Interrogating Redox and Lewis Base Activations of Aminoboranes

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ABSTRACT: Since their discovery, aminoboranes (R-N-BR₂) have been applied as chemical hydrogen storage devices, asymmetric catalysts, semiconductors, and amination reagents. Recently, chemists have extended their application to reagents for difunctionalization reactions, wherein the N–B bond is cleaved and the amine and boronic ester fragments are distributed across an organic molecule. Generally, harsh conditions or loss of the borane fragment as waste is required to enable reactivity of the enthplexically stable partial sp²-hybridized N–B bond. In contrast, we sought to show that mild avenues also exist to disrupt the dative N–B π-bond. Herein, we survey the coordinative capabilities of neutral Lewis bases to (amino)pinacolboranes and whether the partial sp²-hybridized N–B bond can be oxidized electro- or photochemically in analogous fashion to C=C bonds. The results of these studies are strongly in the affirmative and should guide the thought processes of organic chemists when designing new reactions using aminoboranes.

Introduction

Aminoboranes (R-N-BR₂) are a class of molecules comprised of a nitrogen and boron atom covalently coordinated. The N–B bond is further strengthened by π-donation from the nitrogen lone pair to the empty p-orbital on boron leading to an enthplexically favorable, partially sp²-hybridized bond (Figure 1a).¹ Since their discovery, aminoboranes have captivated chemists across a variety of disciplines (Figure 1b). Unsubstituted aminoboranes have been of interest to materials chemists, who identified them as a promising source of H₂ gas for use in fuel cells² while aminoborane-doped poly aromatic hydrocarbons have electron-hole transport properties that are attractive to the semi-conductor industry.¹ In organic chemistry, chiral bicyclic aminoboranes are versatile enantioselective catalysts for numerous reductions and cycloadditions³ among other uses.⁴

A. Partial sp² character of N–B bond

B. Selected examples of aminoboranes across chemistry

Figure 1. A) Unique hybridization of the N–B bond. B) Examples of various aminoborane scaffolds in chemistry.

As reagents, the nitrogen and boron components of the aminoborane archetype are also valuable in synthetic organic chemistry. For example, amines are good pharmacophores for the development of new drugs⁶ or agrochemicals while boronic acids, esters, and boronates are versatile synthetic handles⁵ that can be leveraged to form new C–C,⁶ C–O,⁶ C–N,⁶,¹⁰ and C–X bonds. As such, synthetic chemists have begun investigating aminoboranes as ambiphilic reagents to introduce these important groups on to organic molecules (Figure 2).¹¹ Fernández and coworkers exploited the Lewis acidity of the boron group to reductively aminate enones through activation with sodium tert-butoxide (Figure 2A).¹² Bertrand and coworkers exploited the reactivity of aminoboranes with aldehydes to generate aldimines that cannot be accessed through traditional routes (Figure 2B).¹³ Unfortunately, both methods and other similar methods¹⁴ require loss of the boron group as stoichiometric waste.

A. [1,4]-addition of amminoboranes into enones

B. Aminoborane-mediated imine formation

C. Intramolecular aminoborane insertion

D. Intermolecular aminoborane insertion

E. This work: analysis of aminopinacolborane reactivity

Figure 2. A)–D) Previous incidences of aminoboranes as synthetic handles. E) Studying fundamental aminoborane reactivity trends.

Although their incidence in the literature is rare, difunctionalization protocols using aminoboranes to distribute amines and boronic esters across carbon-carbon bonds are appearing. As of 2017, Blum,¹⁵ Shi,¹⁶ and Wang¹⁷ all independently reported intramolecular 1,2-aminoborations of alkynes to form boryl-substituted indoles (Figure 2C) while Dong developed intermolecular aza-Matteison amination reactions (Figure 2D).¹⁸ These difunctionalization reactions using aminoboranes highlight the ability of these
molecules to serve as reagents in highly atom-economical transformations of organic substrates; however, they all rely on strong Lewis acids/bases to weaken the N–B pseudo double bond.

Inspired by the numerous uses of aminoboranes in chemistry and the recent emergence of aminoboronic esters as difunctionalization reagents, we set out to define the reactivity trends of (amino)pina-colaboranes (1) to facilitate future uses of this versatile molecule (Figure 2E). Herein, we show that addition of neutral Lewis bases (LBs) give rise to trace amounts of aminoborane/neutral LB adducts lying thermodynamically upfield from the starting components. Then, cyclic voltammetry (CV) experiments enabled the determination of the oxidation potentials for a broad range of sterically and electronically diverse aminoboranes. Herein, we show that addition of neutral Lewis bases (LBs) give rise to trace amounts of aminoborane/neutral LB adducts lying thermodynamically upfield from the starting components. Then, cyclic voltammetry (CV) experiments enabled the determination of the oxidation potentials for a broad range of sterically and electronically diverse aminoboranes while Stern-Volmer (SV) quenching studies indicated that commercially available photocatalysts (PC) in their photoexcited states can be effectively quenched by these aminoboranes. The results presented indicate that neutral LBs, electrochemical, and photochemical activation of aminoboranes is feasible and should be used as a resource to expedite the development of future chemistries involving aminoboranes.

**Results and Discussion**

We began by synthesizing a library of 18 sterically and electronically diverse aminoboranes 1a–r (Figure 3). The groups on nitrogen were specifically chosen to interrogate strategic differences between aminoboranes: 1) aryl vs. alkyl, 2) monosubstituted vs. disubstituted, 3) aryl vs. alkyl N-heterocycles, 4) N-heterocycle ring size, and 5) aniline electronic effects.

![Figure 3. Aminoborane derivatives surveyed in the present study.](image)

**Lewis base activation of aminoboranes.** Using $^{11}$B NMR spectroscopy, we surveyed the coordination capabilities of neutral LBs 2a–r (Figure 4) to morpholine-derived aminoborane 1a by monitoring the change in the chemical shift of 1a. We rationalized that stronger coordination of the LB to 1a would lead to greater upfield $^{11}$B NMR shifts of any new adducts. Thus, 2a–r were combined in a 3:1 molar ratio with 1a ([1a] = 0.470 M in CDCl$_3$) and analyzed after 20 minutes at room temperature. In most cases, a new minor resonance was observed upfield of 1a. We attributed this species to the presumed aminoborane/LB adduct 3. Adduct 3 never formed as the major product under any conditions we surveyed nor did the [3] increase further when the reaction was monitored over 24 hours at room temperature.

![Figure 4. Neutral LBs tested for coordination to 1a. Listed pK$_H$’s (measured in H$_2$O) were derived from literature sources.](image)

![Figure 5. Plot of LB pK$_H$ vs. 3a $^{11}$B NMR chemical shift. ’Data points at ~23 ppm correlate to $^{11}$B since no adduct was observed.](image)
From these studies, it is evident that higher concentrations of neutral LBs and lower temperatures are beneficial for activation of aminoboranes by neutral LBs. Since only trace amounts of LB activated intermediates 3 are necessary for catalytic activity, neutral LBs still hold promise for future advances involving aminoboranes as reagents and should not be eliminated from consideration.

**Electrochemical Activation.** Our results show that the CV redox events of aminoboranes are generally irreversible, which is likely the result of rapid decomposition pathways following their oxidation at the electrode surface. Therefore, we elected to report the all \( E_{1/2} \) values of 1a-r against saturated calomel electrode (SCE, Figure 6), which Nicewicz et al. and Moeller et al. determined was a valid strategy for comparing relative thermodynamic redox potentials.

Relative to the parent amines, aminoboranes have more positive oxidation potentials in all cases surveyed here. We attribute this increased difficulty to the dative \( \pi \)-bonding present in aminoboranes. This contribution diminishes the electron density on nitrogen making it harder to oxidize. From another perspective, the double bond character of the N–B bond makes it electronically like an alkene. The oxidation potential of this resonance contributor might mirror those of alkenes, which have \( E_{1/2} > 1.7 \) V. Therefore, we argue that the oxidation potentials of aminoboranes can be viewed as a combination of amine and alkene redox potentials and most are accessible under traditional electrochemical conditions.

For arene-containing aminoboranes, we observed a clear trend between the oxidation potential \( (E_{1/2} = 0.99 – 1.54 \) V) and the substitution pattern at nitrogen (Figure 6, green). Of these, para-methoxy-substituted aniline aminoborane \( 1i \) displays the only reversible oxidation event at \( E_{1/2} = 0.99 \) V, which is easier to oxidize than unsubstituted \( 1j \). In line with this trend, anilines with electron-withdrawing groups para to nitrogen (e.g., 1k) are more difficult to oxidize than \( 1j \) and \( 1i \). Secondary (alkyl)(aryl)aminoboranes 1o–p are also more readily oxidized than \( 1j \) due to the increased inductive donation from the alkyl substituent. By contrast, diphenylaminoborane \( 1l \) is more challenging to oxidize than 1o–p due to the inductively withdrawing second aryl ring compared to alkyl groups. Unsurprisingly, aromatic aminoboranes 1m–u are more difficult to oxidize than other aminoboranes due to the delocalization of the nitrogen lone pair in the aromatic \( \pi \)-system. The observed trends closely align with our assertion that the electron density at nitrogen is an important indicator of ease of aminoborane oxidation.

Non-aromatic aminoboranes also displayed distinctive trends, albeit with \( E_{1/2} > 1.61 \) V (Figure 6, yellow/red). Dialkyl aminoboranes are more readily oxidizable \( (E_{1/2} = 1.61 – 1.68 \) V) than monoalkyl aminoboranes \( (E_{1/2} = 2.15 – 2.65 \) V) resulting from the increased inductive donation of the second alkyl group as compared to a proton. We posit that the difficulty of alkyl aminoborane oxidation relative to aryl aminoboranes can be explained by examining the resulting amminium radical cations (ARCs) furnished after oxidation. The unpaired electron in the former is localized on nitrogen whereas the electron of the latter can be delocalized around the conjugated \( \pi \)-system. Thus, alkyl ARCs are less thermodynamically favorable than aryl ARCs, which makes the latter easier to access than the former.

**Photochemical activation.** We next surveyed aminoboranes 1a–r by Stern-Volmer (SV) analysis to determine how their steric and electronic properties effect their quenching abilities of \( \text{PC}_{12} \) (Figure 8, top, see ESI for details on PC quenching). Although 2,4,6-triphenylpyrylium \( \text{BF}_4 \) (\( \text{PC}_{12} \)) and Rhodamine B (\( \text{PC}_6 \)) were most efficiently quenched by 1a (97% and 81% quenching, respectively), their emission profiles in the presence of specific aminoboranes were altered (representative example depicted in Figure 7). This result suggests an interaction of these aminoboranes with the PC to form a new species exhibiting altered fluorescence. Stoichiometric \( ^1\text{B} \) NMR reactions of \( \text{PC}_{12} \) support this hypothesis (see ESI). Although Eosin Y (\( \text{PC}_4 \)) exhibited 80% fluorescence quenching in the presence of 1a, its solubility in organic solvents is an issue for SV analyses. Thus, even though \( \text{PC}_4 \) might still be useful under catalytic conditions, it was not investigated further here.

![Figure 6. Oxidation potentials of aminoboranes obtained via cyclic voltammetry in acetonitrile + 0.1 M [Bu4N]PF6, scan rate: 100 mV s⁻¹. Potentials are reported against SCE.](image)

![Figure 7. Combination of ('hex)aminoborane 1e with \( \text{PC}_{12} \) in acetonitrile shows altered emission profile as compared to \( \text{PC}_{12} \) alone (left). No change in the emission profile of \( \text{PC}_{12} \) was observed in the presence of 1e (right).](image)
Unlike PC_{13}, the emission profile of Ir-based PC_{11} does not change in the presence of any aminoborane surveyed here (representative example shown in Figure 7, right) and its solubility is significantly higher than PC_{14}. Most importantly, the K_{sv} of PC_{11} with a wide range of primary and secondary aminoboranes exceeded 1,000 M⁻¹ (Figure 8, bottom). There were even cases (1i, 1k, and 1l) where the obtained quenching constants reached the diffusion-controlled limit (K_{sv} > 22,000 M⁻¹). Unfortunately, even with PC_{11}, aminoboranes derived from primary amines were poor quenchers yielding K_{sv} < 200 M⁻¹.

From these quenching studies and the electrochemical data presented above, we can propose promising fluorophores for the future discovery of photocatalytic reactions of aminoboranes. Based upon the oxidation potentials depicted in Figure 6 and the excited state oxidizing power of PC_{11} (E_{1/2} (PC*/PC⁻) = +0.97 V vs. SCE), an energy transfer (EnT) event is expected to be operative rather than an electron transfer (ET) process. In contrast, for the discovery of reactions involving a reductive quench of the excited state of a photocatalyst, 9-mesityl-10-methylacridinium BF₄⁻ (PC_{16}) is a sufficiently strong oxidant to engage in ET with dialkyl and aryl-containing aminoboranes studied here (E_{1/2} (PC*/PC⁻) = +2.18 V vs. SCE). Importantly, PC_{16} was reasonably quenched by 1a in these studies (38.2%).

![Fluorophores investigated](image)

**SV Quenching**

![Quenching figure](image)

**Fluorophore** PC_{11}

**Figure 8. Library of PCs tested in these quenching studies (top). Fluorescence quenching of PC_{11} with various aminoboranes (bottom). N.B.: ‘Bu = tert-butyl, Cy = cyclohexyl, Ph = phenyl, ‘Oct = cyclooctyl.**

**Conclusions.** Neutral LB coordination to aminoboranes showed a strong correlation between LB pK_{a}H and ^{11}B NMR chemical shift of the adduct 3. In all cases where an adduct was observed, it lied in an equilibrium favoring the starting materials, suggesting endergonic aminoborane activation. This conclusion was further supported by variable temperature NMR studies. Future studies should seek to exploit the coordination of LBs to aminoboranes as a strategy to discover new reactions under mild conditions.

Our prepared aminoborane library was surveyed by CV and displayed oxidation potentials ranging from E_{p/2} = 0.99 – 2.65 V, which is anodically shifted relative to their parent amines/anilines. Notably, primary alkyl aminoboranes did not show readily achievable oxidation events (E_{p/2} > 2.15 V). Finally, we surveyed numerous readily accessible chromophores to interrogate whether aminoboranes could serve as efficient quenchers. Fluorescence quenching studies identified PC_{11} as a potential EnT fluorophore for many of the aminoboranes studied here (K_{sv} > 1,000 M⁻¹) while PC_{16} is thermodynamically capable to engage in ET with the same set of aminoboranes. Investigations are ongoing in our lab to discover new reactions of aminoboranes by leveraging both neutral LBs as organocatalysts and electro- and photocatalytic strategies.
ASSOCIATED CONTENT

Supporting Information

Characterization data including NMR spectra of aminoboranes and complexes; methods, and results (PDF).

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Notes

The authors declare no competing financial interest.

Author Contributions

A.A.B. collected the fluorescence data and helped write the manuscript. G.E.L. conducted the preliminary CV studies. Both G.E.L. and A.A.B. studied the interactions between LBs and aminoboranes. E.A.R. helped fund A.A.B. during these investigations and helped with manuscript editing. E.A.R. collected the VT and variable concentration NMR data, performed the finalized CV study, devised and managed the project, and wrote the manuscript. All authors read, commented, and approved the final manuscript version.

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EXPERIMENTAL SECTION

General considerations. All syntheses were performed in an N2-filled glovebox. Acetoniitrile (MeCN) was dried using a Grubbs-type solvent purification system containing activated alumina, degassed by 3 successive freeze-pump-thaw cycles, and stored over activated 4 Å molecular sieves for 24 hours prior to use. Benzene was refluxed in the presence of sodium benzenophenone ketyl, distilled under argon once a dark purple color was obtained, and stored in an N2-filled glovebox. All reactions used new 4 mL vials with Teflon-coated magnetic stir bars that were cleaned using freshly prepared aqueous reagent to remove metal contaminants. Pinacolborane (HBPin) was purchased from commercial suppliers, stored in the glovebox, and used as received. Amines were purchased from commercial suppliers and used as received. In cases where significant hydrolysis was observed during the dehydrocoupling reaction with HBPin, the amines were distilled from CaH2 and stored in the glovebox over 4 Å molecular sieves for 24 hours prior to use or recrystallized and dried under reduced pressure. Triethylamine was distilled from CaH2 and stored in the glovebox. Characterization data for compounds 1a, 1b-h, 1j, and 1r were in accordance with those in the literature. Characterization data for compounds 1p-1t were in accordance with those in the literature.

**Synthesis of novel aminoboranes.** New aminoboranes were synthesized via a dehydrocoupling reaction by modification of a known procedure as described in the following general protocols.

**Procedure 1:** Under an N2 atmosphere, amine (2.0 mmol, 1 equiv.), 0.39 mL of dry acetonitrile, and a Teflon coated magnetic stir bar were added to a 4 mL scintillation vial. HBPin (2.0 mmol, 1 equiv.) was added resulting in vigorous gas extrusion. After the reaction solidifies, another 0.39 mL of dry acetonitrile was added to the mixture to redissolve the solid. Anhydrous triethylamine (0.02 mmol, 1 mol%) was added, the vial was sealed with a pressure release screw cap, and the mixture was left to stir overnight at room temperature. All volatiles were evaporated under reduced pressure and the resulting materials were used without further purification.

**Procedure 2:** Under an N2 atmosphere, amine (2.0 mmol, 1 equiv.), 0.39 mL of dry benzene, and a Teflon coated magnetic stir bar were added to a 4 mL scintillation vial. HBPin (2.0 mmol, 1 equiv.) was added resulting in vigorous gas extrusion. After the reaction solidifies, another 0.39 mL of dry benzene was added to the mixture to redissolve the solid. Anhydrous triethylamine (0.02 mmol, 1 mol%) was added, the vial was sealed with a pressure release screw cap, and the mixture was left to stir overnight at room temperature. All volatiles were evaporated under reduced pressure and the resulting materials were used without further purification.

**1b:** Procedure 1. Colorless oil (203 mg, 48% yield). 1H NMR (CDCl3, 500 MHz): δ = 1.20 ppm (s, 12H), 1.57 ppm (m, 4H), 1.84 ppm (m, 2H), 2.18 ppm (m, 1H), 3.51 ppm (m, 1H). 13C(C)NMR (CDCl3, 125 MHz): δ = 24.0, 24.7, 36.2, 53.4, 83.1 ppm. 11B NMR (CDCl3, 160 MHz): δ = 24.0 ppm. GC-MS(El) m/z: Calc. = 211.2; Exp. = 211.2.

**1d:** Procedure 1. Yellow solid. M.P. 53.5-55.1°C. (342 mg, 81% yield). 1H NMR (CDCl3, 500 MHz): δ = 1.22 ppm (s, 12H), 1.57 ppm (m, 4H), 1.84 ppm (m, 2H), 2.18 ppm (m, 1H), 3.51 ppm (m, 1H). 13C(C)NMR (CDCl3, 125 MHz): δ = 24.0, 24.7, 36.2, 53.4, 83.1 ppm. 11B NMR (CDCl3, 160 MHz): δ = 24.0 ppm. GC-MS(El) m/z: Calc. = 211.2; Exp. = 211.2.

**1e:** Procedure 2. White solid. M.P. 87.8-91.0°C. (404 mg, 81% yield). 1H NMR (CDCl3, 500 MHz): δ = 1.29 ppm (s, 12H), 3.79 ppm (m, 3H), 6.77 ppm (m, 2H), 7.00 ppm (m, 2H). 13C(C)NMR (CDCl3, 125 MHz): δ = 24.8, 55.8, 82.8, 114.5, 118.8, 136.8, 153.7 ppm. 11B NMR (CDCl3, 160 MHz): δ = 23.8 ppm. GC-MS(El) m/z: Calc. = 249.2; Exp. = 249.1.

**1k:** Procedure 2. Yellow solid. M.P. 71.7-73.5°C. (502 mg, 95% yield). 1H NMR (CDCl3, 500 MHz): δ = 1.32 ppm (s, 12H), 7.14 ppm (m, 2H), 1.80 ppm (m, 2H), 8.10 ppm (m, 2H). 13C(C)NMR (CDCl3, 125 MHz): δ = 24.8, 83.9, 117.3, 125.7, 141.0, 150.2 ppm. 11B NMR (CDCl3, 160 MHz): δ = 24.0 ppm. GC-MS(El) m/z could not be obtained.

**1q:** Procedure 1. White solid. M.P. 39.2-41.4°C. (370 mg, 73% yield). 1H NMR (CDCl3, 500 MHz): δ = 1.21 ppm (s, 12H), 1.46 ppm (m, 13H), 1.80 ppm (m, 2H), 2.34 ppm (s, 1H), 3.19 ppm (m, 1H). 13C(C)NMR (CDCl3, 125 MHz): δ = 23.9, 24.7, 25.6, 27.5, 35.5, 51.8, 82.9 ppm. 11B NMR (CDCl3, 160 MHz): δ = 22.3 ppm. GC-MS(El) m/z: Calc. = 253.2; Exp. = 253.2.


