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Rh-catalyzed allylic C–F bond activation: the stereoselective synthesis of trisubstituted monofluoroalkenes and a mechanism study†

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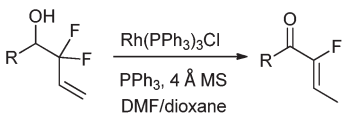
Rhodium-catalyzed allylic C–F bond activation *via* oxidative addition was found to be a promising approach for the conversion of allylic difluoro-homoallylic alcohols into trisubstituted monofluoroalkenes in good yields with excellent stereoselectivity. The mechanism study shows that C–F bond activation *via* oxidative addition is involved and PPh_3 is responsible for the excellent stereoselectivity.

Introduction

The chemical inertness of the C–F bond makes the chemistry of C–F bond activation a specialized field and an area of research that has received a great deal of interest and attention.[1] Outstanding progress has been made recently in the development of novel methods for activation of the C–F bond catalyzed by transition metals, which could activate the C–F bond under mild conditions and further functionalize substrates.[2] Research into transition metal-catalyzed Csp^2–F bond activation has been intensively studied[2a–f] while Csp^3–F bond activation needs much more exploration.[2g–r] In the investigation of transition metal-catalyzed Csp^3–F bond activation, the chemical properties of the C–F bond were well studied but most of these methods led to non-fluorinated products[2g–l,p] or resulted in low chemoselectivity.[2m,n] The selective Csp^3–F bond activation catalyzed by transition metals remains challenging, and has the potential to be a highly efficient approach for the construction of unique partially fluorinated molecules which cannot be easily obtained by other methods.

As an important class of fluorinated molecules, monofluoroalkenes have found potential applications in materials science and medicinal chemistry.[3] As a result, considerable effort has been directed towards their synthesis.[4] Recently, Fujii *et al.* and Paquin *et al.* independently reported that monofluoroalkenes can be synthesized through selective allylic Csp^3–F bond activation catalyzed by palladium. In Fujii's case, monofluoroalkenes were obtained utilizing Pd-catalyzed reductive defluorination.[2q] Paquin *et al.* found that C–F bond activation followed by a coupling reaction can give functionalized fluoroalkenes.[2o] Selective allylic Csp^3–F bond activation is a promising method for the synthesis of functionalized monofluoroalkenes under mild conditions but stereoselectivity is an issue that remains to be addressed.[5]



Scheme 1 This work.

We have reported that disubstituted monofluoroalkenes can be synthesized with excellent stereoselectivity by a coupling reaction.[6] However, in the synthesis of trisubstituted monofluoroalkenes, the same approach gave the required products with only moderate to good stereoselectivity. Herein we report the allylic Csp^3–F bond activation catalyzed by rhodium *via* oxidative addition for the first time and the application of this method to the highly stereoselective conversion of allylic difluoro-homoallylic alcohols into trisubstituted monofluoroalkenes, carbonyl group substituted monofluoroalkenes, which is a class of useful intermediate for the synthesis of biologically active substances (Scheme 1).[7]

Results and discussion

Screening of reaction conditions

Allylic difluoro-homoallylic alcohols could be easily prepared from the reaction of aldehyde with 3-bromo-3,3-difluoropropene in the presence of indium (Scheme 2).[8]

2,2-Difluoro-1-phenylbut-3-en-1-ol (**1a**) was used as the substrate for the screening of reaction conditions because of its

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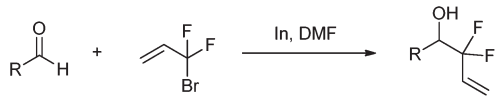


Scheme 2 Preparation of substrates.

straightforward preparation and purification. In our initial attempts, no reaction was observed in the presence of different bases but in the absence of a transition metal catalyst (Table 1, entries 1–3). With CH_3CN as a solvent and at 70 °C, even the use of $Pd(PPh_3)_4$ or $Rh(PPh_3)_3Cl$ as a catalyst led to none of the required products (entries 4 and 5).

However, to our delight, when the reaction was performed at 120 °C in DMF, ^{19}F NMR showed that only a single compound was formed, and this was determined to be the desired product (entry 6). On addition of PPh_3, as well as 4 Å MS to remove traces of water from the DMF, the yield increased to 81% (entry 7). When dioxane was used as a solvent, stereoselectivity and yield were both lower (entry 8). With dioxane as a cosolvent in DMF, a better result was obtained (entry 9). It was also found that $Rh(PPh_3)_3Cl$ was necessary for the reaction (entry 10).

Since 4 Å MS and PPh_3 together were shown to have a significant positive effect on the reaction, it was worth determining the role of each reagent. When 4 Å MS was used without PPh_3, the selectivity dropped sharply (entry 11). On the other hand, without the 4 Å MS, the yield lowered dramatically (entry 12). We believe that the 4 Å MS not only acts as a drying agent, but also absorbs the HF generated, driving the reaction forward. The reason for the improvement in selectivity in the presence of PPh_3 will be discussed in the Mechanism study section.

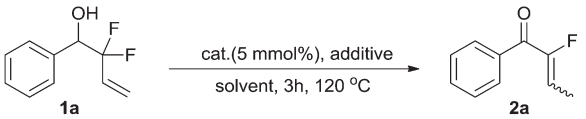
The purity of the $Rh(PPh_3)_3Cl$ used in all the experiments described above was 98%. In order to exclude the possibility that the reaction might be catalyzed by impurities in the catalyst, 99.99% pure $Rh(PPh_3)_3Cl$ was used in an additional experiment. The result was almost the same, which is compelling evidence that it is, indeed, $Rh(PPh_3)_3Cl$ catalyses the reaction (entry 13). Other ligands (PCy_3 or 2,2′-bipyridyl) were also screened but the results were worse (entries 14–15). So the optimal conditions for the reaction are DMF–dioxane as cosolvents, $Rh(PPh_3)_3Cl$ as a catalyst and 4 Å MS and PPh_3 as additives (entry 9).

Reaction scope

With these optimized conditions in hand, we investigated the scope of substrates that could be accommodated and, as shown in Scheme 3, found that the reaction could tolerate various functional groups. Substrates with electron-withdrawing groups were converted smoothly into the products with excellent stereoselectivity and good yields (**2b–2d**, **2h–2i**). No negative effect was observed here when Cl or F was contained (**2e–2f**). However, with Br present in the substrate, much of the unreacted starting material (>40%) remained and the isolated yield was much lower (53%). This might stem from the oxidative addition of the catalyst to the C–Br bond competing with the required reaction (**2g**).[9]

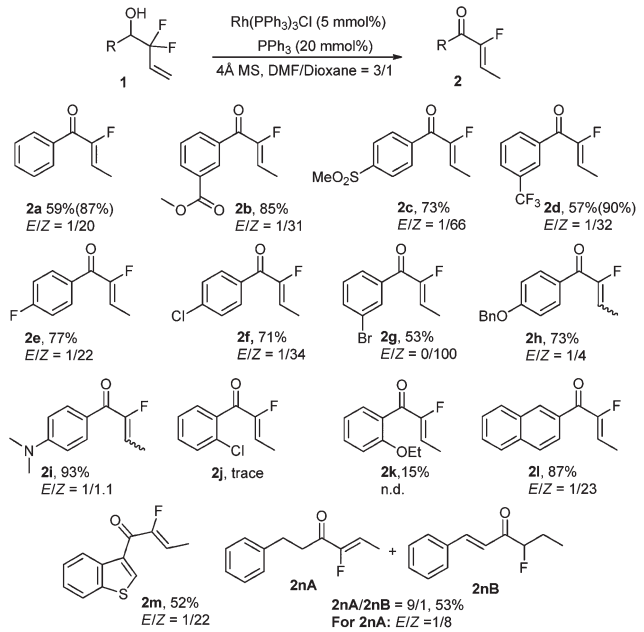
Surprisingly, in the case of substrates substituted by the electron-donating groups, the stereoselectivity of reactions was very low, even though the yields were still good to excellent

Table 1 Optimization of Rh(I)-catalyzed allylic C–F activation[a]



Entry	Catalyst	Additive	Solvent	Z/E^b	Yield[b] (%)
1[c]	—	DBU	CH_3CN	—	NR
2[c]	—	$NaOBu^t$	CH_3CN	—	NR
3	—	Cs_2CO_3	DMF	—	NR
4[c]	$Pd(PPh_3)_4$	—	CH_3CN	—	NR
5[c]	$Rh(PPh_3)_3Cl$	—	CH_3CN	—	NR
6	$Rh(PPh_3)_3Cl$	—	DMF	ND	25
7	$Rh(PPh_3)_3Cl$	PPh_3 + 4 Å MS	DMF	30/1	81
8	$Rh(PPh_3)_3Cl$	PPh_3 + 4 Å MS	Dioxane	12/1	76
9	$Rh(PPh_3)_3Cl$	PPh_3 + 4 Å MS	DMF–dioxane	20/1	87
10	—	PPh_3 + 4 Å MS	DMF–dioxane	—	—
11	$Rh(PPh_3)_3Cl$	4 Å MS	DMF–dioxane	5/1	72
12	$Rh(PPh_3)_3Cl$	PPh_3	DMF–dioxane	—	16
13[d]	$Rh(PPh_3)_3Cl$	PPh_3 + 4 Å MS	DMF–dioxane	20/1	87
14	$Rh(PPh_3)_3Cl$	PCy_3 + 4 Å MS	DMF–dioxane	50/1	78
15	$Rh(PPh_3)_3Cl$	2,2′-Bipyridyl + 4 Å MS	DMF–dioxane	7/1	31

[a] Conditions: a mixture of **1a** (0.5 mmol), a catalyst (0.025 mmol), an additive and a solvent (2 mL) in a sealed tube was stirred at 120 °C; in entries 1–3, 1 equiv. of each additive was used; in the other entries, 4 Å MS was used on a 100 mg scale and PPh_3 or other additives were used on a 0.1 mmol scale. ND = not determined, NR = no reaction. [b] Determined by ^{19}F NMR. [c] The reaction was performed at 70 °C, reaction time was 16 h. [d] The purity of the $Rh(PPh_3)_3Cl$ used is 99.99%.



Scheme 3 Reaction scope. Isolated yields; the *Z*/*E* ratios and the yield in parentheses shown were determined by ^{19}F NMR.

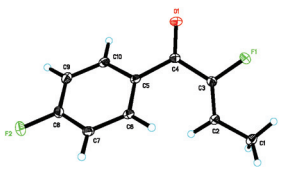


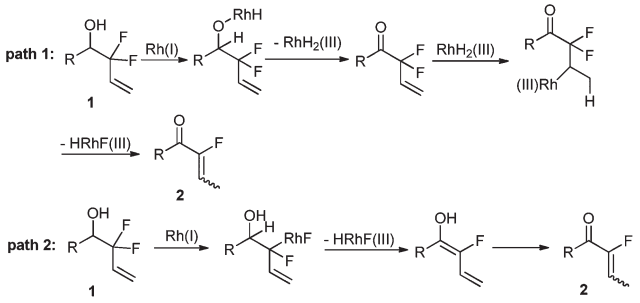
Fig. 1 X-ray structure of **2e**.

(**2h**–**2i**). The reaction is quite sensitive to steric effects. When the 2-position of the phenyl group was substituted, almost no reaction was observed (**2j**–**2k**). For example, the 2-EtO-phenyl-substituted substrate reacted very sluggishly, even when the temperature was increased to 140 °C, and the ^{19}F NMR yield was so low that the stereoselectivity was not determined. For the naphthyl and heteroaromatic substrates, the desired product was the major product and the stereoselectivity was still quite good (**2m**). But for the aliphatic substrates, an isomer of the desired product (**2nA**, **2nB**) was obtained and this is explained in the ESI.†

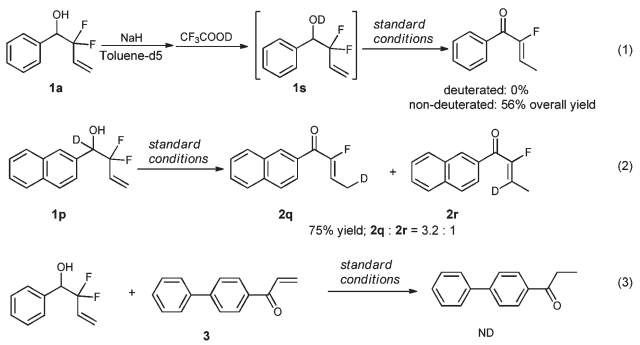
The structure of the product **2e** was determined by single crystal X-ray diffraction (Fig. 1).[10] Other structures were surmised by analogy.

Mechanism study

The transformation might proceed *via* two different pathways, involving dehydrogenation of alcohol (path 1, Scheme 4) or C–F bond activation *via* oxidative addition (path 2), respectively. The coordination of alcohol to Rh(I) followed by dehydrogenation, insertion of a terminal double bond into a Rh–H bond and β-F elimination would give the final product (path 1).[2r,11] On the other hand, C–F bond activation followed



Scheme 4 Possible pathways of the reaction.

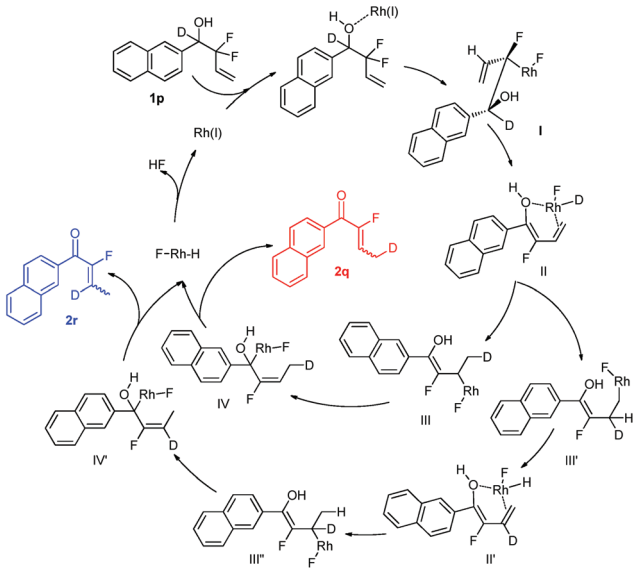


Scheme 5 Evidence to exclude path 1.

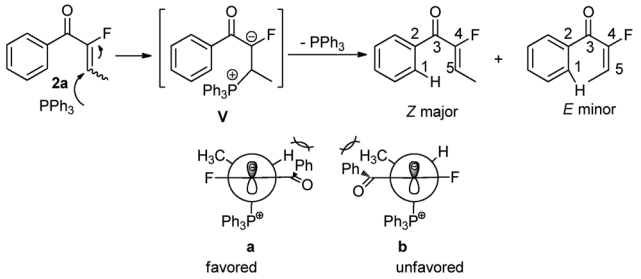
by β-H elimination and rearrangement could also afford the expected product (path 2).[12]

The possibility *via* path 1 was excluded by deuterium-labeling experiments.[13] When the hydroxy was deuterated, the conversion proceeded well but only afforded non-deuterated product, without any sign of the deuterated product (Scheme 5, eqn (1)). Surprisingly, when the benzyl proton was replaced with deuterium in the substrate, the reaction gave two deuterated products, with deuterium locating at terminal methyl and double bond respectively (eqn (2)). The deuterated results clearly demonstrate that dehydrogenation of alcohol is not involved in the reaction, otherwise the deuterated substrates **1p** and **1s** should give the same deuterated products. Furthermore, the failure to reduce activated alkene **3** of the standard reaction system suggests that RhH_2(III) is not generated, which also means path 1 may not be involved (eqn (3)).[11]

Based on the above results, we propose that the mechanism involves Csp^3–F bond activation and β-hydride elimination as illustrated in Scheme 6. Take **1p** as the example. The oxidative addition of the C–F bond to $Rh(PPh_3)_3Cl$ generates a rhodium complex **I**. The subsequent β-D elimination requires Rh(III) and D in the *syn* position. Due to the eclipsed conformation (**I**), the 2-substituted group on phenyl shows strong steric hindrance and leads to a sluggish reaction. That is why **2j** and **2k** were obtained in low yields. The generated intermediate **II** would readily undergo insertion of a double bond into a Rh(III)–D bond, proceeding in two different routes to give intermediates **III** and **III′**. β-H elimination of intermediate **III′** followed by re-insertion affords intermediate **III″**. Finally, isomerization and



Scheme 6 Proposed mechanism.

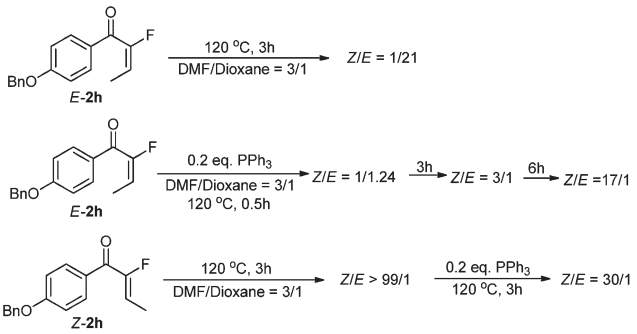


Scheme 7 Proposed mechanism for the isomerization.

β-H elimination of **III** and **III″** lead to deuterated products **2q** and **2r** respectively, and F(H)Rh(III).[14] The reductive elimination of F(H)Rh(III) generates catalyst Rh(I) and HF, which is absorbed by 4 Å MS.

With regard to the excellent stereoselectivity, we believe PPh_3 plays an important role.[15] The carbon–carbon double bond in the product is sufficiently electron deficient to be attacked by PPh_3 to give intermediate **V** (Scheme 7). Two significant conformations of intermediate **V** can be identified, conformations **a** and **b**, and the former is favoured over the latter for steric reasons. The elimination of PPh_3 from conformer a affords the desired product in the *Z*-configuration. In the case of substrates with an electron-donating group on the benzene ring, the double bond is less readily attacked by PPh_3 because it is not sufficiently electron deficient, leading to a larger proportion of *E*-stereoisomeric products.

In order to support our hypothesis for the role of PPh_3 in these reactions, further evidence was collected (Scheme 8). When a solution of *E*-**2h** in DMF–dioxane was kept at 120 °C for 3 h in the absence of PPh_3, only very low levels of isomerization were observed (determined by ^{19}F NMR). In a parallel experiment but with the addition of PPh_3, isomerization



Scheme 8 PPh_3 mediated isomerization of the alkene.

(monitored by ^{19}F NMR at 0.5 h, 3 h, and 6 h) led to *Z*-**2h** as the major isomer. Under the same conditions but starting with *Z*-**2h**, only 3% isomerized to *E*-**2h**. These results indicate that the stereoselectivity is determined by the electrophilicity of the double bond towards PPh_3.

Conclusions

In conclusion, rhodium-catalyzed allylic Csp^3–F bond activation *via* oxidative addition was reported for the first time and found to be an efficient approach for the conversion of allylic difluoro-homoallylic alcohols into trisubstituted monofluoroalkenes in good yields with excellent stereoselectivity. The careful study of the mechanism shows that C–F bond activation *via* oxidative addition is involved and PPh_3 is responsible for the excellent stereoselectivity. The application of C–F bond activation to the synthesis of other important fluorinated molecules is in progress.

Experimental

General information

Reagents and solvents were purchased from commercial sources and used as received. Molecular sieves (4 Å, powder) were dried under vacuum at 220 °C and stored in a glove box before use. Tetramethylsilane or residual proton signals were used as internal standards for ^1H NMR, ^{13}C NMR and ^{19}F NMR spectra. Data for ^1H NMR, ^{13}C NMR and ^{19}F NMR were recorded as follows: chemical shift (δ, ppm), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet or unresolved, brs = broad singlet, coupling constant(s) in Hz, integration).

General experimental procedure for the synthesis of 3,3-difluoropropene derivatives

Compounds **1a–1o** were synthesized using the method reported by Masayuki Kirihara *et al.*[8]

2,2-Difluoro-1-phenylbut-3-en-1-ol (1a). 71% yield. Colorless liquid. ^1H NMR (300 MHz, $CDCl_3$) δ 7.48–7.31 (m, 5H), 5.95–5.75 (m, 1H), 5.59 (d, J = 17.4 Hz, 1H), 5.46 (d, J = 11.0 Hz, 1H), 4.91 (td, J = 9.7, 4.0 Hz, 1H), 2.50 (d, J = 4.0 Hz, 1H);

^{19}F NMR (282 MHz, $CDCl_3$) δ −107.87 (dt, J = 247.2, 10.5 Hz, 1F), −108.95−−109.99 (m, 1F).

Methyl 3-(2,2-difluoro-1-hydroxybut-3-en-1-yl)benzoate (1b). 43% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.06 (s, 1H), 7.94 (d, J = 7.7 Hz, 1H), 7.61 (d, J = 7.7 Hz, 1H), 7.37 (t, J = 7.7 Hz, 1H), 5.99–5.78 (m, 1H), 5.53 (d, J = 17.4 Hz, 1H), 5.42 (d, J = 11.1 Hz, 1H), 4.95 (t, J = 9.6 Hz, 1H), 4.27 (brs, 1H), 3.84 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.06 (s), 136.99 (s), 132.20 (s), 129.53 (s), 129.44 (s), 129.18 (t, J = 25.6 Hz), 128.66 (s), 127.98 (s), 121.38 (t, J = 9.2 Hz), 119.25 (t, J = 244.6 Hz), 74.97 (t, J = 30.1 Hz), 52.00 (s); ^{19}F NMR (282 MHz, $CDCl_3$) δ −107.30 (dt, J = 247.9, 9.6 Hz, 1F), −109.27 to −110.38 (m, 1F); IR (neat) ν = 3466, 2955, 1723, 1449, 1293, 1203, 995, 747 cm^{-1}; HRMS(ESI) calcd for $C_{12}H_{12}F_2NaO_3$ $[M + Na]^+$ 265.06467; found 265.06525.

2,2-Difluoro-1-(4-(methylsulfonyl)phenyl)but-3-en-1-ol (1c). 67% yield. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.81 (d, J = 8.2 Hz, 2H), 7.60 (d, J = 8.2 Hz, 2H), 5.96–5.81 (m, 1H), 5.57 (d, J = 17.4 Hz, 1H), 5.48 (d, J = 11.1 Hz, 1H), 5.00 (t, J = 9.5 Hz, 1H), 3.93 (brs, 1H), 3.03 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.83 (s), 139.89 (s), 129.00 (t, J = 25.6 Hz), 128.70 (s), 126.74 (s), 121.88 (t, J = 9.2 Hz), 119.07 (t, J = 244.4 Hz), 74.63 (t, J = 30.6 Hz), 44.21 (s); ^{19}F NMR (282 MHz, $CDCl_3$) δ −106.08 (dt, J = 248.5, 9.5 Hz), −110.73 (dt, J = 248.5, 9.5 Hz); IR (neat) ν = 3472, 2930, 1601, 1420, 1304, 1149, 959, 766 cm^{-1}; HRMS-(ESI) calcd for $C_{11}H_{12}F_2NaO_3S$ $[M + Na]^+$ 285.03674; found 285.03689.

2,2-Difluoro-1-(3-(trifluoromethyl)phenyl)but-3-en-1-ol (1d). 51% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68 (s, 1H), 7.64–7.51 (m, 2H), 7.44 (t, J = 7.8 Hz, 1H), 5.92–5.72 (m, 1H), 5.54 (d, J = 17.4 Hz, 1H), 5.45 (d, J = 11.1 Hz, 1H), 4.91 (t, J = 9.3 Hz, 1H), 3.66–2.78 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 137.04 (s), 131.07 (s), 130.61 (q, J = 32.5 Hz), 128.88 (t, J = 26.8 Hz), 128.64 (s), 125.48 (q, J = 4.0 Hz), 124.49 (m), 124.03 (q, J = 272.0 Hz), 122.10 (m), 119.38 (t, J = 244.9 Hz), 75.28 (t, J = 30.3 Hz); ^{19}F NMR (282 MHz, $CDCl_3$) δ −63.07 (s, 3F), −107.58 (dt, J = 248.2, 11.3 Hz, 1F), −108.89 to −116.93 (m, 1F); IR (neat) ν = 3441, 1422, 1330, 1167, 1130, 1103, 1075, 997 cm^{-1}; LRMS(ESI) calcd for $C_{11}H_9F_5NaO$ $[M + Na]^+$ 275.0; found 275.0. Anal. calcd for $C_{11}H_9F_5O$: C, 52.39; H, 3.60; found C, 52.26; H, 3.83.

2,2-Difluoro-1-(4-fluorophenyl)but-3-en-1-ol (1e). 68% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38–7.30 (m, 2H), 7.01 (t, J = 8.7 Hz, 2H), 5.88–5.72 (m, 1H), 5.53 (d, J = 17.4 Hz, 1H), 5.43 (d, J = 11.1 Hz, 1H), 4.82 (t, J = 9.5 Hz, 1H), 3.04 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.87 (d, J = 247.1 Hz), 131.81 (s), 129.39 (d, J = 8.1 Hz), 129.15 (t, J = 25.7 Hz), 121.74 (t, J = 9.2 Hz), 119.46 (t, J = 244.2 Hz), 115.05 (d, J = 21.5 Hz), 75.16 (t, J = 30.3 Hz); ^{19}F NMR (282 MHz, $CDCl_3$) δ −108.52 (dd, J = 245.3, 10.4 Hz, 1F), −109.59 to −110.89 (m, 1F), −113.26 to −114.08 (m, 1F); IR (neat) ν = 3441, 1607, 1513, 1422, 1228, 1159, 1068, 995 cm^{-1}; HRMS(EI) calcd for $C_{10}H_9F_3O$ $[M]^+$ 202.0605; found 206.0604.

1-(4-Chlorophenyl)-2,2-difluorobut-3-en-1-ol (1f). 77% yield. Colorless liquid. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.42–7.30 (m, 4H), 5.93–5.73 (m, 1H), 5.58 (d, J = 17.3 Hz, 1H), 5.48 (d, J = 11.0 Hz, 1H), 4.90 (t, J = 8.5 Hz, 1H), 2.58–1.23 (brs, 1H); ^{19}F NMR (282 MHz, $CDCl_3$) δ −107.58 (dt, J = 247.5, 10.2 Hz, 1F), −108.74 to −110.72 (m, 1F).

1-(3-Bromophenyl)-2,2-difluorobut-3-en-1-ol (1g). 75% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (s, 1H), 7.45 (d, J = 7.8 Hz, 1H), 7.29 (d, J = 7.8 Hz, 1H), 7.18 (t, J = 7.8 Hz, 1H), 5.87–5.71 (m, 1H), 5.55 (d, J = 17.4 Hz, 1H), 5.44 (d, J = 11.1 Hz, 1H), 4.78 (t, J = 9.5 Hz, 1H), 3.32 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ138.17 (m), 131.67 (s), 130.53 (s), 129.64 (s), 128.88 (t, J = 25.6 Hz), 126.26 (s), 122.12 (s), 121.93 (t, J = 9.0 Hz), 119.23 (t, J = 244.8 Hz), 74.96 (t, J = 29.3 Hz); ^{19}F NMR (282 MHz, $CDCl_3$) δ −107.35 (dt, J = 248.0, 10.2 Hz, 1F), −108.81 to −110.36 (m, 1F); IR (neat) ν = 3440, 1573, 1421, 1192, 1073, 997, 955, 777 cm^{-1}; GCMS(EI) calcd for $C_{10}H_9BrF_2O$ $[M]^+$ 262.0; found 262.0. Anal. calcd for $C_{10}H_9BrF_2O$: C, 45.65; H,3.45; found C, 45.60; H, 3.78.

1-(4-(Benzyloxy)phenyl)-2,2-difluorobut-3-en-1-ol (1h). 41% yield. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51–7.24 (m, 7H), 7.08–6.86 (m, 2H), 5.93–5.74 (m, 1H), 5.59 (d, J = 17.4 Hz, 1H), 5.45 (d, J = 11.1 Hz, 1H), 5.05 (s, 2H), 4.81 (t, J = 9.7 Hz, 1H), 2.58 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 159.09 (s), 136.80 (s), 129.54 (t, J = 25.6 Hz), 128.89 (s), 128.57 (s), 128.45 (s), 128.00 (s), 127.46 (s), 121.46 (t, J = 9.1 Hz), 119.62 (t, J = 245.4 Hz), 114.54 (s), 75.49 (t, J = 29.9 Hz), 70.00 (s); ^{19}F NMR (282 MHz, $CDCl_3$) δ −108.56 (dt, J = 246.6, 10.7 Hz, 1F), −109.48 to −110.73 (m, 1F); IR (neat) ν = 3437, 2904, 1614, 1513, 1244, 1175, 1066, 993 cm^{-1}; HRMS(EI) calcd for $C_{17}H_{16}F_2O_2$ $[M]^+$ 290.1118; found 290.1115.

1-(4-(Dimethylamino)phenyl)-2,2-difluorobut-3-en-1-ol (1i). 75% yield. Yellow liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37–7.12 (m, 2H), 6.70 (d, J = 8.8 Hz, 2H), 5.95–5.78 (m, 1H), 5.73–5.51 (m, 1H), 5.44 (d, J = 11.1 Hz, 1H), 4.77 (t, J = 10.0 Hz, 1H), 2.95 (s, 6H), 2.49 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.70 (s), 129.89 (t, J = 25.8 Hz), 128.49 (s), 123.72 (s), 121.11 (t, J = 9.2 Hz), 119.75 (t, J = 244.1 Hz), 112.00 (s), 75.76 (t, J = 29.6 Hz), 40.44 (s); ^{19}F NMR (376 MHz, $CDCl_3$) δ −108.21 (dt, J = 245.2, 10.6 Hz, 1F), −109.41 (dt, J = 245.1, 10.4 Hz, 1F); IR (neat) ν = 3420, 2890, 1616, 1525, 1354, 1163, 1064, 992 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{15}F_2NO$ $[M]^+$ 227.1122; found 227.1126.

1-(2-Chlorophenyl)-2,2-difluorobut-3-en-1-ol (1j). 45% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (d, J = 7.5 Hz, 1H), 7.39–7.20 (m, 3H), 5.99–5.83 m, 1H), 5.58 (d, J = 17.3 Hz, 1H), 5.50–5.38 (m, 2H), 2.85 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 133.87 (t, J = 2.0 Hz), 133.62 (s), 129.81 (s), 129.39 (t, J = 25.8 Hz), 129.37 (m), 129.30 (s), 126.81 (s), 121.66 (t, J = 9.3 Hz), 119.49 (t, J = 245.6 Hz), 71.38 (t, J = 29.5 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −109.44 (dt, J = 244.8, 10.6 Hz, 1F), −110.17 (dt, J = 244.8, 11.3 Hz, 1F); IR (neat) ν = 3452, 1443, 1421, 1134, 1071, 1035, 995, 753 cm^{-1}; GCMS(EI) calcd for $C_{10}H_9ClF_2O$ $[M]^+$ 218.0; found 218.1. Anal. calcd for $C_{10}H_9ClF_2O$: C, 54.94; H, 4.15; found C, 54.83; H, 4.26.

1-(2-Ethoxyphenyl)-2,2-difluorobut-3-en-1-ol (1k). 71% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37–7.30 (m, 1H), 7.29–7.18 (m, 1H), 6.92 (t, J = 7.5 Hz, 1H), 6.83 (d, J = 8.3 Hz, 1H), 5.99–5.83 (m, 1H), 5.56 (d, J = 17.4 Hz, 1H), 5.37

(d, J = 11.1 Hz, 1H), 5.11–5.25 (m, 1H), 4.09–3.64 (m, 3H), 1.36 (t, J = 6.4 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.57 (s), 130.35 (t, J = 25.9 Hz), 129.47 (s), 129.38 (s), 124.22 (s), 120.42 (s), 120.31 (t, J = 9.1 Hz), 120.22 (t, J = 248.9 Hz), 111.71 (s), 71.33–71.11 (m), 63.84 (s), 14.51 (s); ^{19}F NMR (282 MHz, $CDCl_3$) δ −109.47 (dt, J = 251.0, 11.3 Hz, 1F), −110.58 (dt, J = 244.2, 12.1 Hz, 1F); IR (neat) ν = 3449, 2983, 1589, 1495, 1420, 1122, 1046, 755 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{14}F_2O_2$ $[M]^+$ 228.0962; found 228.0961.

2,2-Difluoro-1-(naphthalen-2-yl)but-3-en-1-ol (1l). 58% yield. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93–7.76 (m, 4H), 7.60–7.43 (m, 3H), 5.99–5.76 (m, 1H), 5.66–5.52 (m, 1H), 5.44 (d, J = 11.1 Hz, 1H), 5.06 (t, J = 9.5 Hz, 1H), 2.45 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 133.53–133.36 (m), 132.87 (s), 129.36 (t, J = 25.6 Hz), 128.15 (s), 127.88 (s), 127.64 (s), 127.09 (s), 126.39 (s), 126.23 (s), 124.99 (s), 121.64 (t, J = 9.2 Hz), 119.70 (t, J = 244.9 Hz), 76.00(t, J = 29.3 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −107.59 (dt, J = 246.8, 10.4 Hz, 1F), −108.48 to −109.27 (m, 1F); IR (neat) ν = 3442, 2892, 1509, 1420, 1206, 1068, 994, 804 cm^{-1}; HRMS(EI) calcd for $C_{14}H_{12}F_2O$ $[M]^+$ 234.0856; found 234.0859.

1-(Benzo[*b*]thiophen-3-yl)-2,2-difluorobut-3-en-1-ol (1m). 67% yield. Yellow liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86–7.73 (m, 2H), 7.48 (s, 1H), 7.39–7.24 (m, 2H), 5.98–5.78 (m, 1H), 5.67–5.52 (m, 1H), 5.46–5.32 (m, 1H), 5.20 (t, J = 9.5 Hz, 1H), 2.97 (brs, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.25 (s), 137.66 (s), 131.48 (s), 129.48 (t, J = 25.6 Hz), 126.26 (s), 124.61 (s), 124.32 (s), 122.75 (s), 122.59 (s), 121.80 (t, J = 9.2 Hz), 119.71 (t, J = 244.9 Hz), 71.32 (t, J = 31.2 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −106.83 (dt, J = 247.1, 10.2 Hz, 1F), −107.90 to −108.86 (m, 1F); IR (neat) ν = 3449, 1427, 1143, 1099, 1065, 993, 958, 767 cm^{-1} LRMS(ESI) calcd for $C_{12}H_{10}F_2OS$ $[M + Na]^+$ 263.0; found 263.0. Anal. calcd for $C_{12}H_{10}F_2OS$: C, 59.99; H, 4.20; found C, 59.91; H, 4.57.

4,4-Difluoro-1-phenylhex-5-en-3-ol (1n). 34% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32–7.26 (m, 2H), 7.23–7.11 (m, 3H), 6.04–5.84 (m, 1H), 5.76–5.60 (m, 1H), 5.53 (d, J = 11.1 Hz, 1H), 3.82–3.72 (m, 1H), 2.97–2.87 (m, 1H), 2.80–2.64 (m, 1H), 1.98–1.85 (m, 2H), 1.84–1.68 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −108.31 to −109.18 (m, 1F), −111.75 to −112.58 (m, 1F).

General experimental procedure for the synthesis of α-fluoro-α,β-unsaturated ketone derivatives

In a glove box, $Rh(PPh_3)_3Cl$ (19.6 mg, 0.025 mmol), PPh_3 (26.2 mg, 0.2 mmol) and 4 Å MS (100 mg) were added to a sealed tube, then DMF (1.5 mL) and dioxane (0.5 mL) were added. Compound **1** (0.5 mmol) was added to the mixture. The tube was sealed and the mixture was stirred at 120 °C for 3 h. The stereoselectivity was determined by ^{19}F NMR before the reaction was quenched with water (30 mL). The mixture was extracted with 50 mL Et_2O. The Et_2O solution was washed with brine (20 mL × 3), and then dried over Na_2SO_4. The solvent was removed under reduced pressure and the residue was purified by flash chromatography to afford the product **2**.

(*Z*)-2-Fluoro-1-phenylbut-2-en-1-one (2a). 59% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.86–7.72 (m, 2H), 7.62–7.51 (m, 1H), 7.51–7.39 (m, 2H), 6.09 (dq, J = 33.8, 7.3 Hz, 1H), 1.89 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 187.39 (d, J = 27.8 Hz), 155.96 (d, J = 260.2 Hz), 136.17 (s), 132.65 (s), 129.11 (d, J = 3.5 Hz), 128.28 (s), 119.39 (d, J = 13.4 Hz), 10.05 (d, J = 5.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.37 (d, J = 33.4 Hz); IR (neat) ν = 3066, 1724, 1670, 1449, 1276, 1168, 1001, 716 cm^{-1}; HRMS(EI) calcd for $C_{10}H_9FO$ $[M]^+$ 164.0637; found 164.0636.

(*Z*)-Methyl 3-(2-fluorobut-2-enoyl)benzoate (2b). 85% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.45 (s, 1H), 8.23 (d, J = 7.8 Hz, 1H), 7.99 (d, J = 7.8 Hz, 1H), 7.56 (t, J = 7.8 Hz, 1H), 6.14 (dq, J = 33.7, 7.3 Hz, 1H), 3.95 (s, 3H), 1.92 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 186.24 (d, J = 28.7 Hz), 165.92 (s), 155.75 (d, J = 260.4 Hz), 136.33 (s), 133.37 (s), 133.19 (d, J = 3.6 Hz), 130.32 (s), 130.09 (d, J = 4.1 Hz), 128.56 (s), 119.64 (d, J = 13.3 Hz), 52.28 (s), 10.06 (d, J = 5.0 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.49 (d, J = 34.4 Hz); IR (neat) ν = 2953, 1726, 1700, 1437, 1303, 1211, 1081, 732 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{11}FO_3$ $[M]^+$ 222.0692; found 222.0690.

(*Z*)-2-Fluoro-1-(4-(methylsulfonyl)phenyl)but-2-en-1-one (2c). 73% yield. Yellow solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (d, J = 8.0 Hz, 2H), 7.96 (d, J = 8.0 Hz, 2H), 6.17 (dq, J = 33.5, 7.3 Hz, 1H), 3.10 (s, 3H), 1.93 (dd, J = 7.3, 2.6 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.90 (d, J = 29.4 Hz), 155.57 (d, J = 260.1 Hz), 143.69 (s), 140.64 (s), 129.88 (d, J = 3.8 Hz), 127.45 (s), 120.89 (d, J = 13.0 Hz), 44.24 (s), 10.27 (d, J = 4.9 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −126.05 (d, J = 33.4 Hz); IR (neat) ν = 2921, 1690, 1399, 1291, 1152, 1085, 750 cm^{-1}; HRMS(EI) calcd for $C_{11}H_{11}FO_3S$ $[M]^+$ 242.0413; found 242.0408.

(*Z*)-2-Fluoro-1-(3-(trifluoromethyl)phenyl)but-2-en-1-one (2d). 57% yield. Colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07 (s, 1H), 8.00 (d, J = 7.8 Hz, 1H), 7.83 (d, J = 7.8 Hz, 1H), 7.61 (t, J = 7.8 Hz, 1H), 6.17 (dq, J = 33.5, 7.3 Hz, 1H), 1.92 (dd, J = 7.3, 2.8 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.77 (d, J = 29.3 Hz), 155.83 (d, J = 260.7 Hz), 136.68 (s), 132.37 (d, J = 4.2 Hz), 131.02 (q, J = 33.2 Hz), 129.20 (q, J = 3.6 Hz), 129.04 (s), 126.16–125.94 (m), 123.54 (d, J = 272.6 Hz), 119.82 (d, J = 13.2 Hz), 10.18 (d, J = 5.0 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.90 (s, 3F), −125.55 (d, J = 33.4 Hz, 1F); IR (neat) ν = 2928, 1674, 1645, 1437, 1265, 1164, 1131, 750 cm^{-1}; HRMS(EI) calcd for $C_{11}H_8F_4O$ $[M]^+$ 232.0511; found 232.0506.

(*Z*)-2-Fluoro-1-(4-fluorophenyl)but-2-en-1-one (2e). 77% yield. White solid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97–7.77 (m, 2H), 7.13 (t, J = 8.6 Hz, 2H), 6.12 (dq, J = 33.9, 7.3 Hz, 1H), 1.89 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.54 (d, J = 28.9 Hz), 165.48 (d, J = 254.8 Hz), 156.03 (d, J = 261.2 Hz), 132.27 (d, J = 2.4 Hz), 131.91 (dd, J = 9.2, 4.6 Hz), 118.65 (d, J = 13.3 Hz), 115.53 (d, J = 21.9 Hz), 10.00 (d, J = 5.2 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −105.09 to −105.21 (m, 1F), −124.74 (d, J = 34.0 Hz, 1F); IR (neat) ν = 1667, 1648, 1603, 1336, 1169, 1088, 847 cm^{-1}; HRMS(EI) calcd for $C_{10}H_8F_2O$ $[M]^+$ 182.0543; found 182.0546; Anal. calcd for $C_{10}H_8F_2O$: C, 65.93; H, 4.43; found C, 66.20; H, 4.58.

(*Z*)-1-(4-Chlorophenyl)-2-fluorobut-2-en-1-one (2f). 71% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (d, J = 8.3 Hz, 2H), 7.44 (d, J = 8.3 Hz, 2H), 6.12 (dq, J = 33.7, 7.3 Hz, 1H), 1.90 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.86 (d, J = 29.3 Hz), 155.87 (d, J = 260.8 Hz), 139.19 (s), 134.29 (s), 130.63 (d, J = 4.3 Hz), 128.64 (s), 119.14 (d, J = 13.1 Hz), 10.07 (d, J = 5.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.12 (d, J = 33.8 Hz); IR (neat) ν = 2925, 1670, 1588, 1402, 1283, 1093, 929, 755 cm^{-1}; HRMS(EI) calcd for $C_{10}H_8ClFO$ $[M]^+$ 198.0248; found 198.0247.

(*Z*)-1-(3-Bromophenyl)-2-fluorobut-2-en-1-one (2g). 53% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94–7.90 (m, 1H), 7.75–7.67 (m, 2H), 7.34 (t, J = 7.9 Hz, 1H), 6.13 (dq, J = 33.6, 7.3 Hz, 1H), 1.91 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.71 (d, J = 28.8 Hz), 155.73 (d, J = 260.6 Hz), 137.88 (s), 135.59 (s), 132.03 (d, J = 4.0 Hz), 129.92 (s), 127.70 (d, J = 4.1 Hz), 122.52 (s), 119.83 (d, J = 13.3 Hz), 10.17 (d, J = 5.0 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.48 (d, J = 33.6 Hz); IR (neat) ν = 2913, 1670, 1645, 1560, 1284, 1266, 743 cm^{-1}; HRMS(EI) calcd for $C_{10}H_8BrFO$ $[M]^+$ 241.9743; found 241.9741.

(*Z*)-1-(4-(Benzyloxy)phenyl)-2-fluorobut-2-en-1-one (*Z*-2h). 62% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 7.8 Hz, 2H), 7.49–7.28 (m, 5H), 7.00 (d, J = 8.8 Hz, 2H), 6.06 (dq, J = 34.2, 7.3 Hz, 1H), 5.11 (s, 2H), 1.86 (dd, J = 7.3, 2.8 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.60 (d, J = 28.3 Hz), 162.52 (s), 156.29 (d, J = 261.6 Hz), 136.00 (s), 131.72 (d, J = 4.7 Hz), 128.81 (s), 128.61 (s), 128.17 (s), 127.40 (s), 117.54 (d, J = 13.5 Hz), 114.42 (s), 70.04 (s), 9.93 (d, J = 5.2 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.03 (d, J = 34.1 Hz); IR (neat) ν = 1646, 1603, 1259, 1163, 933, 838, 762 cm^{-1}; HRMS(EI) calcd for $C_{17}H_{15}FO_2$ $[M]^+$ 270.1056; found 270.1053.

(*E*)-1-(4-(Benzyloxy)phenyl)-2-fluorobut-2-en-1-one (*E*-2h). 12% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (dd, J = 8.9, 2.0 Hz, 2H), 7.46–7.29 (m, 5H), 7.01 (d, J = 8.9 Hz, 2H), 5.91 (dq, J = 23.0, 7.7 Hz, 1H), 5.12 (s, 2H), 1.91 (dd, J = 7.7, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 186.49 (d, J = 33.6 Hz), 162.90 (s), 154.53 (d, J = 256.8 Hz), 136.03 (s), 131.85 (d, J = 5.8 Hz), 129.16 (d, J = 4.2 Hz), 128.65 (s), 128.22 (s), 127.43 (s), 115.57 (d, J = 20.0 Hz), 114.54 (d, J = 0.9 Hz), 70.11 (s), 11.31 (d, J = 6.8 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −111.71 (d, J = 22.7 Hz); IR (neat) ν = 1674, 1599, 1509, 1252, 1169, 1096, 770 cm^{-1}; HRMS(EI) calcd for $C_{17}H_{15}FO_2$ $[M]^+$ 270.1056; found 270.1055.

(*Z*)-1-(4-(Dimethylamino)phenyl)-2-fluorobut-2-en-1-one (*Z*-2i). 48% yield. Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 8.8 Hz, 2H), 6.63 (d, J = 8.8 Hz, 2H), 6.01 (dq, J = 35.2, 7.3 Hz, 1H), 3.04 (s, 6H), 1.85 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 184.63 (d, J = 27.9 Hz), 156.86 (d, J = 263.0 Hz), 153.39 (s), 131.84 (d, J = 5.3 Hz), 123.10 (s), 115.30 (d, J = 13.6 Hz), 110.45 (s), 39.84 (s), 9.71 (d, J = 5.5 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −122.77 (d, J = 34.6 Hz); IR (neat) ν = 2919, 1630, 1593, 1414, 1328, 1294, 1156, 996 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{14}NFO$ $[M]^+$ 207.1059; found 207.1057.

(*E*)-1-(4-(Dimethylamino)phenyl)-2-fluorobut-2-en-1-one (*E*-2i). 45% yield. Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (dd, J = 9.1, 2.0 Hz, 2H), 6.65 (d, J = 9.1 Hz, 2H), 5.81 (dq, J = 22.9, 7.7 Hz, 1H), 3.06 (s, 6H), 1.86 (dd, J = 7.7, 2.8 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 185.65 (d, J = 31.9 Hz), 155.02 (d, J = 257.7 Hz), 153.65 (s), 131.86 (d, J = 5.3 Hz), 123.60 (d, J = 3.5 Hz), 113.10 (d, J = 20.2 Hz), 110.54 (s), 39.89 (s), 11.14 (d, J = 7.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −110.27 (d, J = 22.8 Hz); IR (neat) ν = 2920, 1594, 1548, 1437, 1374, 1350, 1259, 1191 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{14}NFO$ $[M]^+$ 207.1059; found 207.1056.

(*Z*)-2-Fluoro-1-(naphthalen-2-yl)but-2-en-1-one (2l). 87% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.32 (s, 1H), 7.94–7.78 (m, 4H), 7.54 (dt, J = 18.8, 7.3 Hz, 2H), 6.14 (dq, J = 33.9, 7.3 Hz, 1H), 1.90 (dd, J = 7.3, 2.8 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 187.08 (d, J = 27.9 Hz), 156.15 (d, J = 260.8 Hz), 135.20 (s), 133.30 (s), 132.08 (s), 130.73 (d, J = 4.9 Hz), 129.29 (s), 128.36 (s), 128.19 (s), 127.66 (s), 126.76 (s), 124.88 (d, J = 2.8 Hz), 119.04 (d, J = 13.4 Hz), 10.04 (d, J = 5.1 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.64 (d, J = 34.0 Hz); IR (neat) ν = 3060, 1665, 1627, 1281, 1001, 820, 774 cm^{-1}; HRMS(EI) calcd for $C_{14}H_{11}FO$ $[M]^+$ 214.0794; found 214.0796; Anal. calcd for $C_{14}H_{11}FO$: C, 78.49; H, 5.18; found C,78.60; H, 5.24.

(*Z*)-1-(Benzo[*b*]thiophen-3-yl)-2-fluorobut-2-en-1-one (2m). 52% yield. Colorless oil. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.57–8.51 (m, 1H), 8.37 (d, J = 2.0 Hz, 1H), 7.87–7.84 (m, 1H), 7.51–7.44 (m, 1H), 7.43–7.37 (m, 1H), 6.23 (dq, J = 34.3, 7.3 Hz, 1H), 1.88 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 180.17 (d, J = 29.3 Hz), 156.67 (d, J = 262.8 Hz), 139.23 (s), 137.82 (d, J = 14.3 Hz), 137.26 (s), 132.17 (d, J = 1.9 Hz), 125.65 (s), 125.51 (s), 124.93 (s), 122.17 (s), 116.82 (d, J = 13.5 Hz), 9.93 (d, J = 5.4 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.07 (d, J = 34.3 Hz); IR (neat) ν = 1647, 1628, 1490, 1459, 1422, 1233, 768 cm^{-1}; HRMS(EI) calcd for $C_{12}H_9FOS$ $[M]^+$ 220.0358; found 220.0361.

(*Z*)-4-Fluoro-1-phenylhex-4-en-3-one (2nA). 53% yield. Colorless oil. Contaminated with 10% **2nB**. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31–7.24 (m, 2H), 7.22–7.15 (m, 3H), 6.08 (dq, J = 34.1, 7.3 Hz, 1H), 2.98–2.88 (m, 4H), 1.77 (dd, J = 7.3, 2.9 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.78 (d, J = 31.0 Hz), 155.90 (d, J = 260.4 Hz), 140.71 (s), 128.49 (s), 128.34 (s), 126.18 (s), 114.36 (d, J = 13.1 Hz), 39.45 (s), 29.36 (s), 9.67 (d, J = 5.0 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −130.56 (d, J = 34.1 Hz); IR (neat) ν = 2925, 1660, 1454, 1300, 1199, 1119, 1002, 700 cm^{-1}; HRMS(EI) calcd for $C_{12}H_{13}OF$ $[M]^+$ 192.0950; found 192.0951.

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