Single C–F Bond Activation of the CF_3 Group with a Lewis Acid: CF_3-Cyclopropanes as Versatile 4,4-Difluorohomoallylating Agents

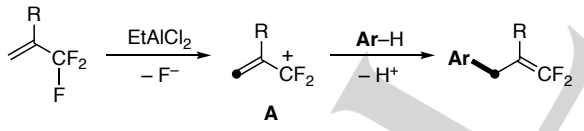
Kohei Fuchibe, Rie Oki, Hibiki Hatta, and Junji Ichikawa*[a]

Abstract: The selective activation of one C–F bond (single activation) of the CF_3 group on cyclopropanes was achieved for the first time. When (trifluoromethyl)cyclopropanes were treated with arenes, allylsilanes, silyl enol ethers, or hydrosilanes in the presence of Me_2AlCl, fluoride elimination and the subsequent ring opening proceeded to afford 4,4-difluorohomoallylated products. In the absence of external nucleophiles, an alkyl group of AlR_3 was effectively introduced to provide the corresponding 1,1-difluoroalkenes.

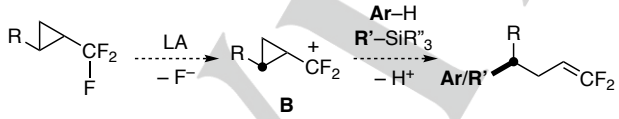
Among the C–F bond activation reactions of CF_3-bearing compounds,[1] the selective activation of one of the C–F bonds constitutes a great challenge, while the other two C–F bonds remain unreacted.[2] This is due to the harsh reaction conditions required to cleave the first sp^3 C–F bond, which is indeed stronger than the second and third C–F bonds. To date, the single activation of the CF_3 group has been mainly performed on $ArCF_3$ platforms,[3] which has facilitated the straightforward synthesis of various fluorine-containing aromatic compounds.[4][5]

Recently, we developed an ethylaluminum dichloride ($EtAlCl_2$)-promoted single activation of the CF_3 group on alkene moieties (2-trifluoromethyl-1-alkenes, CF_3-alkenes, Scheme 1a).[6] In this system, the fluorine substituents stabilize the α-carbocations by donating their unshared electron pair to the vacant p orbital of the cationic centers (*i.e.*, α-cation stabilizing effect of fluorine).[7] Thus, upon elimination of F^- from the CF_3-alkenes promoted by $EtAlCl_2$, stabilized *allylic* CF_2 cations (**A**) are generated, which in turn react with arenes (Ar–H) via a Friedel–Crafts-type mechanism leading to the corresponding 3,3-difluoroallylation products.[8]

(a) Single Activation of CF_3-Alkenes (3,3-Difluoroallylation)



(b) Single Activation of CF_3-Cyclopropanes (4,4-Difluoro-homoallylation): **this work**

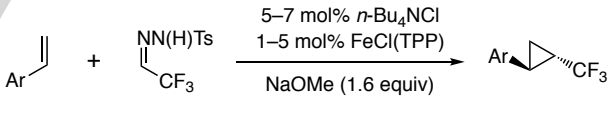


Scheme 1. Single Activation of CF_3-Alkenes and CF_3-Cyclopropanes.

Motivated by this success, we next turned our attention on the single activation of the CF_3 group on cyclopropane moieties [(trifluoromethyl)cyclopropanes, CF_3-cyclopropanes, Scheme 1b]. In this case, the cyclopropane ring, which has electron-donating C–C σ bonds,[9] would promote the elimination of F^- from CF_3-cyclopropanes to generate stabilized *cyclopropyl*-bearing CF_2 cations (**B**). Their ring opening and subsequent bond formation with nucleophiles (Ar–H or R'–$SiR"_3$) might lead to 4,4-difluorohomoallylated products. It is worth noting that there has been only a few ring opening reactions[10] and heterocycle formations[11] involving CF_3-cyclopropanes and that there is little precedent for C–C bond forming reactions of CF_3-cyclopropanes. In this paper, we describe a novel function of CF_3-cyclopropanes in organic synthesis as versatile 4,4-difluorohomoallylating agents.[12]

The required CF_3-cyclopropanes were prepared following our improved procedure for (trifluoromethyl)cyclopropanation. Carreira reported on the FeCl(TPP)-catalyzed (trifluoromethyl)-carbene transfer reaction of styrenes with diazo(trifluoro)ethane

Table 1. Preparation of CF_3-Cyclopropanes **1**.



(1.5–1.7 equiv) **1**

Entry	Ar	Solvent	Conditions	Yield [%] [a] (dr)[b]
1	C_6H_4*p*-Ph	Toluene	40 °C, 21 h	**1a**, 84 (*trans* only)
2	Ph	CH_2Cl_2	reflux, 71 h	**1b**, 35 (96:4)
3	C_6H_4*p*-*i*-Pr	CH_2Cl_2	reflux, 91 h	**1c**, 54 (94:6)
4	C_6H_4*p*-F	CH_2Cl_2	reflux, 132 h	**1d**, 37 (99:1)
5	C_6H_4*p*-Cl	Toluene	80 °C, 29 h	**1e**, 56 (*trans* only)
6	C_6H_4*o*-Cl	THF	40 °C, 22 h	**1f**, 59 (99:1)
7	C_6H_4*p*-O*t*-Bu	THF	40 °C, 63 h	**1g**, 69 (98:2)
8	1-naphthyl	THF	40 °C, 36 h to 60 °C, 25 h	**1h**, 80 (*trans* only)
9	C_6H_4*o*-Tol[c]	THF	40 °C, 6 h to reflux, 1 h	**1i**, 79 (99:1)
10	Ph, Ph[d]	THF	40 °C, 52 h	**1j**, 40

[a] Isolated yield. [b] *Trans*/*cis* ratio determined by ^{19}F NMR spectroscopy. [c] Tol = C_6H_4*p*-Me. [d] 1,1-Diphenylethene.

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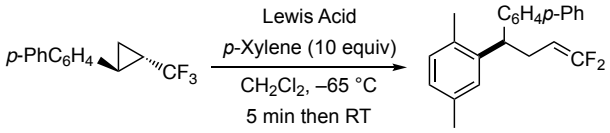
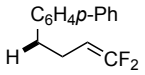
Table 2. Optimization of Lewis Acids.



1a **2a**

Entry	Lewis acid (equiv)	*t* [h]	Products [%][a]	
			2a	**1a**[b]
1	$BF_3{\cdot}OEt_2$ (3.6)	3.5[c]	0	94
2	$EtAlCl_2$ (1.2)	1	88[d]	0
3	Me_2AlCl (1.2)	1	92	–
4	$TiCl_4$ (3.5)	4	85	0
5	$ZrCl_4$ (1.1)	2	73	trace

[a] Ar = C_6H_4*p*-Ph. [a] ^{19}F NMR yield based on $PhCF_3$ as internal standard. [b] Recovery. [c] –65 °C, 5 min then reflux, 3.5 h. [d] Reduction product **3** was obtained in 3% yield.



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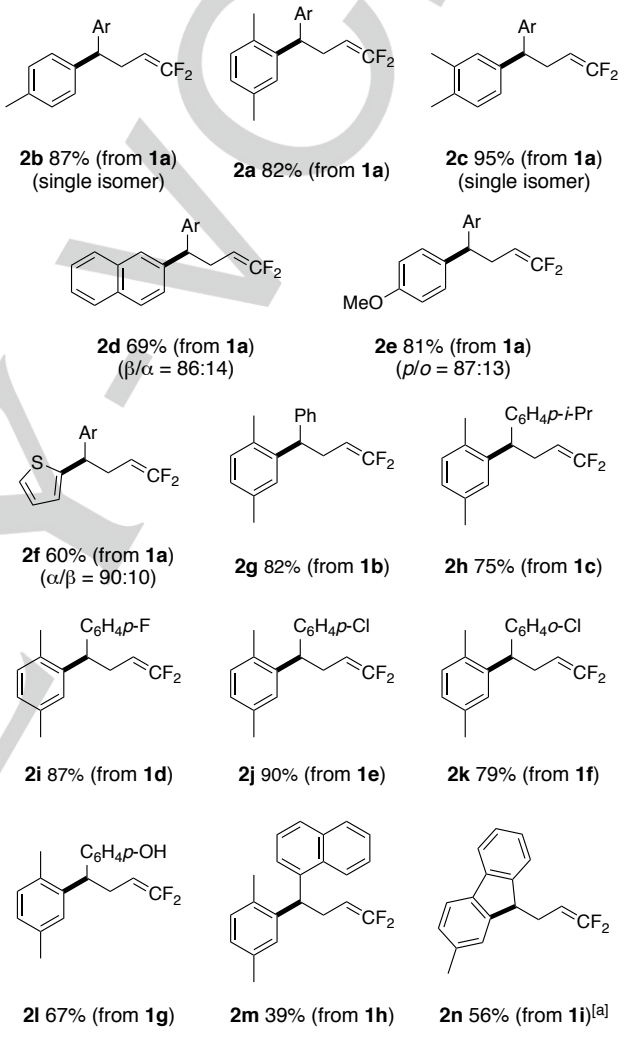
generated in situ from trifluoroethylamine hydrochloride (TPP = tetraphenylporphine).[13] We adopted Aggarwal's method, which facilitates the decomposition of sodiohydrazones to diazoalkanes with quaternary ammonium salt (PTC) at mild temperature (40 °C).[14] Thus, we treated styrenes with trifluoroacetaldehyde tosylhydrazone in the presence of tetrabutylammonium chloride, a FeCl(TPP) catalyst, and sodium methoxide (Table 1). The in situ-generated trifluoroacetaldehyde sodiohydrazone readily underwent decomposition, followed by the desired Fe(III)-catalyzed (trifluoromethyl)cyclopropanation. It should be noted that the generation of diazo(trifluoro)ethane was readily achieved starting from a commercially available trifluoroacetaldehyde hemiacetal.

As expected, the treatment of CF_3-cyclopropane with Lewis acids facilitated the desired single activation of the CF_3 group. A model compound bearing a *p*-phenylphenyl group (**1a**) reacted with *p*-xylene in the presence of aluminum, titanium, or zirconium Lewis acids to afford 4,4-difluorohomoallylation product **2a** in 73–88% yields (Entries 2, 4, and 5, Table 2). Products that would arise from the attack on the CF_2 carbon of **B** (Scheme 1b) were not observed (vide infra). $EtAlCl_2$ generated the hydride reduction product **3** in 3% yield (Entry 2), whereas dimethylaluminum chloride (Me_2AlCl) afforded the desired **2a** in an increased yield (92%) without formation of **3** (Entry 3).[15][16] [4c,d][5j,l,m][6]

With the optimized conditions in hand, the scope of the reaction regarding the arene substrates was investigated (Figure 1). Using Me_2AlCl, alkylated benzenes and naphthalene, anisole, and thiophene reacted with **1a** to afford the corresponding products **2a**–**f** in 60–95% yields. CF_3-Cyclopropanes **1b**–**g** also promoted difluorohomoallylation leading to the products **2g**–**l** in 67–90% yields. In the case of **2l**, removal of a *tert*-butyl group was observed. The reaction of **1h** afforded the corresponding **2m** (39% yield). The intramolecular reaction (**1i**) also proved successful, and the corresponding difluoroallylated fluorene **2n** was obtained in 56% yield.

The regioselectivity concerning the nucleophilic arene nuclei was considerably high, presumably due to steric effects: products **2b** (from toluene) and **2c** (from *o*-xylene) were obtained as single products. Meanwhile, naphthalene, which normally undergoes Friedel–Crafts-type reactions on its α carbon, reacted with CF_3-cyclopropane **1a** predominantly at the β carbon (β/α = 86:14).[17] This high and/or abnormal selectivity suggests that the regioselectivity is controlled by the greater steric hindrance of cation **B** (vide infra).



[a] An external arene was not used.

Figure 1. Difluorohomoallylation of Arenes [Isolated yield; Ar = C_6H_4*p*-Ph; Conditions: CF_3-cyclopropane **1**, arene (3.0 equiv), Me_2AlCl (1.2 equiv), CH_2Cl_2, –65 °C to 40 °C, 10 min].

The following observations could be extracted from a theoretical calculation (structural optimization), which suggest that the cation **B'** generated from a model CF_3-cyclopropane has a charge-localized and distorted structure (Figure 2): (i) In the model **B'**, the carbon at the position α to the fluorine substituents has a positive charge value of +0.52. (ii) In the original three-membered ring, the C–C bond distal to the methylene group is

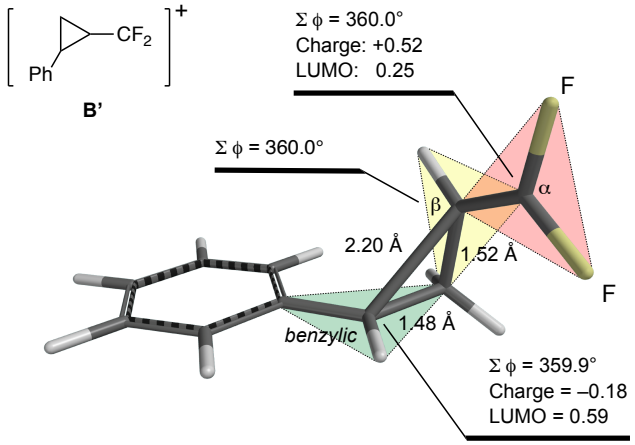
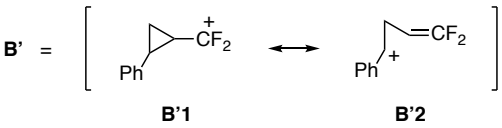


Figure 2. Optimized Structure of the Cation Generated from CF_3-Cyclopropane (DFT, B3LYP/6-31G*).



Scheme 2. Resonance Structures of Cation **B'**.

lengthened to 2.20 Å, which is much longer than the value of 1.51 Å of the parent cyclopropane. (iii) The carbons at the positions α and β to the fluorine substituents and the benzylic carbon have *sp*^{2}-hybridized, planar structures, whose sums of bond angles are almost 360°. Namely, **B'** has a major contribution from the canonical form **B'2** (Scheme 2). The regioselectivity of the reaction involving the CF_3-cyclopropanes stems most likely from the prevented cyclopropyl(difluoro)methylation due to (a) the relative destabilization of the arenium ion **D** compared to **C** (Figure 3)[8] by the electron-withdrawing inductive effect of the two fluorines and/or (b) the larger LUMO coefficient on the benzylic carbon of **B'** (0.59 vs. 0.25, Figure 2).

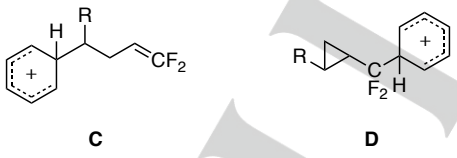
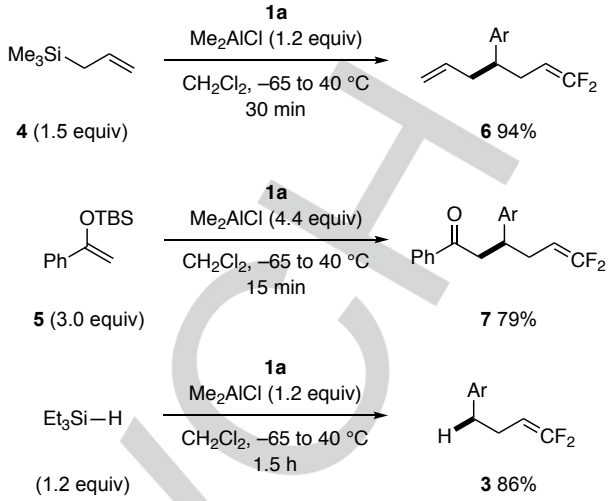


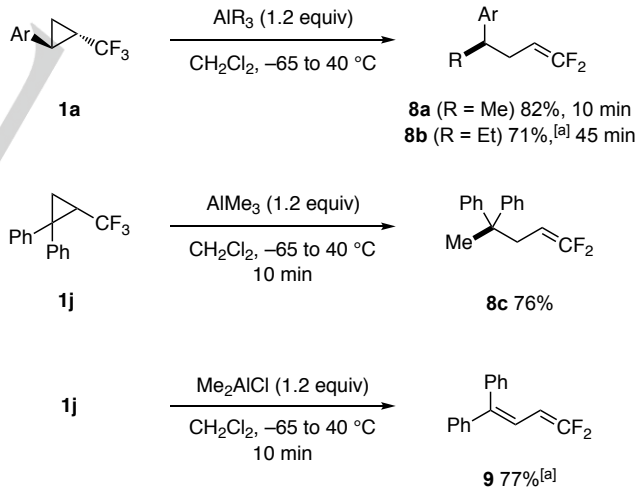
Figure 3. The structures of arenium ions **C** and **D**, leading to **2** and cyclopropyl(difluoro)methylation products (not shown), respectively.

The single activation of CF_3-cyclopropanes was also applicable to silicon nucleophiles (Scheme 3),[5m][15b,f] allowing the synthesis of functionalized 1,1-difluoroalkenes. Thus, allylsilane **4** and silyl enol ether **5** reacted with **1a** in the presence of Me_2AlCl to afford the corresponding difluorohomoallylation products **6** and **7** in 94% and 79% yields, respectively. Introduction of hydride with triethylsilane was facilitated under the identical conditions and the corresponding 1,1-difluoroalkene **3** was obtained in 86% yield.



Scheme 3. Difluorohomoallylation of Silicon Nucleophiles (TBS = Si*t*-BuMe_2, Ar = C_6H_4*p*-Ph).

By conducting the reaction in the absence of external nucleophiles, the alkyl groups on the aluminum Lewis acids were difluorohomoallylated with CF_3-cyclopropanes (Scheme 4).[4c][5l] When CF_3-cyclopropanes **1a** and **1j** were treated with trimethyl- or triethylaluminum, 1,1-difluoroalkenes **8a**–**c** were obtained in 82%, 71%, and 76% yields, respectively, whereas dimethylaluminum chloride reacted with **1j** to promote elimination (not methylation), leading to 1,1-difluoro-1,3-diene **9** in 77% yield.



[a] ^{19}F NMR yield based on $PhCF_3$.

Scheme 4. Alkylation and HF Elimination of CF_3-Cyclopropanes.

In summary, the aluminum Lewis acid-promoted single activation of CF_3-cyclopropanes was achieved for the first time. The reaction was triggered by the elimination of fluoride to generate difluorocarbocations, which were effective for the selective introduction of a 4,4-difluorohomoallyl unit into external and internal nucleophiles such as arenes and organosilicons. A significant regioselectivity was observed in arene nucleophiles.

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Keywords: bond activation • carbocations • cyclopropane • fluorine • trifluoromethyl group

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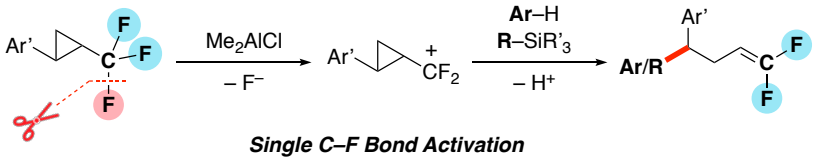
[17] It should be noted that toluene, *o*-xylene, and naphthalene afforded "normal" regioisomeric mixtures when subjected to the previous CF_3-alkene/$EtAlCl_2$ system (ref 6).

COMMUNICATION



Single C–F Bond Activation

The selective activation of one C–F bond (single activation) of the CF_3 group on cyclopropanes was achieved for the first time. When (trifluoromethyl)cyclopropanes were treated with arenes, allylsilanes, silyl enol ethers, or hydrosilanes in the presence of Me_2AlCl, fluoride elimination and the subsequent ring opening proceeded to afford 4,4-difluorohomoallylated products. In the absence of external nucleophiles, an alkyl group of AlR_3 was effectively introduced to provide the corresponding 1,1-difluoroalkenes.

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