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Lutidine/B(C_6F_5)$_3$: At the Boundary of Classical and Frustrated Lewis Pair Reactivity

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The reaction of Lewis acids and bases pervades all of chemistry. Indeed, the fundamental axiom that donor and acceptor molecules interact impacts our understanding of most synthetic inorganic and organic chemistry. The combination of amine and borane to give a donor−acceptor adduct is a clear demonstration of Lewis acid−base theory. While rare exceptions to this behavior have been cited in the literature over the years,[1,2] in general, the chemistry of such combinations was thought to be well understood. However, in 2006, we described reversible loss of H_2 from [(2,4,6-$C_6H_2Me_3$)$_2$P(H)(C_6F_4)B(H)-(C_6F_5)$_2$].[3] The ability of the phosphine-borane (2,4,6-$C_6H_2Me_3$)$_2$-P(C_6F_4)B(C_6F_5)$_2$ to activate H_2 was attributed to the steric congestion about the P and B that precluded donor−acceptor dative bond formation. Subsequently, simple, sterically encumbered phosphines and boranes were shown to also effect the rapid, facile, and heterolytic cleavage of H_2.[4,5] We have also shown that such sterically "frustrated" combinations of Lewis acids and bases can activate other small molecules including THF,[6,7] terminal olefins,[8] and catecholborane.[9] In a related system, where the donor and acceptor sites reside on the same atom, Bertrand and co-workers[10] showed that (alkyl)(amino)carbenes alone will activate both H_2 and NH_3. More recently, our group[11] and that of Tamm[12] have simultaneously reported that combinations of sterically congested N-heterocyclic carbenes and B(C_6F_5)$_3$ can also form "frustrated" systems capable of H−H and N−H bond activation. In a unique example, the species R_2PB(C_6F_5)$_2$ have also been shown to react with H_2.[13] In this case, despite the proximity of the donor and acceptor, the energetic mismatch of π-interaction between the lone pair on P and the acceptor orbital on free B(C_6F_5)$_3$ presumably accounts for the FLP-type reactivity.[13] Employing the activation of H_2 by such "*frustrated Lewis pairs*" (FLPs), we[14,15] and others[16−20] have developed metal-free hydrogenation catalysts for the reduction of of imines, aziridines, borane-bound nitriles, enamines, and silylenol-ethers under mild conditions.

While our discovery of FLP reactivity provides exciting, new avenues of development for unique main group reactivity and "green" catalysts, the relation of such reactivity to that of classical Lewis acid−base adducts remains a fundamental question. Some hint of this relationship is offered by the observation of Erker et al. that the ring strain in (2,4,6-$C_6H_2Me_3$)$_2$PCH_2CH_2B(C_6F_5)$_2$ provides access to the FLP.[16] Otherwise, the combination of a Lewis acid and base exhibits one of two exclusive extremes of behavior. Most commonly a classical donor−acceptor adduct is formed. However, should the pair of reagents be sufficiently sterically frustrated, no reaction will take place, providing the potential for FLP reactivity upon addition of another reagent. Thus it seems that FLP reactivity is a corollary to classical Lewis behavior. In this report, we probe the notion that classical and FLP behavior are *not* exclusive regimes of reactivity by probing systems where equilibria govern the formation of the classical Lewis acid−base adduct.

In general, reactions of pyridines with Lewis acids such as B(C_6F_5)$_3$ are known to result in the formation of classical Lewis acid−base adducts of the form (py)B(C_6F_5)$_3$.[21,22] However, in setting out to uncover systems that might exhibit *both* classical and FLP reactivity, we considered Lewis pairs involving pyridine. In 1942 Brown et al.[1] reported the formation of pyridines adducts with BF_3 and BMe_3.[23] Interestingly, the authors noted that 2,6-lutidine was an exceptional case. While it was basic enough to form an adduct with BF_3, it was too sterically encumbered to bind to BMe_3. Similarly, we observed no reaction of BEt_3 and 2,6-lutidine inferring the presence of an FLP. Nonetheless, this mixture yielded no reaction upon addition of H_2 (4 atm). This observation is consistent with the notion that a mimimum combined acidity/basicity is required to afford activation of H_2. Thus, we were prompted to employ a more Lewis acidic borane. At 25 °C, a 1:1 mixture of 2,6-lutidine and B(C_6F_5)$_3$ gave rise to broad signals in the ^{1}H and ^{19}F NMR spectra, suggesting the establishment of an equilibrium between free lutidine/B(C_6F_5)$_3$ and the Lewis acid−base adduct (2,6-$Me_2C_5H_3N$)B(C_6F_5)$_3$ (**1**). Monitoring the reaction as a function of temperature showed a shift in the relative abundance of the species in solution. Upon cooling to −10 °C, the ^{19}F NMR resonances sharpen reflecting the presence of primarily **1**. The ^{19}F NMR spectrum of **1** showed evidence of molecular dissymmetry: three peaks attributable to the *ortho*- and *meta*-fluorines and two peaks for the *para*-F atoms. This observation is consistent with inhibited rotation of the lutidine fragment about the B−N bond, generating inequivalent C_6F_5 ring environments in a 2:1 ratio. Such inhibited rotation is presumably a result of the steric conflicts arising between the *ortho*-methyl substitutents and the arene rings on B. At this temperature, a single resonance is observed in the ^{11}B NMR spectrum at −3.9 ppm. Analysis of the NMR data permitted the determination of the equilibrium constants as a function of temperature and subsequently the thermodynamic parameters associated with the equilibrium process. ΔH and ΔS were found to be −42(1) kJ/mol and −131(5) J/mol•K, respectively. X-ray crystallographic analysis of **1** confirmed the formulation and affirmed the presence of two distinct C_6F_5 ring environments (Figure 1) arising from the orientation of the lutidine with respect to the C_6F_5 groups. The data also revealed a B−N bond length of 1.661(2) Å, significantly longer than that seen in (py)B(C_6F_5)$_3$ (1.628(2) Å).[21,22] This shows that steric demands weaken the B−N bond in **1** despite the increased basicity of 2,6-lutidine over pyridine.

The existence of an equilibrium involving the adduct **1** and free Lewis acid and base[24] suggests that this system may also be exploited for frustrated Lewis pair reactivity. Addition of H_2 (1 atm, 2 h) to the mixture resulted in the isolation of a solid (**2**) in 87% yield. The ^{1}H NMR spectrum exhibited resonances attributable to NH and BH units at 12.01 and 3.55 ppm, respectively. The latter signal shows the expected coupling to B. These data, together with the ^{19}F and ^{11}B NMR resonances, were consistent with the formulation of **2** as [2,6-$Me_2C_5H_3$NH] [HB(C_6F_5)$_3$] which was also confirmed by X-ray diffraction (Figure 1).[25] The metric parameters of this salt were as expected although it is noteworthy that the ions

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pack in a pairwise fashion in the solid state such that the NH and BH units are oriented toward each other with a N−H···H−B interaction at 1.853 Å. Intermolecular interactions of ammonium-hydridoborates with similar geometries have been described by Richardson et al.[26] as "unconventional hydrogen bonds". This distance stands in contrast to the corresponding distance seen for $[C_5H_6Me_4NH_2][HB(C_6F_5)_3]$[20] (2.97 Å). Interestingly, **2** shows loss of H_2 upon heating,[27] whereas $[C_5H_6Me_4NH_2][HB(C_6F_5)_3]$ does not.

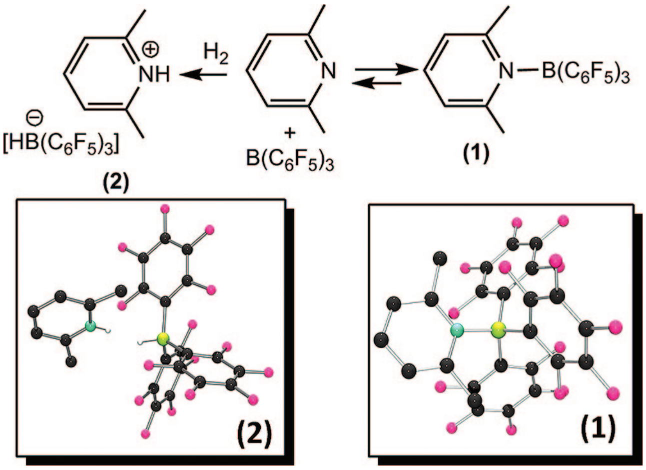

Figure 1. Classical and FLP reactions of $2,6\text{-}Me_2C_5H_3N$ with $B(C_6F_5)_3$.

In a further example of FLP reactivity,[6,7] addition of THF to the reaction mixture of $2,6\text{-}Me_2C_5H_3N/B(C_6F_5)_3$ was shown to result in the ring opening of THF to give **3**. The ^{11}B NMR spectrum of **3** showed a resonance at −6.3 ppm. Together with the ^{19}F and ^{1}H NMR signals were consistent with the formulation of **3** as the zwitterionic species $2,6\text{-}Me_2C_5H_3N(CH_2)_4OB(C_6F_5)_3$. This was also confirmed via X-ray crystallography (Figure 2).[25]

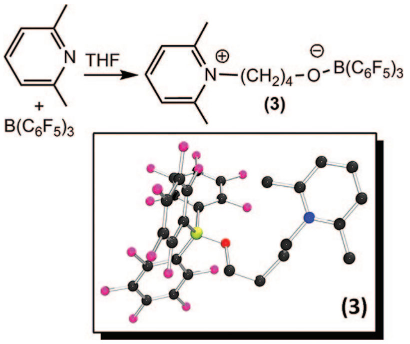

Figure 2. Ring opening of THF by $2,6\text{-}Me_2C_5H_3N/B(C_6F_5)_3$.

The formation of **1**−**3** demonstrates an unprecedented situation in which the combination of a Lewis acid and Lewis base exhibit *both* classical Lewis acid−base and FLP reactivity. This affirms that these reaction pathways are *not* mutually exclusive. The equilibrium generating access to both modes of reactivity in the present case results from the competition between steric congestion and inherent basicity. As a result of dissociation of the B−N dative bond, 2,6-lutidine and $B(C_6F_5)_3$ are available to activate H_2 or effect ring opening of THF, two reactions that have been previously shown to typify the reactivity of FLPs.[28] Thus, we have shown classical Lewis acid−base adducts, previously thought to be unreactive, can provide access to FLP reactivity. Efforts to utilize this finding for the activation small molecules continues to be an area of focus in our laboratories.

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Supporting Information Available: Experimental procedures and X-ray crystallographic details of **1**, **2**, and **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

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