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E–H (E = R_3Si or H) bond activation by $B(C_6F_5)_3$ and heteroarenes; competitive dehydrosilylation, hydrosilylation and hydrogenation†

Cite this: *Chem. Commun.*, 2014, **50**, 5270

Received 26th September 2013,
Accepted 27th November 2013

DOI: 10.1039/c3cc47372d

www.rsc.org/chemcomm

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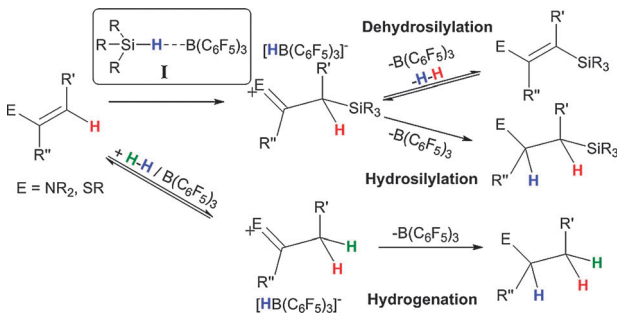
In the presence of $B(C_6F_5)_3$ five-membered heteroarenes undergo dehydrosilylation and hydrosilylation with silanes. The former, favoured on addition of a weak base, produces H_2 as a by-product making the process catalytic in $B(C_6F_5)_3$ but also enabling competitive heteroarene hydrogenation.

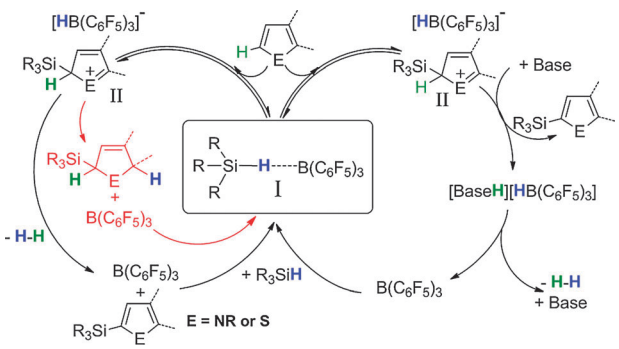
The activation of H_2 and silanes by boron Lewis acids and a nucleophile is developing into a powerful metal-free approach to hydrogenate, hydrosilylate and dehydrosilylate a range of substrates.[1,2] $B(C_6F_5)_3$, and its derivatives, are the Lewis acids of choice combining considerable electrophilicity with sufficient bulk to 'frustrate' Lewis adduct formation.[2] $B(C_6F_5)_3$ activates R_3Si–H *via* species **I** (Scheme 1),[3] with subsequent transfer of R_3Si^+ to a nucleophile.[4] To date the combination of **I** with a nucleophile forms products from either hydrosilylation (*e.g.*, with ketones) or dehydrosilylation (*e.g.*, with alcohols).[4] However, with substrates such as heteroarenes and heteroatom substituted alkenes these outcomes are not necessarily mutually exclusive. Indeed, Oestreich *et al.*, have shown that both the hydrosilylation and the dehydrosilylation of enolizable carbonyl compounds is possible with a related silicon cation.[5,6] Furthermore, the generation of H_2 from dehydrosilylation permits frustrated Lewis pair (FLP) mediated hydrogenation as an additional, potentially competitive, reaction pathway (Scheme 1, bottom).[2]



Scheme 1 Dehydro-/hydro-silylation and hydrogenation with $B(C_6F_5)_3$.

We were interested in determining how **I** reacts with nucleophilic heteroarenes, particularly as related silicon cations have been recently demonstrated to exclusively dehydrosilylate arenes.[7–9] Whilst $B(C_6F_5)_3$ reacts with highly nucleophilic arenes such as *N*-alkyl-indoles, this occurs only extremely slowly.[10] As many heteroarenes actually have lower nucleophilicities than R_3SiH[11] compound **I** will form in their presence. Nucleophilic attack on **I** by a heteroarene will initially generate $[R_3Si\text{–arenium}][HB(C_6F_5)_3]$, **II**, with multiple outcomes then possible. Herein we report a study into these competing pathways which include: (i) dehydrosilylation by the direct reaction of $[HB(C_6F_5)_3]^-$ with arenium cation **II** (Scheme 2, left), or by base catalysis where a Lewis base deprotonates the arenium cation **II** before dehydrocoupling with $[HB(C_6F_5)_3]^-$ (Scheme 2, right).[2] (ii) Hydrosilylation by hydride transfer from $[HB(C_6F_5)_3]^-$ to $[R_3Si\text{–arenium}]^+$ (Scheme 2, red), and (iii) hydrogenation. These processes are all catalytic in $B(C_6F_5)_3$, but turnover is limited by competing deactivation pathways that have also been elucidated.

Studies commenced with 2-methylthiophene (2-MT) and Ph_3SiH. 2-MT is less nucleophilic than Ph_3SiH and does not react with $B(C_6F_5)_3$. The combination of equimolar Ph_3SiH, $B(C_6F_5)_3$ and 2-MT produced 2-Me-5-(Ph_3Si)-thiophene, **2** (Table 1, entry 1). However, aliphatic 2-MT derived species were



Scheme 2 Dehydro-/hydro- (red) silylation catalysed by $B(C_6F_5)_3$.

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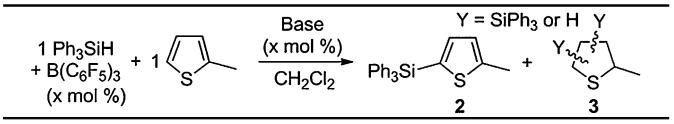
† Electronic supplementary information (ESI) available: Experimental procedures and characterisation. See DOI: 10.1039/c3cc47372d

Table 1 Stoichiometric and catalytic electrophilic silylation of 2-MT



Entry	Base	$B(C_6F_5)_3$/base (mol%)	Time (h)	Temp. (°C)	2[a] (%)	3[a] (%)
1	—	100/0	42	20	34	31
2	$^tBu_2$-py	100/100	72	20	39	10
3	Cl_2-py	100/100	24	20	51	33
4	Cl_2-py	20/20	24	60	56	34
5	Cl_2-py	5/5	24	60	42	18
6	Cl_2-py	5/100	36	60	51	27
7[b]	Cl_2-py	5/5	24	60	46	32
8[c]	Cl_2-py	100/100	24	60	0	0

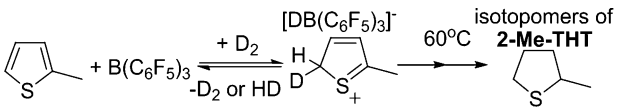
[a] Yields based on conversion of 2-MT by ^{1}H NMR spectroscopy, remaining material is 2-MT. [b] With 1.5 equivalents of Ph_3SiH. [c] In the presence of 1 eq. of tetrahydrothiophene.

observed and unreacted 2-MT remained despite consumption of all Ph_3SiH, indicating a non-stoichiometric reaction. $B(C_6F_5)_3$ remained the dominant borane species (by ^{11}B and ^{19}F NMR spectroscopy), therefore an additional 4 equivalents of Ph_3SiH and 2-MT were added. This produced further equivalents of **2** indicating a catalytic process. Throughout, the aliphatic region of the ^{1}H NMR spectrum was complex but contained three doublets corresponding to three 2-Me groups (collectively termed **3**) each representing a different substituted tetrahydrothiophene derived from hydrosilylation.[12] At no point were vinylic resonances of substituted dihydrothiophene intermediates observed.

The ability of base to increase the proportion of **2** formed by facilitating the deprotonation of the arenium cation was next investigated. Addition of 2,6-ditertbutylpyridine ($^tBu_2$-py, entry 2) increased the ratio of **2** relative to **3**. However, to be catalytic the resultant [H(amine)][$HB(C_6F_5)_3$] has to evolve H_2, a reaction requiring a weakly nucleophilic amine to be energetically favoured.[2] This precludes $^tBu_2$-py and 2,6-lutidine, the latter the optimal base in stoichiometric Sila-Friedel–Crafts reactions.[9] As the steric bulk of the base strongly affects the barrier to deprotonation of silylated arenium cations isosteric bases to 2,6-lutidine were explored.[8,9] Using 2,6-dichloropyridine (Cl_2-py) as a suitably weak base, the amount of **2** produced (relative to **3**) increased (entry 3). Replacing CH_2Cl_2 with benzene resulted in no silylation (24 h, 20 °C). In contrast, the silylation of carbonyl moieties with $B(C_6F_5)_3/R_3SiH$ is more rapid in non-polar solvents than in CH_2Cl_2 which obviated ionic intermediates.[3a] The necessity for polar solvents for heteroarene silylation implies the formation of unobserved ionic species, for example **II** (Scheme 1). The silylation of 2-MT with various silanes using $B(C_6F_5)_3/Cl_2$-py was also explored, but Ph_3SiH produced the highest amount of **2** relative to **3**, with less dehydrosilylation observed on decreasing silane steric bulk.[12]

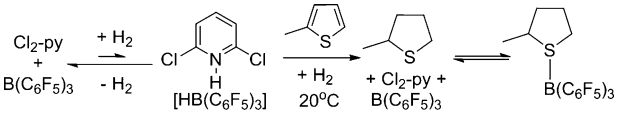
Catalytic loadings of $B(C_6F_5)_3/Cl_2$-py required heating for reasonable reaction times (entries 4 and 5) and led to similar ratios of **2**:**3**. Attempts with excess Cl_2-py did not significantly improve the selectivity for **2** (entry 6). Full consumption of 2-MT was not achieved even at longer times and using 1.5 eq. of Ph_3SiH (entry 5 *vs.* 7), suggesting catalyst deactivation. During catalysis one new boron containing species gradually increased in intensity (by ^{11}B NMR spectroscopy where one new resonance moved progressively upfield to a limiting δ −5 ppm). We surmised that aliphatic sulfides, **3**, were forming $R_2S \rightarrow B(C_6F_5)_3$ species retarding the catalysis. Indeed, equimolar tetrahydrothiophene and $B(C_6F_5)_3$ produced ^{11}B and ^{19}F NMR spectra comparable to those at the end of the catalytic runs.[12] Importantly, this mixture was inactive in silylation (entry 8), thus **3** may be an effective catalyst poison.

It was noteworthy that the overall conversion in reactions with Cl_2-py (*e.g.*, entries 3 and 4) would be greater than 100% based on Ph_3SiH if all the 2-MT derived aliphatic products were from the double hydrosilylation of 2-MT. As H_2 is the by-product from dehydrosilylation this results in competitive hydrogenation thus products from; (i) hydrosilylation and hydrogenation of 2-MT and (ii) the hydrogenation of 2-MT to 2-methyl-tetrahydrothiophene (2-Me-THT) dominate.[12] Related alkene and heteroarene hydrogenation by FLPs has been reported.[13,14] To determine what components in the reaction mixture are activating H_2 equimolar $B(C_6F_5)_3$/2-MT was placed under D_2 (4 atm.) in the absence of Cl_2-py. At 20 °C no reduction occurred but deuterium incorporation into the alpha position of 2-MT was observed indicating reversible activation of dihydrogen. On heating to 60 °C aliphatic resonances were now also observed in the ^{2}H NMR spectrum indicating 2-MT reduction to partially deuterated isotopomers of 2-Me-THT (eqn (1)).[12] $B(C_6F_5)_3$/2-MT is a rare example of a FLP in which an aromatic carbon nucleophile (2-MT) is activating dihydrogen.[14,15] The reduction of 2-MT with $B(C_6F_5)_3$ in the presence of Cl_2-py was more facile, with 66%



(1)

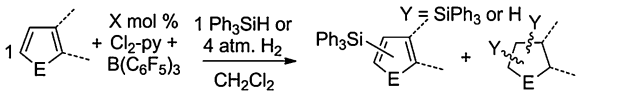
conversion of 2-MT to 2-Me-THT at only 20 °C (16 h, 4 atm. H_2, eqn (2)) indicating that Cl_2-py/$B(C_6F_5)_3$ is more effective for 2-MT hydrogenation, analogous to the high reduction activity of FLPs with other weak bases.[16] Complete reduction of 2-MT at 20 °C is retarded by coordination of 2-Me-THT to $B(C_6F_5)_3$.[12] The necessity for Cl_2-py for 2-MT reduction at 20 °C is consistent with the complete absence of 2-Me-THT in base free reactions (Table 1, entry 1, by NMR spectroscopy).[12] As previous reactions were performed in a closed system the H_2 concentration increases as dehydrosilylation proceeds enabling competitive hydrogenation. Silylation with $B(C_6F_5)_3/Cl_2$-py performed in a tube sealed under vacuum (to minimise build up of dissolved H_2) produced no 2-Me-THT, but whilst there was a relative increase in **2**, aliphatic species (from hydrosilylation) were still present.[12]



(2)

The product distribution in the silylation of other heteroarenes using $Ph_3SiH/B(C_6F_5)_3/Cl_2$-py was also explored. Thiophene, 2,2′-bithiophene and thieno-[3,2,*b*]-thiophene all resulted in no reaction at 20 °C presumably due to reduced arene nucleophilicity relative to 2-MT. 2-^{t}Bu-thiophene, 2-BT, was amenable to stoichiometric and catalytic electrophilic silylation which occurs with

Table 2 Electrophilic functionalisation of select heteroarenes

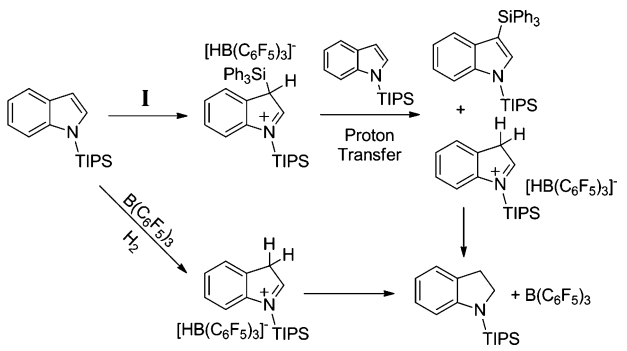


Entry	Substrate	Y–H	$B(C_6F_5)_3$/Cl_2-py (mol%)	t (h)	T (°C)	Sila-FC[a] (%)	Red[a] (%)
1	2-BT	Si–H	100/100	18	20	54	32
2	2-BT	Si–H	5/5	24	60	70	17
3	*N*-TIPS pyrrole	Si–H	100/100	48	20	42	45
4	*N*-TIPS-indole	Si–H	100/100	24	20	59	19[b]
5	*N*-TIPS-indole	H–H	100/100	16	20	—	80[b]
6	2-BT	H–H	100/100	24	20	—	80[c]
7	*N*-TIPS-indole	Si–H	100/0	24	20	30	21[b]
8	*N*-TIPS-indole	H–H	100/0	24	20	—	16[b]
9	*N*-TIPS-indole	H–H	100/0	24 + 24	20 + 60	—	35[b]

[a] Conversion by consumption of the substrate and growth of products as determined by ^{1}H NMR spectroscopy, unreacted starting material also present. [b] Combined conversion to the indoline and protonated indoline. [c] Acid induced ^{t}Bu migration results in multiple reduction products.

concomitant hydrogenation (Table 2, entries 1 and 2). Electrophilic silylation *via* **I** could be extended to 5-membered N-heterocycles. Whilst *N*-TIPS protected pyrrole and indole were amenable to silylation, hydrogenation was again competitive (entries 3 and 4), although no hydrosilylation was observed in either case. Hydrogenation products were confirmed by independent reduction under 4 atm. H_2 (*e.g.*, entry 5). Catalytic (in $B(C_6F_5)_3$) reductions were limited as (i) the hydrogenation of *N*-TIPS-indole produces a better Brønsted base, *N*-TIPS-indoline, that cleaves H_2 with $B(C_6F_5)_3$ to form [*N*-H-*N*-TIPS-indolinium][$HB(C_6F_5)_3$] thus sequestering $B(C_6F_5)_3$ and preventing turnover, (ii) the catalytic hydrogenation of ^{t}Bu-thiophene was retarded by coordination of 2-^{t}Bu-tetrahydrothiophene to $B(C_6F_5)_3$ (entry 6).[12]

The dehydrosilylation of *N*-TIPS-indole without Cl_2-py led to increased proportions of the reduction product, *N*-TIPS-indoline, (entry 7 *vs.* 4) analogous to 2-MT reactivity. Furthermore, in the absence of Cl_2-py the FLP hydrogenation of *N*-TIPS-indole with $B(C_6F_5)_3$ also proceeds confirming that *N*-TIPS indole is also a viable carbon nucleophile for FLP H_2 activation (entries 8 and 9).[12] It is noteworthy that there is less reduction of *N*-TIPS-indole at 20 °C under H_2 than there is during silylation (entry 7 *vs.* 8) thus another reduction mechanism must be operating in silylation. Reduction presumably proceeds by silylation of *N*-TIPS-indole followed by proton transfer to another molecule of *N*-TIPS-indole, as observed in electrophilic borylations,[17] and finally reduction to *N*-TIPS-indoline by hydride transfer (Scheme 3).



Scheme 3 Reduction of *N*-TIPS-indole by competing mechanisms.

In conclusion, R_3Si–H–$B(C_6F_5)_3$, **I**, still forms in the presence of activated heteroarenes, which for the first time are shown to be viable nucleophiles towards **I**. Catalytic silylation pathways are demonstrated, but the competitive activation of Si–H and H–H bonds by boron Lewis acids/weak nucleophiles leads to multiple products. Furthermore, the formation of aliphatic R_2S species from thiophene hydrosilylation/hydrogenation inhibits catalyst turnover by coordination to $B(C_6F_5)_3$. Finally, the hydrogenation of both 2-MT and *N*-TIPS-indole with only $B(C_6F_5)_3/H_2$ confirms both these heteroarenes are carbon nucleophiles capable of activating H_2 in a FLP. This suggests that many other arenes will be viable as carbon nucleophiles for H_2 cleavage in a FLP.

We thank the Royal Society (M. J. I.), the Leverhulme Trust (E. R. C), the European Research Council under FP7 (J. J. D.) and the University of Manchester (L. D. C.) for support.

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