Hydrazine Capture and N–N Bond Cleavage at Iron Enabled by Flexible Appended Lewis Acids

John J. Kiernicki,* Matthias Zeller,† and Nathaniel K. Szymczak*‡

†Department of Chemistry, University of Michigan, Ann Arbor, Michigan 48109, United States
‡H. C. Brown Laboratory, Department of Chemistry, Purdue University, West Lafayette, Indiana 47907, United States

ABSTRACT: Incorporation of two 9-borabicyclo[3.3.1]nonyl substituents within the secondary coordination sphere of a pincer-based Fe(II) complex provides Lewis acidic sites capable of binding 1 or 2 equiv of N₂H₄. Reduction of the 1:1 Fe:N₂H₄ species affords a rare Fe(NH₂)₂ complex in which the amido ligands are stabilized through interactions with the appended boranes. The NH₃ units can be released as NH₃ upon protonation and exchanged with exogenous N₂H₄.

The pyridine(dipyrazole) (PDP) ligand platform presents a highly modular framework to introduce flexible boranes that capture substrates and occupy positions of varied distance from the metal (Figure 1).10 Fe(II) adducts within this ligand set were recently shown to facilitate the disproportionation of hydrazine to ammonia and N₂.11 We hypothesized that an appropriately modified ligand structure containing appended Lewis acidic sites could enable a reduction sequence involving nitrogenous substrates and also provide snapshots of a reduction sequence.

Control of Lewis acidity is a critical design aspect that is necessary to enable both capture and release of substrates/products. 9-Borabicyclo[3.3.1]nonyl (9-BBN) substituents were selected because they possess moderate Lewis acidity (acceptor number = 23.4) compared with B(O₂C₂(CH₃)₄) (10.0) or B(C₆F₅)₂ (71.8) (see the Supporting Information (SI)). The target ligand was prepared in 64% yield over two steps from 2,6-bis(5-tert-butyl-1H-pyrazol-3-yl)pyridine.12 Metalation of the allylic ligand precursor, 2,6-bis(1-allyl-5-tert-butyl-1H-pyrazol-3-yl)pyridine, with 9-BBN quantitatively afforded the anti-Markovnikov product, 9BNPDPBu. Metalation with FeX₃ (X = Br, Cl) in CH₂Cl₂ afforded light-orange 9BNPDPBuFeX₃ (1-X). The ¹H NMR spectra (CDCl₃) contained 12 paramagnetically shifted resonances, consistent with C₂ᵥ symmetry. Solution magnetic susceptibility studies (25 °C, CDCl₃) were consistent with high-spin Fe(II) (μeff = 4.80(2)μB (1-Cl) and 4.88(2)μB (1-Br)). Finally, an X-ray diffraction experiment of 1-Cl revealed a distorted square

Received: October 27, 2017
Published: December 11, 2017

DOI: 10.1021/jacs.7b11465

Figure 1. Design utility of flexible appended Lewis acids.
The ability of the tethered trialkylboranes to capture substrates within the metal’s secondary coordination sphere was probed using hydrazine (N₂H₄). Addition either 1 or 2 equiv of N₂H₄ to 1-X afforded distinct products, as assessed by ¹H NMR spectroscopy (CDCl₃). For the reaction with 1 equiv of N₂H₄, we observed complete conversion to a new compound, (BuPDPBu)FeX₂(N₂H₄) (2-X), which featured a resonance at −9.61 ppm. In contrast, addition of 2 equiv of N₂H₄ to 1-X afforded a pair of N₂H₄ resonances between −12 and −15 ppm, consistent with a 2:1 N₂H₄:Fe species, (BuPDPBu)FeX₂(N₂H₄)₂ (3-X). The C₅-symmetric spectra of either 2-Br or 3-Br remained unchanged upon heating to 50 °C with no evidence of interconversion.

We interrogated the structural metrics of 2-X and 3-X by X-ray diffraction (XRD) experiments. The solid-state structure of 2-Br revealed a five-coordinate iron (τ = 0.423) with a single molecule of N₂H₄ bridging between the two trialkylboranes (Figure 2). 2-Br is only the second crystallographically characterized example containing B–N interactions with both nitrogen lone pairs of N₂H₄. The geometry of 2-Br is pyramidal (Σ = 318.88(12)° and Σ = 319.96(13)°) and features B–N distances (1.697(2) and 1.698(2) Å) that are longer than those in the related BH₃N₃H₄BH₃ (1.609 Å), likely as a result of both steric constraints of the 9-BBN within the ligand scaffold and the higher Lewis acidity of BH₃. 2-Cl displayed similar metrical parameters. 3-Cl possesses one N₂H₄ coordinated to each 9-BBN motif with shorter B–N distances (1.637(7) and 1.646(6) Å) than 2-X. The geometries at iron in complexes 3-X are best described as square-pyramidal (τ = 0.210 (3-Br) and 0.164 (3-Cl)). Notably, in 2-X and 3-X, the N₂H₄ moieties do not interact with the metal center (shortest Fe–N contact = 4.09 Å in 3-Cl). The solid-state structures of the 1:1 adducts, 2-X, display weak intramolecular hydrogen bonding between the hydrazine and adjacent Fe–X with N–X distances of 3.438 and 3.273 Å for 2-Br and 2-Cl, respectively.

The requirements of the appended borane groups to facilitate N₂H₄ binding were assessed using complementary control ligands and metals. A PDP ligand with a similar profile was synthesized with the –(CH₃)₂BBN units replaced by n-butyl groups and metalated with FeBr₂ to afford (BuPDPBu)-FeBr₂. The (BuPDPBu) ligand presents a similar ligand field as BuPDPBu, as noted by the similar electrochemical profiles of (BuPDPBu)FeBr₂ and 1-Br (Fe/I/Fe ΔEₚ = 50 mV). However, in contrast to 1-Br, the addition of 1 equiv of N₂H₄ to (BuPDPBu)FeBr₂ resulted in rapid demetalation without production of ammonia (Figure 3A).¹⁴

We prepared the analogous zinc complex, (BuPDPBu)ZnCl₂, to evaluate the generality of ligand-templated capture of N₂H₄. The addition of 1 equiv of N₂H₄ afforded the 1:1 Zn:N₂H₄ adduct, (BuPDPBu)ZnCl₂(N₂H₄). Similar to 2-Cl, the ¹H NMR spectrum displays C₆ symmetry and a symmetric NH₂ resonance at 6.38 ppm. Capture of the hydrazine by the appended boranes was confirmed by ¹H NMR spectroscopy, which exhibits a resonance at −10.41 ppm, consistent with a tetrahedral boron. Single-crystal XRD confirmed that (BuPDPBu)ZnCl₂(N₂H₄) is isostructural to 2-Cl with a single N₂H₄ moiety bridging the pendent trialkylboranes.

Although N₂H₄ adducts of Fe(PDP) complexes have not been reported, a related variant bearing the proton-responsive ligand 2,6-bis(5-tert-butyl-1H-pyrrozol-3-yl)pyridine was recently shown to catalytically disproportionate N₂H₄ to NH₃ and N₂.¹¹ In this case, ligand deprotonation was proposed to initiate the N–N bond cleavage. With Lewis acidic rather than Bronsted acidic groups appended on the BuPDPBu framework, we sought to evaluate the extent to which such appended acids could facilitate reductive cleavage of hydrazine.

Electrochemical investigation of 1-Cl using cyclic voltammetry (0.2 M [Bu₄N][PF₆], THF) revealed a reversible reductive event at −2.07 V vsFc/Fc⁺—similar to the previously reported complex (BuPDPBu)FeCl₂ (Epc = −2.3 V vs Fc/Fc⁺).¹⁵ Upon N₂H₄ coordination, the reversible reductive wave for 2-Cl was modestly shifted to −1.98 V vs Fc/Fc⁺ (Δ = +90 mV), consistent with minimal perturbations of the overall geometry (Δτ = 0.008) and electronic environment at iron. To examine the reductive chemistry of 2-X using chemical reagents, 2 equiv of KC₈ was added to a thawing THF solution of 2-Br, which resulted in a rapid color change to dark green then light orange on warming to room temperature (Figure 3A). Analysis by ³¹P NMR (CDCl₃) revealed that the reaction had proceeded to completion, providing a single compound with the same spectroscopic properties as observed for the 3-X complex. This result is in contrast to the previously reported chemistry of (BuPDPBu)Fe(N₂H₄)₂ (4) (80% isolated yield). Complex 4 is markedly less soluble than its precursors—consistent with higher rigidity—and gradually decomposes at room temperature in solution (CDCl₃, DCM, or THF) over 24 h.

Analysis of single crystals of 4 by XRD confirmed N–N bond scission to afford a rare bis(amido)iron complex in which the

Figure 2. (left) Formation of 2-X and 3-X from 1-X. (right) Molecular structures of 1-Cl (middle), 2-Cl (bottom), and 3-Cl (top) (50% probability ellipsoids, selected H atoms omitted).
amido substituents are capped by the trialkylboranes (Figure 3C). Following N–N cleavage, the resulting amido substituents are separated by 3.980 Å with nearly square-pyramidal geometry about iron \( (\tau_e = 0.017) \). The molecular structures of 2-Br and 4 demonstrate considerable flexibility of the appended boranes with respect to the iron center. The distance between iron and a centroid defined by B1–B2 decreases from 4.79 Å in 2-Br to 1.85 Å in 4. The Fe–NH2 distance (2.075(2) Å) is markedly longer than in the Fe–NH3 complexes reported by Peters and co-workers, likely because of quenching of the amido lone pair by the boranes \( (B–N = 1.633(3) \text{ Å}) \), and is most similar to that observed in \( \text{LFe(NH3)2} \text{Br} \text{Et}_2 \) \( (L = 2,4-
olimits\text{bis(2,6-diisopropylphenylimino)pent-3-yl}) \). Isolation of \( \text{M(NH2)2} \) complexes often requires sterically encumbering ancillary ligands. Appended Lewis acidic groups provide an alternative strategy to stabilize these otherwise highly reactive units by attenuating the nucleophilicity of the amido nitrogen atoms.

Hydrazine can generate ammonia (or \( \text{NH}_3^- \)) either by reductive scission of the N–N bond or by disproportionation, the latter of which affords \( \text{N}_2 \) or \( \text{NH}_2/\text{H}_2 \) mixtures in addition to \( \text{NH}_3 \). Disproportionation pathways are chemically less efficient because the stoichiometry of \( \text{NH}_3^- \) (or \( \text{NH}_3 \)) to \( \text{N}_2/\text{H}_2 \) will necessarily be unequal to 2:1. Experiments were performed to evaluate whether the reduction of hydrazine by 2-X proceeds through a disproportionation pathway or, alternatively, through homolytic N–N bond scission mediated by iron. The stoichiometry of \( \text{N}_2/\text{H}_2 \) to \( \text{NH}_3 \) for a series of control compounds was assessed by quenching the products of reduction with HCl and quantifying the amount of \( \text{NH}_3/\text{Cl} \) produced by \( ^1\text{H} \) NMR spectroscopy. To confirm the \( \text{NH}_3^- \) quantification method, addition of 2 equiv of \( \text{KC}8 \) to a freshly thawed \( \text{THF} \) solution of 2-Br followed by HCl provided \( \text{NH}_3^- \) in high yield (1.74 equiv, 87% yield). In contrast, the analogous reaction with 2-Zn afforded only 0.28 equiv of \( \text{NH}_3^- \). Similarly, control reactions with \( \text{KC}8 \) and \( \text{NH}_3 \) produced only modest amounts of \( \text{NH}_3^- \) upon quenching (0.42 equiv; see the SI). Finally, addition of HCl to either 2-Cl or 1-Cl did not produce any \( \text{NH}_3^- \). Collectively, these experiments confirm the requirements of a reductant and a redox-active metal to promote the stoichiometric cleavage of \( \text{N}_2\text{H}_4 \) into two \( \text{NH}_3^- \) equivalents.

Although metal complexes have been used to promote hydrazine N–N bond scission, these reactions commonly proceed through disproportionation pathways. Within this context, and on the basis of the results of the stoichiometric studies noted above, we sought to investigate whether the reductive cleavage of \( \text{N}_2\text{H}_4 \) by 2-X is inter- or intramolecular. Although oxidative addition of the N–N bond of \( \text{N}_2\text{H}_4 \) at a single metal center has not been reported, a recent report demonstrated homolysis of \( \text{N}_2\text{H}_4 \) to afford a \( \text{Ni}^{(II)} \)–amido from a Ni(II)–metal radical. To probe the molecularity of hydrazine reduction, we performed a crossover experiment using \( ^{15}\text{N} \)-labeled \( \text{N}_2\text{H}_4 \). Reducing an equivolular solution of 2-Br and 2-Br\(^{15}\text{N} \) can result in a two limiting scenarios: (1) formation of \( 4^{(14}\text{N}^{14}\text{N}) \) and \( 4^{(14}\text{N}^{15}\text{N}) \) if the reaction is unimolecular or (2) a statistical mixture of \( 4^{(14}\text{N}^{14}\text{N}), 4^{(14}\text{N}^{15}\text{N}) \), and \( 4^{(15}\text{N}^{15}\text{N}) \) if an intermolecular pathway is operative. Analysis of the reduction products by mass spectrometry (MALDI-TOF, anthracene matrix) revealed data consistent with a unimolecular N–N bond scission pathway (Figures 3B and S46). These data highlight the utility of secondary coordination sphere interactions not only to capture a substrate and stabilize highly reactive fragments but also to enable new reaction pathways.

To complete a reduction cycle and release the captured \( \text{NH}_3^- \) equivalents, 4 was treated with a Bronsted acid. Addition of 2 equiv of [\( \text{HNEt}_3\text{][Cl} \)] afforded \( \text{BBNPDPBrBu} \). \( \text{FeCl}_2(\text{NH}_3)_2 \) (5-Cl), wherein the \( \text{NH}_3 \) was released from iron and retained by the appended 9-BBN moieties. Single-crystal diffraction studies of 5-Cl (Figure 4) confirmed the coordination of \( \text{NH}_3 \) to the 9-BBN units as well as coordination of the conjugate base \( (\text{Cl}^-) \) to iron. In 5-Cl, metrical parameters analogous to those of 3-Cl were observed. Finally, the \( \text{NH}_3 \) units were exchanged by the addition of \( \text{N}_2\text{H}_4 \). Addition of 1 equiv of \( \text{N}_2\text{H}_4 \) to a freshly thawed \( \text{CH}_2\text{Cl}_2 \) solution of 5-Cl regenerated 2-Cl with only trace 3-Cl observed (1.00:0.03 ratio by NMR spectroscopy). The exchange reaction clearly demonstrates that Lewis acids of appropriate strength can be used to capture, stabilize, and importantly release nitrogenous substrates.

In conclusion, we have described a new ligand framework wherein Lewis acidic 9-BBN fragments play key roles to...
mediate the binding and reduction of nitrogenous substrates. The acidic groups serve to capture $N_2H_4$, stabilize reactive Fe–NH$_2$ intermediates generated upon N–N scission, and finally release the reaction product, NH$_3$ upon addition of N$_2$H$_4$. This rare example of hydrazine N–N homolytic addition was confirmed to occur at a single metal center by using $^{15}$N-labeled N$_2$H$_4$. The tethered boranes are positionally flexible and adjust their distance by ca. 3 Å (borane centroid–Fe distance) to stabilize either the NH$_3$, NH$_2$, or N$_2$H$_4$ groups. The requirements of the Fe and Lewis acid groups were established by replacement of the appended boranes with inert substituents and substitution of iron with redox-inactive zinc: these variants inhibited a homolytic reduction pathway of N$_2H_4$.

Finally, appropriate electronic matching of acid/base pairs was exploited to enable a product/substrate exchange reaction (NH$_3$/N$_2$H$_4$). The ability of acid/base pairs to equilibrate with small-molecule substrates and reduction products represents an important and underused design criterion that is required for turnover and underscores the value of selecting modestly acidic appended groups. Work is ongoing to interrogate the mechanism(s) of substrate redox transformations and also to capture more oxidized nitrogenous units.

**ASSOCIATED CONTENT**

* Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.7b11465.

Crystallographic data (ZIP)

Synthesis and characterization data (PDF)

**AUTHOR INFORMATION**

*Corresponding Author*

*nszym@umich.edu*

Nathaniel K. Szymczak: 0000-0002-1296-1445

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was supported by the NIH (Grant 1R01GM111486-01A1). N.K.S. is a Camille Dreyfus Teacher–Scholar. The X-ray diffractometers were funded by the Major Research Instrumentation Program under Grant CHE 1625543. J.J.K. thanks Dr. James Anderson for statistical modeling.

**REFERENCES**


(3) (a) Arashiba, K.; Miyake, Y.; Nishibayashi, Y. Nat. Chem. 2011, 3, 120. (b) Yandulov, D. V.; Schrock, R. R. Science 2003, 301, 76.


(23) Treatment with PhOH and [HNEt$_3$][NO$_3$] produced the analogous complexes (see the SI).