

Nonmetal Catalyzed Hydrogenation of Carbonyl Compounds

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S Supporting Information

ABSTRACT: Solutions of the Lewis acid $B(C_6F_5)_3$ in 1,4-dioxane are found to effectively catalyze the hydrogenation of a variety of ketones and aldehydes. These reactions, the first to allow entirely metal-free catalytic hydrogenation of carbonyl groups under relatively mild reaction conditions, are found to proceed via a “frustrated Lewis pair” mechanism in which the solvent, a weak Brønsted base yet moderately strong donor, plays a pivotal role.

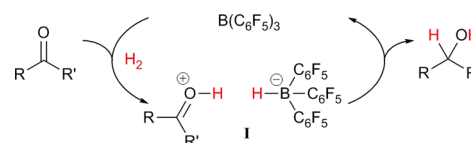
Catalytic hydrogenations represent one of the most important families of all chemical transformations and are routinely employed at all scales of chemical production.¹ The catalysts that facilitate these reactions are predominantly based on rare, expensive, and often toxic transition metals (TMs); consequently there exists a strong incentive for chemists to develop new catalysts based on more abundant and benign elements, which mimic the reactivity of existing systems. In recent years this has led researchers to investigate potential catalysts based on inexpensive and readily available TMs such as iron² and systems that consist solely of main group elements.

In the latter category the most notable successes have been achieved using “frustrated Lewis pairs” (FLPs).^{3,4} Rational design of these systems, in which H_2 is activated in a cooperative manner by Lewis acidic and Lewis basic moieties, has led to the development of metal-free compounds capable of effecting catalytic hydrogenation of many unsaturated organic substrates including imines, enamines, aziridines, enol ethers, alkenes, and aromatics.^{5,6} Nevertheless, one important class of functional group remains conspicuous by its absence from this list: the C=O bond in organic carbonyl compounds. In fact, Wei and Du have very recently stated that “the direct hydrogenation of ketones to secondary alcohols under FLP catalysis still remains as an unsolved problem”.⁷

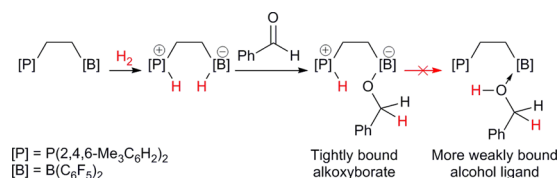
In 2009, Nyhlén and Privalov reported the results of a theoretical study into possible $B(C_6F_5)_3$ (**1a**) catalyzed hydrogenation of simple aldehydes and ketones,⁸ suggesting that an FLP mechanism analogous to that for the related hydrogenation of imines (and hydrosilylation of carbonyl compounds)^{9–13} ought to be kinetically accessible (Scheme 1). Nevertheless, attempts to realize this prediction experimentally have thus far been unsuccessful. Repo et al. have reported that the **1a**-mediated hydrogenations of benzaldehyde and benzophenone proceed only stoichiometrically in the noncoordinating solvents d_8 -toluene and CD_2Cl_2 ,¹⁴ due to rapid decomposition of the borane. More recently, Stephan et al. have reported similar results using aliphatic ketones.¹⁵

Other attempts at FLP-catalyzed carbonyl hydrogenation have also been unsuccessful. A number of stoichiometric reductions

Scheme 1. Proposed Mechanism of $B(C_6F_5)_3$ -Catalyzed Hydrogenation from Theoretical Studies by Nyhlén and Privalov,⁸ Involving Direct H_2 Activation by the Substrate



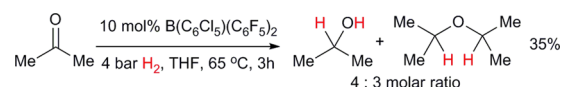
Scheme 2. Example of Stoichiometric FLP-Mediated Carbonyl Hydrogenation¹⁶



have been observed upon reaction with prehydrogenated FLP systems, with a representative example shown in Scheme 2.^{4,16–18} No turnover is observed, which has been attributed to the strength of the B–O bonding interaction.¹⁹ This could also be explained by the weak conjugate acids of the phosphine and amine Brønsted bases employed, which prevents protonation of the reduced alkoxyborate product; this ensures the organic group exists as a potent Lewis basic alkoxide moiety (strongly bound to the borane) rather than the less basic alcohol,^{20,21} and hence leads to strong product inhibition. Indeed, hydroxylic substrates have been shown to be activated via coordination to **1a** generating strong acids of comparable pK_a to HCl (8.4 in MeCN).²² Clearly protonation of an alkoxyborate in an FLP-mediated catalytic hydrogenation cycle would require a very weak Lewis base as one component.

We have recently reported that THF and 1,4-dioxane solutions of the boranes $B(C_6Cl_5)_x(C_6F_5)_{3-x}$ ($x = 0–3$) are capable of reversibly cleaving H_2 to generate the related borohydride anions, in addition to strongly Brønsted acidic solvated protons ($pK_a < -2.5$ in H_2O ;²³ Scheme 3).²⁴ Although the equilibrium greatly disfavors the hydrogen activation products, these stable

Scheme 3. Metal-Free Hydrogenation of an Enolizable Ketone Catalyzed by $B(C_6Cl_5)(C_6F_5)_2$



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systems were found to be effective at catalyzing the hydrogenation of weakly basic substrates, including electron-poor imines, which are electronically very similar to organic carbonyls. Given the electronic similarities, we reasoned that these might also be good systems to investigate for C=O hydrogenation. In particular, these systems have already proven capable of generating powerful Brønsted acids without suffering from borane decomposition. Furthermore, we anticipated that a donor solvent might competitively bind the Lewis acid, thereby aiding product dissociation and facilitating catalytic turnover.

Our previous work identified $B(C_6Cl_5)(C_6F_5)_2$ (**1b**) in THF as the most catalytically competent system, and consequently this was selected for initial investigation. Gratifyingly, admission of H_2 to a THF solution of acetone with **1b** (10 mol %) led to catalytic consumption of the starting material under mild conditions (4 bar of H_2 , 65 °C; Scheme 3). To the best of our knowledge this is the first example of TM-free catalytic hydrogenation of an enolizable ketone or of any organic carbonyl under such mild conditions.^{25,26} Yet, although technically catalytic, the reaction proceeds with limited turnover, and the conversion is not significantly improved with increased reaction times.

This limited turnover may partially be attributed to inhibition by the product, whereby the alcohol reversibly binds to the highly electrophilic Lewis acid; this is supported by the observation that addition of stoichiometric *i*PrOH (relative to **1b**) at the start of the reaction leads to a significant decrease in conversion (*ca.* 20%). Analysis of the initial ^{11}B NMR spectrum for this reaction shows a slight upfield shift for the borane resonance from 8.2 ppm in the absence of *i*PrOH to 7.1 ppm, which also indicates some interaction. The 1H NMR spectrum of the reaction mixture showed the formation of an additional set of isopropyl methine resonances, consistent with formation of iPr_2O ,²⁷ which presumably results from acid-catalyzed condensation of *i*PrOH and must result in formation of H_2O . To examine the effect that H_2O may have on the catalysis, 1 equiv of H_2O relative to **1b** was added at the start of the reaction, which led to a complete loss of hydrogenation reactivity, demonstrating that its formation has a potent inhibitory effect. Although coordination of H_2O to **1b** is known to be reversible in toluene,²⁸ the related adduct **1a**· OH_2 can form a variety of H-bonding interactions in the presence of hydroxylic species such as H_2O and simple alcohols, which stabilize it significantly;²² it is likely that in the reaction mixture the **1b**· OH_2 adduct is stabilized to a similar extent.

Initially we speculated that the specific problem of product inhibition might be resolved by slightly increasing the steric bulk of the borane catalyst; however, when **1b** was replaced with the larger borane $B(C_6Cl_5)_2(C_6F_5)$ (**1c**) minimal reduction was observed (<5% after 60 h at 80 °C). This reduced reactivity relative to **1b** is consistent with previous observations regarding the reduction of imines (though in this case the difference is far more pronounced)²⁴ and is attributed to the increased steric bulk of the $[1c \cdot H]^-$ reducing agent, which prevents close approach of the substrate. Based on this analysis we reasoned the reverse strategy might be more effective and that reducing the bulk of the borane catalyst might lead to generation of a less hindered, and hence kinetically more reactive borohydride intermediate. Our further investigations therefore focused on commercially available **1a**, which has been studied extensively for its use in metal-free hydrogenation chemistry.¹⁹

Our previous investigations had demonstrated that **1a** in THF is capable of effecting catalytic hydrogenation in the same manner as **1b** and **1c**. However, the reduced steric bulk, and

hence increased Lewis acidity of this borane, leads to stronger coordination to the solvent and hence a need for relatively higher reaction times and temperatures. In order to circumvent this problem, THF was replaced with 1,4-dioxane,²⁹ which is a weaker donor (and which has also previously been shown to be a viable component for borane/solvent H_2 activation).²⁴

Gratifyingly, the **1a**/1,4-dioxane system demonstrated significantly improved turnover (albeit at the cost of increased reaction times; Table 1, entry 1). Also, *i*PrOH was produced as the only product, with no evidence for formation of iPr_2O .³⁰

It must be noted that the significantly improved reactivity of **1a** relative to **1b** in this 1,4-dioxane-based system stands in contrast to the results of our previous investigations using THF, where **1a**

Table 1. $B(C_6F_5)_3$ -Catalyzed Hydrogenation of Aldehydes and Ketones

		R, R' = H, alkyl, aryl		cat. $B(C_6F_5)_3$, H_2 1,4-dioxane, T, t		Product	
	$B(C_6F_5)_3$ / mol%	Substrate	T / °C	t / h	Product ^d	Conv. / % ^b	
1	5 ^c		100	92		83	
2	5 ^c		100	6		99 ^d	
3	5		100	90		60	
4	10		100	67		80	
5	10		100	24		0	
6	20 ^c		100	25		>99	
7	5		100	17		0	
8	10		100	39		92 ^d	
9	10		80	120		84	
10	20		80	110		82	
11	20		80	24		>99 ^d	
12	10		80	25		0	
13	10		80	24		75 74 ^{f,g}	
14	10		80	19		97 87 ^f	
15	10		80	90		82	
16	10		80	90		78	
17	10		100	30		14	

^aReactions typically performed on 0.1 mmol scale in 0.4 mL of solvent under 5 bar of H_2 . ^bAll conversions measured by 1H NMR integration (capillary insert containing either 1,3,5-trimethoxybenzene or PPh_3 in C_6D_6 typically used as internal standard; see SI). ^c0.2 mmol of substrate. ^d12–13 bar of H_2 . ^eWith respect to *i*PrCOMe. ^f1 mmol scale. ^gIsolated yield.

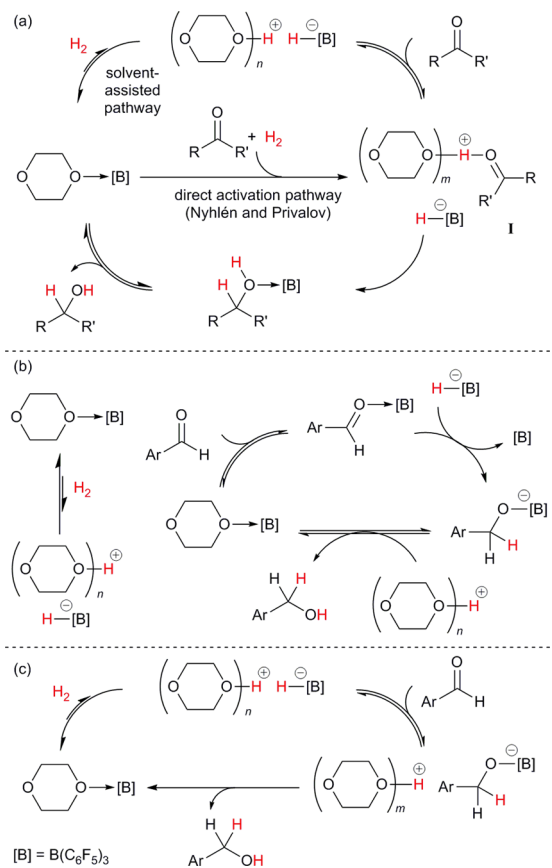
was found to give inferior results.²⁴ This apparent discrepancy can be explained by considering the different basicities of the two solvents: in THF very little uncoordinated **1a** is ever present, even at elevated temperatures, and so the extent of H₂ activation is low and hydrogenation occurs only very slowly. In the weaker donor 1,4-dioxane, more free **1a** can be formed, and hence hydrogenation occurs more readily (by contrast, **1b**, which is sterically more demanding, dissociates appreciably in either solvent as shown by VT ¹¹B NMR; see Supporting Information (SI)). The weaker binding of 1,4-dioxane relative to THF is demonstrated by variable temperature NMR studies, which show a large downfield shift for the ¹¹B resonance of a stoichiometric **1a**/1,4-dioxane mixture in C₇D₈ at higher temperatures, and only a much smaller shift for **1a**/THF (see SI). Even so, the *absolute* degree of dissociation for **1a** in *neat* 1,4-dioxane must still be low; for this system no significant perturbation in the ¹¹B and ¹⁹F NMR resonances is observed at elevated temperatures (up to 100 °C).²⁴ Indeed, this low degree of dissociation likely explains the reduced initial rate of this hydrogenation reaction relative to the **1b**/THF system.

Other simple aliphatic ketones of moderate steric bulk were hydrogenated effectively under identical conditions (Table 1, entries 3 and 4). More hindered substrates were not reduced, in line with the steric arguments outlined earlier (Table 1, entries 5 and 7). These observations are qualitatively consistent with theoretical calculations (*vide supra*), which predicted a much larger Gibbs free energy barrier for hydride transfer from [**1a**·H]⁻ to more sterically hindered ketones,⁸ and can be exploited to allow selective reduction of a smaller ketone in the presence of a more hindered substrate (Table 1, entry 6). The system can also be applied to aromatic ketones, subject to similar steric limitations (Table 1, entries 9, 10, and 12), and aromatic aldehydes (Table 1, entries 13–16), with a range of electron-poor carbonyl compounds reduced in good to excellent yields. Reduction of *ortho*-substituted aldehydes was particularly effective; presumably the increased steric bulk facilitates dissociation of the primary alcohol. Reactions were less clean for more electron-rich aromatic substrates. For example, reduction of acetophenone (Table 1, entry 17) is followed by dehydration, with the resultant H₂O limiting the observed turnover, as previously seen for **1b**/THF.

Although many of the above hydrogenations require significant reaction times to achieve good conversion under 5 bar of H₂, it should be noted that these can be shortened substantially by increasing the partial pressure of H₂. Even a relatively modest increase can lead to dramatically improved reaction rates (Table 1, entries 2 and 11). Higher pressures also allow reduction of some substrates that are not transformed under milder conditions (Table 1, entry 8).

By analogy with our previous work, we propose that ketone hydrogenation occurs via a mechanism in which the carbonyl substrate is activated by coordination to a solvated proton (generated by activation of H₂ by **1a**/1,4-dioxane)³¹ prior to hydride transfer (Scheme 4a, solvent-assisted pathway); subsequent displacement by the solvent facilitates dissociation of the alcohol product. This proposal is supported by some preliminary mechanistic studies. [*n*Bu₄N][**1a**·H] is not observed to reduce acetone even after several hours at 100 °C in 1,4-dioxane, indicating a need for *O*-activation of the carbonyl. Addition of **1a** to this reaction mixture *does* lead to some reduction, suggesting that sufficient activation can occur via coordination of **1a**. However, in this reaction <0.5 equiv of acetone is consumed after 1 h; given that the *catalytic* reaction

Scheme 4. Proposed Mechanism of B(C₆F₅)₃-Catalyzed Hydrogenation of Ketones (a), and Possible Alternative Mechanisms for Hydrogenation of Aldehydes (b, c)



mixture contains only very small amounts of [**1a**·H]⁻,³² reduction by this mechanism does not seem rapid enough to account for the rate of the catalytic hydrogenation. Furthermore, significant decomposition is observed during the reaction of acetone with **1a**/[*n*Bu₄N][**1a**·H], most likely via C₆F₅ group transfer to **1a**, as indicated by the observation of species such as B(C₆F₅)₄⁻ by mass spectrometry (ES⁻) and ¹¹B NMR; it should be noted that these species are not observed in the catalytic reaction. Similar results are obtained using the aromatic substrate 4'-nitroacetophenone in place of acetone; no reaction is observed with [*n*Bu₄N][**1a**·H] after heating to 80 °C in 1,4-dioxane for 16 h, and only slow reduction is observed when **1a** is also added (although no borane decomposition is observed in this case; see SI). Collectively, these results suggest that ketone activation occurs not by Lewis acid catalysis and that instead the reaction proceeds via Brønsted acid activation of the substrate.³³ Note, however, that these observations could also be consistent with the mechanism proposed by Nyhlén and Privalov, which differs only in the means of generation of the activated carbonyl intermediate **I** (see Schemes 1 and 4a, direct activation pathway).

Slightly different results are observed when ketones are replaced with aldehydes in the above experiments. Addition of [*n*Bu₄N][**1a**·H] to a mixture of **1a** and 4-nitrobenzaldehyde or 2,6-dichlorobenzaldehyde in 1,4-dioxane at rt leads to immediate reduction of the carbonyl, as evidenced by the disappearance of the resonances attributed to the aldehyde in the ¹H NMR spectrum, concomitant with the appearance of sharp resonances at *ca.* -2.5 ppm in the ¹¹B NMR spectra, consistent with formation of the **1a**-alkoxide adducts;³⁴ this suggests an

alternative, Lewis acid catalyzed reaction pathway may also be feasible for these substrates (Scheme 4b). In fact, similar reactivity is observed for these aldehydes even without addition of **1a**,³⁵ suggesting that their reductions may even proceed without any prior activation of the carbonyl (Scheme 4c). Nevertheless, Brønsted or Lewis acid catalysis cannot be ruled out, and further studies are needed to confirm the validity and generality of our proposed mechanisms.

In conclusion, we have developed a protocol for TM-free, FLP-mediated catalytic hydrogenation of aliphatic and aromatic ketones and aldehydes to their respective alcohols. Preliminary mechanistic studies suggest that ketone reduction likely occurs via Brønsted acid activation of the substrate followed by hydride transfer, but that alternative mechanisms may be feasible for more electrophilic aldehyde substrates. We anticipate that, with further rational variation of both the solvent and borane catalyst, hydrogenation of more challenging carbonyl substrates should be possible using systems of this type. Investigations in this area are ongoing, and will be reported in due course.

■ ASSOCIATED CONTENT

📄 Supporting Information

Supplementary information includes full experimental details and spectroscopic characterization of products. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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- (27) Confirmed by independent addition of *i*PrOH and *i*Pr₂O to **1b** in d₈-THF in the appropriate molar ratios.
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- (29) At no point during the course of our studies was any evidence for ring-opening or polymerization of the solvent observed.
- (30) The different outcome in 1,4-dioxane may simply be attributable to its reduced polarity ($\epsilon_{1,4\text{-dioxane}} = 2.22$, $\epsilon_{\text{THF}} = 7.52$) and Brønsted basicity relative to THF. This should reduce the concentration of ionic species, including solvated 'H⁺', present in the reaction mixture. Since the condensation mechanisms are likely to proceed via carbocationic intermediates in the acidic media, condensation/dehydration pathways are more likely to be suppressed in 1,4-dioxane.
- (31) For our previous **1b**/THF system the hydrogen activation product [(THF)_nH][H-**1b**] could be observed directly by low temperature ¹¹B NMR.²⁴ Such direct observation is not possible in this case due to the high melting point of 1,4-dioxane. Yet, admission of HD (1 bar) to a solution of **1a** in 1,4-dioxane leads to formation of H₂ (clearly visible by ¹H NMR) over several hours at rt, clearly demonstrating that reversible activation must occur (see SI).
- (32) No resonances attributable to [1a-H]⁻ are observed by ¹H, ¹⁹F, or ¹¹B NMR for solutions of **1a** in 1,4-dioxane under H₂ (5 bar) at 100 °C.
- (33) This activation is perhaps best characterized as a H-bonding interaction in which the substrate enters the inner coordination sphere of the solvated proton. The pK_a of protonated acetone, for example, is much lower than that of protonated 1,4-dioxane (-7.2 vs -2.92²³ in H₂O), but its acidity is known to drop appreciably upon interaction with H-bond acceptors such as H₂O. See: Campbell, H. J.; Edward, J. T. *Can. J. Chem.* **1960**, *38*, 2109. Palm, V. A.; Haldna, U. L.; Talvik, A. J.; Patai, S. *Basicity of carbonyl compounds; The Carbonyl Group: Vol. 1*; John Wiley & Sons, Ltd.: Chichester, U.K., 1966 and references therein.
- (34) The product resonances are not observed in the ¹H NMR spectrum, due to precipitation of [nBu₄N][1a-OCH₂Ar] from the reaction mixture; yet, removal of the solvent *in vacuo* and subsequent addition of CD₂Cl₂ allow the products to be clearly observed, most notably by their diagnostic CH₂ singlet resonances at ~4.5 ppm.
- (35) For 2,6-dichlorobenzaldehyde the reduction is significantly slower in the absence of additional **1a**, and for neither substrate does the reaction proceed to completion. Both observations may simply be attributable to coprecipitation of [nBu₄N][1a-OCH₂Ar] and [nBu₄N][1a-H] from the 1,4-dioxane solvent, which results in separation of the substrate and reductant into different phases. Repeating the experiments using CD₂Cl₂ as the solvent (or removing 1,4-dioxane *in vacuo* and replacing it with CD₂Cl₂) prevents phase separation, and complete reduction is observed to occur immediately for both substrates.