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Frustrated Lewis Pair Behavior of Monomeric (boryl)iminomethanes Accessed from Isocyanide 1,1-Hydroboration

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The activation of carbon dioxide, organonitriles, and terminal acetylenes by (boryl)iminomethanes derived from isocyanide 1,1-hydroboration is described. Also detailed is the generality of hydroboration of m-terphenylisocyanides with hydroboranes of differing Lewis acidities.

With the advent of phosphine/borane Frustrated Lewis Pairs (FLPs) by Stephan, there has been significant interest in the development of transition-metal-free small-molecule activation processes. While a number of intra- and inter-molecular FLP platforms have been uncovered, most feature strongly Lewis basic and acidic groups to enhance reactivity toward small molecule substrates. Recently however, computational investigations have suggested that enhanced reactivity profiles might be displayed by intramolecular FLP platforms that contain frontier orbitals mutually oriented in the direction of an incoming substrate. Such “preorganized” FLPs should remain highly active, but decrease reliance on strongly Lewis acidic groups (e.g. perfluorinated aryllboranes and alanes), which can inhibit the imperative substrate release step in catalytic applications. Accordingly, new, readily-prepared FLPs that feature a ‘preorganized’ architecture promise to be of broad interest.

Recently, we reported the synthesis of the platinum-(boryl)iminomethane complex, Pt(k^2-N,B-Cy2-BIM)(CNArDipp)(Cys-BIM = Cy2BC(H)=NArDipp; ArDipp = 2,6-(2,6-(i-Pr)2C6H3)2C6H3) and demonstrated that the rigid, bidentate Cy2BIM ligand promoted a significant reverse-dative C-atom interaction between the Pt and boron centers. We also showed that the free (boryl)iminomethane Cys-BIM could be easily prepared by 1,1-hydroboration of the m-terphenyl isocyanide CNArDipp and that it readily activated both H2 and H2O in a manner consistent with FLP behavior. To our knowledge, this constitutes the first report of (boryl)iminomethane formation by 1,1-hydroboration of an isocyanide. While both the ease of synthesis and reactivity profile of Cys-BIM suggest that the (boryl)iminomethane (BIM) framework may be generally competent for small-molecule activation processes, it is critical to note that kinetically persistent (boryl)iminomethane monomers are rare. Indeed, when unencumbering substituents are present, (boryl)iminomethanes rapidly dimerize to heterocyclic 1,3-diaza-2,4-diboretidines (Scheme 1).

Furthermore, of the few structurally-characterized (boryl)iminomethane monomers that have been reported, all possess an anti relationship between the borane center and the imino nitrogen lone pair, thus precluding exploitation of their ambiphilic properties toward exogenous substrates. In an effort to further detail the reaction profile available to monomeric (boryl)iminomethanes, we report here the reactivity of Cy2BIM toward unsaturated organic substrates and provide clear evidence for its “preorganized” intramolecular FLP-type behavior. Accordingly, despite the presence of a dicyclohexylboryl group of moderate Lewis acidity, Cy2BIM readily activates carbon dioxide, organonitriles, and terminal acetylenes. In addition, we demonstrate that the formation of syn-N,B monomeric (boryl)iminomethanes is a general stereochemical outcome in the 1,1-hydroboration of m-terphenyl isocyanides.

Scheme 1. Regioisomers of monomeric (boryl)iminomethanes and dimerization of sterically unencumbered syn-N,B (boryl)iminomethanes to 1,3-diaza-2,4-diboretidines.
The ability of Cy₂BIM (1a) to act as a competent Frustrated Lewis Pair allows it to effect the facile C=O bond reduction of carbon dioxide. Placing a frozen benzene solution of Cy₂BIM (1a) under 1 atm of CO₂ causes an immediate color change from bright yellow to colorless upon thawing. Analysis of the solution by ¹H and ¹¹B NMR spectroscopy indicates complete conversion of the C=N double bond of Cy₂BIM (1a), while the appearance of a strong infrared absorbance at 1772 cm⁻¹ suggests the presence of an ester group. The solid-state structure as determined by X-ray diffraction reveals this product to be the borolactone (2a; Fig. 1) derived from nucleophilic attack of the imine nitrogen at the CO₂ carbon atom and coordination of one oxygen atom to boron. As opposed to the vast majority of FLP-activated CO₂ adducts which are zwitterionic, the endocyclic C₂-O₁ distance in 2a (1.391(9) Å) is consistent with that of a carbon-oxygen single bond, suggesting a larger degree of activation than is typically seen in such species. Formation of the five-membered ring is accompanied by a 1,2-cyclohexyl shift, as observed previously for Cy₂BIM (1a) in the heterolycic H-O bond cleavage of water. This boron-to-carbon cyclohexyl migration, reminiscent of a Wagner-Meerwein rearrangement, has been observed with other (borilyliminomethanes following their head-to-tail dimerization. Relevantly, this 1,2-cyclohexyl shift may be at least partially responsible for the irreversibility of CO₂ reduction by Cy₂BIM (1a), as heating solutions of 2a to 80 °C under an N₂ atmosphere (or, alternatively, heating solid samples to 150 °C under vacuum) produces no evidence of reversion to Cy₂BIM (1a) and free CO₂. This supposition is supported by Density Functional Theory calculations, which indicate that 2a is stabilized by 18.2 kcal/mol with respect to its zwitterionic constitutional isomer 2a* (Fig. 1 and ESI†). In the absence of cyclohexyl migration, the formation of 2a* from Cy₂BIM (1a) and CO₂ is computed to be enthalpically favored by 12.7 kcal/mol, indicating that the cyclohexyl migration event provides significant stabilization to the resulting adduct, and as such represents a substantial portion of the driving force toward irreversible CO₂ capture.

Despite the widespread progress that has been made in recent years toward the FLP-mediated activation of unsaturated organic molecules, examples of nitrile C=N bond reduction remain extremely limited. As most FLP systems utilize strongly Lewis acidic fluorinated aryl-borane or alane moieties, there is likely a thermodynamic preference toward formation of a Lewis adduct with the nitrile in lieu of addition to its triple bond. It is therefore remarkable that treatment of Cy₂BIM (1a) with acetonitrile results in formation of the eneamine 3 (Scheme 2), which undoubtedly is derived from 1,2-addition to the nitrile functionality accompanied by tautomerization of the resultant imine. Pursuant to this is the observation that benzonitrile, which lacks hydrogen atoms at the carbon alpha to the nitrile group, is similarly activated by Cy₂BIM (1a) to give the 1,2-addition product imine 4 (Scheme 2). Both transformations are essentially complete upon mixing as evidenced by an immediate decolorization of the reaction solutions upon nitrile addition. We suggest that the observed activity of Cy₂BIM (1a) toward nitriles is largely due the presence of a relatively weakly Lewis acidic – BC₃ fragment that decreases the stabilization associated with formation of a nitrile-borane adduct. As is the case with CO₂ activation, the cyclohexyl migration event in the formation of 3 and 4 likely provides further driving force toward 1,2-addition to the nitrile.

Cy₂BIM (1a) is also reactive toward t-butylaacetylene, effecting protonation of the acetylenic proton to give an alkynylborane (5, Scheme 2). No evidence of products derived from 1,2-addition to the alkene triple bond is seen. Both 1,2-addition and deprotonation reactions of terminal alkynes effected by FLPs have been reported, although t-butylaacetylene appears to typically undergo preferential deprotonation, likely due to the steric encumbrance that the t-butyl group imposes at the internal sp carbon atom.

In an effort to explore the generality of (borilyliminomethane formation via isocyanide hydrotoboration, we targeted the synthesis of a BIM derived from 9-borabicyclo[3.3.1]nonane (9-BBN), due to both its commercial availability and the presence of a tethered carbon backbone. The latter trait was particularly attractive, as we envisioned that it might discourage 1,2-alkyl migration in the corresponding BIM. Carrying out the reaction of CNAr⁹⁻⁹⁻ with 0.5 equivalents of 9-BBN dimer in the presence of THF allows for the hydrotoboration reaction to proceed smoothly to the THF-complexed (borilyliminomethane ⁹⁻⁹⁻BIM-THF (1b-THF, Scheme 3), which has been structurally characterized (Fig. 2). The boron atom is oriented syn to the nitrogen lone pair across the imine double bond, as is seen with Cy₂BIM (1a). The ¹⁵B NMR spectrum of 1b-THF features a singlet at 7.5 ppm, suggesting that the dative THF-borane interaction remains intact in solution. Indeed, successive n-pentane washes and exposure to high vacuum fail to liberate THF from 1b-THF. Attempts to synthesize 1b in the absence of THF resulted in the formation of several products. Although complete separation of these mixtures has proven unsuccessful, one of these species (6) was
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Fig. 2. Molecular structures of 9-BBN·BIM·THF (1b·THF) and its CO₂ adduct 2b.

identified as the product of formal 1,1 and 1,2-double hydroboration of CNAr<sub>Dipp2</sub> by an independent synthesis (Scheme 3). Presumably, this reaction proceeds via initial hydroboration of CNAr<sub>Dipp2</sub> to give the (boryl)iminomethane 9-BBN·BIM (1b) which, in the presence of additional 9-BBN, undergoes hydroboration of its imine functionality to furnish 6. Indeed, addition of 9-BBN dimer to 1b·THF in benzene solution results in conversion to 6 with release of THF (Scheme 3), lending credence to this proposed synthetic pathway.

Despite the THF-complexed nature of the borane unit in 9-BBN·BIM·THF (1b·THF), frustrated Lewis pair reactivity is still accessible. Addition of CO₂ to a benzene solution of 1b·THF results in imidization and irreversible conversion to a new product (2b, racemic mixture, Scheme 4) with liberation of one equivalent of THF as assayed by <sup>1</sup>H NMR. This product displays a <sup>1</sup>B NMR resonance at 55.7 ppm indicating the presence of a three-coordinate boron center. Crystallographic characterization of 2b (Fig. 2) revealed the formation of a borolactone where the bicycloalkyl has undergone a ring expansion to produce a substituted 9-borabicyclo[3.3.2]decane structure. Concomitant with this process is the eradication of the imine C=N double bond. The ring expansion process of the bicycloalkyl group, which has been observed in other systems containing the 9-BBN framework, amounts to a 1,2-alkyl shift that is analogous to the cyclohexyl migration seen in reactions of <sup>5</sup>·BIM (1a). Likewise, this process appears to be general to the 9-BBN·BIM framework, as ring expansion also occurs upon the heterolytic H-O bond cleavage of water by 9-BBN·BIM·THF (1b·THF) to give the borinic acid 7 (racemic mixture, Scheme 4). These results indicate that a more judicious choice of borane substituents will be required if alkyl migration is to be circumvented in the reaction chemistry of (boryl)iminomethanes.

The dialkylboryl substituents in the (boryl)iminomethanes 1a and 1b are among the most weakly Lewis acidic components of a frustrated Lewis pair reported to date. Indeed, the competency of 1a and 1b to effect FLP-type reactivity is undoubtedly tied to the geminal relationship of the acidic and basic sites, as well as the rigid geometry enforced by the imine double bond, the same structural traits that allow (boryl)iminomethanes to foster reverse-dative σ-interactions between a Lewis-basic metal center and the borane unit. In order to test the limits of this approach, we synthesized the pinacolboryl-substituted 9-BBN·BIM (1c; Fig. 3), which contains a boron center of even further attenuated Lewis acidity. Unlike the syntheses of 1a and 1b, the use of excess borane and prolonged heating are required to drive the formation of 1c to completion. Fractional crystallization from n-pentane/hexamethyldisiloxane mixtures allows for isolation of analytically pure samples of 9-BBN·BIM (1c) in modest yields. Examination of the crystal structure of 1c reveals a syn orientation of the imine lone pair and boron atom, as well as a nearly planar orientation of the C(H)N-BO₂ units (dihedral angle = 5.8(2)°). Interestingly, the presence of the more weakly Lewis acidic pinacolboryl group inhibits the reactivity of the (boryl)iminomethane framework with CO₂, as 9-BBN·BIM (1c) and CO₂ fail to react under the conditions utilized in the syntheses of 2a and 2b. Furthermore, a broadening of signals suggestive of reversible formation of a CO₂ adduct is not observed by <sup>1</sup>H NMR spectroscopy. These observations suggest that more strongly Lewis acidic groups are necessary for stoichiometric FLP-type reactivity to occur between (boryl)iminomethanes and CO₂, while also illustrating the limits of a preorganized FLP architecture.

In conclusion, we have synthesized a series of ambipolar and monomeric (boryl)iminomethanes (BIMs) via the 1,1-hydroboration of an m-terphenyl isocyanide. The same structural and electronic properties that allow (boryl)iminomethanes to behave as LZ-type chelating ligands toward electron-rich transition metal centers also promote the activation of unsaturated and protic substrates in an FLP manner. While this reactivity is accessible when a BIM bears a moderately Lewis acidic dialkylboryl group, switching to the more weakly Lewis acidic pinacolboryl substituent inhibits reactivity with carbon dioxide. Further explorations of such weakly Lewis acidic (boryl)iminomethanes are currently being pursued, with an eye...
toward tailoring them to effect catalytic transformations of small molecules. 

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† Electronic supplementary information (ESI) available: Synthetic details, results of computational studies and X-ray crystallographic data (CCDC 1028214 – 1028222). See DOI: 10.1039/b000000x

Notes and references


Fig. 3. Synthesis (top) and molecular structure (bottom) of tert-BIM (1c).