in situ* generated bis(3-hexyl)borane (from (*E*)-3-hexene and $BH_2Br•SMe_2$) was added to **1**. Again a doublet appeared in the ^{11}B NMR spectrum, this time at δ −16.9 ppm, J_{BH} = 83 Hz. We assign this to (3,3)-**6**, NHC-$BH[CH(C_2H_5)C_3H_7)]_2$, which again did not survive chromatography. Complex (3,3)-**6** was stable in solution and did not rearrange over 1 day at rt. The ^{11}B NMR shift is not sensitive to relative configuration; only one signal was observed even though (3,3)-**6** is presumably a mixture of diastereomers (*d,l* and *meso*). The sensitivity of the ^{11}B NMR shifts to the substitution pattern of the alkyl groups but not to the stereochemistry proved convenient in later experiments when migrations were followed.

Armed with an understanding of the acid-base chemistry and two product standards, we then conducted direct hydroboration experiments of hexene isomers with NHC-borane **2** and sub-

stoichiometric amounts of triflimide. The structures of the possible products are shown in Figure 2 and the observed hydroboration product ratios are summarized in Table 2. Preliminary NMR experiments with 5% triflimide progressed slowly or not at all; however, increasing the triflimide loading to 15–25% promoted smooth reactions. The need for additional triflimide in the NMR experiments is probably because they were conducted in NMR tubes without the aid of a glovebox.

In a typical experiment, triflimide (0.25 equiv) was added to a solution of **2** (1 equiv) in CH_2Cl_2 in an NMR tube at 25 °C. After 1 min, 1-hexene (3.0 equiv) was added, then the ^{11}B NMR spectrum was recorded after 15 min. Two doublets were present in a ratio of 80/20. The major doublet at δ −19.0 ppm matches that of the standard (1,1)-**6**, while the minor doublet at δ −15.8 ppm was assigned to isomer (1,2)-**6** bearing a 1-hexyl group and a 2-hexyl group (entry 1). The product ratio did not change over several hours in solution, so we suspect that this is a kinetic ratio.

No boron singlets (indicative of triple hydroboration) were evident even though ample 1-hexene was added, nor were proton-coupled boron triplets seen (indicative of mono-hydroboration). Evidently, the two hydroborations occur quickly in succession. The combined regioselectivity of the two hydroborations (linear/branched) is 90/10. It seems likely that the second hydroboration is more regioselective than the first due to steric effects, but this could not be shown since no intermediate mono-hydroboration products were observed.[24]

Hydroboration of *E*-2-hexene by a similar procedure provided a ^{11}B NMR spectrum after 10 min that exhibited three doublets at δ −13.6, −15.2 and −16.9 ppm in a ratio of about 85/13/2 (entry 2). The resonance of the minor product (2%) matches that of bis(3-hexyl)borane complex (3,3)-**6**. We assign the major product as the bis(2-hexyl)borane complex (2,2)-**6** and the intermediate product (15%) as the (2-hexyl)(3-hexyl) complex (2,3)-**6**. Over some hours, a small resonance for (1,2)-**6** began to appear.

With all five possible regioisomeric bis-hydroboration products identified, we then revisited the hydroboration of (*E*)-3-hexene. Unlike the static or slowly changing behavior of the HB products obtained from the isomeric 1- or -2-hexenes, the product ratios now changed relatively quickly. Indeed, we had to decrease the amount of triflimide to see the unrearranged product (3,3)-**6**. Table 2 shows the results of two time course experiments with 3-hexene as substrate and 15% (entry 3) or 25% (entry 4) triflimide.

Three representative ^{11}B NMR spectra from these experiments are shown in Figure 3, while complete sets of spectra from both experiments are shown in the Supporting Information.

The spectrum from the first time point (entry 3, 15 min) with 15% triflimide is shown in Figure 3-top. We observed 42% of the kinetic product (3,3)-**6** along with 47% of the product (2,3)-**6** of one migration of one hexyl group and 11% of product (2,2)-**6** of one migration of both hexyl groups. This ratio changed rapidly to a final ratio after 90 min of 10% (2,3)-**6**, 85% (2,2)-**6**, and 5% of the product (1,2)-**6** corresponding to two successive migrations along one of the hexyl groups. This spectrum is shown in Figure 3-middle. The product ratio did not change on further standing up to 48 h.

The starting spectrum at 15 min with 25% triflimide resembled the final spectrum with 15% triflimide. The kinetic product (3,3)-**6** was already gone, and (2,3)-**6**, (2,2)-**6** and (1,2)-**6** were present in a ratio of about 10/85/5. This ratio evolved slowly, eventually stopping at 48 h with the complete disappearance of (2,3)-**6** and leaving (2,2)-**6** and (1,2)-**6** in a 50/50 ratio

(Figure 3-bottom). The ultimate rearranged product, (1,1)-**6**, was not detected at any time in either of these experiments.

Scope and limitations study

The data presented so far support a catalytic hydroboration where the initially formed activated intermediate **3** reacts with *E*-3-hexene via hydroborated adducts **4** and **5**, both of which are capable of undergoing migration of the C–B bond. Further studies were therefore initiated to clarify the scope of the hydroboration and selective migration process using **2** and catalytic Tf_2NH with several alkenes as summarized in Table 3 and Scheme 4. The results indicate that a subset of simple alkenes can be hydroborated using the lower 5% triflimide loading in standard sealed vials if sufficient care is taken to exclude moisture and air.

Reactivity is sensitive to the substitution pattern, and so is the selective migration to C(2), as illustrated for the octene examples in entries 1–7 (Table 3; all entries assayed after oxidative cleavage). Both 1-octene and 2-octene were hydroborated readily at RT (Table 3, entries 1, 2), and only traces of migration were detected after 1.5 h (entry 2) as evidenced by the formation of the primary alcohol (1-octanol). This is the same behavior as seen with 1- and 2-hexenes (Table 2). Similarly, 3-octene was reactive at RT, but extensive migration as well as high C(2) selectivity were observed when the reaction time was limited to 1.5 h (entry 3). Prolonged exposure at room temperature (entry 4) resulted in substantial migration to the primary carbon, while an experiment conducted at 50 °C using 30% Tf_2NH finally gave 1-octanol as the dominant product (61%, entry 5).

In contrast to entries 1–4, Table 3, neither *E*- nor *Z*-4-octene gave substantial conversion under the room temperature conditions with 5% Tf_2NH catalyst. Conversion did take place using 30% Tf_2NH at RT (entry 6) to give a 4.3:1 preference for the rearranged 2-octanol:1-octanol along with lesser amounts of the isomeric 3- and 4-octanols. When the 4-octenes were reacted at 50 °C using 30% Tf_2NH, rearranged products were obtained almost exclusively (entries 7, 8), but C(2) selectivity was lower.

As shown in Table 3, entry 9, good reactivity at room temperature was also observed with 1-cyclohexyl-2-butene (**10**) to give the expected products **11** and **12** (80–84% yields). No evidence of migration products was detected by GLPC assay for the room temperature experiment, although hydroboration at 50 °C formed 7% of the rearranged primary alcohol **13** along with traces of **14** (entry 10). Isolated yields varied somewhat at the higher temperature (77% and 86% for two runs), probably due to catalyst decomposition, but the product distributions were similar.

Prolonged heating at 50 °C (entry 11) resulted in more of the primary alcohol migration product **13** (7% after 24 h) and a corresponding decrease in the recovery of **12**. In contrast, hydroboration of the isomeric alkene 1-cyclohexyl-1-butene **15** (entry 12) gave extensive migration already at RT with about 3:1 selectivity in favor of the rearranged C(2) alcohol **12** compared to the unrearranged **11** and **14** after oxidative workup. This behavior resembles the 3-hexene case (Table 1), but it stands in contrast to the 3-octene example (Table 3, entry 3) where substantial rearrangement did not occur at RT. When the experiment of entry 12 was modified for reaction at 50 °C, 3 h (entry 13), the proportion of the migration-derived C(2) alcohol **12** increased at the expense of **14** and **11**, and significant conversion to the primary C(1) alcohol **13** was also observed (79–83% recovery). Prolonged (24 h) heating at 50 °C increased the amount of **13** to 16% and resulted in virtually complete conversion of the kinetic products **14** and **11** (entry 14, 77% recovery).

These findings resemble the results of entries 10 and 11 using the isomeric 1-cyclohexyl-2-butene **10** at the same temperature (50 °C). However, conversion to the primary C(1) alcohol **13** in all of the experiments at 50 °C was considerably lower than for the 3-octene example using the same 5% catalyst loading at room temperature (31% 1-octanol, entry 4). The contrasting extent of migration (entry 4 ≫ entries 9–14) suggests that the remote cyclohexyl substituent retards the rate of the final migration step from C(2) to C(1), but the nature of this effect remains unknown.

Variations in reactivity (based on % conversion) and migration behavior were also encountered with other alkenes. For example, the hydroboration of 5-phenyl-2-pentene proceeded readily at RT to form a 1:1 mixture of the expected unrearranged products (Table 3, entry 15). The product ratio was somewhat displaced toward the C(2) alcohol after heating to 50 °C followed by oxidative workup (entry 16), but further rearrangement to the primary alcohol was not detected, in contrast to the other entries in Table 3. Surprisingly, alkenes containing a phenyl substituent closer to the alkene double bond, including β-methylstyrene, 1-phenyl-2-butene, or 1-phenyl-1-butene gave little conversion (<10%) under typical catalytic hydroboration conditions (**2** activated with 5% Tf_2NH, 3 h at RT).

The β-methylstyrene case was investigated using increasingly exacting procedures (to ensure the absence of contaminants); however, conversion of the alkene did not proceed beyond 8% according to NMR assay and alcohol products were not seen above the NMR detection limit (3–4%) after oxidative workup. On the other hand, a stoichiometric activation experiment (2:1:1 alkene:**2**:Tf_2NH) shown in Scheme 5 proceeded within 3 h at RT, and oxidative workup returned the alcohols **16** and **17** (ca. 4:1 ratio) along with a trace of the primary alcohol **18** (combined 83% recovery). Apparently, the stoichiometric reaction proceeds normally but that catalyst turnover does not occur with these alkenes.[25]

A brief evaluation of oxygen-containing alkenes **19–21** containing a benzyl ether as Lewis base within two or three carbons of the alkene provided one a case where the benzyloxy substituent suppressed the catalytic HB pathway (<10% conversion with **19** at 50 °C) and two cases where conversion was slow (56% of **20** recovered after after 3 h at 50 °C along with 22% of primary alcohol and 3% of secondary alcohol; 80% of **21** recovered after 3 h at 50 °C, along with 9% of the expected C(2) and C(3) alcohols in a 1:2 ratio). Rearranged products were not detected starting from **21**.

Conclusions

In summary, we have discovered that bis-hydroboration of alkenes can be accomplished at room temperature simply by adding a catalytic amount of triflimide to the NHC borane prior to addition of the alkene. The kinetic hydroboration products often further evolve at room temperature by migration of the boron atom along the alkyl chain. The kinetic or migrated products can be obtained depending on how long the reaction is run before addition of the oxidant. The alkylborane migrations are unusual because they occur at low temperatures and because they often pause before the boron atom reaches a terminal carbon atom.

The accumulated evidence shows that borenium ion equivalents (like boryltriflimide **3** or H-bridged dimer **9**) are the active catalysts that effect hydroboration of alkenes. Hydride transfer from the starting NHC-borane then gives the HB product (ultimately a dialkylborane) and regenerates the catalyst.

The subsequent migration of the dialkylboranes is slower than the initial dihydroboration itself, yet still rather fast. In the most selective examples (3-hexene; 3-octene; 1-cyclohexyl-1-butene **15**) the hydroboration intermediates undergo facile boron migration on

a timescale of minutes to hours at room temperature with accumulation of the C(2) isomers. As far as we know, these are the first examples where hydroboration of *3*-alkenes produce large amounts of a *2*-alkanols after oxidation.

The migration mechanism needs further study, but results can tentatively be understood by considering intermediates in the representative hydroboration of 3-hexene as shown in Scheme 6. The sequence parallels the corresponding migration steps in conventional hydroboration,[20c] but the presence of the cationic NHC substituent apparently lowers the energy barrier for migration within the chain but not to the end of the chain.

We propose that migration occurs at the stage of activated intermediates **5** via equilibration with a borenium salt **22**. Heterolysis and departure of the bistriflimidate anion results in tricoordinate boron, allowing B-C and C–H cleavage via a 4-center bond reorganization to generate the **π**-complex **23** followed by re-hydroboration to complete the first migration event resulting in **24**. A second migration event is also possible by a similar sequence from **24** to **25** and **26**, but this sequence must be considerably slower than the migration from **22** to **24** because products (1,1)-**6** and (1,2)-**6** derived from **24** do not accumulate unless the reaction mixture is heated.

The new NHC-borenium ion catalyzed hydroborations are fundamentally different processes from standard hydroborations of borane-Lewis base complexes,[10] and they have only a few prior parallels in amine-borane chemistry.[16] However, even these parallels are inadequate because amine-borane adducts have not been observed to migrate while NHC-borane adducts migrate quickly. There are already other potential NHC-borenium ion equivalents known[4c] (boryl halides and boryl triflates, for example) and the array of possible NHC substituents is vast. Thus, a broad new avenue to modify a classic reaction is now open.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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ABBREVIATIONS

GLPC	gas-liquid partition chromatography
HB	hydroboration
LB	Lewis base
LG	leaving group
NHC	N-heterocyclic carbene
RT	room temperature
Tf	trifluoromethanesulfonyl (CF_3SO_2)
Tr	trityl (Ph_3C)

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17. Only small hints of HB were observed at 50 °C when a mixture of *E*-3-hexene and the relatively hindered 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene borane was treated with 30 mol% Tf_2NH.

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21. With some cyclic alkenes migrations also occur from one secondary carbon to another driven by the presence of large, adjacent branching substituents. See, Hupe E, Denisenko D, Knochel P. Tetrahedron. 2003; 59:9187–9198.

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24. With decreased loading (1.7 mol%) of catalyst $TrB(C_6F_5)_4$ in C_6D_5Br, a minor triplet was observed at –25 ppm starting from E-3-hexene and 2 that may be a monoalkyl borane, but experiments in bromobenzene were not pursued due to the greater convenience of DCM.

25. 2-Methyl-4-phenylbutene undergoes catalyzed hydroboration under the usual conditions with **2** and 5% Tf_2NH as catalyst, suggesting that the inhibiting effect of a phenyl substituent is lower for the terminal alkene compared to the 1,2-disubstituted substrates. This inhibiting effect may be due to the Lewis basicity of the nearby phenyl ring. However, we have already identified modified reagents that react with phenyl-substituted alkenes, and the scope of these reactions is under study.

26. In preliminary experiments, 61% conversion was found with the terminal alkene benzyl 2-allylcyclohexyl ether using **2** and 5% Tf_2NH loading, 3 h at room temperature, but the disubstituted 2-butenyl analogue of the benzyl ether **20**gave <3% hydroboration product under these conditions.

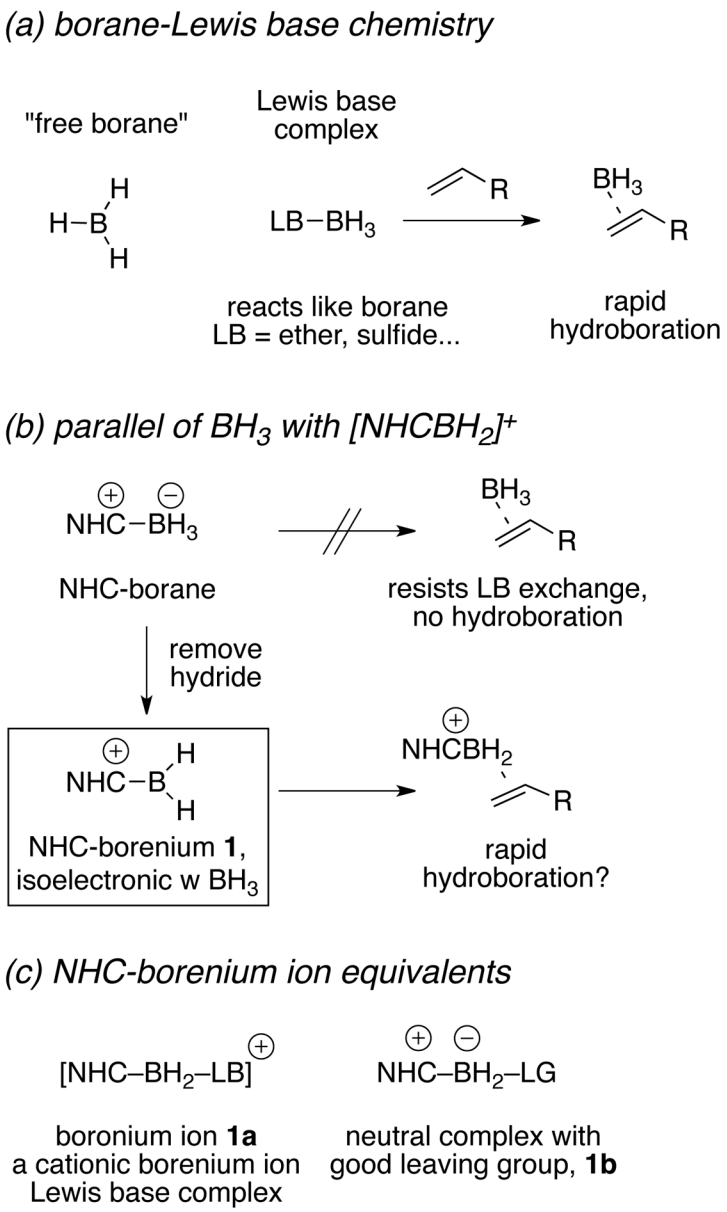


Figure 1.
Analogies between (a) boranes, (b) NHC-borenium ions, and (c) reactive equivalents of NHC-borenium ions

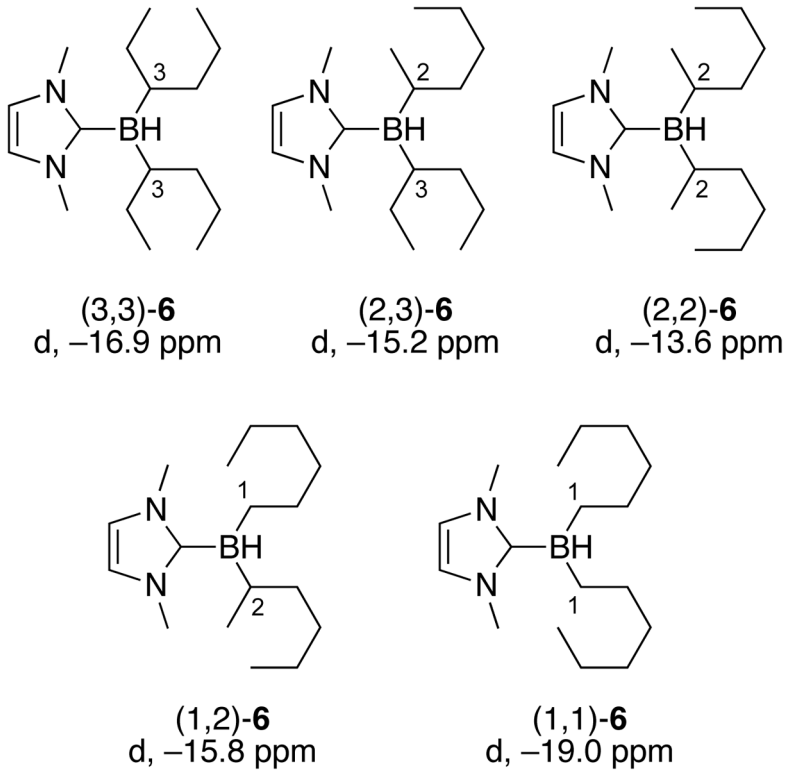


Figure 2.
Structures of constitutional isomers of NHC-dihexylboranes **6** with assigned ^{11}B NMR chemical shifts and multiplicities (d). Formal charges are not shown.

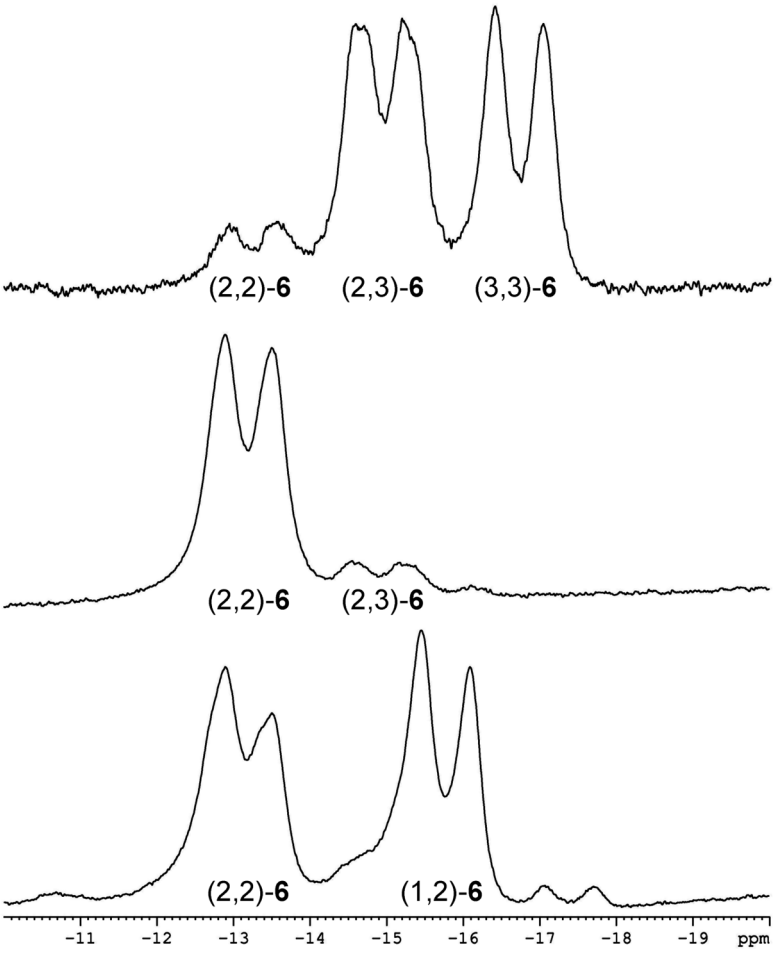
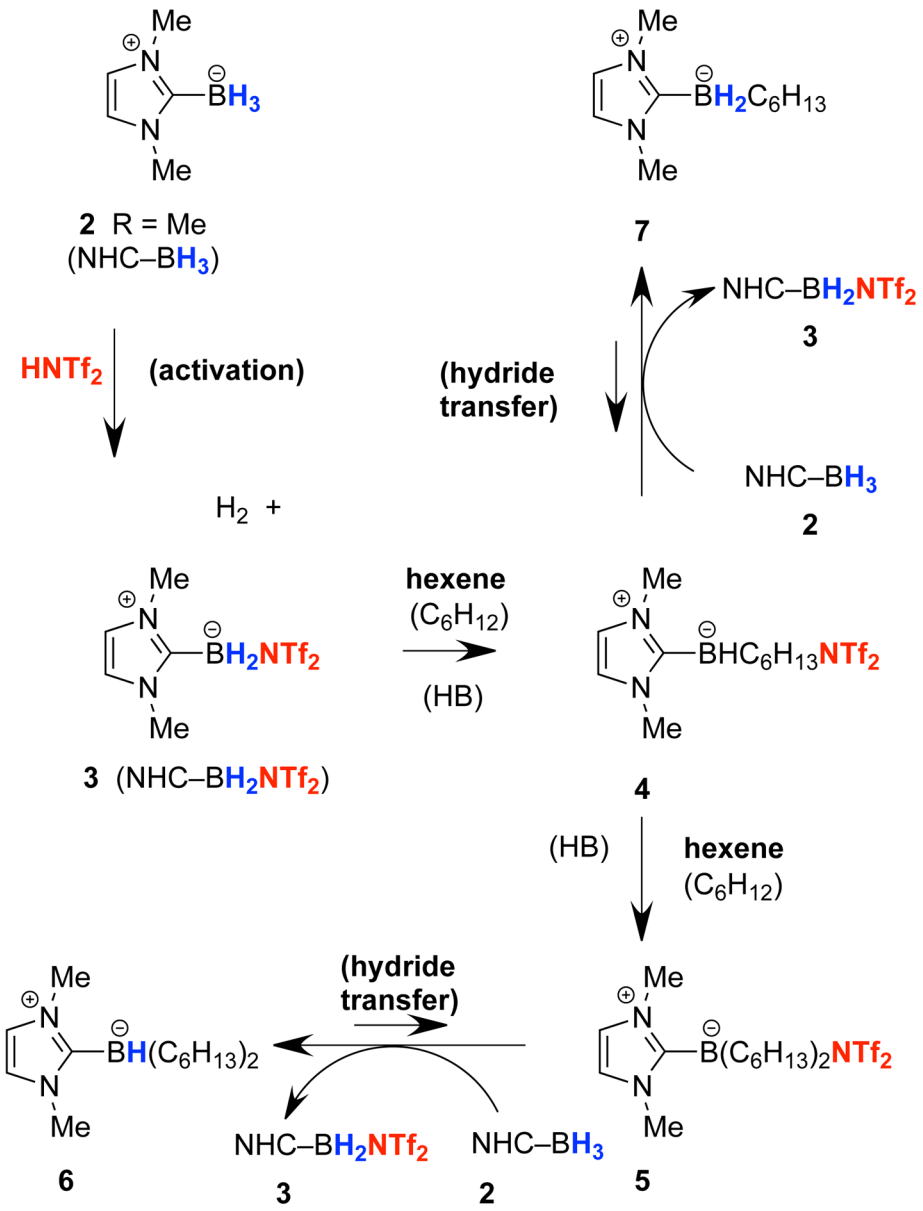
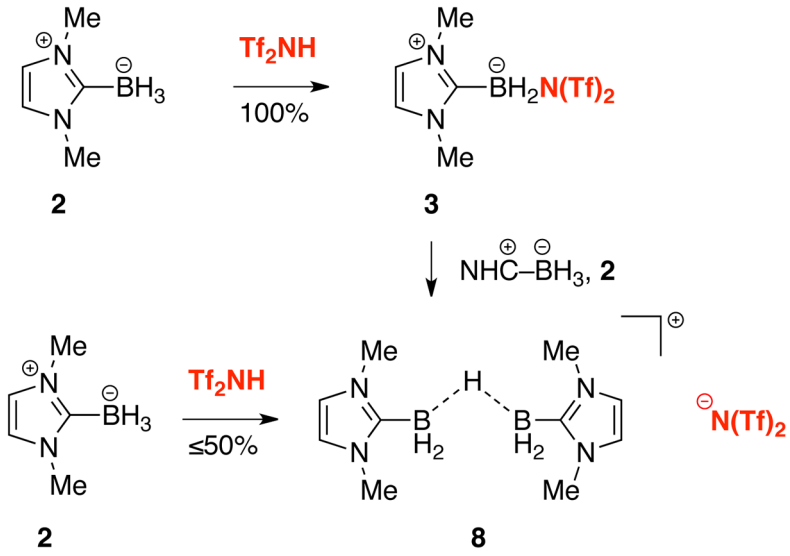


Figure 3.

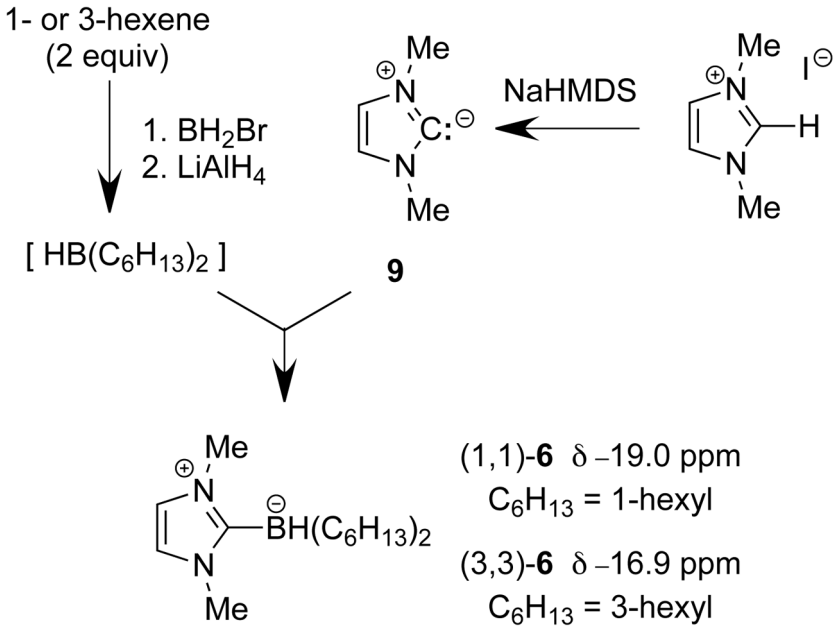
Representative ^{11}B NMR spectra in the hydroboration of 3-hexene that show the product evolution as a function of time and % Tf_2NH: top, entry 3 at 15 min; middle, entry 3 at 90 min; bottom, entry 4 at two days.



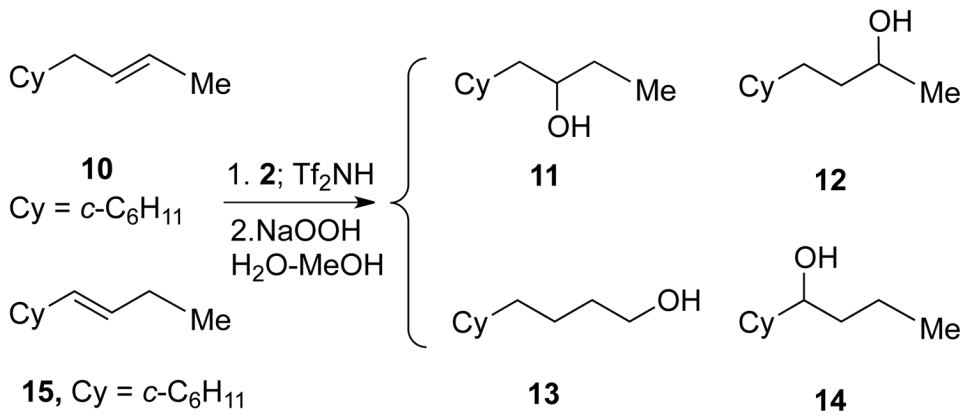
Scheme 1.
Catalytic hydroboration with NHC-boranes



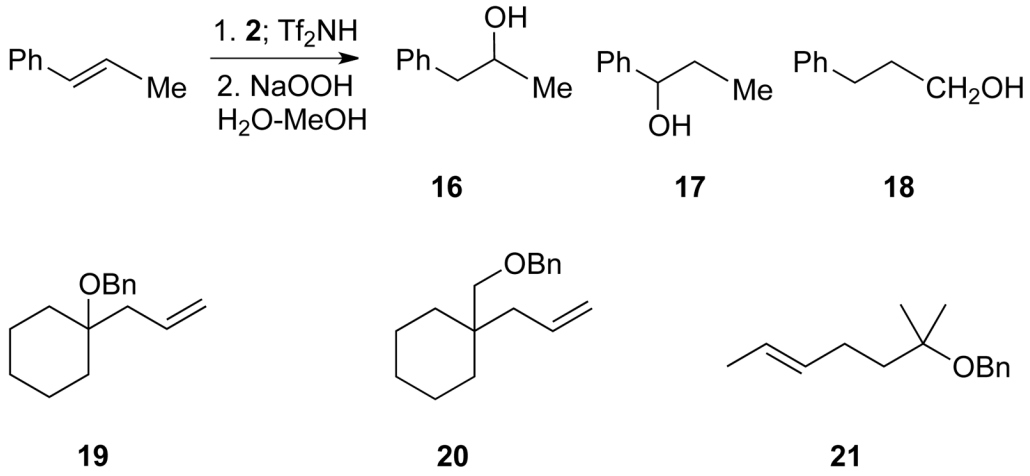
Scheme 2.
Acid-base reactions of NHC-borane 2 with Tf_2NH



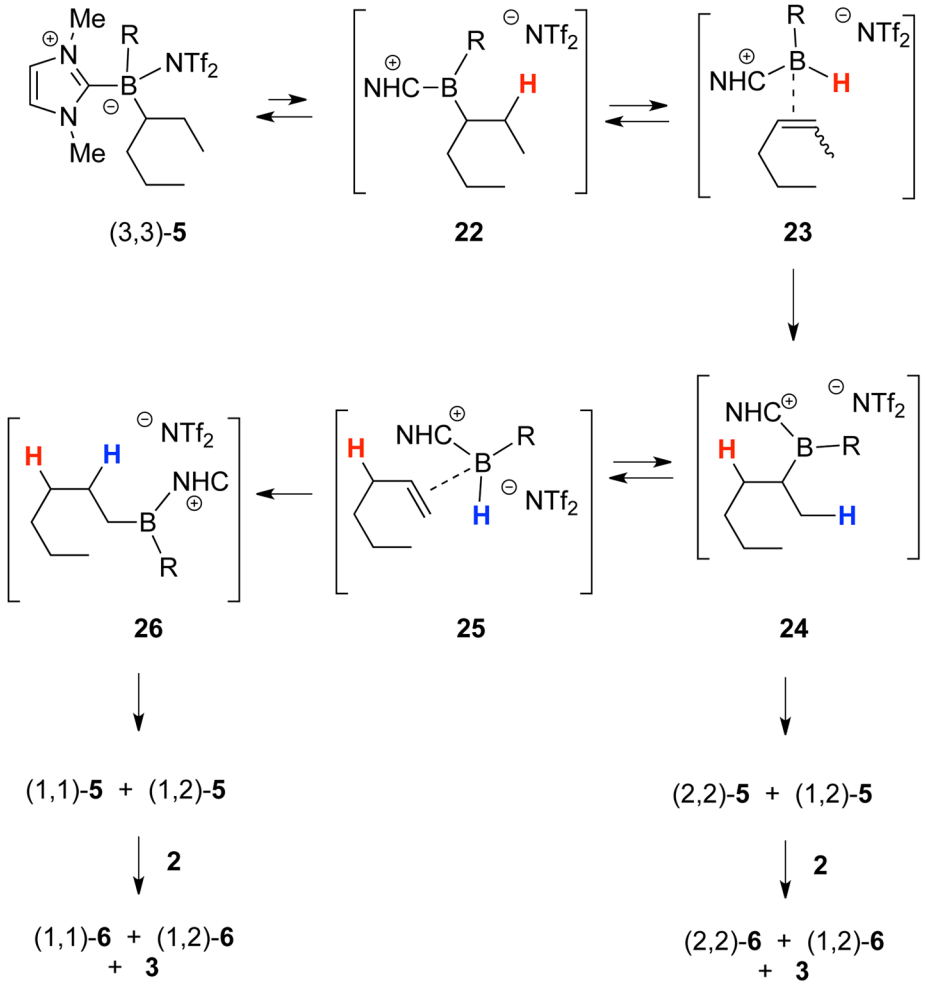
Scheme 3.
Preparation of authentic (1,1)-6 and (3,3)-6 and ^{11}B NMR chemical shifts



Scheme 4.
Hydroboration of 2- and 3-Octene



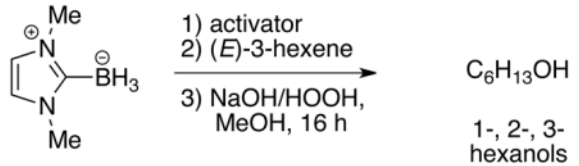
Scheme 5.
Hydroborations of functionalized alkenes



Scheme 6.
Suggested migration pathways (R = C_6H_{13})

Table 1

Isomer distribution and conversion in hydroboration/oxidation of *E*-3-hexene with electrophilic activation of 2[a]



2

entry[a]	activator	time	3-[b]	2-[b]	1-[b]	conv[c]
1	Tf_2NH	20 min	91%	9%	--	75%
2	Tf_2NH	1.5 h	6%	91%	3%	78%
3[d]	Tf_2NH	4 h	6%	76%	18%	90%
4	$TrB(C_6F_5)_4$	1.5 h	6%	91%	3%	80%

[a] A solution of **2** in CH_2Cl_2 was placed in a sealed vial, activated with 5% catalyst, and a 3.5-fold molar excess of *E*-3-hexene was added for the indicated time, followed by NaOOH-MeOH workup, 16 h at RT;

[b] product ratio of 3-/2-/1-hexanol by NMR assay;

[c] conversion based on NMR integration vs. internal standard, assuming 2:1 stoichiometry of alkene:**2** (see Scheme 2);

[d] warmed to 50 °C

Table 2

Ratios of isomeric NHC-dihexylboranes **6** from hydroborations of hexene isomers with **2** and Tf_2NH[a]

entry	hexene	time	3,3	2,3	2,2	1,2	1,1
1	1-	10 min	–	–	–	20%	80%
2	*E*-2-	10 min	2%	13%	85%	–	–
3[b]	*E*-3-	15 min	42%	47%	11%	–	–
		30 min	–	15%	85%	–	–
		90 min	–	10%	85%	5%	–
		2 days	–	10%	85%	5%	–
4	*E*-3-	15 min	–	10%	85%	5%	–
		30 min	–	8%	84%	8%	–
		90 min	–	5%	77%	18%	–
		2 days	–	–	50%	50%	–

[a] triflimide (0.25 equiv) was added to a solution of **2** (1 equiv) in CH_2Cl_2 in an NMR tube, then the alkene (3 equiv) was added and the ^{11}B NMR spectrum was recorded;

[b] reduced triflimide loading (0.15 equiv) to retard isomerization

Table 3

Hydroboration/oxidation using 2 with catalytic Tf_2NH activation[a]

entry	alkene $R'HC_{\alpha}=C_{\beta}HR''$	cat	Time	Temp	% C_{α}OH (unrearr)	% C_{β}OH (unrearr)	% migration products
1	1-octene[b]	5%	1.5 h	25 °C	2-octanol (5%)	1-octanol (94%)	--
2	*E*-2-octene[b]	5%	1.5 h	25 °C	3-octanol (5%)	2-octanol (85%)	4-octanol (tr) 1-octanol (tr)
3	*E*-3-octene[b]	5%	1.5 h	25 °C	4-octanol (9%)	3-octanol (8%)	2-octanol (74%) 1-octanol (tr)
4	*E*-3-octene[b]	5%	19 h	25 °C	4-octanol (5%)	3-octanol (5%)	2-octanol (57%) 1-octanol (31%)
5	*E*-3-octene[b]	30%	2 h	50 °C	4-octanol (tr)	--	2-octanol (15%) 1-octanol (61%)
6	*E*-4-octene[b]	30%	1.5 h	25 °C	4-octanol (8%)	--	3-octanol (7%) 2-octanol (65%) 1-octanol (15%)
7	*E*-4-octene[b]	30%	2 h	50 °C	4-octanol (7%)	--	3-octanol (tr) 2-octanol (25%) 1-octanol (62%)
8	*Z*-4-octene[b]	30%	2 h	50 °C	4-octanol (tr)	--	3-octanol (tr) 2-octanol (21%) 1-octanol (32%)
9	*E*-$CyCH_2CH=CHMe$[b] (**10**)	5%	3 h	25 °C	$CyCH_2CHOHEt$ (**11**; 1–2%)[c]	$Cy(CH_2)_2CHOHMe$ (**12**; 78–82%)[c]	$Cy(CH_2)_4OH$ (**13**; <0.2%)[c] $CyCHOHCH_2Et$ (**14**; 0.1–1%)[c]
10	*E*-$CyCH_2CH=CHMe$[d] (**10**)	5%	3 h	50 °C	$CyCH_2CHOHEt$ (**11**; 2–4%)[c]	$Cy(CH_2)_2CHOHMe$ (**12**; 72–81%)[c]	$Cy(CH_2)_4OH$ (**13**; 0.2–0.3%)[c] $CyCHOHCH_2Et$ (**14**; 1–3%)[c]
11	*E*-$CyCH_2CH=CHMe$[d] (**10**)	5%	24 h	50 °C	$CyCH_2CHOHEt$ (**11**; 3%)	$Cy(CH_2)_2CHOHMe$ (**12**; 68%)	$Cy(CH_2)_4OH$ (**13**; 7%) $CyCHOHCH_2Et$ (**14**; 0.2%)
12	*E*-CyCH=CHEt[b] (**15**)	5%	3 h	25 °C	$CyCHOHCH_2Et$ (**14**; 4–6 %)[c]	$CyCH_2CHOHEt$ (**11**; 14–16%)[c]	$Cy(CH_2)_2CHOHMe$ (**12**; 55–63%)[c] $Cy(CH_2)_4OH$ (**13**; <0.2%)[c]
13	*E*-CyCH=CHEt[d] (**15**)	5%	3 h	50 °C	$CyCHOHCH_2Et$ (**14**; 0.1–0.8%)[c]	$CyCH_2CHOHEt$ (**11**; 2–6 %)[c]	$Cy(CH_2)_2CHOHMe$ (**12**; 70–76%) $Cy(CH_2)_4OH$ (**13**; 1–6 %)[c]
14	*E*-CyCH=CHEt[d] (**15**)	5%	24 h	50 °C	$CyCHOHCH_2Et$ (**14**; 0.1%)	$CyCH_2CHOHEt$ (**11**; 1%)	$Cy(CH_2)_2CHOHMe$ (**12**; 60%) $Cy(CH_2)_4OH$ (**13**; 16%)
15	*E*-$BnCH_2CH=CHMe$[b]	5%	3 h	25 °C	$BnCH_2CHOHEt$ (40%)	$Ph(CH_2)_3CHOHMe$ (40%)	--
16	*E*-$BnCH_2CH=CHMe$[d]	5%	3 h	50 °C	$BnCH_2CHOHEt$ (32%)	$Ph(CH_2)_3CHOHMe$ (51%)	--

[a] entries 1–8, 3.5:1 alkene:**2**; entries 9–14, 2:1 molar ratio of alkene:**2**, followed by NaOOH/H_2O-MeOH workup, 16 h at RT; qualitative product ratios by NMR integration or GLPC

[b] CH_2Cl_2 solution

[c] GLPC relative yields, two runs

[d] $ClCH_2CH_2Cl$ solution.