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The air-stable carbocation salt $[(MeOC_6H_4)CPh_2][BF_4]$ in Lewis acid catalyzed hydrothiolation of alkenes†

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Markovnikov hydrothiolation of 1,1-disubstituted and trisubstituted olefins (20 examples) is catalyzed by Lewis acids, including the air-stable trityl-cation salt $[(MeOC_6H_4)CPh_2][BF_4]$ 3.

The installation of sulfur in organic compounds and materials has important applications including the generation of synthetic intermediates, reagents, pharmaceuticals or as functional materials.[1] One transformation that has garnered attention for the introduction of sulfur has been the addition of thiols to unsaturated organic molecules. While such "hydrothiolations" have been known for over 100 years,[2] the promotion of such reactions by free radicals,[3] strong acids,[4] or bases,[5] results in mixtures of addition products as well undesired by-products. In recent years, transition metal catalysts have offered significant improvement in selective hydrothiolations. Such catalysts have drawn much recent attention and have been reviewed in several publications.[6]

The hydrothiolation reaction of alkynes has been extensively studied, while the analogous reactions of thiols and alkenes have drawn lesser attention.[7] Where such additions have been studied the majority of cases known to date exploit transition-metal catalysts. For example, Ogawa and co-workers have developed a palladium catalyst for the hydrothiolation of heteroatom-substituted olefins.[6h,8] Stoichiometric addition of Lewis acids such as $SnCl_4$, $AlCl_3$, and $TiCl_4$ were shown to generate similar moieties, albeit in inferior yields[9] while a recent study has also shown that $Sc(OTf)_3$-catalyzed hydrothiolation proceeds in an anti-Markovnikov fashion.[10]

Metal-free strategies to hydrothiolation of olefins are underdeveloped. It is noteworthy that in 2006, Duñach and coworkers reported the use of the Lewis acid $InBr_3$ as an effective catalyst for the Markovnikov hydrothiolation of olefins.[11] In 2015 the group of Sinha reported ionic liquid mediated hydrothiolations,[12] while in a recent report, we have described the efficient and facile hydrothiolation of alkenes using $[(C_6F_5)_3PF][B(C_6F_5)_4]$.[13] In a very recent publication, electron-rich olefins with thiophenols were shown to undergo a one-pot auto-oxidation-mediated hydroxysulfenylation.[14] In this communication, we expand metal-free catalysis of hydrothiolation of olefins to include carbon-, boron- and phosphorus-based Lewis acid catalysts. Subsequently, we exploit an air-stable trityl salt for the hydrothiolations of di- and trisubstituted olefins using both alkyl and aryl thiols.

Treatment of α-methylstilbene with benzylthiol in the presence of a catalyst affords the hydrothiolated product. Efforts to use 10 mol% trifluoroacetic acid were unsuccessful, even on standing for 3 d. On the other hand, use of Lewis acids proved successful. $B(C_6F_5)_3$ (10 mol%) catalyzed hydrothiolation of the olefin, affording the product in 95% yield in 2 h. Analogous to previous reports,[13] the reaction of α-methylstilbene with benzylthiol was catalyzed to 99% completion using 1 mol% of the phosphonium salt $[FP(C_6F_5)_3][B(C_6F_5)_4]$.

Given that boranes and carbocations both derive Lewis acidity from a low-lying vacant p orbital, hydrothiolation of α-methylstilbene with benzylthiol was also performed in the presence of 1 mol% $[Ph_3C][B(C_6F_5)_4]$ **1**. In this case, the reaction was significantly faster than with $B(C_6F_5)_3$, being complete in 15 min at 25 °C. The addition product observed is derived from a Markovnikov-type addition of the S–H bond across the olefin (Table 1).

In a similar fashion, 1 mol% **1** catalyzes the addition of benzylthiol to 2-methyl-2-butene to give the corresponding sulfide product, $BnSCMe_2CH_2Me$, in 99% yield in 6 h. Similarly, the analogous hydrothiolation of $ClC_6H_4(Me)C{=}CH_2$, $Ph_2C{=}CH_2$, and $MeC_6H_4(Me)C{=}CH_2$ proceed to afford $BnSCMe_2(R)$ ($R = ClC_6H_4$, Ph, MeC_6H_4) in a quantitative fashion in 15 minutes. In contrast, efforts to effect hydrothiolation of benzophenone or cyclohexene were unsuccessful, whereas the addition to stilbene proceeds slowly, achieving 75% conversion in 72 h (Table 2).

Seeking to further improve this catalysis, the known methoxy-derived trityl cation salts $[(MeOC_6H_4)_3C][BF_4]$ **2** and $[(MeOC_6H_4)CPh_2][BF_4]$ **3** were prepared following a modified

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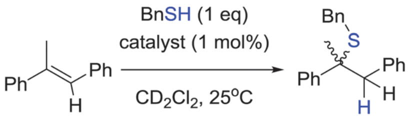
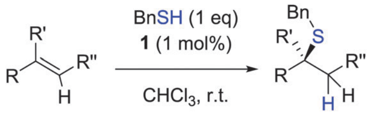
Table 1 Lewis acid catalysed hydrothiolation of methyl stilbene



Catalyst	Loading (mol%)	Time	Conv. (%)
1	1	15 min	99
$[FP(C_6F_5)_3][B(C_6F_5)_4]$	1	15 min	99
$B(C_6F_5)_3$	10	2 h	95
Trifluoroacetic acid	10	3 d	N.R.

All reactions carried out at 25 °C; N.R. = no reaction; conversions were determined by ^1H NMR spectroscopy.

Table 2 Trityl cation catalyzed hydrothiolation of olefins

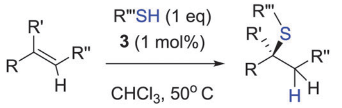


Entry	Substrate	*T* (h)	Conv. (%)
1	$Me_2C{=}CHMe$	6	99
2	$ClC_6H_4(Me)C{=}CH_2$	0.25	99
3	$Ph_2C{=}CH_2$	0.25	96
4	$Ph(Me)C{=}CH_2$	0.25	99
5	$MeC_6H_4(Me)C{=}CH_2$	0.25	99
6	$Ph_2C{=}O$	0.25	4
7	C_6H_{10}	24	3
8	*trans*-Ph(H)C=C(H)Ph	72	75

Conversion determined by ^1H NMR spectroscopy. General procedure: 1 mmol substrate, 1 mmol benzyl thiol combined in 5 mL $CHCl_3$ and added to 1 mol% of **1** as catalyst, 25 °C.

literature procedure[15] involving treatment of the corresponding alcohol with ethereal tetrafluoroboric acid. The crystal structure of **3** (see ESI†) confirmed the expected trigonal planar nature of the central carbon; however the $C_{central}$–C bond lengths were found to be 1.418(7) Å, 1.455(7) Å and 1.454(7) Å, with the shortest corresponding to the ring bearing the methoxy-substituent. These data are consistent with the resonance stabilization of **3** which presumably accounts for air-stability observed for compounds **2** and **3**. Indeed these compounds can be stored for extended periods of time and handled openly in the air without degradation. However, compound **2** does not act as a catalyst for hydrothiolation of olefins under conditions analogous to those described for **1**, or upon heating for prolonged reaction times.

Table 3 Hydrothiolation of olefins catalysed by **3**



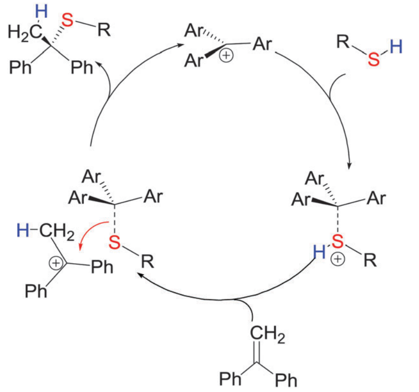
Entry	Substrate	*T* (h)	Conv. (%)
$PhCH_2SH$			
1	$Me_2C{=}CHMe$	2	99(95)
2	$Ph(Me)C{=}CH_2$	1	99(99)
3	$MeC_6H_4(Me)C{=}CH_2$	1	96(92)
4	$ClC_6H_4(Me)C{=}CH_2$	1	99(64)
5	$FC_6H_4(Me)C{=}CH_2$	1	95(34)
6	$Ph_2C{=}CH_2$	2	70[a]
7	MeC_6H_9	2	99(99)
8	Ph(Me)C=C(H)Ph	6	99(39)
9	C_4H_4O	24	0
10	C_4H_6O	24	0
11	*trans*-Ph(H)C=C(H)Ph	24	0
iPrSH			
12	$Ph(Me)C{=}CH_2$	2	92(86)
13	MeC_6H_9	2	99(12)
1,4-$C_6H_4(SH)_2$[b]			
14	$Ph(Me)C{=}CH_2$	2	80(61)
15	$ClC_6H_4(Me)C{=}CH_2$	1	95(18)

Conversion determined by ^1H NMR spectroscopy; isolated yields in brackets. General procedure: 1 mmol substrate, 1 mmol thiol combined in 5 mL $CHCl_3$ and added to 5 mol% catalyst. Heated to 50 °C, reaction times as indicated. [a] Product not isolated due to equilibrium. [b] Ratio of dithiol : olefin was 1 : 2.

In contrast, compound **3** proved to be an effective catalyst for the hydrothiolation of olefins upon heating to 50 °C (Table 3). For example, a series of olefins including $Me_2C{=}CHMe$, $XC_6H_4(Me)C{=}CH_2$ (X = H, Cl, F, Me), $Ph(Me)C{=}CHMe$, $Ph_2C{=}CH_2$ and MeC_6H_9 were all shown to undergo hydrothiolation with benzylthiol to give the Markovnikov addition products, $Me_2C(SCH_2Ph)CH_2Me$, $(XC_6H_4Me_2)C(SCH_2Ph)$ (X = H, Cl, F, Me), $Ph(Me)C(SCH_2Ph)CH_2Me$, $Ph_2(Me)C(SCH_2Ph)$ and $Me(SCH_2Ph)C_6H_{10}$ with conversion of 70–99% in 1–2 h with isolated yields ranging from 18–99% after work up. Efforts to effect addition to furan, dihydrofuran or *trans*-stilbene were unsuccessful even on heating for 24 h (Table 3). This may be a reflection of the lower Lewis acidity of **3** in comparison to **1**. However, hydrothiolation of $Ph(Me)C{=}CH_2$ and MeC_6H_9 with isopropylthiol gave $(Ph)Me_2CS(iPr)$ and $MeS(iPr)C_6H_{10}$ in 92% and 99% conversion in 2 h, respectively, although the isolated yields were 86% and 12%. Double hydrothiolation was also possible, using the olefins $Ph(Me)C{=}CH_2$ and $ClC_6H_4(Me)C{=}CH_2$ and 1,4-$C_6H_4(SH)_2$ affording the addition products 1,4-$((Ph)Me_2CS)_2C_6H_4$ and 1,4-$((ClC_6H_4)Me_2CS)_2C_6H_4$ in 80% and 95% conversions and these products were subsequently isolated in 61% and 18% respectively.

While the use of **3** as a catalyst requires elevated temperature in contrast to **1**, all of the hydrothiolations presented in Table 3 were carried out on the bench using commercial grade $CHCl_3$ without the need for further purification of solvents or reagents. Following reactions *via* ^1H NMR spectroscopy showed only traces of the triarylmethanol, likely as a result of some small degree of hydrolysis of the cation. It appears that this occurs following catalysis as yields of the products were consistently high (by ^1H NMR spectroscopy). In addition, the products were readily separated from the catalyst and the traces of triarylmethanol *via* elution of a hexanes solution of the crude mixture through a short silica plug.

The mechanism of hydrothiolation of diphenylethylene using **1** or **3** as the catalyst is thought to be analogous to that previously proposed for fluorophosphonium cations.[13] In the present case, the catalysis is initiated by interaction of the thiol with the carbocation. The resulting enhancement in acidity of the thiol proton prompts protonation of the disubstituted



Scheme 1 Proposed mechanism of trityl catalysed hydrothiolation of 1,1-diphenylethylene.

olefin affording a transient carbocation. This view is supported by the observation of a weak interaction of benzylthiol with the cation of **3** by NMR spectroscopy (see ESI†). This carbocation is more sterically accessible prompting thiolate transfer, thus affording the Markovnikov hydrothiolation product and regeneration the carbocation catalyst (Scheme 1). This mechanism is consistent with the lack of reactivity of primary and 1,2-disubstituted alkenes where the generation of primary or secondary carbocations presents a significant thermodynamic barrier. The proposed mechanism is distinct from known routes[6j] involving thiol activation where reactions are triggered by formation of free radicals, deprotonation by a base or by oxidative addition of SH to a metal center.

Herein, we have demonstrated that the air- and moisture-stable trityl cation, $[(MeOC_6H_4)CPh_2][BF_4]$ **3** is a potent catalyst for the hydrothiolation of alkenes. These reactions proceed under mild conditions without the use of dried or degassed solvents or reagents. The further application of such C-based Lewis acids in catalysis continues to be the subject of interest in on-going efforts. The results of these studies will be reported in due course.

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