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Nucleophilic difluoromethylation and difluoromethylenation using bromodifluoromethyl phenyl sulfone

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Abstract

Tetrakis(dimethylamino)ethylene (TDAE) was found to be an effective electron-transfer agent that promoted the reactions of bromodifluoromethyl phenyl sulfone with aldehydes to give structurally diverse (benzenesulfonyl)difluoromethylated alcohols in good yield, which can be further transformed into difluoromethyl alcohols and 1,1-difluoro-1-alkenes via reductive desulfonylation and Julia olefination, respectively.

Keywords: Fluorine; Bromodifluoromethyl phenyl sulfone; Difluoromethyl alcohol; 1,1-Difluoro-1-alkene

1. Introduction

gem-Difluorinated compounds, such as difluoromethyl alcohols and 1,1-difluoro-1-alkenes, are highly useful for pharmaceutical or agrochemical applications, since the difluoromethylene functionality (CF_2) is known to be an isostere and isopolar to an oxygen atom [1]. Difluoromethyl group (CF_2H) can act as both a liphophilic isostere of hydroxyl group (OH) and a hydrogen donor through hydrogen bonding [2], while *gem*-difluorovinyl functionality can act as a bioisostere for aldehydes and ketones [3] with a different reactivity pattern. Many functionalized difluoromethyl compounds and 1,1-difluoro-1-alkenes are used as enzyme inhibitors [4], pesticides [5], among others. Moreover, 1,1-difluoro-1-alkenes can be further converted into different fluorinated compounds and polymers [6]. Thus, the development of effective ways for the preparation of these two classes of *gem*-difluorinated compounds is of great significance. Recently, we have reported methods [7] to introduce difluoromethyl and difluoromethylene functionalities using a difluoromethyl phenyl sulfone as a synthon under highly basic conditions.

Bromodifluoromethyl phenyl sulfone ($PhSO_2CF_2Br$) was first synthesized by Burton and coworkers in 1981 [8], however, its synthetic application has rarely been explored. Recently, we have reported the use of bromodifluromethyl phenyl sulfone for the preparation of fluroalkylsilanes [9]. Tetrakis(dimethylamino)ethylene (TDAE), as an efficient reductant to generate substituted difluoromethylated carbanions from halo-difluoromethyl precursors, has been reported by Dolbier and coworkers [10]. However, the reaction between TDAE and bromodifluoromethyl phenyl sulfone to generate (benzenesulfonyl)difluoromethyl anion ($PhSO_2CF_2^-$), has not been reported. In this paper, we describe the efficient TDAE-mediated nucleophilic reactions between bromodifluoromethyl phenyl sulfone (**1**) and aldehydes (**2**). The resulting (benzensulfonyl)difluoromethyl alcohols (**3**) can be further transformed into difluoromethyl alcohols (**4**) and 1,1-difluoro-1-alkenes (**6**) via reductive desulfonylation and Julia olefination, respectively (Scheme 1) [11].

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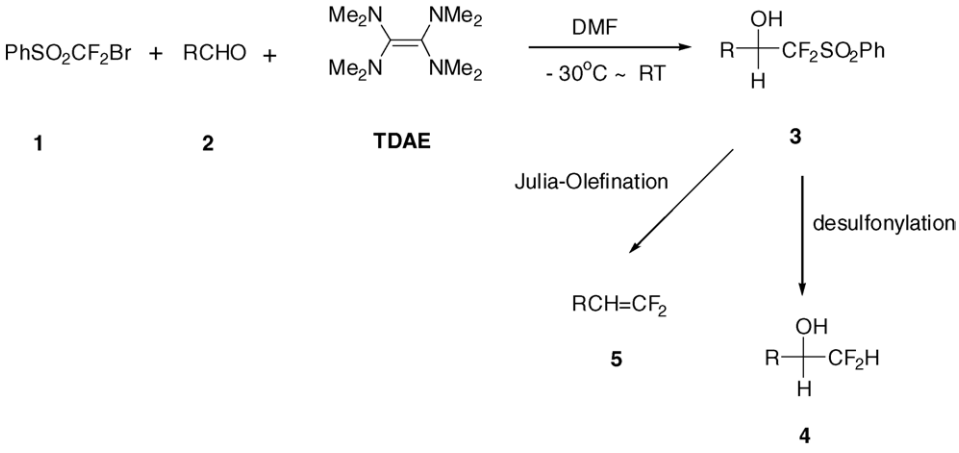


Scheme 1. Difluoromethylation of aldehydes using **1**.

2. Results and discussion

Nucleophilic addition reactions between **1** and **2** were carried out according to the following procedure: under an argon atmosphere, the TDAE was added dropwise to the mixture of **1** and **2** in DMF solution under 60 W sun lamp irradiation. The reaction conditions were carefully optimized by using different reactant ratios, reaction temperatures and light intensities, and we found the best product yields can be obtained with the following reaction conditions: 2.2 equivalents of TDAE, 2.2 equivalents of sulfone (**1**) and 1.0 equivalents of aldehyde (**2**) in DMF were stirred under the sun lamp at −30 °C for 1 h and then at room temperature for 6 h. A variety of (benzenesulfonyl)difluoromethylated alcohols (**3**) were prepared in moderate to good yields as shown in Table 1. However, the reactions of 1/TDAE system with ketones gave very poor yields of products (10–30%) because of steric constrains.

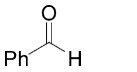
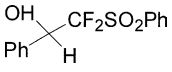
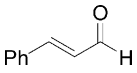
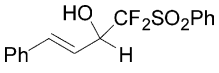
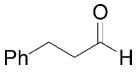
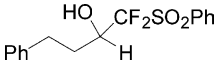
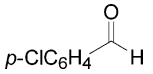
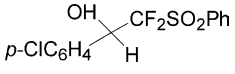
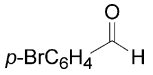
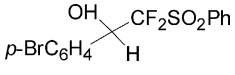
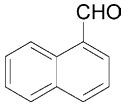
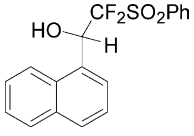
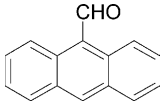
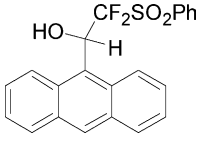
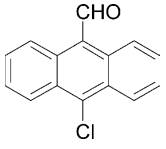
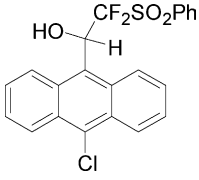
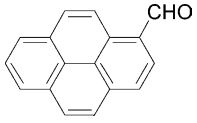
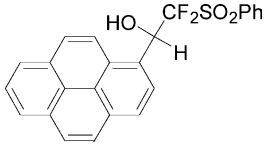
The mechanism of this reaction is proposed in Scheme 2, which is similar to the early reports [10]. Initially, an orange–red charge-transfer complex is formed between **1** and TDAE. Then two electrons from TDAE is transferred to bromodifluoromethyl phenyl sulfone to generate (benzenesulfonyl)difluoromethyl anion ($PhSO_2CF_2^-$) and Br^-. (Benzenesulfonyl)difluoromethyl anion undergoes further addition into aldehydes to give (benzenesulfonyl)difluoromethyl alcohols **3**. Here, the sun lamp irradiation is necessary for inducing the electron transfer from TDAE to **1**.

The resulting (benzenesulfonyl)difluoromethyl alcohols are very useful intermediates, which can be further converted into various fluorinated materials [12]. Two types of reactions of the difluoromethyl alcohols were carried out to demonstrate the utility of alcohols: the reductive desulfonylation to give difluoromethyl compounds **4** and the Julia olefination to give 1,1-difluoro-1-alkenes **6**. The results are outlined in Scheme 3.

Reductive desulfonylations of **3** were completed to give difluoromethyl alcohols **4** in good yields by using 5 equivalents 10% Na(Hg) amalgam and 5 equivalents of Na_2HPO_4 in methanol at −20 to −10 °C over 1 h. The results of desulfonylations are shown in Table 2.

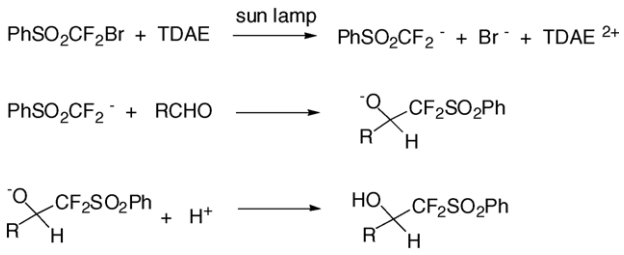
Julia-type olefination of **3** were also successfully achieved to give 1,1-difluoro-1-alkenes **6** in good yields. First, the alcohols were converted into the mesylates by using 2 equivalents of MsCl, 4 equivalents of Et_3N, and catalytic amount of 4-dimethylaminopyridine (DMAP) in CH_2Cl_2 at 0 °C over 2 h. Then the mesylates underwent the reductive elimination to give 1,1-difluoro-1-alkenes **5** by treatment with 6 equivalents of 10% Na(Hg), 4 equivalents of Na_2HPO_4 in CH_3OH at −40 to 0 °C for 1 h. The Julia olefinations of (benzenesufonyl)difluoromethyl alcohols (**3**) are more difficult than that of the alcohols without fluorine atoms because the high electronegativity of fluorine atoms in the carbanion intermediate make it easier to undergo the protonation to form difluoromethyl compounds **4**. From the ^{19}F NMR spectrum of the reaction mixture, we can see that both the 1,1-difluoro-1-alkenes and the difluoromethyl alcohols are formed. Thus, the choice of the right leaving group becomes very important for the elimination of these (benzenesulfonyl)difluoromethyl alcohol derivatives. We explored acetate (Ac), tosylate (Ts), triflate, and mesylate groups as the protecting groups for the alcohol, and found that the mesylates were the best for the further reductive elimination to give 1,1-difluoro-1-alkenes **6**. This suggests that neither the good leaving groups such as the triflate ($-OSO_2CF_3$) and tosylate ($-OSO_2C_6H_4CH_3$) nor the relatively stable leaving group such as acetate (OAc) were suitable for this olefination protocol. This can be surmised by considering that reactive leaving groups can be easily displaced before the desulfonylation step and making further reductive elimination difficult, while the stable leaving group is difficult to be removed in the reductive elimination of the carbanion intermediate, resulting in the formation of difluoromethyl compounds. Considering the protonation side-reaction, we also tried SmI_2 as the reducing agent [11] in the reductive elimination step to avoid using the protic solvent MeOH, which is necessary in Na(Hg) reduction. However, the result was not ideal and other products were

Table 1
Nucleophilic (benzenesulfonyl)difluoromethylation of aldehydes using $PhSO_2CF_2Br$/TDAE in DMF at −30 °C ∼ RT under sun-lamp irradiation

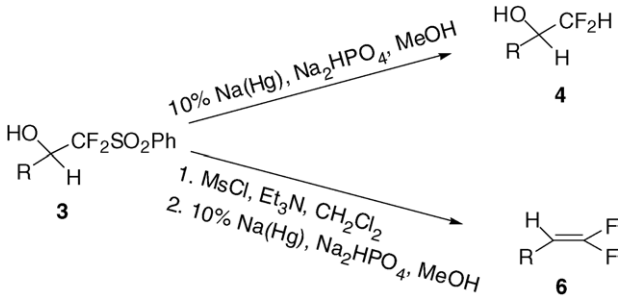
Entry	Aldehyde **2**	Product **3**	Yield[a] (%)
a			74
b			40
c			53
d			65
e			55
f			70
g			82
h			57
i			80

[a] Isolated yields.

formed rather than the expected alkenes. Finally, we optimized the Julia olefination reaction of (benzenesulfonyl)difluoromethyl alcohols with the OMs group as the leaving group and the Na(Hg) as the reducing reagent for the elimination step. The results are listed in Table 3.



Scheme 2. Mechanism of nucleophilic reaction of aldehydes with $PhSO_2CF_2Br$/TDAE reagent.



Scheme 3. Reductive desulfonylation and Julia olefination of **3**.

3. Conclusions

The nucleophilic reactions of bromodifluoromethyl phenyl sulfone with aldehydes in the presence of TDAE were completed successfully. The resulting difluoromethyl alcohols are very useful intermediates, which can undergo both reductive desulfonylation to give difluoromethyl alcohols and via Julia olefination to give 1,1-difluoro-1-alkenes in good yields. The methodology provides convenient and efficient ways to introduce the difluoromethyl group and 1,1-difluorovinyl functionality into the organic compounds.

4. Experimental

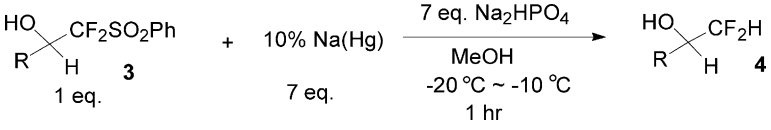
4.1. General

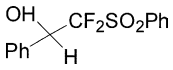
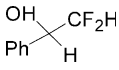
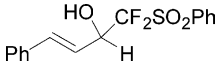
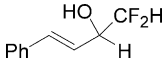
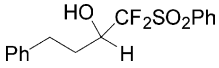
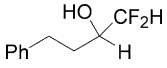
Materials and Instrumentation. Unless otherwise mentioned, all chemicals were purchased from commercial sources. Bromodifluoromethyl phenyl sulfone **1** was prepared using known procedures [8]. CH_2Cl_2 was distilled over calcium hydride. Silica gel column chromatography was used to isolate the products using 60–200 mesh silica gel. ^1H, ^{13}C, and ^{19}F NMR spectra were recorded on either a 400 MHz or 360 MHz NMR spectrometer. ^1H NMR chemical shifts were determined relative to the signal of residual proton in $CDCl_3$ δ 7.26 or Acetone-d_6 δ 2.04. ^{13}C NMR chemical shifts were determined relative to the ^{13}C signal of sovent: $CDCl_3$ δ 77.0 or Acetone-d_6 δ 29.8. ^{19}F NMR chemical shifts were determined relative to internal $CFCl_3$ at δ 0.0. High-resolution mass data of low boiling compounds were recorded on a GC chromatograph with micromass GCT (time of flight) mass spectrometer. Other high-resolution mass data were recorded on a high-resolution mass spectrometer in the EI mode.

4.2. Typical procedure for nucleophilic reactions of *1* with aldehydes

Under an argon atmosphere, bromodifluoromethyl phenyl sulfone **1** (600 mg, 2.2 mmol), 5 mL DMF, and benzaldehyde (106.1 mg, 1 mmol) were added into a dry Schlenk flask and contents were cooled to −30 °C. After

Table 2
Desulfonylation of (benzenesulfonyl)difluoromethyl alcohols **3** using Na(Hg) amalgam



Entry	Carbinol **3**	Product **4**	Yield[a] (%)
a			79
b			84
c			86

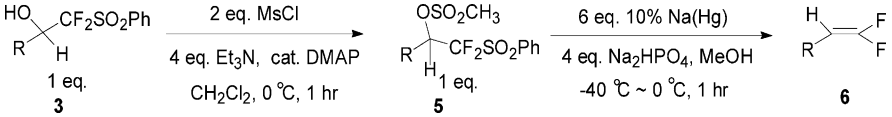
[a] Isolated yields.

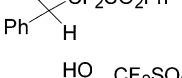
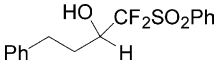
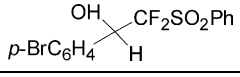
stirring the mixture for 15 min, TDAE (440 mg, 2.2 mmol) was added in dropwise. Under the irradiation of sun lamp, the reaction mixture was stirred at −30 °C for 1 h and then at room temperature for 6 h. The completion of the reaction was monitored by ^{19}F NMR. The resulting orange–red solution was filtered and the solid was washed with 100 mL ether. After the ether layer was separated from the DMF layer, the DMF layer was hydrolyzed with 50 mL brine and extracted by ether (20 mL × 3). Then the combined ether layer was washed by brine five times and dried over magnesium sulfate. After removing the solvent by a rotary evaporator, the crude product was further purified by silica gel column chromatography (first hexane: ethyl acetate = 7:1, then hexane:ethyl acetate = 1:1) to give pure *2-benzenesulfonyl-2,2-difluoro-1-phenylethanol* (**3a**) (221 mg, 74% yield) as a colorless crystal. ^{1}H NMR ($CDCl_3$): δ 3.92 (d, J = 4.4 Hz, 1H); 5.60 (dd, J = 21 Hz, 3 Hz, 1H); 7.36 (m, 3H); 7.48 (m, 2H); 7.56 (t, J = 8 Hz, 2H); 7.70 (t, J = 8 Hz, 1H); 7.98 (d, J = 8 Hz, 2H). ^{19}F NMR ($CDCl_3$): δ −104.4 (dd, J = 238 Hz, 3 Hz, 1F); −119.9 (dd, J = 238 Hz, 21 Hz, 1F). MS (EI, *m/z*): 298 (M^+), 156, 140, 127, 107, 77. The data are consistent with the previous report [12].

(E)-1-Benzenesulfonyl-1,1-difluoro-4-phenyl-3-buten-2-ol **(3b):** 40% yield, white solid. ^{1}H NMR ($CDCl_3$): δ 3.07 (d, J = 5.5 Hz, 1H); 5.15 (m, 1H); 6.25 (dd, J = 15.8 Hz, 6.7 Hz, 1H); 6.89 (d, J = 15.8 Hz, 1H); 7.29–7.43 (m, 5H); 7.63(t, J = 8 Hz, 2H); 7.77 (t, J = 8 Hz, 1H); 8.00 (d, J = 8 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 70.8 (dd, J = 23 Hz, 21 Hz); 120.3 (dd, J = 293 Hz, 290 Hz); 120.3 (t, J = 2.3 Hz); 126.9; 128.5; 128.6; 129.3; 130.6; 132.8; 135.5; 135.6; 136.4. ^{19}F NMR ($CDCl_3$): δ −107.0 (dd, J = 237 Hz, 6 Hz, 1F); −116.6 (dd, J = 237 Hz, 17 Hz, 1F). MS (EI, *m/z*): 324 (M^+), 207, 133, 115, 105, 77. HRMS (EI): *m/z* calcd for $C_{16}H_{14}F_2O_3S$ (M^+) 324.0632, found 324.0642.

1-(Benzenesulfonyl)difluoromethyl-3-phenylpropanol **(3c):** 53% yield, colorless liquid. ^{1}H NMR ($CDCl_3$): δ 2.09 (m, 2H); 2.77 (m, 1H); 2.97 (m, 1H); 3.05 (b, 1H); 4.45 (m, 1H); 7.22–7.34 (m, 5H); 7.62 (t, J = 8 Hz, 2H); 7.77 (t, J = 8 Hz, 1H); 8.00 (d, J = 8 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 30.9 (b, 2C); 68.6 (dd, J = 24 Hz, 20 Hz); 121.2 (dd, J = 294 Hz, 292 Hz); 126.2; 128.4; 128.5; 129.3; 130.5; 132.7; 135.5; 140.5. ^{19}F NMR ($CDCl_3$): δ −109.2 (dd, J = 238 Hz, 6 Hz, 1F); −116.9 (dd, J = 238 Hz, 19 Hz, 1F). MS (EI, *m/z*): 326 (M^+), 308, 167, 143, 104, 91, 77. HRMS

Table 3
Julia olefination reactions of (benzenesulfonyl)difluoromethyl alcohols **3**



Entry	Carbinol **3**	RCH=CF_2 **6**	Yield[a] (%)
a		PhCH=CF_2	60
c		Ph$(CH_2)_2$CH=CF_2	84
e		*p*-BrC_6H_4CH=CF_2	70

[a] Isolated yields.

(EI): *m/z* calcd for $C_{16}H_{16}F_2O_3S$ (M^+) 326.0788, found 326.0795.

4-Chloro-[difluoro(phenylsulfonyl)methyl]-benzenemethanol **(3d):** 65% yield, white solid. ^{1}H NMR ($CDCl_3$): δ 3.46 (s, 1H); 5.57 (dd, J = 20.9 Hz, 2.3 Hz, 1H); 7.35 (d, J = 8.5 Hz, 2H); 7.42 (d, J = 8.4 Hz, 2H); 7.62 (t, J = 8.1 Hz, 2H); 7.78 (t, J = 8.1 Hz, 1H); 7.99 (d, J = 8.1 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 70.6 (dd, J = 26.4 Hz, 20.2 Hz); 119.8 (dd, J = 298.7 Hz, 289.6 Hz); 128.6; 129.38; 129.41; 130.6; 131.9; 132.3; 135.5; 135.7. ^{19}F NMR ($CDCl_3$): δ −104.6 (d, J = 241.5 Hz, 1F); −119.8 (dd, J = 241.5 Hz, 20.1 Hz, 1F). MS (EI, *m/z*): 332 (M^+), 143, 141, 77.

4-Bromo-[difluoro(phenylsulfonyl)methyl]-benzenemethanol **(3e):** 55% yield, light yellow solid. ^{1}H NMR ($CDCl_3$): δ 3.57 (s, 1H); 5.55 (d, J = 21.0 Hz, 1H); 7.35 (d, J = 8.4 Hz, 2H); 7.51 (d, J = 8.6 Hz, 2H); 7.62 (t, J = 8.2 Hz, 2H); 7.77 (t, J = 7.4 Hz, 1H); 7.99 (d, J = 8.1 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 70.6 (dd, J = 25.5 Hz, 19.5 Hz); 119.8 (dd, J = 300.4 Hz, 289.8 Hz); 123.7; 129.4; 129.7; 130.6; 131.6; 135.7. ^{19}F NMR ($CDCl_3$): δ −104.6 (d, J = 235.8 Hz, 1F); −119.7 (dd, J = 239.8 Hz, 21.0 Hz, 1F). MS (EI, *m/z*): 376 (M^+), 306, 235, 218, 185, 157, 136, 125, 106, 94. HRMS (EI): *m/z* calcd for $C_{14}H_{11}O_3SF_2Br$ (M^+) 375.9580, found 375.9577.

α-[(Benzenesulfonyl)difluoromethyl]-1-naphthalenemethanol **(3f):** 70% yield, white solid. ^{1}H NMR ($CDCl_3$): δ 3.72 (d, J = 4.2 Hz, 1H); 5.77 (ddd, J = 21.6 Hz, 4.2 Hz, 2.9 Hz, 1H); 7.48–7.60 (m, 5H); 7.71 (t, J = 7.4 Hz, 1H); 7.81–7.87 (m, 3H); 7.95–8.03 (m, 3H). ^{13}C NMR ($CDCl_3$): δ 71.3 (dd, J = 26.4 Hz, 19.7 Hz); 120.3 (dd, J = 298.9 Hz, 289.1 Hz); 124.9; 126.3; 126.7; 127.6; 128.0; 128.18; 128.21; 129.3; 130.6; 131.0; 132.6; 132.8; 133.7; 135.5. ^{19}F NMR ($CDCl_3$): δ −104.0 (d, J = 238.6 Hz, 1F); −119.2 (dd, J = 241.8 Hz, 21.6 Hz, 1F). MS (EI, *m/z*): 348 (M^+), 157, 129, 77.

α-[(Benzenesulfonyl)difluoromethyl]-9-anthracenemethanol **(3g):** 82% yield, yellow solid. ^{1}H NMR ($CDCl_3$): δ 3.63 (d, J = 4.2 Hz, 1H); 7.33 (dd, J = 26.9 Hz, 4.2 Hz, 1H); 7.42-7.66 (m, 6H); 7.76 (t, J = 7.5 Hz, 1H); 8.01 (dd, J = 14.2 Hz, 8.5 Hz, 2H); 8.10 (d, J = 7.8 Hz, 2H); 8.21 (d, J = 8.9 Hz, 1H); 8.52 (s, 1H); 9.02 (d, J = 9 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 67.8 (dd, J = 28.4 Hz, 20.0 Hz); 121.5 (dd, J = 305.3 Hz, 289.3 Hz); 122.6; 123.8; 124.8; 125.0; 126.0; 127.3; 128.9; 129.4; 130.67; 130.75; 132.3; 135.7. ^{19}F NMR ($CDCl_3$): δ −101.9 (d, J = 237.3 Hz, 1F); −113.6 (ddd, J = 236.8 Hz, 26.8 Hz, 3.9 Hz, 1F). MS (EI, *m/z*): 398 (M^+), 207, 179, 178, 77.

α-[(Benzenesulfonyl)difluoromethyl]-10-chloro-9-anthracenemethanol **(3h):** 57% yield, yellow solid. ^{1}H NMR ($CDCl_3$): δ 3.69 (d, J = 4.4 Hz, 1H); 7.35 (dd, J = 26.6 Hz, 4.3 Hz, 1H); 7.49-7.71 (m, 6H); 7.77 (t, J = 7.5 Hz, 1H); 8.09 (d, J = 7.9 Hz, 2H); 8.24 (d, J = 8.2 Hz, 1H); 8.61 (dd, J = 18.1 Hz, 8.6 Hz, 2H); 9.07 (d, 8.2 Hz, 1H). ^{13}C NMR ($CDCl_3$): δ 67.7 (dd, J = 27.9 Hz, 19.6 Hz); 121.3 (dd, J = 305.2 Hz, 289.7 Hz); 122.9; 123.7; 125.2; 126.0; 126.2; 126.5; 127.5; 129.4; 130.8; 132.0; 132.7; 135.8. ^{19}F NMR ($CDCl_3$): δ −101.8 (d, J = 237.8 Hz, 1F); −113.3 (ddd, J = 237.3 Hz, 27.1 Hz, 3.6 Hz, 1F). MS (EI, *m/z*): 432 (M^+), 243, 241, 240, 212, 178, 176, 77.

α-[(Benzenesulfonyl)difluoromethyl]-1-Pyrenemethanol **(3i):** 80% yield, yellow solid. ^{1}H NMR (CD_3COCD_3): δ 6.18 (d, J = 6.2 Hz 1H); 6.80 (ddd, J = 21.7 Hz, 5.9 Hz, 3.4 Hz, 1H); 7.71 (t, J = 8.0 Hz, 2H); 7.84 (t, J = 7.6 Hz, 1H); 8.01–8.33 (m, 9H); 8.40 (t, J = 8.8 Hz, 2H). ^{13}C NMR (CD_3COCD_3): δ 67.9 (dd, J = 27.9 Hz, 19.6 Hz); 122.8 (dd, J = 299.2 Hz, 286.6 Hz); 123.5; 125.1; 125.2; 125.6; 126.3; 126.6; 127.1; 127.3; 128.2; 128.9; 129.0; 130.00; 130.05; 130.2; 131.3; 131.4; 132.1; 132.6; 135.4; 136.2. ^{19}F NMR (CD_3COCD_3): δ −102.7 (d, J = 239.1 Hz, 1F) −116.6 (dd, J = 239.7 Hz, 21.3 Hz, 1F). MS (EI, *m/z*): 422 (M^+), 231, 203, 202, 77.

4.3. Typical procedure for reductive desulfonylation

In a 50-mL Schlenk flask with Argon protection, 2-benzenesulfonyl-2, 2-difluoro-1-phenylethanol (**3a**) (150 mg, 0.5 mmol) and Na_2HPO_4 (497 mg, 3.5 mmol) in 10 mL anhydrous methanol were added in. After the solution was cooled to −20 °C, Na/Hg amalgam (10 wt.% Na in Hg, 805 mg, 3.5 mmol) was added. The reaction mixture was stirred at −20 to 0 °C for 1.5 h. Then the solution was diluted with Et_2O and the liquid was decanted from the solid. After removing the solvent of the liquid phase by rotate evaporator, 30 mL saturated NaCl solution was added, which was then extracted by Et_2O three times. The combined ether solution was dried with $MgSO_4$ and the solvent was removed to give pure product *2,2-difluoro-1-phenylethanol* **(4a)** (62 mg, 79% yield) as a white solid. ^{1}H NMR ($CDCl_3$): δ 2.44 (b, 1H); 4.82 (td, J = 10.5 Hz, 4.8 Hz, 1H); 5.77 (td, J = 56.4 Hz, 4.8 Hz, 1H); 7.41 (m, 5H). ^{13}C NMR ($CDCl_3$): δ 73.6 (t, J = 20.0 Hz); 115.8 (t, J = 245.9 Hz); 127.1; 128.6; 129.0; 135.8 (t, J = 3.7 Hz). ^{19}F NMR ($CDCl_3$): δ −127.8 (ddd, 284.8 Hz, 56.5 Hz, 9.9 Hz, 1F); −128.3 (ddd, 284.8 Hz, 56.5 Hz, 11 Hz, 1F). MS (EI, *m/z*): 158 (M^+), 107, 79, 77. The data are consistent with the previous report [13].

1-Benzenesulfonyl-1,1-difluoro-3-buten-2-ol **(4b):** 84% yield, colorless liquid. ^{1}H NMR ($CDCl_3$): δ 2.71 (b, 1H); 4.42 (m, 1H); 5.69 (td, J = 56 Hz, 4.6 Hz, 1H); 6.18 (dd, J = 16 Hz, 6.4 Hz, 1H); 6.76 (d, J = 16 Hz, 1H); 7.24-7.41 (m, 5H). ^{13}C NMR ($CDCl_3$): δ 72.1 (t, J = 24.5 Hz); 115.4 (t, J = 245 Hz); 122.4 (t, J = 4 Hz); 126.7; 128.4; 128.6; 134.8; 135.7. ^{19}F NMR ($CDCl_3$): δ −128.7 (ddd, J = 285 Hz, 56 Hz, 11 Hz, 1F); −129.6 (ddd, J = 285 Hz, 56 Hz, 10 Hz, 1F). MS (EI, *m/z*): 184 (M^+), 133, 115, 77. The data are consistent with the previous report [14].

1,1-Difluoro-4-phenyl-2-butanol **(4c):** 86% yield, colorless liquid. ^{1}H NMR ($CDCl_3$): δ 1.85 (m, 1H); 1.92 (m, 1H); 2.13 (b, 1H); 2.75 (m, 1H); 2.91 (m, 1H); 3.74 (m, 1H); 5.63 (td, J = 56 Hz, 4.2 Hz, 1H); 7.20–7.35 (m, 5H). ^{13}C NMR ($CDCl_3$): δ 30.9; 31.5 (t, J = 3.3 Hz); 70.2 (t, J = 23.5 Hz);

116.3 (t, J = 244 Hz); 126.2; 128.4; 128.5; 140.9. ^{19}F NMR ($CDCl_3$): δ −130.0 (dd, J = 56 Hz, 11 Hz). MS (EI, m/z): 186 (M^+), 168, 117, 91, 77. The data are consistent with the previous report [13].

4.4. Typical procedure for Julia olefination of **3**

A solution of **3a** (150 mg, 0.5 mmol) and 4-*N,N*-dimethylaminopyridine (DMAP) (catalytic amount) in 5 mL CH_2Cl_2 under Ar was cooled to 0 °C and treated with Et_3N (0.28 mL, 2 mmol). After stirring for 20 min, methanesulfonyl chloride (0.08 mL, 1 mmol) was added dropwise and the reaction mixture was stirred at 0 °C for 2 h. The reaction mixture was quenched by buffer solution and extracted with EtOAc (3 × 25 mL). The combined organic solution was washed by brine (2 × 25 mL) and dried over $MgSO_4$. After removing the solvent, the crude product was purified by column chromatography (9:1 hexane: EtOAc) to give mesylate **5a** 169 mg, 90% yield. ^{1}H NMR ($CDCl_3$): δ 3.06 (s, 3H); 6.26 (dd, J = 16.5 Hz, 6.7 Hz, 1H); 7.44 (m, 3H), 7.53 (d, J = 7.8 Hz, 2H); 7.61 (t, J = 7.2 Hz, 2H); 7.76 (t, J = 7.7 Hz, 1H); 7.97 (d, J = 8.2 Hz, 2H). ^{19}F NMR ($CDCl_3$): δ −105.5 (dd, J = 243.0 Hz, 6.7 Hz, 1F); −113.2 (dd, J = 243.9 Hz, 16.5 Hz, 1F). MS (EI, m/z): 376.1 (M^+), 185, 140, 107, 77. The mesylate **5a** (100 mg, 0.27 mmol) in anhydrous MeOH (5 mL) was cooled to −40 °C and treated with Na_2HPO_4 (151 mg, 1.06 mmol) and 10% Na(Hg) (368 mg, 1.60 mmol). After stiring for 1 h at −20 °C, the reaction mixture was diluted with 30 mL EtOAc and decanted from the solid Hg residue. The organic solution was washed by brine 30 mL and the brine was extracted with EtOAc (3 × 25 mL). The combined organic solution was dried over $MgSO_4$, condensed by reduced pressure and purified by column chromatography (20:1 hexane: EtOAc) to give 2,2-difluoroethenylbenzene **(6a)** 22 mg, 60% yield as colorless liquid. ^{19}F NMR ($CDCl_3$): δ −82.9 (dd, J = 33.6 Hz, 27.4 Hz, 1F), −84.8 (d, J = 31.7 Hz, 1F). The characterization data is consistent with that early reported [15].

Mesylate **(5c):** 87% yield, white solid. ^{1}H NMR ($CDCl_3$): δ 3.20 (s, 3H); 5.46 (m, 1H); 7.29 (m, 3H); 7.37 (t, J = 6.9 Hz, 2H); 7.68 (t, J = 7.4 Hz, 2H); 7.85 (t, J = 7.9 Hz, 1H); 8.01 (d, J = 8.4 Hz, 2H). ^{13}C NMR ($CDCl_3$): δ 30.7; 31.1; 39.1; 76.2 (dd, J = 26.0 Hz, 20.4 Hz); 119.5 (dd, J = 286.0 Hz, 283.2 Hz); 126.4; 128.5; 128.6; 129.5; 130.7; 132.2; 135.9; 139.6. ^{19}F NMR ($CDCl_3$): δ −107.2 (d, J = 242.9 Hz, 1F); −110.0 (d, J = 245.0 Hz, 1F).

Mesylate **(5e):** 86% yield, light yellow solid. ^{1}H NMR ($CDCl_3$): δ 3.14 (s, 3H); 6.22 (dd, J = .7 Hz, 6.8 Hz, 1H); 7.41 (d, J = 8.3 Hz, 2H); 7.57 (dd, J = 8.7 Hz, 2H); 7.62 (t, J = 7.9 Hz, 2H); 7.78 (t, J = 7.5 Hz, 1H); 7.96 (d, J = 7.4 Hz, 2H). ^{19}F NMR ($CDCl_3$): δ −105.6 (d, J = 243.1 Hz, 1F); −113.3 (d, J = 249.9 Hz, 1F).

(4,4-Difluoro-3-butenyl)-benzene **(6c):** 84% yield, colorless liquid. ^{19}F NMR ($CDCl_3$): δ −89.6 (d, J = 49 Hz, 1F); −91.6 (dd, J = 49 Hz, 28 Hz, 1F). The characterization data is consistent with an early report [16].

1-Bromo-4-(2,2-difluoroethenyl)-benzene **(6e):** 70% yield, colorless liquid. ^{19}F NMR ($CDCl_3$): δ −81.7 (dd, J = 30.1 Hz, 26.2 Hz, 1F); −83.6 (d, J = 30.1 Hz, 1F). The characterization data is consistent with an early report [17].

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Erratum

Erratum to "Nucleophilic difluoromethylation and difluoromethylenation using bromodifluoromethyl phenyl sulfone" [J. Fluorine Chem. 126 (9–10) (2005) 1361–1367]

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The authors regret that there were many mistakes in the reference section of this article. The corrected references are listed below. We apologize for any inconvenience caused to those concerned.

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