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Transition metal-free hydrodefluorination of acid fluorides and organofluorines by Ph_3GeH promoted by catalytic $[Ph_3C][B(C_6F_5)_4]$

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It has been shown that the germane Ph_3GeH converts aryl and aliphatic acid fluorides directly to their corresponding aldehydes without over-reduction via the conversion of Ph_3GeH to the germylium cation $[Ph_3Ge]^+$ by a catalytic amount of the tritylium salt $[Ph_3C][B(C_6F_5)_4]$. Here, no transition metal catalyst is required and there is no decarbonylation of the acid fluoride, which are advantages over existing methods. The fluorine atoms can also be abstracted from organofluorine compounds using this method.

The preparation of aldehydes from acid chlorides can be achieved using a variety of reagents, including transition metal hydrides,[1-3] tin hydrides in the presence of transition metals,[4-6] aluminum hydrides,[7-10] or boron hydrides.[9] Furthermore, the non-decarbonylative conversion of acid chlorides to aldehydes using hydrosilanes has been known for some time, and these processes are catalyzed by the use of transition metal complexes.[11-17] In some cases, these conversions can be carried out for a variety of substrates under mild reaction conditions[11-12] with chemoselectivity and the tolerance of different functional groups,[11] and the transition metal catalysts can be recovered and recycled.[11, 13]

Due to their ready availability from either carboxylic acids or acid chlorides and their stability towards hydrolysis,[18-19] acid fluorides represent a useful class of carboxylic acid derivatives for use in organic synthesis. One key synthetic transformation of acid fluorides is their reduction to either aldehydes or their reductive decarbonylation to hydrocarbons. However, only a few reports of such conversions have appeared.

An initial report of such reactivity involved the palladium-catalyzed conversion of 3-trifluoromethylbenzoyl fluoride to 3-trifluoromethylbenzaldehyde, but the reactions employed typically proceeded in low yields and also resulted in the formation of trifluorotoluene via decarbonylation of the acid fluoride, and the product distribution was also difficult to control.[20]

Ogiwara, Sakai, *et al*. recently reported a versatile conversion of alkyl and aryl acid fluorides to aldehydes using triethylsilane that was catalyzed by palladium(II) acetate in the presence of a phosphine ligand.[21] When PCy_3 was used as the phosphine the reaction proceeded without decarbonylation, but decarbonylation of the acid fluoride to yield the corresponding hydrocarbon could also be selectively achieved by changing the ligand to a bidentate phosphine. These findings will likely have a significant impact on the catalytic synthesis of a variety of important molecules.[22]

Also of interest is the hydrodefluorination of aliphatic and aromatic organofluorine compounds, with aliphatic carbon – fluorine bonds being the most difficult to activate. Ozerov *et al.* have reported the hydrodefluorination of a wide variety of aliphatic organofluorine compounds by the conversion of silanes to silylium cations promoted by tritylium salts of halogenated carborane ions.[23,24] The conversion of alkyl fluorides to their corresponding alkanes was achieved using Et_3SiH and a catalytic amount of $B(C_6F_5)_3$ as reported by Stephan *et al*, which can also be achieved stoichiometrically using FLP chemistry.[25] The same $R_3SiH/B(C_6F_5)_3$ system also was used by Piers *et al.* for the hydrosilation of carbon-oxygen double bonds, converting aldehydes and ketones to silyl ethers and esters to aldehydes in generally high yields,[26] as well as the reduction of alcohols to hydrocarbons,[27] and the formation of siloxanes.[28-33]

During our recent successful preparation of the branched germanium fluoride compound $(Ph_3Ge)_3GeF$, it was observed that germanium was highly fluorophilic and also that germylium cations exhibited a tendency to abstract fluorine from several substrates including the $[BF_4]^-$ anion.[34] Although the germylium cation $[(Ph_3Ge)_3Ge]^+$ that was used to obtain $(Ph_3Ge)_3GeF$ was found to be unstable with respect to rearrangements, the simple germylium cation $[Ph_3Ge]^+$ does

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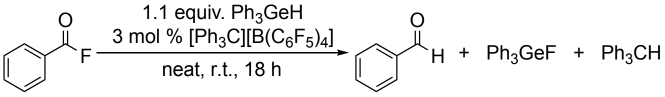
not have this complication. The aforementioned use of silylium cations as fluorine abstraction reagents[21-25] prompted us to investigate if this germylium cation would function in the same capacity. We wish to report that $[Ph_3Ge]^+$ can indeed serve to convert acid fluorides directly to aldehydes, and that this process occurs in the absence of transition metal catalysts. This species can also abstract fluorine from aliphatic carbon atoms.

The conversion of benzoyl fluoride to benzaldehyde without decarbonylation to generate benzene and also without over-reduction to benzyl alcohol was achieved using $[Ph_3Ge]^+$ as the fluorine abstraction agent. This species is readily generated from triphenylgermane Ph_3GeH via hydride abstraction by the tritylium cation $[Ph_3C]^+$. The reaction can be conveniently monitored using NMR spectroscopy since the ^1H NMR resonances for the hydrogen atoms in Ph_3GeH and the Ph_3CH formed during the course of the reaction are distinctive, appearing at δ 5.81 and 5.44 ppm in C_6D_6 solvent, respectively. In addition, ^{19}F NMR spectroscopy in C_6D_6 can be used to monitor the disappearance of the resonance at δ 17.9 ppm for benzoyl fluoride and the appearance of the peak at δ – 202.4 ppm corresponding to Ph_3GeF.

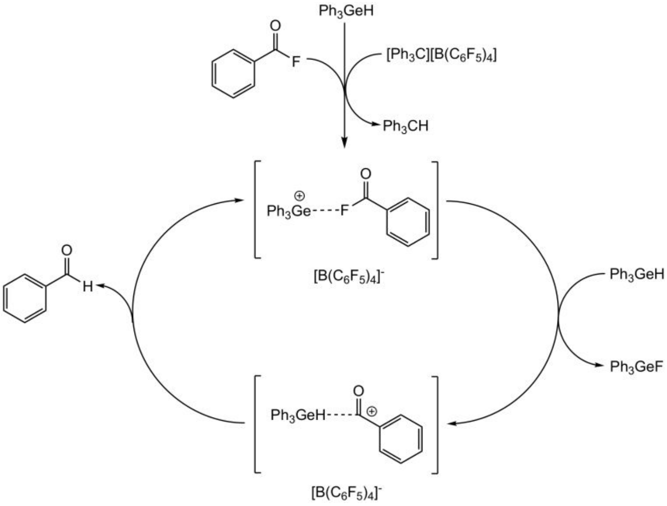
A mixture of benzoyl fluoride, 1.1 equiv. of Ph_3GeH and 3 mol % of $[Ph_3C][B(C_6F_5)_4]$ were combined and the mixture was stirred at room temperature for 18 h under nitrogen as shown in Equation 1. The product was obtained as a white solid that was analyzed by ^1H and ^{19}F NMR spectroscopy in C_6D_6. A singlet at δ 9.69 ppm in the ^1H NMR spectrum indicated the presence of benzaldehyde, and the 19F NMR spectrum exhibited a singlet at δ – 202.4 ppm corresponding to Ph_3GeF while no resonance was visible at δ 17.9 ppm indicating the absence of benzoyl fluoride. Analysis of the reaction product using GC/MS led to the observation of a peak with a retention time of 6.95 minutes, and the mass spectrum for the eluted material contained a peak at *m/z* = 105.00 corresponding to the parent ion $C_6H_5CO^+$. The GC/MS data for the reaction mixture, including the fragmentation pattern in the mass spectrum, is identical to that observed for an authentic sample of benzaldehyde.



Equation 1. Hydrodefluorination of benzoyl fluoride using Ph_3GeH.

The same reaction was repeated in the absence of solvent in order to isolate the benzaldehyde product. The ^1H and ^{19}F NMR spectra as well as the GC/MS data of the product obtained after stirring the reaction mixture at room temperature for 18 h was identical to that observed for the pervious reaction. The reaction was monitored using TLC, and after the reaction was complete the benzaldehyde product was extracted from the reaction mixture using water. The benzaldehyde was then extracted from the water phase with Et_2O, and the solvent was then removed under vacuum to provide benzaldehyde in 47 % yield. In a separate experiment Ph_3GeF could be isolated in 75 % yield using column chromatography on silica gel with benzene as the eluent.

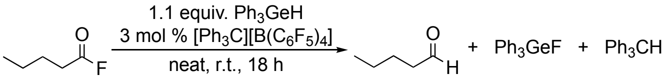
In order to verify that the $[Ph_3Ge]^+$ cation serves as the fluorine abstraction agent, a neat mixture of benzoyl fluoride and Ph_3GeH was stirred in the absence of $[Ph_3C][B(C_6F_5)_4]$ for 24 h, and also a mixture of benzoyl fluoride and 3 mol % of $[Ph_3C][B(C_6F_5)_4]$ in the absence of Ph_3GeH was stirred for 24 h. Neither reaction resulted in conversion of the benzoyl fluoride to benzaldehyde. Based on these findings, we propose that the reaction proceeds according to the pathway shown in Scheme 1. The tritylium cation $[Ph_3C]^+$ abstracts the hydrogen atom from Ph_3GeH to generate the active species $[Ph_3Ge]^+$, which in turn abstracts the fluorine atom from benzoyl fluoride to generate Ph_3GeF and the benzoyl cation. The benzoyl cation then proceeds to abstract a hydrogen from Ph_3GeH to yield benzaldehyde and regenerates the $[Ph_3Ge]^+$ cation.



Scheme 1. Proposed reaction pathway for the hydrodefluorination of benzoyl fluoride.

During the course of the reaction, the germylium cation is likely stabilized an interaction of the weakly coordinating anion $[B(C_6F_5)_4]^-$, as has been determined for hydrodefluorination processes involving silylium cations.[35] The degree of coordination of the anion can have an affect on the geometry and reactivity of the cation. A minimal interaction of the anion with the cation would result in an essentially trigonal planar $[Ph_3Ge]^+$ cation, while more significant interactions would result in pyramidalization and a decrease in the electrophilicty.[36] The structure of the $[Ph_3Ge]^+$ cation with no interaction of the $[B(C_6F_5)_4]^-$ anion by DFT can be found in the ESI. Both the $[Ph_3Ge]^+$ and $PhC(O)^+$ cations that are formed during the reaction also likely interact with the PhC(O)F and Ph_3GeH reagents, respectively, as proposed in Scheme 1.[37,38]

The germylium cation $[Ph_3Ge]^+$ can also convert aliphatic acid fluorides to aldehydes, as demonstrated by the reaction of Ph_3GeH with pentanoyl fluoride in the presence of $[Ph_3C][B(C_6F_5)_4]$ (Equation 2). After stirring the reaction mixture in the absence of solvent at room temperature for 18 h the ^{19}F NMR spectrum in CD_2Cl_2, which was used in place of C_6D_6 due to the product being poorly soluble in C_6D_6, indicated the formation of Ph_3GeF and the resonance at δ 45.1 ppm corresponding to pentanoyl fluoride was absent, while a singlet at δ 9.11 ppm in the ^1H NMR spectrum indicated the presence of pentanal. The identity of the product was further confirmed by GC/MS. The GC of the product mixture exhibited a peak with a retention time of 12.18 min that is identical to the GC of an authentic sample, and the mass spectrum for the eluted material contained a peak at $m/z = 85.10$ corresponding to the parent ion $C_5H_9O^+$.



Equation 2. Hydrodefluorination of pentanal using Ph_3GeH.

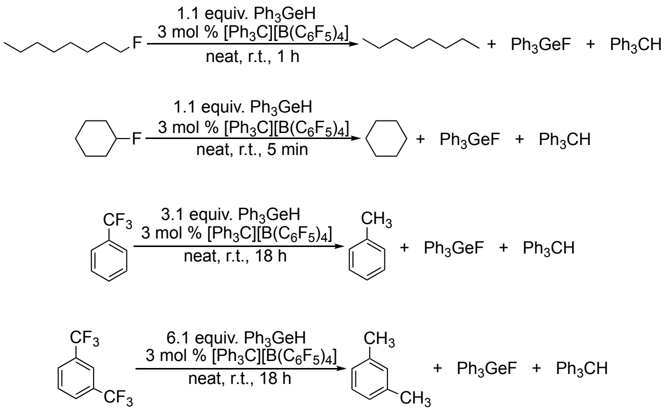
In addition to acid fluorides, Ph_3GeH also abstracts the fluorine atoms from fluoroalkanes, as shown by its reaction with 1-fluorooctane, 1-fluorocyclohexane, 1,1,1-trifluorotoluene, and 1,3-bis(trifluoromethyl)benzene (Scheme 2). In each case, one equivalent of Ph_3GeH was used for each fluorine atom present in the substrate. Both octane and cyclohexane were formed from 1-fluorooctane and 1-fluorocyclohexane, respectively, in over 99 % conversion. The ^{19}F NMR signals at δ – 217.0 and – 173.0 ppm, respectively, for these starting materials were absent after the reaction was complete and the ^1H NMR spectra and GC/MS of the products were identical to those of authentic samples. These reactions also proceed rapidly, as that for 1-fluorooctane was complete within 1 h and that for fluorocyclohexane is complete in less than 5 min.

The reactions of Ph_3GeH with 1,1,1-trifluorotoluene and 1,3-bis(trifluoromethyl)benzene are significantly slower and conversions of only 56 and 74 %, respectively, were achieved after 18 h. The conversion in each case was determined by integration of the ^{19}F NMR resonances for the starting materials and Ph_3GeF. Furthermore, the $[Ph_3Ge]^+$ cation appears to be selective for the abstraction of fluorine atoms bound to aliphatic carbon atoms since no fluorine abstraction was observed in the reactions of fluorobenzene and octafluorotoluene with Ph_3GeH in the presence of $[Ph_3C][B(C_6F_5)_4]$.

These reactions can also be carried out in solvent, provided the solvent is not very Lewis basic. However, benzene cannot be used as the solvent since the $[Ph_3Ge]^+$ cation is sufficiently electrophilic to undergo Friedel-Krafts reactions with benzene, as reported by Fu *et al.*.[39] The reactions shown in Equations 1 and 2 and Scheme 2 were carried out in hexane solvent and identical products were obtained as those from the reactions carried out in the absence of solvent, as shown by NMR spectroscopy and GC/MS.

The borane $B(C_6F_5)_3$ was shown to activate alkyl carbon – fluorine bonds both catalytically and stoichiometrically.[25] Furthermore, this same species serves for the catalytic hydrosilylation of carbon – oxygen double bonds.[26] In order to determine if a similar reactions to those described above would proceed using a catalytic amount of $B(C_6F_5)_3$ in the presence of Ph_3GeH, the hydrodefluorination reactions of 1,1,1-trifluorotoluene and benzoyl fluoride were attempted using $B(C_6F_5)_3$ as the catalyst. In this case, no hydrodefluorination of 1,1,1-trifluorotoluene was observed and although the hydrodefluorination of benzoyl fluoride did occur the conversion was only 18 % after 18 h.

Since Ozerov *et al.* reported that hydrodefluorination could be achieved using Et_3SiH in the presence catalytic amounts of tritylium halocarborane salts,[23] the reaction of Ph_3SiH with 1,1,1-trifluorotoluene and benzoyl fluoride in the presence of $[Ph_3C][B(C_6F_5)]$ was attempted. Upon addition of $[Ph_3C][B(C_6F_5)]$ to the mixture of the substrate and Ph_3SiH, a highly exothermic reaction was observed and partial conversion to toluene or benzaldehyde occurred. The reaction was also attempted using Ph_3CH in place of Ph_3GeH and, unsurprisingly, no reaction was observed.



Scheme 2. Defluorination of alkyl fluorides using Ph_3GeH.

In summary, the hydrodefluorination of acid fluorides by the $[Ph_3Ge]^+$ cation offers several advantages over previously reported methods. The reaction occurs without the need for a transition metal catalyst, the reaction is selective in that it avoids decarbonylation of the acid fluoride to the hydrocarbon and also over-reduction to the corresponding alcohol, and it is sustainable since the Ph_3GeF produced in the reaction can be easily recovered by chromatography or recrystallization and subsequently converted to Ph_3GeH using lithium aluminum hydride. This chemistry might serve for the remediation of organofluorine compounds that are currently known to be environmental hazards, such as the known carcinogen perfluorooctanoic acid (PFOA) and its related derivatives. It might also be possible to achieve partial hydrodefluorination of organofluorine compounds, which would be highly useful for the synthesis of pharmaceutical agents. Further investigations into this chemistry are presently underway.

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Conflicts of interest

There are no conflicts to declare.

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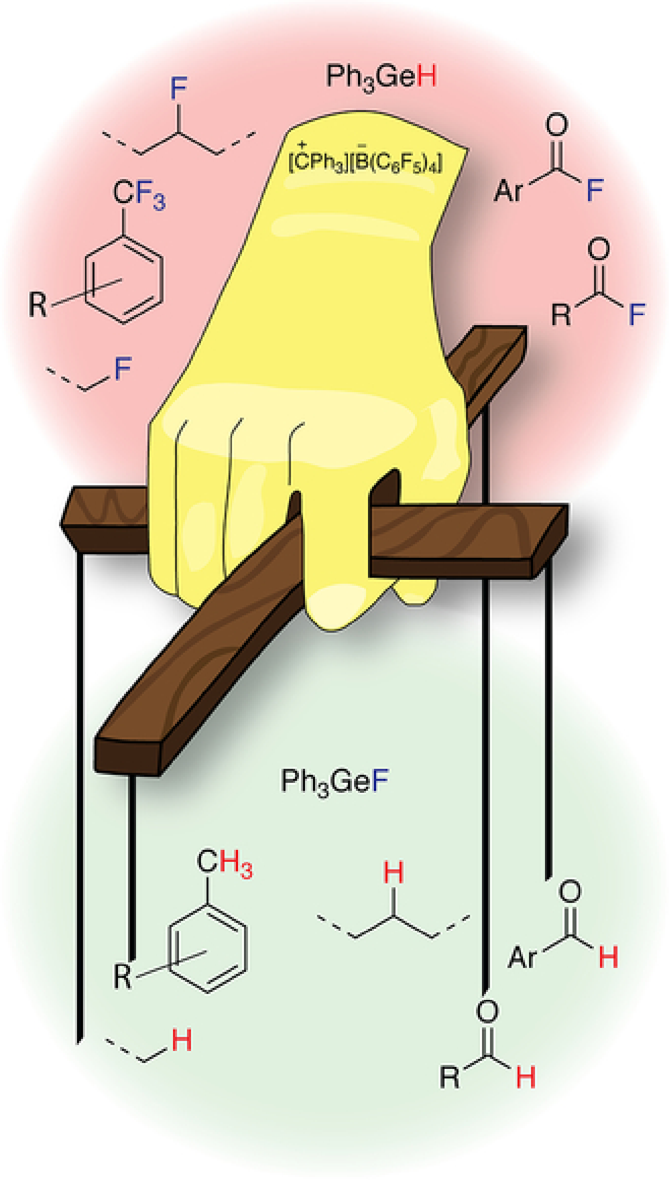

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