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# New Direct $^{11}$B NMR-Based Analysis of Organoboranes through Their Potassium Borohydrides

Jesus R. Medina,[†,‡] Gabriel Cruz,[†,§] Carlos R. Cabrera,[†,§] and John A. Soderquist*[,†]

*Department of Chemistry and Materials Characterization Center, University of Puerto Rico, Rio Piedras, Puerto Rico 00931-3346*

*jas@janice.uprr.pr*

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Representative organoborane mixtures were quantitatively converted to their borohydrides through their reaction with activated KH (KH*), permitting their detailed analysis by $^{11}$B NMR. Through the treatment of commercial KH with a THF solution of lithium aluminum hydride (LAH), a dramatic change in the surface morphology results as revealed by scanning electron microscopy (SEM). Energy dispersed spectroscopy (EDS) was employed to reveal that the LAH treatment deposits a significant amount of an unknown aluminum-containing species on the surface of the KH, which imparts a unique reactivity to the KH*. Even highly hindered organoboranes are quantitatively converted to their borohydrides by replacing electronegative groups (e.g., OR, halogen) with hydrogen, retaining only the carbon ligation. Through this simple KH* treatment, complex organoborane reaction mixtures are converted to the corresponding borohydrides whose $^{11}$B NMR spectra normally exhibit resolved signals for the individual species present. The integration of these signals provides quantitative information on the relative amounts of each component of the mixture. New generalities for the effect of α-, β-, and γ-substituents have also been determined that provide a new, simple technique for the determination of the isomeric distribution in organoborane mixtures resulting from common organoborane processes (e.g., hydroboration). Moreover, the $^{1}$H-coupled $^{11}$B NMR spectra of these mixtures reveal the extent of alkylation for each species present. Representative organoboranes were examined by this new technique permitting a simple and convenient quantitative analysis of the regio- and diastereomeric composition of a variety of asymmetric organoborane processes. Previously unknown details of pinene-based hydroborations and reductions are revealed for the first time employing the KH* $^{11}$B NMR technique.

The widespread use of organoboranes in chemical synthesis provides a clear need for the development of new, more convenient analytical methods for assessing the composition of the intermediates formed in a wide variety of organoborane processes.[1,2] Commonly, $^{11}$B NMR is employed to determine the extent of alkylation,[1,2,4] but the isomeric composition of the organoboranes cannot be directly assessed because of the broad overlapping signals observed. On occasion, organoborane derivatives can be prepared and analyzed by NMR[2,5,6] or by chromatography,[3] but it is normal practice to oxidatively convert these intermediates to the corresponding alcohols whose quantitative analysis by gas chromatography provides their isomeric composition indirectly.[1a]

We felt that the use of $^{11}$B NMR in this regard could be markedly enhanced by taking advantage of the narrower peak widths exhibited by $sp^3$ vs $sp^2$ boron, which dramatically enhances the likelihood of being able to observe individual boron species present in organoborane mixtures. While this is a well-established phenomenon, to our knowledge, the technique has never been used to identify the individual species or establish that the peak areas correspond to the molar composition of these mixtures.[7] Common practice is to employ $^{11}$B NMR to determine the extent of alkylation of organoborane mixtures as their trialkylboranes and boron esters, rather than as their borohydrides.[2,4a] Such data provides little useful structural information on the boron ligands themselves because isomeric compounds exhibit resonances that lie within broad overlapping signals. By contrast, it

* To whom correspondence should be addressed.
† Department of Chemistry, University of Puerto Rico.
‡ Graduate student supported by a fellowship from the U.S. Department of Education GAANN program (P200A70219-97A).
§ Material Characterization Center, University of Puerto Rico.

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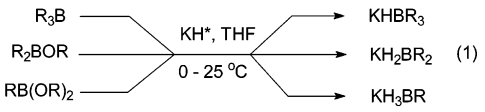
is well-known that borohydrides exhibit much sharper $^{11}$B NMR signals than their trigonal organoborane counterparts.[4a] This is due to their more symmetrical electronic environment around the boron atom, which lowers the electrical field gradient at the quadrupolar boron nucleus, resulting in longer relaxation times and, hence, sharper signals.[4] We felt that a new general protocol based upon our "activated KH" reagent,[7b] which retains only the carbon ligation in organoboranes while quantitatively converting all of the boron species to their corresponding borohydrides, could be developed as a new analytical method for organoborane chemistry. This would provide not only the extent of alkylation of each species but also the isomeric composition of these mixtures. We anticipated that the quadrupolar relaxation would still dominate the relaxation process sufficiently so that the relative areas of the species present would be proportional to the mole fraction of each component. Thus, from these simple NMR measurements, we foresaw that a wealth of new, more detailed information could be obtained for organoboranes and their reactions.

Various hydride sources, including LAH have been used for the generation of organoborohydrides.[8−11] Unfortunately, these procedures are not general because of $AlH_3$-promoted redistribution processes. The reaction of alkali metal hydrides with organoboranes represents the most straightforward route to the corresponding borohydrides.[8,12,13] Of these hydrides, KH[14] has the greatest general utility because of its high reactivity,[13] a feature that is further enhanced with its LAH activation.[7b,c,15] This reagent (KH*), unlike its commercial precursor, quantitatively converts even the most hindered trialkylboranes to their borohydrides at 25 °C in <30 min.[7b] While we initially viewed this as a "surface cleaning", the extraordinary reducing properties of this reagent differed from those of KH itself.[7b] For example, both organoboron esters and halides are smoothly converted to borohydrides, retaining only their organic ligands (eq 1).




This reactivity is in contrast to the normal behavior of KH, which gives either *B*-alkoxydialkylborohydrides ($KHBR_2(OR')$) or mixtures of $KBR_2(OR')_2$ and $KH_2BR_2$ from borinic esters.[16] The clean, predictable reactivity of KH* made it seem to be the ideal reagent for the development of a new $^{11}$B NMR-based analytical method for organoboranes. We chose to: (1) examine the properties of KH* in more detail, (2) evaluate the simple quantitative conversion of representative organoboranes and mixtures to their borohydrides, (3) develop a general protocol for the preparation of samples for $^{11}$B NMR analysis, (4) systematically evaluate the potential of the method to provide detailed quantitative data on the isomeric composition of organoborane mixtures, (5) determine the role of substituent effects on the chemical shifts observed for the individual borohydrides formed, and (6) apply these methods to known organoborane processes to provide previously unknown information on the actual intermediates involved.

## Results and Discussion

**KH* Surface Analysis.** With KH* exhibiting an unusual hydride transfer capability compared to even the best commercial product, we chose to conduct a more detailed surface analysis of the material before and after LAH treatment. Secondary electron imaging (SEI) of the KH with a scanning electron microscope (SEM) before and after LAH treatment revealed a dramatic change in the morphology of the surface (Figure 1). By controlling the accelerating voltage, the kinetic energy of the incident electrons is varied, and this affects the depth of their penetration. Through X-ray fluorescence experiments, significant quantities of oxygen and carbon are observable on the KH surface (5 kV), with the bulk being essentially pure KH (10 kV) consistent with our original hypothesis. However, contrary to our expectations, we could still observe these impurities on the surface of the treated material (Figure 1). More significantly, the treated surface was covered with an aluminum species that resulted from the LAH treatment.

While the precise identity of this new aluminum species is unknown, it seems reasonable to assume that it is a hydridoaluminate such as $AlH_4^{-1}$ or a higher-order derivative (e.g., $AlH_6^{-3}$).[17] This Al-modified KH* is clearly a more powerful hydride donor than KH itself, a fact that explains its unusual ability to rapidly convert even highly hindered organoboranes to their borohydrides and even deoxygenate boron esters cleanly to produce alkylborohydrides. Washing this material several additional times with dry purified THF does not diminish its reactivity or produce solutions that contain any detectable aluminum species by $^{29}$Al NMR analysis.[7b] With this new information, we view this enhanced reactivity as a surface phenomenon with the aluminum acting as a hydride transfer agent for the reaction of the solid KH with the borane. This extremely pyrophoric "activated" material is easily prepared on a mole scale and, after drying *in vacuo*, the powder can be weighed and transferred in a drybox under a nitrogen (or argon) atmosphere to small septum-sealed vials that can be stored indefinitely.

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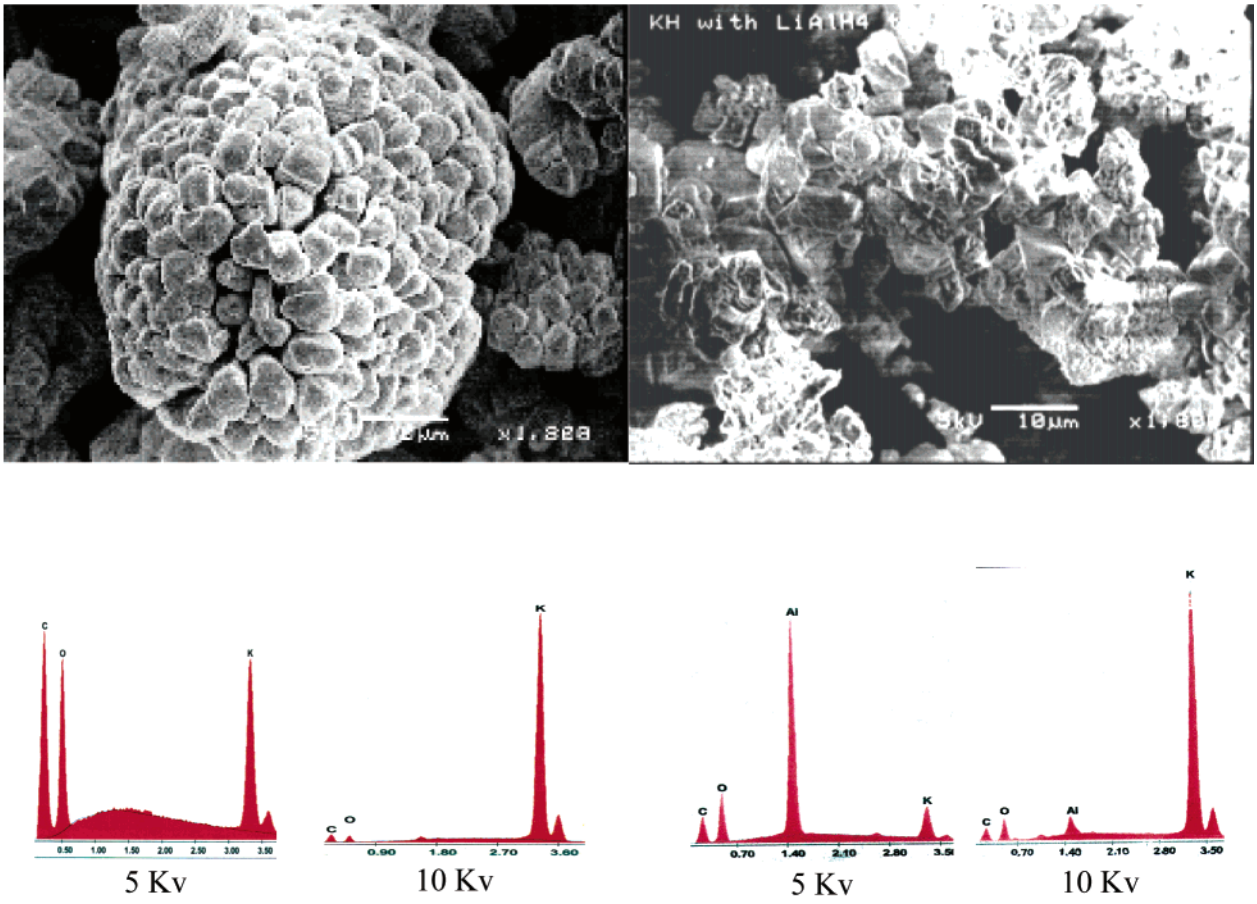
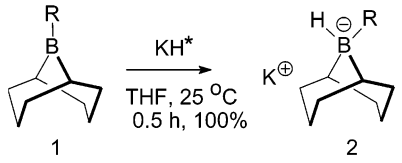



**FIGURE 1.** Secondary electron imaging (SEI) of KH with a scanning electron microscope before (top left) and after LAH treatment (top right). Surface elemental analysis through X-ray fluorescence with the kinetic energy of the incident electrons probing either mainly the surface (5 kV) or the bulk (10 kV) composition of the KH (bottom).

**Quantitative Evaluation of the Borohydride $^{11}$B NMR Method.** To evaluate the potential of this new analytical procedure, *n*-, *s*- and *i*-Bu-9-borabicyclo[3.3.1]-nonanes (**1**) were prepared through the hydroboration with 9-BBN-H of 1-butene, *cis*-2-butene, and 2-methyl-propene, respectively. Synthetic mixtures of either **1a** and **1b** or **1b** and **1c** were prepared with weighed quantities of the boranes. The addition of these boranes under a nitrogen atmosphere to stirred slurries of KH* and THF at 0 °C followed by warming to 25 °C over 30 min produces solutions of the trialkylborohydride (**2**) mixtures. Transferring a portion of the clear supernatant via syringe to a nitrogen-flushed septum-sealed NMR tube provides a simple method for NMR analysis. The $^{1}$H-decoupled $^{11}$B NMR signals for each of the species were fully resolved in these mixtures, and these signals were integrated (Figure 2). In every case, the experimental values obtained were in excellent agreement with the actual molar composition of each mixture over a wide range of compositions.

**Substituent Effects in the $^{11}$B NMR Chemical Shifts of Borohydrides.** For a series of alkylated boranes, we had previously observed that increasing the extent of alkylation causes a downfield shift for the chemical shifts observed in the borohydrides (e.g., $KH_3B$-(Hx-*c*) $\delta$ −23.5 (q, $J$ = 77 Hz); $KH_2B$(Hx-*c*)$_2$ $\delta$ −10.3 (t, $J$ = 72 Hz); KHB(Hx-*c*)$_3$ $\delta$ −7.5 (d, $J$ = 68 Hz)).[7d] While these data provide a clear picture of the extent of alkylation on boron, it also suggested that quantitative information on the isomeric distribution of similarly alkylated species could be obtained. From the data presented in Figure 2, it is evident that the isomeric




$^{11}$B NMR R = *s*-Bu (**a**) : R = *n*-Bu (**b**)

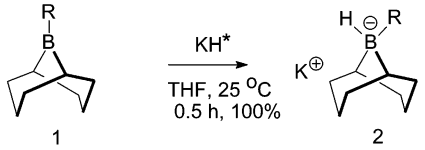
| Mixture | Actual | Measured (NMR) |
|---|---|---|
| | 74:26 | 75:25 |
| | 51:49 | 52.48 |
| | 26:74 | 27:73 |

R = *n*-Bu (**b**) : R = *i*-Bu (**c**)

| Actual | Measured (NMR) |
|---|---|
| 74:26 | 72:28 |
| 50:50 | 50:50 |
| 25:75 | 26:74 |

**FIGURE 2.** Comparison of the $^{11}$B NMR area ratios ($^{1}$H decoupled) to the actual values for various organoborohydride mixtures after treatment with KH*: **2a** $\delta$ −10.8 (d, $J$ = 69.7 Hz); **2b** $\delta$ −13.3 (d, $J$ = 69.1 Hz); **2c** $\delta$ −14.6 (d, $J$ = 70.8 Hz).

**TABLE 1. Evaluation of the α-, *β*-, *γ*-, and *δ*-Substituent Effects for Various 9-BBN Derivatives (2)**



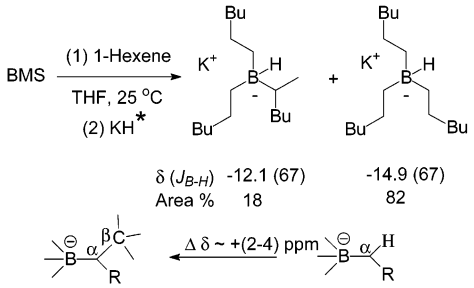

| α-effect | | β-effect | | γ-effect | |
|---|---|---|---|---|---|
| R | $^{11}$B NMR δ ($J_{B-H}$) | R | $^{11}$B NMR δ ($J_{B-H}$) | R | $^{11}$B NMR δ ($J_{B-H}$) |
| H **d** | -16.2 (73) | $CH_2CH_3$ **f** | -11.8 (68) | $CH_2CH_2CH_3$ **i** | -13.2 (68) |
| $CH_3$ **e** | -15.8 (72) | $CH(CH_3)_2$ **g** | -10.0 (71) | $CH_2CH(CH_3)_2$ **c** | -14.4 (70) |
| | | $C(CH_3)_3$ **h** | -8.8 (70) | | |

Bu-9-BBNs do give individually resolved signals. We chose to examine more of these readily available systems (Table 1). From these data, it is evident that α-, *β*-, and *γ*-substituent effects analogous to those commonly observed in $^{13}$C NMR are also operative in the $^{11}$B NMR spectra of borohydrides. For example, in the data presented in the caption of Figure 2, it can be noted that compared to an *n*-Bu group, its *s*-Bu counterpart contains an additional *β*-methyl group that shifts the signal downfield by 2.5 ppm. Similarly, a comparison between *n*-Bu and *i*-Bu reveals that the addition of an additional *γ*-methyl substituent shifts the signal upfield by 1.1 ppm.

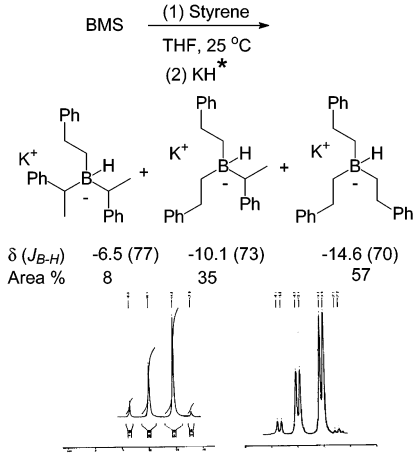
From the data presented in Table 1, a small α-effect (+0.4 ppm) is observed by comparing the borohydrides from 9-BBN-H and *B*-Me-9-BBN. Similarly, comparing the borohydrides derived from *B*-Me-9-BBN (*δ* −15.8) and *B*-Et-9-BBN (*δ* −11.8) suggests that the *β*-effect is larger (+4.0 ppm) but that this effect is attenuated with increasing *β*-substitution (*B*-*i*-Pr-9-BBN *δ* −10.0 (+1.8); *B*-*t*-Bu-9-BBN *δ* −8.8 (+1.2)) (cf. **e**−**h**). The *γ*-effect (−1.4 ppm) can be obtained from the borohydrides derived from *B*-Et-9-BBN (*δ* −11.8) vs *B*-Pr-9-BBN (*δ* −13.2). This effect is only slightly attenuated with the addition of another *γ*-methyl group (*B*-*i*-Bu-9-BBN *δ* −14.4) to *δ* −1.2 ppm (cf. **f**, **i**, and **c**). Comparing the borohydrides from *B*-Pr-9-BBN (**2i** *δ* −13.2) and *B*-Bu-9-BBN (**2b** *δ* −13.3) suggests that the *δ*-effect is negligible in these systems. Most significantly, one can consistently observe that in the borohydrides derived from 2-alkyl vs 1-alkyl boranes, the chemical shift will be shifted downfield (∼+2−4 ppm) due to the additional *β*-substituent.

**Regioisomeric Composition of Alkylboranes.** In hydroboration, the regioisomeric distribution obtained is reagent dependent. We examined the hydroboration of 1-hexene with borane−dimethyl sulfide complex (BMS) at 25 °C, which gives two $^{11}$B NMR signals at *δ* −14.9 and −12.1 in an 82:18 area ratio after the KH* treatment (Scheme 1). Since an overall distribution of 94:6 is observed for 1-boryl vs 2-boryl adducts, the major borane isomer resulting from the hydroboration must be *B*(Hx-*n*)$_3$, whose borohydride is therefore assigned to the *δ* −14.9 (d, *J* = 67 Hz) signal accounting for 82% of the *n*-Hx groups in the overall distribution. Recognition that the extra *β*-methyl group in a *s*-Hx vs an *n*-Hx group would be expected to shift the signal from the borohydride originating from (*s*-Hx)B(Hx-*n*)$_2$ downfield by 2−4 ppm

**SCHEME 1**




**SCHEME 2**




gives good agreement with the observed value of *δ* −12.1 (d, *J* = 67 Hz) (Δ*δ* = +2.8 ppm). With two *n*-Hx and one *s*-Hx groups, this accounts for an additional 12% of the 1-Hx groups and the 6% of the 2-Hx groups observed in the overall product distribution, in complete agreement with the reported values.

A more complicated system is found in the hydroboration of styrene with BMS, which is less selective (81:19), placing more of the boron at the internal position of the C=C double bond. This produces additional regioisomeric products (Scheme 2). The trialkylborane products exhibit a featureless broad $^{11}$B NMR signal at *δ* 86.2, which is converted to three distinct $^{1}$H-decoupled signals at *δ* −6.5, −10.1, and −14.6 in an 8:35:57 area ratio (bottom left, Scheme 2). The $^{1}$H-coupled spectrum (bottom right, Scheme 2) reveals each signal to be a trialkylboro-

**TABLE 2. Comparison of the Regioisomeric Distribution of the Boron Placement Calculated from the KH* $^{11}B$ NMR Method vs the Reported GC Analysis of the Isomeric 1- and 2-Alcohols Formed after Oxidation of the Trialkylborane Intermediates[18]**

| | | Bu | | $^{11}B$ NMR δ ($J_{B-H}$) | Ph | | $^{11}B$ NMR δ ($J_{B-H}$) |
|---|---|---|---|---|---|---|---|
| BMS | KH* | **94** | **6** | -14.9 (67), -12.1 (67) | **83** | **17** | -14.6 (70), -10.1 (73), -6.5 (77) |
| | GC | **94** | **6** | | **81** | **19** | |
| 9-BBN-H | KH* | **>99** | | -13.3 (68) | **97** | **3** | -12.9 (68), -7.7 (72) |
| | GC | **>99** | | | **98** | **2** | |
| $ThxBH_2$ | KH* | **93** | **7** | -11.4 (59), -8.7(66) | **92** | **8** | -11.4 (69), -7.2 (73) |
| | GC | **94** | **6** | | **94** | **6** | |

hydride attributable to the various isomeric terminally and internally placed boryl adducts. Consideration of the above $\beta$-effect leads to the assignment of these signals as the ($\alpha$,$\alpha$,$\beta$)-, ($\alpha$,$\beta$,$\beta$)-, and ($\beta$,$\beta$,$\beta$)-adducts, respectively. From the data, an overall $\alpha/\beta$-boron placement of 17:83 is calculated, a value that compares well with the reported 19:81 distribution determined from the GC analysis of the 1- and 2-phenylethanols derived from an oxidative workup. We hasten to add that since we only observed one $\alpha$,$\alpha$,$\beta$-diastereomer, it is quite possible that the other lies under the larger peaks and that this could account for our slightly lower measured $\alpha/\beta$ value. Nonetheless, the KH* technique is very useful and can even detect trace quantities of borinic esters formed from the air oxidation of the trialkylborane products, which gives rise to an upfield triplet ($\delta$ −18, see Scheme 2). Thus, for the first time, it is possible to actually observe in detail the individual boron species obtained in the hydroboration process. The calculated regioisomeric distributions for the hydroboration of 1-hexene and styrene with BMS, thexylborane, and 9-BBN-H are shown in Table 2 and compared to reported values.[18]

The agreement between these NMR-derived values and the GC analysis of the alcohol oxidation products is remarkably good in all cases. In fact, with thexylborane, the technique easily detects dehydroboration, if the reaction temperature is allowed to rise above −25 °C, by the formation of signals from $[HB(Hx)_3]^{-1}$ (cf. Scheme 1) rather than those exclusively from $[HB(Hx\text{-}t)(Hx)_2]^{-1}$. In each of these examples, the internal boron placement results in an additional $\beta$-methyl group compared to its terminal counterpart giving rise to a downfield shift (∼+2.8 (Hx); +4.2 ($PhC_2H_4$)) related to, but attenuated from, the $\beta$-effects commonly associated with $^{13}C$ NMR spectroscopy.[19]

**Stereo- and Regioisomeric Composition of Vinylboranes.** Since an upfield $\gamma$-effect (1.2−1.4 ppm) had been observed (Table 1), it was felt that a related phenomenon may also be operative for *cis*- vs *trans*-vinylborohydrides analogous to the shifts observed for the allylic carbons in $^{13}C$ NMR. We examined potassium *trans*-propenyl-9-BBN borohydride, which exhibits a $^{11}B$ NMR signal $\delta$ −14.0 (d, $J$ = 72 Hz), while the signal of its cis counterpart is found at $\delta$ −16.4 ppm (d, $J$ = 72 Hz) (Figure 3). Once again, $^{11}B$ NMR spectra of these isomeric vinylborohydrides follow trends similar to those phenomena commonly observed in $^{13}C$ NMR (i.e., $\gamma$-cis effect) but with reduced magnitude (Δ (cis vs trans) −2.4 ppm).[19]

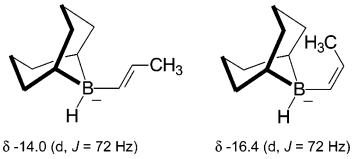



**FIGURE 3.** Comparison of the $^{11}B$ NMR chemical shifts for the borohydrides derived from *B*-(*t*- and *c*-1-propenyl)-9-BBNs.

It was also felt that the determination of the regioisomeric distribution of the vinylboranes obtained from the hydroboration of alkynes may be possible with this method. Mixtures of vinylboranes obtained from the hydroboration of 2-hexyne with 9-BBN-H as well as with dicyclohexylborane were converted to their borohydrides and analyzed by $^{11}B$ NMR (Figure 4).[20] The ratios of 2- vs 3-boryl adducts obtained from hydroboration were compared to the ratio determined from the $^1H$ NMR data of the corresponding isolated vinylboranes and with the reported values that were determined by the GC analysis of the 2- and 3-hexanones resulting from an oxidative workup.[20] For the 9-BBN adducts, the $^{11}B$ and $^1H$ NMR data and the GC analysis of the corresponding ketones are all in good agreement. Unfortunately, the borohydrides derived from the dicyclohexylborane adducts were only partially resolved even at high fields (160 MHz ($^{11}B$)). Nevertheless, only a 4% discrepancy was obtained between the ratio calculated by the borohydride method and that from the $^1H$ NMR and the reported GC values from the ketone distribution. Thus, even partially resolved signals can provide useful data for the semiquantitative screening of reaction mixtures.

**Chemoselectivity of TMANO in the Partial Oxidation of Organoboranes.** Having previously[21] examined the selective oxidation of organoboranes with trimethylamine *N*-oxide (TMANO) through the rather tedious process of the transesterification of boron esters followed by the GC analysis of the alcohol products, we considered the present technique to be an attractive alternative. Bulkier groups in unsymmetrical trialkylboranes are preferentially oxidized in the presence of smaller groups (3°>2°>1°) with 1.0 equiv of TMANO (see

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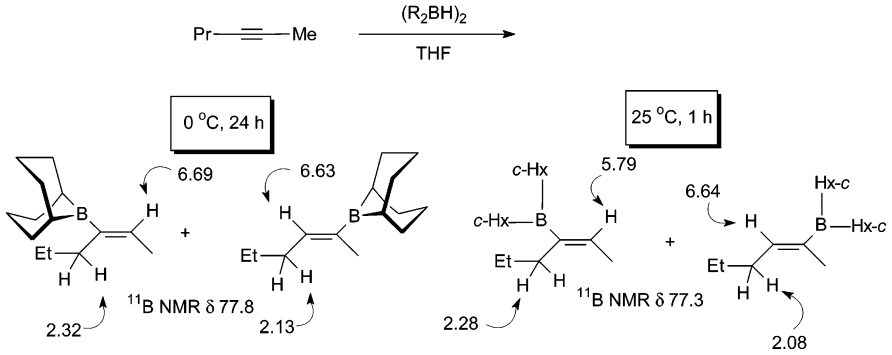
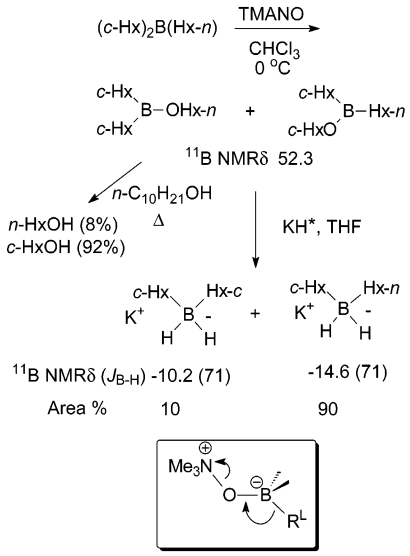


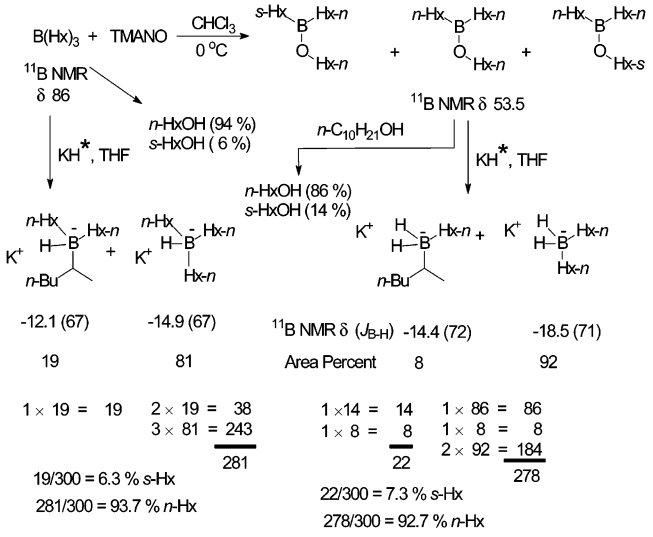

| | | | | |
|---|---|---|---|---|
| $^{11}$B NMR (KHBR$_3$) δ ($J_{B-H}$) | -13.2 (74) | -12.6 (71) | -6.7 (70) | -5.6 (67) |
| Area % | 33 | 67 | 37 | 63 |
| $^{1}$H NMR | | | | |
| Ratio from the integration of vinylic protons. | 31 | 69 | 33 | 67 |
| Ratio from the integration of allylic protons. | 30 | 70 | 33 | 67 |
| Ratio from GC of ketones | 29 | 71 | | |
| Reported (GC of ketones)[20] | 22 | 78 | 33 | 67 |

**FIGURE 4.** Comparison of the measured regioisomeric distributions of the isomeric vinylboranes derived from the hydroboration of 2-hexyne with 9-BBN-H and (*c*-Hx)$_2$BH.

**SCHEME 3**




**SCHEME 4**

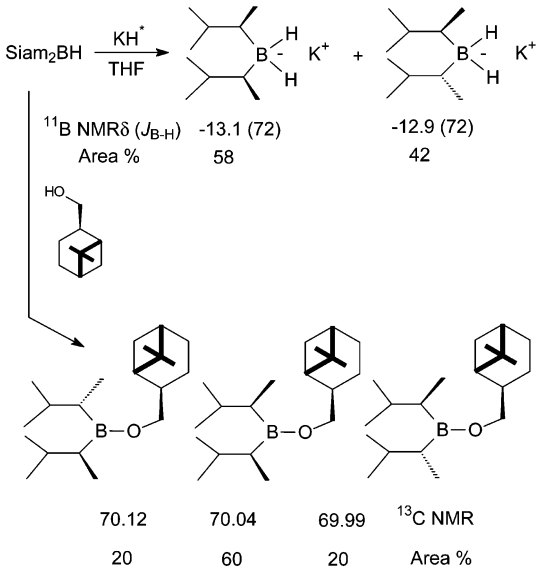



insert, Scheme 3). The borinate esters derived from the TMANO oxidation produce different dialkylborohydrides upon treatment with KH* depending upon which group was oxidized in the trialkylborane. Thus, after the monooxidation of (*n*-Hx)B(Hx-*c*)$_2$ with TMANO (1.0 equiv), $^{11}$B NMR analysis reveals a single broad peak at $\delta$ 52.3 for the borinate esters, which are resolved by the KH* treatment into two $^{1}$H-decoupled sharp peaks at $\delta$ −10.2 (10%) and $\delta$ −14.6 (90%) attributable to K(*c*-Hx)$_2$BH$_2$ and K(*c*-Hx)(*n*-Hx)BH$_2$, respectively, in good agreement with the complementary oxidative data (i.e., *n*-HxOH/*c*-HxOH = 8:92) (Scheme 3).

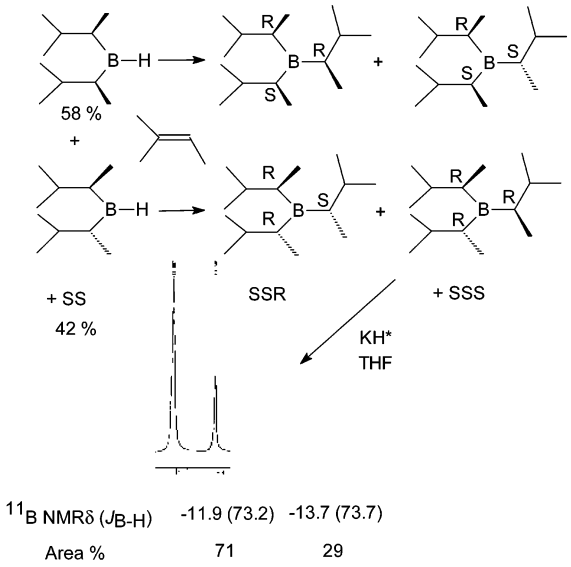
The analyses of the trihexylboranes obtained from the hydroboration of 1-hexene with BMS reveals an overall 94:6 distribution of 1- and 2-hexyl products both by GC (HxOHs from oxidative workup) and by $^{11}$B NMR (after KH* treatment) (Scheme 4). The monooxidation of these boranes with TMANO (1.0 equiv) affords the corresponding boronic esters (Scheme 4). Transesterification with an excess of *n*-decanol followed by distillation and GC analysis provides *n*-HxOH (86%) and *s*-HxOH (14%). The borinic ester mixture was treated with KH* to provide two well-resolved dialkylborohydride $^{11}$B NMR signals at $\delta$ −14.4 and −18.5 in an 8:92 ratio. Combining the 1-Hx vs 2-Hx data from both experiments results in an overall calculated value of 93:7 for the boron placement at the terminal vs internal position of the C−C double bond in the original hydroboration of 1-hexene with BMS, in excellent agreement with the GC and $^{11}$B NMR value of 94:6 determined prior to TMANO oxidation (cf. calculations in Scheme 4).

**Diastereomeric Distribution of Disiamylborane and Trisiamylborane.** With the borohydride method providing extremely useful detailed information on the composition of complex mixtures of regioisomeric orga-

**SCHEME 5**




**SCHEME 6**




noboranes, we chose to also examine its potential utility for the analysis of diastereomeric mixtures. The siamylboranes were selected as a representative system since disiamylborane has been an important reagent since the early days of hydroboration and lithium trisiamylborohydride (LS-Selectride) and its sodium and potassium counterparts are important reducing agents.[7a,8,12b] All are known from NMR to exist as diastereomeric mixtures, but their actual compositions have never been rigorously determined.[7a,12b,14b]

Disiamylborane is formed as two diastereomers, a feature that can be observed through the $^{11}$B NMR analysis of the borohydrides that exhibit signals at $\delta$ −13.1 and −12.9 in a 58:42 ratio (Scheme 5). To determine which signals were due to the *meso* vs *dl* components, disiamylborane was also allowed to react with *cis*-myrtanol to form the corresponding borinic esters. From the nonequivalence of the $^{13}$C NMR signals that are observed in a 20:20:60 ratio for the alkoxymethylene carbons in the *d*-, *l*-, and *meso*-diastereomers, the major disiamylborane diastereomer formed in the hydroboration of 2-methyl-2-butene is therefore the *meso*-diastereomer (58%).[22]

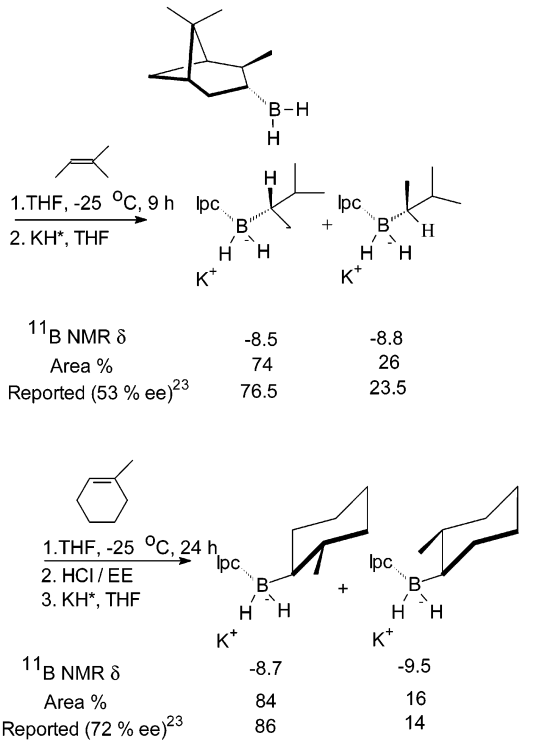
With this diastereomeric distribution in mind, we further hydroborated 2-methyl-2-butene with this mixture to produce trisiamylborane as a 71:29 mixture of diastereomers as judged from the areas of the $\delta$ −11.9 and −13.2 peaks observed for their borohydrides (Scheme 6). We recognized that only one diastereomer can result from the hydroboration of 2-methyl-2-butene with *meso*-disiamylborane (i.e., *R*,*S*,*R* and *R*,*S*,*S* are enantiomers). However, the *dl*-isomer can produce two diastereomers, *R*,*R*,*R* (or its enantiomer, *S*,*S*,*S*) and R,R,S (or its enantiomer, *S*,*S*,*R*). The latter diastereomer (*R*,*R*,*S* and *S*,*S*,*R*) is also formed from the *meso*-disiamylborane. Since this unsymmetrical diastereomer can be no less than 58% of the mixture, it follows that it is the major isomer (71%) in the trisiamylborane mixture, while the symmetrical isomer (*R*,*R*,*R* and *S*,*S*,*S*) is the minor component (29%). It is therefore possible to easily determine that the *dl*-disiamylborane (42% $(Siam)_2BH$ mixture hydroborates 2-methyl-2-butene at room temperature to give 29% yield of the symmetrical B (Siam)3 and 13% yield of the unsymmetrical adduct. This translates into 38% de for this hydroboration process and indicates clearly that the unknown optically pure disiamylborane would be a poor asymmetric hydroborating agent for such alkenes. Thus, the $^{11}$B NMR analysis of the potassium borohydrides derived from even diastereomeric mixtures provides highly detailed information on the precise composition and reactivity of these mixtures.

**Enantiofacial Selectivity in the Hydroboration of Alkenes with $IpcBH_2$.** The importance of (α-pinene)-derived borane reagents in synthesis[23] prompted us to examine the asymmetric hydroboration of prochiral alkenes with $IpcBH_2$ through our $^{11}$B NMR technique. The hydroboration process results in the formation of diastereomeric mixed dialkylborane intermediates from both trans and trisubstituted olefins.[24] The alcohols derived from these mixtures are traditionally derivatized to form diastereomeric Mosher esters that can be analyzed by GC or NMR. We felt that the simpler borohydride $^{11}$B NMR method could be used to directly observe the diastereomeric borane adducts as their borohydrides. As representative examples, the hydroboration of 2-methyl-2-butene and 1-methylcyclohexene were performed following the reported procedures (Scheme 7).[24] KH* treatment followed by $^{11}$B NMR analysis gave the diastereomeric ratio directly and well within the experimental errors of both methods.[24] Considering the problems that are possible with the standard analysis methodology (e.g., stereochemical drift in the organoborane oxidation, kinetic resolution in the alcohol esterification, and changes in the GC response factors), the KH* $^{11}$B NMR method seems preferable.

We also conducted simple MMX calculations[25a,b] employing transition-state modeling parameters for the hydroboration of 2-methyl-2-butene with (3*R*)-$IpcBH_2$ that gave a $\Delta\Delta G^{\ddagger}$ (MMX) = 0.52 kcal/mol, which, at −25 °C, translates into a predicted 74:26 mixture of (*S*)- and (*R*)-adducts, precisely the experimental (KH*) $^{11}$B NMR value.

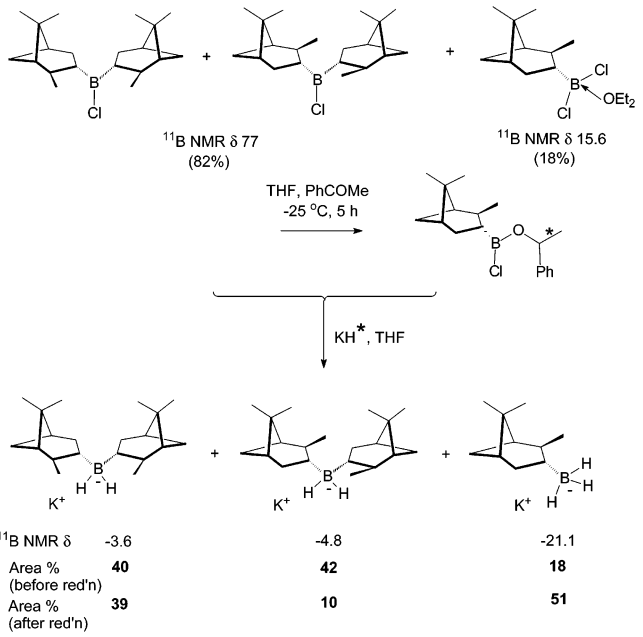
**Kinetic Resolution in the Reduction of Acetophenone with $Ipc_2BCl$.** As part of the synthesis of LTD4

**SCHEME 7**




Antagonist L-699392,[26] Merck scientists reported an asymmetric amplification obtaining an alcohol product in 95% ee from the reduction of a prochiral ketone intermediate with *B*-chlorodiisopinocampheylborane ($Ipc_2BCl$)[27] which had been prepared from α-pinene of only 70% ee. It was concluded that the *meso*-diastereomer of $Ipc_2BCl$ was inactive or very slow reacting. This phenomenon and related "asymmetric amplifications" have been more extensively examined both experimentally[3] and theoretically[28] recently within the context of the Kagan model.[29] Numerous questions still remain unanswered regarding the reasons for this nonlinear behavior between reagent vs product ee, but the fact that it exists in this case has been firmly established. Our KH* method

**SCHEME 8**




appeared to be a particularly simple method for measuring the relative reactivities of *meso*- vs *dl*-$(Ipc)_2BCl$ if each would provide resolved $^{11}B$ NMR signals for their borohydrides ($K(Ipc)_2BH_2$). Equally important is the fact that our method, unlike HPLC techniques,[3] should also provide quantitative corroborative product formation data (i.e., IpcBCl(OR) converted to $K(Ipc)BH_3$). This phenomenon was examined by first determining the composition of the borane mixture before and after a ketone reduction (Scheme 8). The (±)-$Ipc_2BCl$ reagent was prepared from the $Ipc_2BH$ produced from the hydroboration of racemic α-pinene with BMS (5 h, 25 °C). Under these conditions, the $^{11}B$ NMR before and after the KH* treatment revealed that the reagent was a nearly 50:50 mixture of *meso*- and *dl*-isomers together with $IpcBCl_2$ etherate (Scheme 8). This represents a remarkably simple new way to determine Kagan's $\beta$ value for this process.[3,29] The composition of the (±)-$Ipc_2BCl$ was found to be time dependent (e.g. 24 h, *meso*/*dl* = 30:70) consistent with the well-known equilibration of $Ipc_2BH$ dimer in the presence of α-pinene.[30] After the addition of acetophenone to the ∼50:50 *meso*/*dl* mixture, treatment with KH* followed by $^{11}B$ NMR analysis, revealed that essentially only the *dl*-$Ipc_2BCl$ component (∼97%) is used for reduction, which nicely matches the formation of the monoisopinocampheylborane byproduct (IpcBCl(OR*) which, along with the $IpcBCl_2$, is observed as the borohydride ($K(IpcBH_3)$ $\delta$ −21.1).

We again examined this process, following the acetophenone reduction at −25 °C employing a 30:70 *meso*/*dl* $Ipc_2BCl$ mixture. Simply adding aliquots from the reaction mixture to vials containing KH* at different time intervals allows the progress of the reduction to be conveniently monitored by $^{11}B$ NMR (Figure 5). The *dl* component reacts smoothly, while the *meso*-$Ipc_2BCl$ remains virtually unchanged. The relative rates of the

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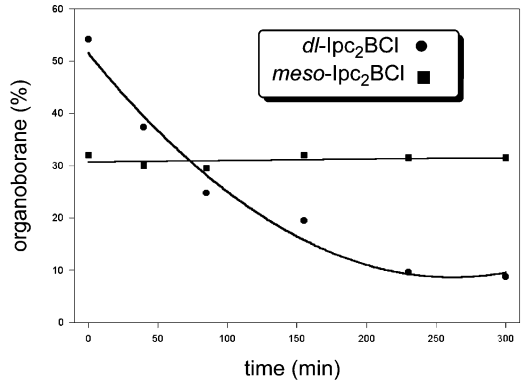


**FIGURE 5.** Plot of the disappearance of $Ipc_2BCl$ diastereomers vs time for the reduction of acetophenone at −25 °C.

*meso*- vs *dl*-isomers has been estimated at <0.05 (Kagan *g*-value).[3,31] In our case, the relatively low concentration of *meso*-$Ipc_2BCl$ compared to that in other studies,[3] which employed $H_2BCl$ for the hydroboration of α-pinene, evidently precludes any significant contribution to the reduction of acetophenone by this diastereomer. These results are in agreement with the conclusions originally made by the Merck chemists regarding the origin of the asymmetric amplification.[26]

To better understand the observed variations in the *meso*/*dl* compositions of these $Ipc_2BCl$ mixtures, we chose to briefly examine this process. The origin of chirality transfer has been of interest since the discovery of asymmetric hydroboration.[32] From our data, it is clear that hydroboration of α-pinene with $IpcBH_2$ kinetically favors the formation of the *meso*-$Ipc_2BH$ over its *dl* counterpart. We had examined pinene-based organoborane processes,[33] including hydroboration with $IpcBH_2$,[34] a process that had been modeled from calculations.[35] With the (+)-α-pinene derived $IpcBH_2$ (i.e., (3*R*)-isomer), there is a well-known tendency to form (*S*)-adducts, a fact that would translate into the selective formation of *meso*-$Ipc_2BH$ (3*R*,3′*S*) over *l*-$Ipc_2BH$ (3*R*,3′*R*). With the optically pure (3*R*)-$IpcBH_2$, (±)-α-pinene (1:2) was hydroborated at 25 °C, and following the KH* treatment, a 65:35 mixture of the *meso*- and (3*R*,3′*R*)-$Ipc_2BH_2^{-1}$ species was observed. Since the pinene enantiomers are consumed unequally, we can apply the Ingold−Shaw relationship[36] to obtain $k_{meso}/k_l$ = 71:29 for the hydroboration of α-pinene with $IpcBH_2$. Applying simple MMX calculations to this process as described above, we calculated a $\Delta\Delta G^{\ddagger}$ = 0.5 kcal/mol for the relative transition-state energies. At 25 °C, this converts to a calculated $k_{meso}/k_l$ = 70:30, in remarkable agreement with experiment (Figure 6). Moreover, the above diminution of this *meso*/*dl* (±)-$Ipc_2BCl$ isomer ratio with time can be attributed to the well-known thermodynamically driven solution-phase equilibration,[30] which favors the *dl* form that ultimately becomes the dominant diastereomer.

While the question as to why the *dl* form of the reagent is so much more reactive than its *meso* counterpart was not rigorously addressed, recent semiempirical calculations suggest that these $Ipc_2BCl$ reductions occur through the reversible formation of a borane−carbonyl complex followed by its collapse through a cyclic "chairlike" transition state.[37] A brief examination of these processes with the *meso* vs *dl* suggests that to reach such a transition state, the spectator Ipc group experiences added C-2 Me repulsions with the reacting Ipc group that are absent in the *dl* reagent. This leads to added reorganization and a higher TS energy (∼2 kcal/mol). Further work is ongoing to corroborate this result.

## Conclusions

Through the highly reactive reagent KH*, mono-, di-, and trialkylboranes and related boron esters are converted to their borohydrides retaining only the carbon groups originally bonded to the boron atom. Through the $^{11}B$ NMR analysis of these borohydrides, it was demonstrated that sharp, resolved signals can be observed for isomeric organoborane mixtures whose areas are proportional to the mole fraction of each isomer present in the mixture. Through a systematic study of a series of organoborohydrides, the effect of α-, *β*-, *γ*-, and *δ*-substitution was evaluated with the conclusion that the effects are similar to those observed in $^{13}C$ NMR but with an attenuated magnitude. Most significantly, the *β*-effect (+2−4 ppm) makes the evaluation of branched vs straight chain alkylboranes formed in hydroboration mixtures a trivial process. The degrees of boron alkylation are also readily obtained through the chemical shifts and multiplicity of the $^1H$-coupled spectra of these borohydrides. The *γ*-effect is an upfield effect (1−2 ppm) that not only is observable in alkyl systems but also clearly permits *cis* vs *trans* vinylboranes to be differentiated. The method was applied to the complex mixtures providing a clear quantitative picture of the borane intermediates formed in each process.

The method also affords quantitative information on the diastereomeric composition of many organoborane intermediates and processes at a level that has not been previously possible. The mixed dialkylboranes (i.e., IpcBHR*) resulting from the asymmetric hydroboration of prochiral alkenes with $IpcBH_2$ are easily analyzed, as are important pinene-based asymmetric reductions. The method is operationally simple, rapid, and efficient

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providing detailed quantitative data that has widespread potential application to many organoborane intermediates and processes.

## Experimental Section

**General Methods.** All experiments were carried out in predried glassware (1 h, 150 °C) under a nitrogen atmosphere. Standard handling techniques for air-sensitive compounds were employed throughout this study.[1] NMR spectra were recorded in either $CDCl_3$ or $C_6D_6$ as indicated: $^1$H (either 500 or 300 MHz), $^{13}$C (either 126 or 75 MHz); $^{11}$B (either 160.5 or 96.5 MHz) and GC data were obtained with a 30 m × 0.25 mm i.d. fused silica capillary column. Scanning electron microscope−energy dispersive spectroscopy (SEM-EDS) analysis was performed with a scanning electron microscope equipped with an EDAX X-ray fluorescence CDU leap detector. The SEM is used in the analysis to obtain a magnified view of the sample and focus the electron bean on the sample. Also, it is used to control the accelerating voltage and, therefore, the kinetic energy and penetration depth of the incident electrons. The EDS system is used in combination with the SEM system to obtain the elemental composition of the sample (atom % ranging from ±5% for lighter elements to ±0.5% for heavier elements).

**9-*sec*-Butyl-9-borabicyclo[3.3.1]nonane (1a).**[1] Into a 50 mL round-bottomed flask was placed 9-BBN (3.05 g, 25.0 mmol) followed by dry pentane (20 mL). The solution was cooled with an ice bath, and *cis*-propene (3.5 g, 62 mmol) was added at 0 °C. The reaction mixture was stirred overnight at room temperature. The solvents were removed under high vacuum, and distillation afforded 4.28 g (96% yield, >97% pure by $^{11}$B NMR) of **1a** (bp 86 °C, 4.0 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ 0.97 (m, 6H), 1.22 (m, 2H), 1.36 (m, 2H), 1.60−1.76 (m, 7H), 1.76−1.88 (m, 6H) ppm; $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 14.1, 14.3, 23.6, 25.6, 30.4, 32.7, 33.6, 33.7 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 87.2 (bs) ppm; MS *m*/*z* 178 (M+, 100), 121 (44), 108 (25), 93 (89), 79 (62), 67 (55), 53 (84).

**9-Butyl-9-borabicyclo[3.3.1]nonane (1b).**[1] As for **1a**, to 9-BBN (3.0 g, 24.6 mmol) in dry pentane (20 mL) was added 1-butene (3.5 g, 62 mmol) at 0 °C. The bath was removed, and the mixture was stirred overnight at room temperature. The solvents were removed under high vacuum, and distillation afforded 3.7 g (84% yield, >98% pure by $^{11}$B NMR) of **1b** (bp 85 °C, 0.9 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ 0.95 (t, $J$ = 7.2 Hz, 3H), 1.18 (m, 2H), 1.24−1.42 (m, 4H), 1.43−1.55 (m, 2H), 1.6−2.0 (m, 12H) ppm; $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 14.4, 23.7, 26.4, 27.1, 28.2, 31.4, 33.5 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 87.9 (bs) ppm; MS *m*/*z* 178 (M+, 84), 121 (48), 108 (32), 93 (79), 79 (68), 67 (66), 53 (100). Compounds **1f** and **1i** were similarly prepared from ethylene and propylene.[2]

**9-Isobutyl-9-borabicyclo[3.3.1]nonane (1c).**[1] As for **1a**, to 9-BBN (3.05 g, 25.0 mmol) in dry pentane (20 mL) was added 2-methylpropene (3.6 g, 64 mmol) at 0 °C. The reaction mixture was stirred overnight at room temperature. The solvents were removed under high vacuum, and distillation afforded 3.83 g (86% yield, >98% pure by $^{11}$B NMR) of **1c** (bp 79 °C, 0.75 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ 0.97 (d, $J$ = 6.6 Hz, 6H), 1.22 (m, 2H), 1.35 (d, $J$ = 7.0 Hz, 2H), 1.6−1.76 (m, 6H), 1.78−1.85 (m, 6H), 2.02 (m, 1H) ppm; $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 23.6, 25.5, 26.1, 31.5, 33.6, 39.6 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 88.5 (bs) ppm.

**9-Isopropyl-9-borabicyclo[3.3.1]nonane (1g).**[38] To 9-(triisopropylsilylthio)-9-BBN[39] (1.5 g, 4.8 mmol) in THF (10 mL) was added isopropylmagnesium bromide in THF (7 mmol) at 0 °C. The reaction mixture was stirred for 30 min at room temperature. The solvent was removed, and the ate complex was heated to decomposition under a vacuum to generate **1g**, which was distilled in situ to afford 0.7 g (89% yield, >98% pure by $^{11}$B NMR) of pure **1g** (bp 36 °C, 0.25 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ 1.03 (d, $J$ = 7.4 Hz, 6H), 1.11−1.21 (m, 2H), 1.45 (septet, $J$ = 7.3 Hz, 1H), 1.57−1.90 (m, 12H) ppm; $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 17.4, 23.7, 24.4, 30.3, 33.6 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 86.2 (bs) ppm; MS *m*/*z* 164 (M+, 100), 121 (52), 108 (24), 93 (87), 79 (61), 67 (43), 53 (82).

**9-*tert*-Butyl-9-borabicyclo[3.3.1]nonane (1h).** Following Kramer's procedure,[38] a 50 mL centrifuge tube equipped with a rubber septum and a stirring bar was charged with 9-methoxy-9-BBN (1.52 g, 10.0 mmol) followed by dry hexane (20 mL). The solution was cooled to −78 °C using a dry ice bath and *tert*-butyllithium (6.5 mL, 1.7 M, 11.0 mmol) was added dropwise via syringe. The mixture was stirred at −78 °C for 15 min, and the bath was removed and allowed it to stir for 3 h at room temperature. The reaction mixture was centrifuged, and the clear supernatant was decanted into another flask. The remaining solid was washed with hexane (2 × 15 mL). The solvents were evaporated, and distillation afforded 1.64 g (92% yield, >98% pure by $^{11}$B NMR) of **1h** (bp 28 °C, 0.02 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ 0.98 (s, 9H), 1.18 (m, 2H), 1.61−1.67 (m, 4H), 1.78−1.88 (m, 8H); $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 23.5, 26.0, 28.7, 33.7 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 85.6 (bs) ppm; MS *m*/*z* 178 (M+, 59), 121 (23), 93 (48), 78 (16), 68 (100), 53 (48). Compound **1e** was similarly prepared from LiMe.[38]

***trans*-1-(9-Borabicyclo[3.3.1]non-9-yl)-1-propene.**[40] To a 100 mL flask were added 9-BBN-H (7.53 g, 62.0 mmol) and 100 mL of THF. To a 250 mL round-bottomed flask (RBF) equipped with a dry ice condenser were added propyne (16.6 mL, 248 mmol) and 20 mL of THF cooled in an ice−water bath. The 9-BBN-H solution was added to the propyne solution dropwise. The reaction mixture was stirred at 0 °C until the precipitated 9-BBN-H had completely disappeared (3−4 h). The clear solution was allowed to stand overnight. The solvent was evaporated, and distillation afforded 5.56 g (55% yield, >98% pure by $^{11}$B NMR) of the *B-t*-(1-propenyl)-9-BBN (bp 66 °C, 0.9 Torr): $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ 1.32 (m, 2H), 1.78 (m, 6H), 1.93 (m, 6H), 2.01 (dd, $J$ = 1.5 Hz, 3H), 6.31 (dq, $J$ = 17.1, 1.5 Hz, 1H), 6.89 (dq, $J$ = 17.1, 6.3 Hz, 1H) ppm; $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ 21.3, 23.5, 30.0, 33.8, 136.5, 150.8 ppm; $^{11}$B NMR (96 MHz, $CDCl_3$) $\delta$ 77.0 (bs) ppm; MS *m*/*z* 162 (M+, 42), 147 (10), 133 (35), 120 (65), 105 (36), 91 (100), 79 (66), 53 (85).

***cis*-1-(9-Borabicyclo[3.3.1]non-9-yl)-1-propene.** To a 100 mL RBF was added Mg (1.56 g, 64 mmol) followed by THF (20 mL). The *cis*-1-bromo-1-propene (7.02 g, 58 mmol) was added very carefully, and the reaction mixture was stirred for 1 h at room temperature. More THF (20 mL) was added. Simultaneously, a solution of 9-methoxy-9-BBN (7.6 g, 50 mmol) in hexane (30 mL) was prepared and cooled to −78 °C. The solution with the Grignard reagent was added dropwise; the bath was removed, and the reaction mixture was stirred for 1 h. The THF was evaporated under a water aspirator vacuum, and the salts were washed with dry hexane (3 × 20 mL). The combined washes were concentrated, and distillation afforded 2.31 g (29% yield, 90% cis and 10% trans) of these vinylboranes (bp 39 °C, 0.15 Torr): $^1$H NMR (300 MHz, $C_6D_6$) $\delta$ vinylic CH $\alpha$ to the boron [6.22 (dq, $J$ = 13.5, 1.3 Hz)], vinylic CH $\beta$ to the boron [6.41 (dq, $J$ = 13.6, 6.9 Hz), observed as a sextet] ppm; $^{13}$C NMR (75 MHz, $C_6D_6$) $\delta$ 18.7, 23.7, 32.9, 33.8, 135.8, 146.6 ppm; $^{11}$B NMR (96 MHz, $C_6D_6$) $\delta$ 80.6 (bs) ppm.

**Representative Procedure for the Activation of KH with $LiAlH_4$.** Into a 100 mL RBF equipped with a rubber septum and a stirring bar was added a 35% dispersion of KH in mineral oil (9.0 g). The contents were washed with dry pentane (3 × 50 mL), decanting the supernatant each time with a cannula under a positive pressure of $N_2$. To this mixture was added LAH (60 mL, 1 M in THF), and the mixture was

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stirred for 0.5 h at room temperature. The supernatant liquid was decanted as above, and the KH* was washed with fresh, dry THF (2 × 50 mL) and dried in vacuo (~0.1 Torr). This activated material can be weighed in a drybox and transferred to small vials for further use. *Caution! This wildly pyrophoric material can explode upon exposure to the open atmosphere. Extreme care should be exercised when handling or storing this material to avoid any potential contact with oxygen (oxidants) or moisture (proton sources).*

**Quantitative Evaluation of the Borohydride $^{11}B$ NMR Method and the Regioisomeric Composition of Organoboranes.** After the organoboranes had been prepared as described, they were added dropwise via syringe to a suspension in THF of 2 equiv of KH* at 0 °C. After the addition was completed, the mixture was stirred for 30 min at room temperature. $^{11}B$ NMR analysis of the supernatant liquid showed the complete formation of the desired borohydride species. The results are given in Figure 2 and Table 2.

**Hydroboration of 2-Hexyne with 9-BBN.** Following the reported procedure of Scouten, Liotta, and Brown,[16] solid 9-BBN (6.1 g, 50 mmol) was dissolved in 90 mL of dry THF. The resulting solution was added slowly to a cold (0 °C) stirred solution containing 4.52 g of 2-hexyne (55 mmol, 10% excess) in 19 mL of dry THF. The reaction mixture was stirred at 0 °C, until the solid had completely dissolved (7−8 h), and maintained at 0 °C for an additional 16 h to ensure complete reaction. The reaction mixture was warmed to 25 °C and stirred for an additional 1 h. Solvent evaporation afforded 10.3 g of crude material (95% crude yield) which upon short-path distillation afforded 8.77 g (81% yield, >96% pure by $^{11}B$ NMR) of the vinylborane mixture (bp 82−110 °C at 0.1 Torr): $^1H$ NMR (500 MHz, $C_6D_6$) terminal $CH_3$ [0.87 (t, $J$ = 7.4 Hz), 0.93 (t, $J$ = 7.3 Hz)], allylic $CH_3$ [1.85 (s), 1.68 (d, $J$ = 6.7 Hz)], allylic $CH_2$ [2.13 (td, $J$ = 7.1, 6.3 Hz), 2.32 (t, $J$ = 7.7 Hz)], vinylic CH [6.63(t, $J$ = 6.3 Hz), 6.69 (q, $J$ = 6.7 Hz)] ppm; $^{13}C$ NMR ($C_6D_6$) $\delta$ 14.2, 14.6, 14.7, 15.2, 22.5, 23.9, 24.3, 31.2, 31.7, 34.1, 34.3, 143.2, 148.3 ppm; $^{11}B$ NMR (96 MHz, $C_6D_6$) $\delta$ 78.2 (bs) ppm.

**Borohydride Analysis of the 2-Hexyne Hydroboration with 9-BBN.** The hydroboration of 2-hexyne with 9-BBN was performed as described above. After the hydroboration was completed, an aliquot from the reaction mixture was withdrawn and treated with KH*. $^{11}B$ NMR analysis of the supernatant liquid showed the complete formation of the borohydride species. $^{11}B$ NMR (160 MHz, $C_6D_6$) $\delta$ −12.6 (d, $J$ = 71 Hz), −13.2 (d, $J$ = 74 Hz) ppm. Careful analysis revealed the ratio of C-2/C-3 boron placement to be 67:33. The solvent from the mother liquor vinylborane mixture was removed under high vacuum, and analysis by $^1H$ NMR (500 MHz,$C_6D_6$) vinylic [6.69 (q, $J$ = 6.7 Hz); 6.63 (t, $J$ = 6.3 Hz)] and allylic $CH_2$ [2.32 (t, $J$ = 7.7 Hz); 2.13 (td, $J$ = 7.1, 6.3 Hz)] protons revealed a ratio of 31:69 and 30:70, respectively.

**Oxidation of the Vinylborane Mixture.** After the hydroboration of 2-hexyne (5.5 mmol) with 9-BBN was performed, an aliquot of a buffer solution of pH 8−9 (5 mL) and 1.5 mL of 30% $H_2O_2$ were mixed at 0 °C following the reported procedure.[21] To this stirred solution was slowly added the vinylborane mixture in THF. The mixture was stirred for 2 h at 0 °C before separating the organic and aqueous layers. Analysis of the organic layer by GC using decane as an internal standard revealed the presence of 79% 2- and 3-hexanones in a 71:29 ratio.

**Hydroboration of 2-Hexyne with Dicyclohexylborane.** Into a predried centrifuge tube containing cyclohexene (2.47 g, 30.1 mmol) in ether (20 mL) was added BMS at 0 °C BMS (1.5 mL, 10.0 M, 15 mmol). After 3 h of stirring at 0 °C and 1 h at 25 °C, the white slurry was centrifuged. The solid (dicyclohexylborane) was washed with dry ether (3 × 10 mL) and dried under a stream of nitrogen. Fresh dry ether (16 mL) was added followed by addition of 2-hexyne (1.24 g, 15 mmol). After 1 h at 25 °C, the solvent was removed under a stream of nitrogen to afford 3.0 g of the regioisomeric vinylboranes (77%, >97% pure by $^{11}B$ NMR): $^1H$ NMR (300 MHz,$C_6D_6$) allylic $CH_2$ [2.08 (td, $J$ = 6.8 Hz), 2.28 (t, $J$ = 7.6 Hz)], vinylic CH [5.54 (broad), 5.79 (q, $J$ = 6.6 Hz)]; $^{13}C$ NMR ($C_6D_6$) $\delta$ 14.1, 14.7, 15.0, 23.1, 24.4, 27.6, 28.2, 28.3, 28.4, 30.4, 32.0, 36.7, 130.0, 135.1 ppm; $^{11}B$ NMR (96 MHz, $C_6D_6$) $\delta$ 77.3 (bs) ppm. A sample of the vinylborane mixture was treated with KH*. $^{11}B$ NMR analysis of the supernatant liquid showed the complete formation of the borohydride species. $^{11}B$ NMR (160 MHz,$C_6D_6$) $\delta$ −5.8 (d, $J$ = 67 Hz), −6.7 (d, $J$ = 70 Hz).

**Oxidation of Unsymmetrical Organoboranes.** After the organoboranes were prepared in THF solution as described,[21a] 1 equiv of anhydrous TMANO [21b] dissolved in $CHCl_3$ was added to the stirred mixture at 0 °C. After 2 h, the solvents were removed under high vacuum and the borinic ester mixture was transferred dropwise to a THF suspension of 4 equiv of KH* at 0 °C. The mixture was stirred for 30 min at room temperature. Schemes 3 and 4 show the $^{11}B$ NMR analysis of the clear supernatant in each case.

**Diastereomeric Distribution of Disiamylborane.** A 25 mL RBF was charged with BMS (0.5 mL, 10.0 M) and dry THF (5 mL). The flask was immersed into an ice−water bath, and 2-methyl-2-butene (0.73 g, 10 mmol) was added dropwise via syringe. The mixture was stirred for 2 h at room temperature. An aliquot from the reaction mixture was treated with KH* as described before. $^{11}B$ NMR (160 MHz, $C_6D_6$) $\delta$ −13.1 (t, $J$ = 72 Hz), −12.9 (t, $J$ = 72 Hz). These two signals appeared in a 58:42 ratio. The disiamylborane reaction mixture was treated with *cis*-myrtanol (0.77 g, 5 mmol). The solvent was removed, and the $^{13}C$ NMR analysis for the oxygenated carbons shows three signals at 70.12, 70.04, and 69.99 ppm in a 20:60:20 ratio, respectively. This crude mixture was treated with KH*, which shows by $^{11}B$ NMR the disiamylborohydride signals in a 58:42 ratio.

**Diastereomeric Distribution of Trisiamylborane.**[7a] Into a 50 mL RBF was added dry THF (10 mL) via syringe. The 2-methyl-2-butene (5 g, 71 mmol) was added, and the solution was cooled to 0 °C with an ice−water bath. BMS (2.0 mL, 10.0 M, 20 mmol) was added dropwise. After the addition was completed, the ice bath was removed and the mixture was stirred for 7 h at room temperature. The solvent was removed under high vacuum and distillation afforded 3.98 g (89% yield, >97% pure by $^{11}B$ NMR) of trisiamylborane (bp 61 °C, 0.05 Torr): $^1H$ NMR (500 MHz, $C_6D_6$) $\delta$ 0.83−0.86 (m, 11H), 0.89−0.91 (m, 7H), 0.93−0.95 (m, 9H), 1.33−1.44 (m, 3H), 1.73−1.91 (m, 3H) ppm; $^{13}C$ NMR ($C_6D_6$) $\delta$ 12.4, 12.6, 13.1, 21.0, 21.1, 21.3, 25.26, 25.33, 25.5, 29.7, 30.4, 35.9, 36.9 ppm; $^{11}B$ NMR ($C_6D_6$) $\delta$ 85.9 (bs) ppm. A sample of this material was treated with KH*. $^{11}B$ NMR analysis of the supernatant liquid showed the complete formation of the two borohydrides. $^{11}B$ NMR ($C_6D_6$) $\delta$ −11.9 (d, $J$ = 73 Hz), −13.7 (d, $J$ = 74 Hz).

**Asymmetric Hydroboration of 2-Methyl-2-butene, 1-methylcyclohexene and (±)-α-Pinene.** The hydroborations of the first two alkenes were performed following the reported procedures.[24] After completion of the hydroboration reaction, aliquots were withdrawn, treated with KH*, and analyzed by $^{11}B$ NMR. These data are presented in Scheme 7. For the α-pinene study, the optically pure $IpcBH_2$ reagent was again prepared as reported;[24] (±)-α-pinene (2.0 equiv) was added, and the mixture was allowed to stir for 5 h. The product ratios were determined using the KH* technique as above. The ratios did not change significantly over this time, nor did they change significantly over an additional 24 h.

**Reduction of Acetophenone with $Ipc_2BCl$.** Into a 100 mL RBF were added BMS (1.5 mL, 10.0 M, 15.0 mmol) and EE (8 mL) followed by the dropwise addition at room temperature of racemic α-pinene (4.5 g, 33 mmol). After the mixture was stirred for 5 h, dry HCl in EE (12.5 mL, 1.2 M) was added at 0 °C and the stirring was continued until all of the solid dissolved and gas evolution had ceased. $^{11}B$ NMR analysis showed two signals at 77.1 and 15.6 ppm in a ratio of 82:18, respectively. The solvent was removed, THF (11 mL) was added, and the solution was cooled to −25 °C. An aliquot from

the solution was withdrawn and treated with KH*. $^{11}$B NMR $\delta$ −3.6 (t, $J$ = 73 Hz), −4.8 (t, $J$ = 69 Hz), −21.1 (q, $J$ = 77 Hz). The ratio for these signals was 40:42:18, respectively. Acetophenone (1.56 g, 13.0 mmol) was added. After 5 h, another aliquot was withdrawn from the reaction mixture and treated with KH* to perform the $^{11}$B NMR, analysis which showed the same three previous signals in a ratio of 39:10:51, respectively.

**Kinetic Resolution Graph.** The reduction of acetophenone was performed as described above. Aliquots were treated with KH* at periodic intervals and analyzed by $^{11}$B NMR measuring the relative areas of the borohydride species. These data are shown in Figure 5.

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**Note Added After ASAP Posting.** In the version posted May 14, 2003, the captions for Figures 3 and 4 were interchanged. The corrected version was posted May 16, 2003.

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