ORGANOMETALLICS
Communication
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Activation of Alkyl C−F Bonds by $B(C_6F_5)_3$: Stoichiometric and Catalytic Transformations

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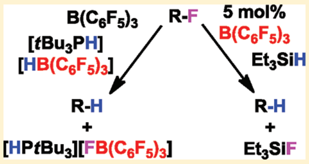
Supporting Information

ABSTRACT: The Lewis acid $B(C_6F_5)_3$ is shown to activate a series of alkyl fluorides. In stoichiometric reactions, treatment of sterically demanding phosphines with $B(C_6F_5)_3$/alkyl fluorides gives phosphonium fluoroborate salts while treatment of $B(C_6F_5)_3$/alkyl fluorides with the salts $[tBu_3PX][XB(C_6F_5)_3]$ (X = H, PhS) gives the alkane and the salt byproduct $[tBu_3PX][FB(C_6F_5)_3]$. These fluoroalkanes are also catalytically converted to the corresponding alkanes by reaction of the fluoroalkane and Et_3SiH using $B(C_6F_5)_3$ as the catalyst.



C−F bonds are renowned for their stability. Indeed, they are among the most inert bonds in all of organic chemistry, with a bond energy of 490 kJ/mol. While transition-metal systems have been employed to effect C−F activation,[1−17] this can also be achieved by interaction with strong Lewis acids. It was in 1964 when Olah et al. first reported Friedel−Crafts-type alkylation of alkyl fluorides using BF_3.[18,19] Since then, others have exploited BF_3[20] and related Al reagents[21] to effect alkylation of a variety of substrates. Alkyl fluorides react stoichiometrically with alane derivatives of the form $R_2Al(X)$, affording the formation of C−X bonds (X = Cl, C, H, O, S, Se, Te, N).[22] Similarly, defluorinative allylic alkylation was achieved by reaction of difluorohomoallyl alcohols with AlR_3 followed by hydrolysis.[23] More recently, carbo[24] and silyl cations[25] have been employed to abstract fluorides from organofluorine compounds. The Müller and Ozerov groups have exploited the Lewis acidity of carbonium[24] and disilylium[26] as well as silylium and alumenium cations[27,28] to activate C−F bonds and effect catalytic hydrodefluorination or alkylative defluorination. The driving force for these latter systems is the fluorophilicity of Al and Si cations. In our own work, we have utilized the Lewis acidity of B-based Lewis acids to generate frustrated Lewis pairs (FLPs).[29−32] We and others have demonstrated the unique reactivity of FLPs, activating a variety of small molecules, including olefins, alkynes, CO_2, and N_2O among others. Perhaps most remarkably, FLPs provide a facile avenue to the heterolytic cleavage of the strong H−H bond (bond energy 426 kJ/mol) of H_2. While the mechanism of H_2 activation by phosphine/borane FLPs is not fully resolved, it is clear that interaction with the borane Lewis acid plays a key role. Gabbai and co-workers[33,34] have employed the fluorophilicity of a variety of B derivatives to design highly sensitive fluoride sensors. Herein, we exploit the fluorophilicity of the B-based Lewis acid $B(C_6F_5)_3$ to activate C−F bonds for stoichiometric reactions with FLPs. This strategy for the activation of alkyl fluorides by $B(C_6F_5)_3$ is further applied to stoichiometric reactions with $[tBu_3PH][HB(C_6F_5)_3]$ or by catalytic reactions with silanes to give the corresponding alkanes.

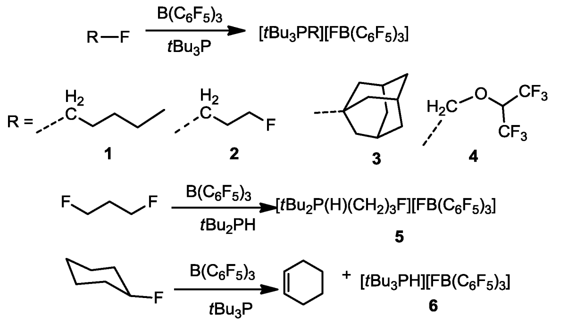
To examine the reactivity of P/B FLPs with fluoroalkanes, $B(C_6F_5)_3$, tBu_3P, and 1-fluoropentane, 1,3-difluoropropane, 1-fluoroadamantane, or 1,1,1,3,3,3-hexafluoro-2-(fluoromethoxy)-propane were combined in a 1:1:1 ratio in CH_2Cl_2. In all cases, this resulted in the rapid formation of the new species **1**−**4**, respectively, which were isolated in yields of 88−94%. All the products exhibit a ^{11}B signal at ca. −0.6 ppm, with B−F coupling of about 65 Hz consistent with a direct B−F bond. These chemical shifts, together with the comparatively small gap between the ^{19}F resonances attributable to the meta and para aryl fluorine atoms, support the presence of the fluoroborate anion $[FB(C_6F_5)_3]^-$. The BF fragments give rise to ^{19}F resonances between −185 and −192 ppm. The ^{31}P NMR spectra for these species gave rise to shifts ranging from 45 to 49 ppm consistent with the alkylation of the phosphine, a view further supported by ^1H NMR data. These data were thus consistent with the formulation of these products as $[tBu_3P(CH_2)_4CH_3][FB(C_6F_5)_3]$ (**1**), $[tBu_3P(CH_2)_3F][FB(C_6F_5)_3]$ (**2**), $[tBu_3P(Adamantyl)][FB(C_6F_5)_3]$ (**3**), and $[tBu_3PCH_2OCH(CF_3)_2]$ $[FB(C_6F_5)_3]$ (**4**), respectively (Scheme 1). These formulations were further supported via a crystallographic study of **2** (Figure 1a). The metric parameters of this salt are typical and unexceptional. The analogous reaction of $B(C_6F_5)_3$, 1,3-difluoropropane, and tBu_2PH afforded $[tBu_2PH(CH_2)_3F][FB(C_6F_5)_3]$ (**5**). This species exhibited similar spectral parameters for the fluoroborate anion in addition to a ^{31}P signal at 48.3 ppm with a P−H coupling of 458 Hz and a ^{19}F resonance at −221.13 ppm consistent with the retention of one C−F bond. The formulation was also unambiguously confirmed via crystallography (Scheme 1, Figure 1b).

The corresponding reaction of $B(C_6F_5)_3$, tBu_3P, and fluorocyclohexane also led to a similarly rapid reaction. However, in this case, ^1H NMR data revealed the formation of an olefinic resonance at 5.66 ppm attributable to cyclohexene with the concurrent emergence of a PH doublet at 5.43 ppm

Received: September 21, 2011
Published: December 14, 2011

dx.doi.org/10.1021/om200885c | *Organometallics* 2012, 31, 27−30

Scheme 1. Stoichiometric Reactions of Phosphine/Borane FLPs and Fluoroalkanes



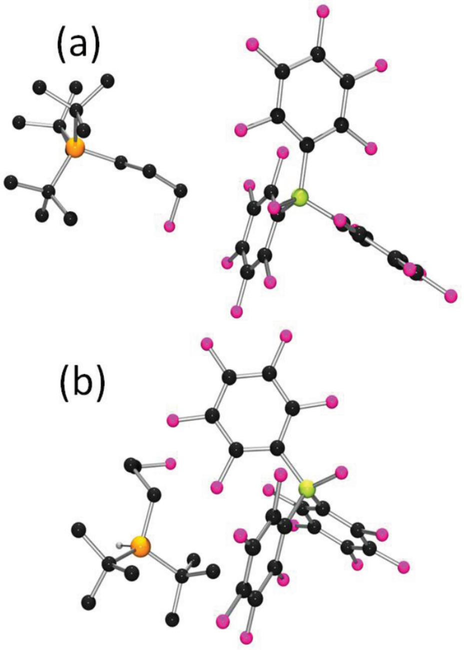


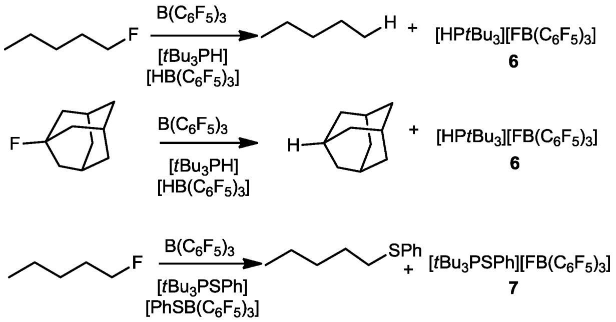
Figure 1. POV-ray depictions of the salts (a) **2** and (b) **5**: C, black; B, yellow-green; F, pink; P, orange; H, gray. All hydrogen atoms except P—H are omitted for clarity.

($^1J_{H-P}$ = 442 Hz) and a ^{31}P signal at 57.1 ppm. The corresponding ^{19}F and ^{11}B NMR data showed resonances at −187.3 and −0.5 ppm ($^1J_{B-F}$ = 70 Hz), respectively, consistent with the presence of the fluoroborate anion. These data confirm the formation of the salt [*t*Bu$_3$PH][FB(C$_6$F$_5$)$_3$] (**6**)[35] via dehydrofluorination of fluorocyclohexane, giving cyclohexene. This alternative reaction pathway presumably results from a combination of the steric and electronic effects associated with the transition state. The basicity of *t*Bu$_3$P undoubtedly plays a role in the deprotonation of the Lewis acid activated fluorocyclohexane. Previous work has demonstrated the ability of *t*Bu$_3$P/B(C$_6$F$_5$)$_3$ to deprotonate terminal alkynes.[36,37]

The formation of **1**−**5** results from the interactions of the C—F bond with the Lewis acid, which makes the C susceptible to nucleophilic attack by phosphine. Since the combination of phosphine and borane employed is a FLP, borane—phosphine adduct formation does not occur, thereby allowing alkylation of P to proceed. In this regard, a single example of C—F bond activation by a carbon-based FLP was previously described by Alcazaro and co-workers.[38] Attempts to effect analogous reactions of *t*Bu$_3$P/B(C$_6$F$_5$)$_3$ with polyfluorinated alkanes or fluoroarenes were unsuccessful, suggesting the possibility that only alkyl monofluorides are activated by borane. Although this is expected to be a weak interaction, it is noteworthy that we have previously documented the weak van der Waals interaction between olefin and borane.[39]

Expanding the reactivity via Lewis acid C—F activation, the reaction with a hydridoborate anion as an alternative nucleophile was probed. To a 1:1 mixture of B(C$_6$F$_5$)$_3$ and 1-fluoropentane was added 1 equiv of the salt [*t*Bu$_3$PH][HB(C$_6$F$_5$)$_3$].[40] This results in the formation of pentane and a mixture of **6** and B(C$_6$F$_5$)$_3$. It is noteworthy that the salt [*t*Bu$_3$PH][HB(C$_6$F$_5$)$_3$] does not react on its own with 1-fluoropentane, implying that borane activation of the C—F bond is required for the hydride attack. In the same vein, treatment of B(C$_6$F$_5$)$_3$ and 1-fluoroadamantane with the salt [*t*Bu$_3$PH][HB(C$_6$F$_5$)$_3$] yielded clean stoichiometric production of adamantane and a mixture of the salt **6** and B(C$_6$F$_5$)$_3$ (Scheme 2).

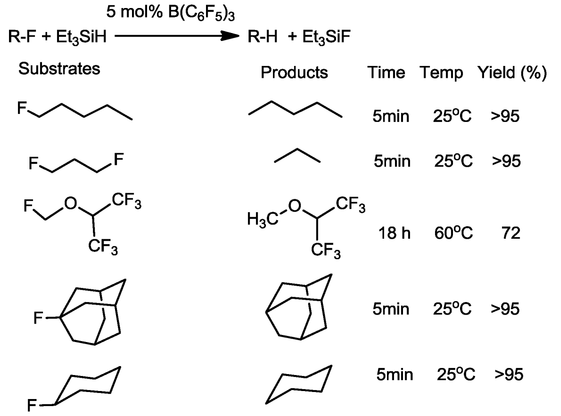
Scheme 2. Stoichiometric Reactions of Lewis Acid Activation of Fluoroalkanes and [*t*Bu$_3$PX][XB(C$_6$F$_5$)$_3$] (X = H, SPh)



In a similar fashion, the salt [*t*Bu$_3$PSPh][PhSB(C$_6$F$_5$)$_3$] is readily generated via reaction of (SPh)$_2$ with *t*Bu$_3$P and B(C$_6$F$_5$)$_3$.[41] Addition of a mixture of fluoropentane and B(C$_6$F$_5$)$_3$ results in the anion of the disulfide salt acting as a nucleophile toward the Lewis acid activated fluoroalkane. This results in the formation of the salt [*t*Bu$_3$PSPh][FB(C$_6$F$_5$)$_3$] (**7**) and the thioether C$_5$H$_{11}$SPh. The salt **7** gives rise to the expected ^{31}P, ^{19}F, and ^{11}B NMR peaks,[41] while the ^{1}H NMR data for the thioether were consistent with literature data.[42]

As the above reactions demonstrate the utility of borane C—F activation in stoichiometric transformations, extension of this chemistry to a catalytic process was sought. To that end, 5 mol % of B(C$_6$F$_5$)$_3$ was combined with Et$_3$SiH and one of the following fluorocarbons: 1-fluoropentane, 1,3-difluoropropane, 1-fluorocyclohexane, and 1-fluoroadamantane. In these cases the ^{1}H and ^{19}F NMR data revealed the complete conversion of the fluorocarbon used to the corresponding alkane and Et$_3$SiF in a quantitative yield in about 5 min (Scheme 3). In the case of 1,1,1,3,3,3-hexafluoro-2-(fluoromethoxy)propane, the reaction was much slower and required warming to 60 °C for 24 h, resulting in the selective reaction of the fluoromethoxy fragment, affording CH$_3$OCH(CF$_3$)$_2$ in 72% yield (Scheme 3). The slower reaction in this case is attributed to the presence of the ethereal oxygen rendering the C—F bond less polar, while offering the potential of a weak donor—acceptor interaction with the Lewis acid, thereby sequestering some portion of the Lewis acid catalyst. Conceptually, this finding is related to the pioneering work from the Piers,[43] Gevorgyan,[44] Rubinstajn,[45] and Brook groups[46−50] in the use of B(C$_6$F$_5$)$_3$ in

Scheme 3. F/H Exchange of Some Alkyl Fluorides with Et_3SiH Catalyzed by $B(C_6F_5)_3$[a]



[a] Yields were determined by NMR spectroscopy.

the catalysis of hydrosilylation of ketones and the formation of silicone oligomers and polymers.

In conclusion, an approach to C−F bond activation employing the commercially available Lewis acid $B(C_6F_5)_3$ has been reported. Stoichiometric reactions of alkyl fluorides with FLPs afford salts of the general formula $[R_3PR'][FB(C_6F_5)_3]$. Alternatively, activation of alkyl fluorides by $B(C_6F_5)_3$ in the presence of borate anions of the form $[XB(C_6F_5)_3]^-$ (X = H, SPh) are effective for X/F exchange. Similarly, the activation of the C−F bonds by interaction with the Lewis acid $B(C_6F_5)_3$ can be used to catalytically effect hydride/fluoride exchange between alkyl fluorides and silanes. This reactivity is certainly interesting from the perspective of C−F bond activation; however, in addition it provides a strategy to derivatize products derived from FLP reactivity. It is this application as well as a fuller understanding of mechanistic issues that are of particular emphasis in our continuing research efforts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Text, figures, and CIF files giving experimental, computational, and crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ACKNOWLEDGMENTS

D.W.S. gratefully acknowledges the financial support of the NSERC of Canada, the award of a Canada Research Chair, and a Killam Research Fellowship. C.B.C. is grateful for the support of an NSERC-CGS Scholarship.

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