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The perfluoroallylation of alkynes and transformation of the products

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Abstract

The addition of perfluoroallyl iodide to alkynes **1** initiated by AIBN in the absence of solvent 65 °C gave the corresponding 1:1 adducts (1,1,2,3,3-pentafluoro-5-iodopenta-1,4-dienes) **2**. The reaction of **2** with boronic acids **3** and terminal alkynes **1** in the presence of catalytic palladium afforded the cross-coupling products **4** and **5,** respectively.

Keywords: Perfluoroallylation; Suzuki cross-coupling reaction; Sonogashira cross-coupling reaction

1. Introduction

There has been considerable interest in organofluorine compounds as pharmaceutical and agrochemical agents due to their unique properties arising from altered electron density, acidity, and hydrogen-bonding patters [1]. Accordingly, the development of methods for the synthesis of organofluorine compounds continues to be an important area of research [1]. Among these, the perfluoroalkylation of organic molecules has been widely used for the synthesis of organofluorine compounds. Although the perfluoroalkylation of alkenes [2] and alkynes [3] has been extensively investigated with perfluoroalkyl iodides, few reports of perfluoroallylation have been documented. To the best our knowledge, only Burton and co-workers [4] described the addition of perfluoroallyl iodide (*F*-allyl iodide) to alkenes in the presence of copper, and there was no report on the perfluoroallylation of alkynes. Herein, we wish to report the addition of *F*-allyl iodide to alkynes initiated by AIBN and the transformation of the 1:1 adduct products.

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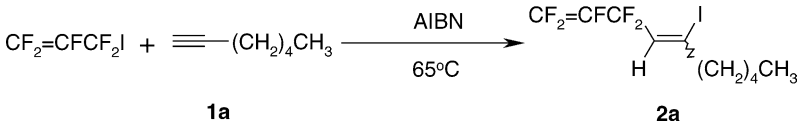
2. Results and discussion

2.1. Addition of F-allyl iodide to alkynes

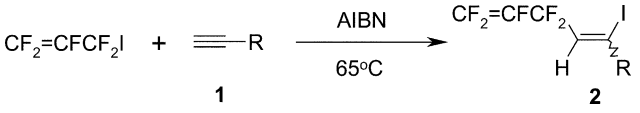
Addition of perfluoroalkyl iodide to alkynes can be readily achieved by initiation with $Na_2S_2O_4/NaHCO_3$ [3b] or $Pd(PPh_3)_4$ [3e]. We began our investigation by examining the addition of *F*-allyl iodide to 1-heptyne (**1a**) in the presence of $Na_2S_2O_4/NaHCO_3$ in CH_3CN. Contrary to perfluoroalkyl iodide [3b], we observed no reaction after 4 h at 0–5 °C. When a mixture of *F*-allyl iodide, **1a** and catalytic $Pd(PPh_3)_4$ was heated at 60 °C for 8 h, the polymerization of *F*-allyl iodide occurred and the adduct product was not obtained. Fortunately, the addition of *F*-allyl iodide to **1a** initiated by AIBN in the absence of solvent at 65 °C proceeded smoothly, the addition reaction was complete in 16 h and the adduct product **2a** was isolated in 75% yield as a mixture of *E*- and *Z*-isomers. The ratio of *E*/*Z* was 4/1 as determined by ^{1}H NMR (Scheme 1). The alkenyl hydrogen of *E*-isomer appeared lower field than that of *Z*-isomer [3b]. To the best our knowledge, this was the first example of the perfluoroallylation of alkynes. The generality of the reaction was demonstrated by the addition of *F*-allyl iodide to a



1a 2a

Scheme 1.

Table 1
AIBN-mediated addition of *F*-allyl iodide to terminal alkynes **1**



1 2

Entry	R (**1**)	Product **2**	Yield (%)[a]	*E*/*Z* ratio[b]
1	n-C_5H_{11} (**1a**)	**2a**	75	4/1
2	C_6H_5 (**1b**)	**2b**	64	3/1
3	CO_2CH_3 (**1c**)	**2c**	34	1/3
4	CH_2OH (**1d**)	**2d**	66	1/1
5	$C_6H_5OCH_2$ (**1e**)	**2e**	44	1/1
6	$(CH_3)_3Si$ (**1f**)	**2f**	68	1/1
7	$C_6H_5CH_2OCH_2$ (**1g**)	**2g**	62	1/1
8	$CH_3CO_2CH_2$ (**1h**)	**2h**	42	1/1

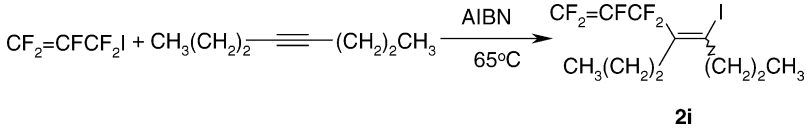
[a] Isolated yield.
[b] Determined by ^{19}F NMR and ^{1}H NMR after of purification of the crude product by column chromatography.

variety of other terminal alkynes. All examples of the addition reactions were summarized in Table 1. As shown in Table 1, a variety of functionalized groups were tolerated under the reaction conditions. The isolated yields of the adduct products were from moderate to good, except for **2c**. The adduct products **2a–c** were obtained with low levels of stereoselectivities (entries 1–3). In the case of terminal alkynes **1d–h**, there were no stereoselectivities in the perfluoroallylation reaction (entries 4–8). It was noteworthy the pure *E*-**2b**, *E*-**2h** and *Z*-**2h** could be obtained by column chromatography. Under the same reaction conditions, AIBN also initiated the addition of *F*-allyl iodide to internal alkyne such as 4-octyne (Scheme 2). However, the adduct product **2i** was isolated in low yield (24%) with no stereoselectivity (*E*/*Z*: 1/1).

2.2. The Suzuki cross-coupling of 1,1,2,3,3-pentafluoro-5-iodopenta-1,4-dienes 2 with boronic acids

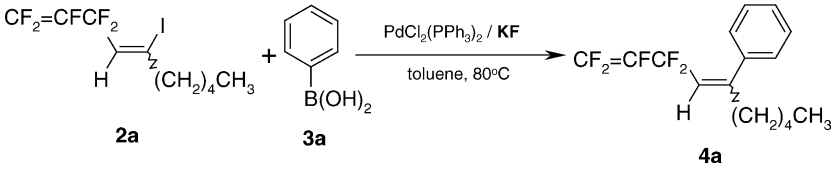
Having the fluorinated electrophiles **2** in hand, our attention was turned to palladium-catalyzed Suzuki coupling reactions [5]. Compound **2a** was chosen as a model substrate to examine the reaction conditions. When the reaction of **2a** and phenylboronic acid **3a** was carried out in typical Suzuki cross-coupling conditions (in the presence of 3 mol% $PdCl_2(PPh_3)_2$ and K_2CO_3 in refluxing THF) [3a, 6], the reaction was very complex as indicated by ^{19}F NMR of the reaction mixture. When K_3PO_4 was used as base instead of K_2CO_3, ^{19}F NMR of the reaction mixture showed that perfluoroallyl group disappeared. These results suggested that perfluoroallyl group was labile to strong base. Accordingly, we have chosen a weak base for this reaction. We were pleased to find that the desired compound **4a** was obtained in 49% yield in the case of $NaHCO_3$ being used as a base. Finally, when KF was used as base [7], the Suzuki cross-coupling of **2a** and **3a** in the presence of 3 mol% $PdCl_2(PPh_3)_2$ in toluene at 80 °C gave the desired product **4a** in 79% isolated yield (Scheme 3). The configuration of double bond was intact in this Suzuki cross-coupling reaction.

The cross-coupling of fluorinated electrophiles **2** with aryl boronic acid **3** in the presence of $PdCl_2(PPh_3)_2$/KF was summarized in Table 2. As shown in Table 2, the reaction of **2a** and **2b** with phenyl boronic acid **3a** and *p*-methylphenyl boronic acid **3b** gave the corresponding cross-coupling products **4a-d** in good yields (entries 1–4). However, a mixture of **2d** and **3a** in the presence of $PdCl_2(PPh_3)_2$/KF resulted in polymerization and the cross-coupling product was not detected (entry 5). This result showed that the perfluoroallyl group could be attacked by hydroxy group



2i

Scheme 2.



Scheme 3.

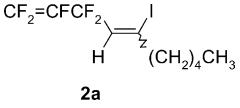
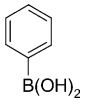
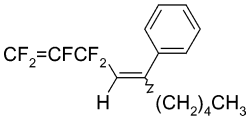
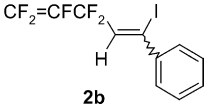
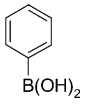
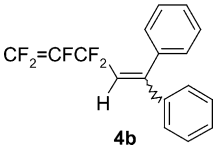
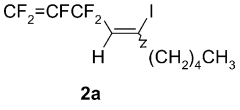
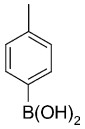
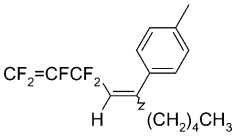
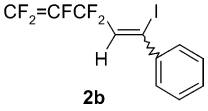
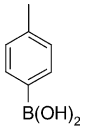
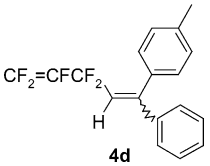
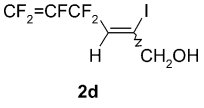
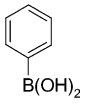
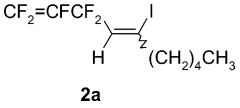
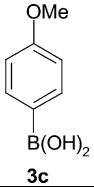
under the cross-coupling reaction conditions. It was noteworthy that there was no reaction in the cross-coupling of **2a** with *p*-methoxylphenyl boronic acid **3c** (entry 6).

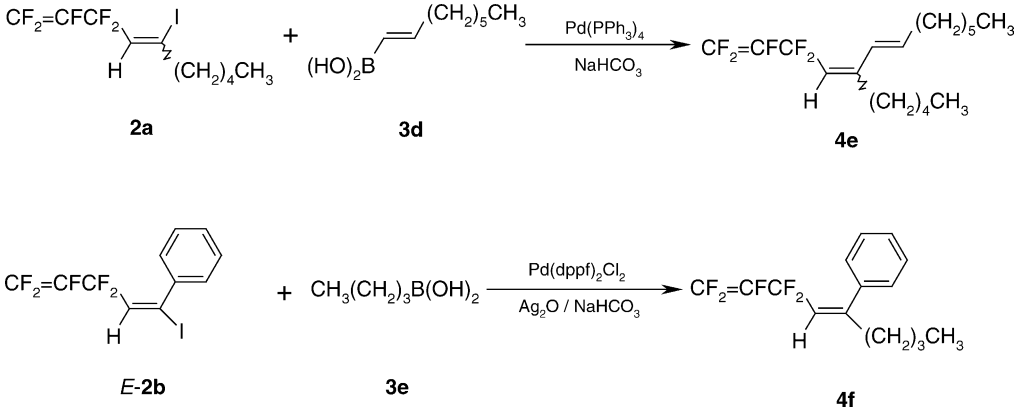
The cross-coupling of fluorinated electrophiles **2** with alkenyl(alkyl) boronic acids was also investigated. Treatment of **2a** with alkenyl boronic acid **3d** in the presence of $PdCl_2(PPh_3)_2$/KF resulted in no reaction. Fortunately, the reaction of **2a** with **3d** in toluene at 80 °C under the catalyst of 3 mol% $Pd(PPh_3)_4$ in the presence of $NaHCO_3$ gave the desired product **4e** in 87% yield (Scheme 4). Furthermore, the cross-coupling of *E*-2b with alkyl boronic acid **3e** under the catalyst of $Pd(dppf)_2Cl_2$ in the presence of $NaHCO_3/Ag_2O$ [8] proceeded smoothly to give compound 4f (Scheme 4).

2.3. The Sonogashira cross-coupling of 1,1,2,3,3-pentafluoro-5-iodopenta-1,4-dienes 2 with terminal alkynes

The Sonogashira coupling reaction is one of the very useful methods for the synthesis of fluorinated conjugated enynes [3a, 9]. We examined the Sonogashira cross-coupling of perfluoroallyl vinyl iodides **2** with terminal alkynes **1**. When Et_3N was used as both solvent and base, treatment of **2** with **1** in the presence of $Pd(PPh_3)_4$ at 40–50 °C for 16 h gave compounds **5** in high yields. It was noteworthy that the Sonogashira reaction in the presence of $PdCl_2(PPh_3)_2$/CuI was not complete, even the

Table 2
$PdCl_2(PPh_3)_2$/KF-mediated cross-coupling of **2** with aryl boronic acid **3**

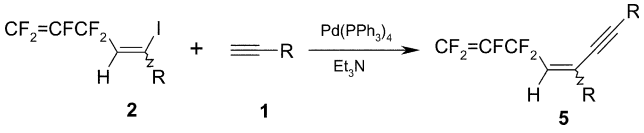
Entry	2	Boronic acid 3	Product 4	Isolated yield (%)
1	 **2a**	 **3a**	 **4a**	79
2	 **2b**	 **3a**	 **4b**	74
3	 **2a**	 **3b**	 **4c**	72
4	 **2b**	 **3b**	 **4d**	87
5	 **2d**	 **3a**	Polymerisation	
6	 **2a**	 **3c**	No reaction	

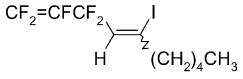
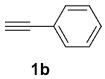
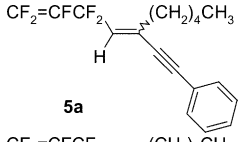
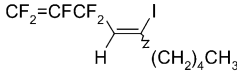
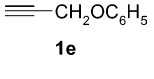
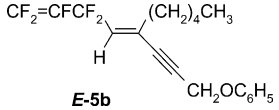
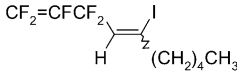
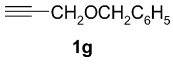
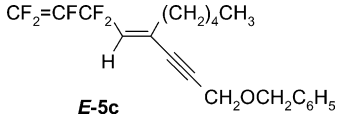
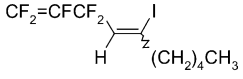
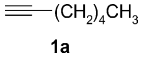
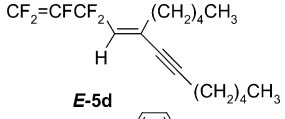
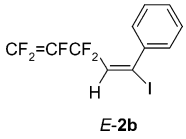
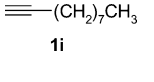
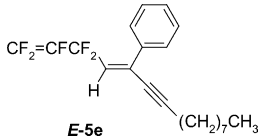
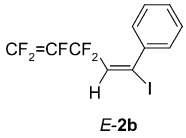
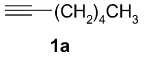
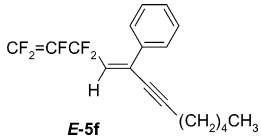
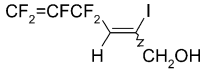
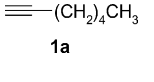


Scheme 4.

reaction time was prolonged to 24 h. The coupling reaction results were summarized in Table 3. As shown in Table 3, pure *E*-5b, *E*-5c and *E*-5d were obtained by column chromatography. The coupling of **2d** with terminal alkyne **1a** in the presence of $Pd(PPh_3)_4/Et_3N$ resulted in polymerization, which was similar to the Suzuki coupling of **2d** with boronic acid in the presence of $PdCl_2(PPh_3)_2/KF$.

Table 3
$Pd(PPh_3)_4$-mediated cross-coupling of **2** with terminal alkyne **1**



Entry	**2**	Alkyne **1**	Product **5**	Isolated yield (%)
1	 **2a**	 **1b**	 **5a**	84
2	 **2a**	 **1e**	 ***E*-5b**	55 (75)[a]
3	 **2a**	 **1g**	 ***E*-5c**	48 (69)[a]
4	 **2a**	 **1a**	 ***E*-5d**	51 (82)[a]
5	 ***E*-2b**	 **1i**	 ***E*-5e**	60
6	 ***E*-2b**	 **1a**	 ***E*-5f**	78
7	 **2d**	 **1a**	Polymerization	

[a] Isolated yield of a mixture of *Z* and *E* isomers.

3. Conclusion

We have developed a procedure for the first perfluoroallylation of alkynes. By utilizing AIBN as initiator, the perfluoroallyl vinyl iodides was obtained in high yields. We have also developed a facile method for the preparation of perfluoroallyl trisubstituted olefins, dienes and enyenes via palladium-catalyzed cross-coupling of perfluoroallyl vinyl iodides with boronic acids and alkynes.

4. Experimental section

^{1}H NMR spectra were recorded on a Bruker AM 300 (300 MHz) spectrometer with Me_4Si as internal standard. ^{19}F NMR spectra were obtained on Bruker AM 300 (282 MHz) spectrometer in $CDCl_3$ with $CFCl_3$ as external standard, downfield shifts being designated as negative. All chemical shifts (δ) are expressed in ppm, coupling constants (J) are given in Hz. Mass spectra were recorded on a Finnigan-MAT-8430 instrument using EI ionization at 70 eV. IR spectra were recorded on a Shimadzu IR-440 spectrometer. Perfluoroallyl iodide was prepared according to the literature procedure [10].

4.1. General procedure for addition of F-allyl iodide to alkyne

Under nitrogen atmosphere, a mixture of *F*-allyl iodide (5.0 mmol), alkyne **1** (6.0 mmol) and AIBN (100 mg) was stirred at 65 °C for 16 h. The reaction mixture was directly purified by flash column chromatography (silica gel, eluting with hexane) to give **2**.

4.1.1. 1,1,2,3,3-Pentafluoro-5-iododeca-1,4-diene (**2a**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.40 (t, J = 12.6 Hz, 0.8H), 6.30 (t, J = 10.6 Hz, 0.2H), 2.56 (t, J = 15.0 Hz, 1.6H), 2.63 (t, J = 3.6 Hz, 0.4H), 1.62–1.28 (m, 6H), 0.92 (t, J = 7.1 Hz, 3H). ^{19}F NMR (282 MHz) δ: −93.0 (m, 2F), −94.7 (m, 1F), −106.6 (m, 1F), −185.9 (m, 1F). IR: 1784, 1635, 1346, 1292 cm^{-1}. MS *m/z*: 171 (17), 147 (100), 105 (67), 77 (34). HRMS Calcd. For $C_{10}H_{12}F_5I$: 354.1012, found: 353.9953.

4.1.2. 1,1,2,3,3-Pentafluoro-5-iodo-5-phenylpenta-1,4-diene (**2b**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.49–7.27 (m, 5H), 6.71 (t, J = 9.3 Hz, 0.75H), 6.50 (t, J = 10.5 Hz, 0.25H). ^{19}F NMR (282 MHz) δ: −90.5 (m, 1.5F), −93.5 (m, 0.5F), −94.4 (m, 1F), −106.4 (m, 1F), −185.4 (m, 1F). IR: 3062, 1787, 1631, 1348, 1299 cm^{-1}. MS *m/z*: 360 (M^+, 9), 233 (100), 213 (49), 133 (33), 102 (30). HRMS Calcd. for $C_{11}H_6F_5I$: 360.0649, found: 359.9415.

4.1.3. Methyl 4,4,5,6,6-pentafluoro-2-iodohexa-2,5-dienoate (**2c**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.66 (t, J = 10.8 Hz, 0.25H), 6.61 (t, J = 12.0 Hz, 0.75H). ^{19}F NMR (282 MHz) δ: −92.8 (m, 0.25F), −93.6 (m, 0.75F), −96.2 (m, 2F), −105.9 (m, 1F), −187.2 (m, 1F). IR: 2960, 1787, 1638, 1352, 1295 cm^{-1}. MS *m/z*: 342 (M^+, 15), 131 (100), 91 (24), 69 (27), 59(38). HRMS Calcd. for $C_7H_4F_5IO_2$: 342.0089, found: 341.9196.

4.1.4. 4,4,5,6,6-Pentafluoro-2-iodohexa-2,5-diene-1-ol (**2d**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.77 (t, J = 10.9 Hz, 0.5H), 6.54 (t, J = 12.9 Hz, 0.5H), 4.35 (s, 1H), 4.33 (s, 1H), 2.54 (s, 0.5H), 2.28 (s, 0.5H). ^{19}F NMR (282 MHz) δ: −97.3 (m, 1F), −98.2 (m, 0.5F), −98.9 (m, 1F), −99.5 (m, 0.5F), −111.0 (m, 1F), −191.6 (m, 1F). IR: 3367, 1786, 1654, 1346, 1295 cm^{-1}. MS *m/z*: 314 (M^+, 40), 139 (100), 131 (51), 119 (68), 69 (41). Anal. Calcd. for $C_6H_4F_5IO$: C, 22.95; H, 1.28. found: C, 23.18; H, 1.48.

4.1.5. 1,1,2,3,3-Pentafluoro-5-iodo-6-phenoxhexa-2,5-diene (**2e**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.34–6.89 (m, 5H), 6.79 (t, J = 10.5 Hz, 0.5H), 6.68 (t, J = 13.2 Hz, 0.5H), 4.78 (s, 1H), 4.73 (s, 1H). ^{19}F NMR (282 MHz) δ: −92.9 (m, 1F), −93.8 (m, 1F), −94.1 (m, 1F), −105.9 (m, 1F), −186.3 (m, 1F). IR: 1786, 1641, 1600, 1349, 1294. MS *m/z*: 390 (M^+, 25), 263 (80), 131 (60), 94 (91), 65 (100). Anal. Calcd. for $C_{12}H_8F_5IO$: C, 36.95; H, 2.07. found: C, 36.45; H, 2.21.

4.1.6. 1,1,2,3,3-Pentafluoro-5-iodo-5-trimethylsilylpenta-2,5-diene (**2f**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.38 (t, J = 15.9 Hz, 0.4H), 6.80 (t, J = 10.2 Hz, 0.6H), 0.32 (s, 3.5H), 0.26 (s, 5.5H). ^{19}F NMR (282 MHz) δ: −93.4 (m, 3F), −105.8 (m, 1F), −186.4 (m, 1F). IR: 2961, 1784, 1587, 1348, 1291. MS *m/z*: 356 (M^+, 13), 245 (100), 137 (28), 77 (44). HRMS Calcd. for $C_8H_{10}F_5ISi$: 356.1490, found: 355.9485.

4.1.7. 6-Benzyloxy-1,1,2,3,3-pentafluoro-5-iodohexa-2,5-diene (**2g**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.45–7.20 (m, 5H), 6.75 (t, J = 10.8 Hz, 0.5H), 6.63 (t, J = 12.9 Hz, 0.5H), 4.54 (d, J = 3.6 Hz, 1H), 4.49 (d, J = 4.8 Hz, 1H), 4.26–4.17 (m, 2H). ^{19}F NMR (282 MHz) δ: −92.2 (m, 1F), −93.2 (m, 0.5F), −93.6 (m, 1F), −94.2 (m, 0.5F), −106.2 (m, 1F), −186.0 (m, 1F). IR: 3067, 1785, 1639, 1348, 1293 cm^{-1}. MS *m/z*: 404 (M^+, 1), 171 (14), 105 (10), 91 (100), 77(12). Anal. Calcd. for $C_{13}H_{10}F_5IO$: C, 38.64; H, 2.49, found: C, 38.69; H, 2.65.

4.1.8. E-4,4,5,6,6-Pentafluoro-2-iodohexa-2,5-dienyl acetate (**2h**)

^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.62 (t, J = 12.60 Hz, 1H), 4.84 (s, 2H), 2.15 (s, 3H). ^{19}F NMR (282 MHz, $CDCl_3$)

δ: −92.7 to −92.6 (m, 2F), −92.9 to −92.7 (m, 1F), −105.9 to −105.4 (m, 1F), −187.2 to −186.7 (m, 1F). IR: 2980, 1784, 1750, 1347, 1292, 1218, 1163, 1041, 984 cm^{-1}. MS *m/z*: 229 (46), 131 (25), 119 (10), 43 (100). Anal. Calcd. for $C_8H_6F_5IO_2$: C, 26.69; H, 1.69; F, 26.97, found: C, 26.97; H, 1.85; F, 26.86.

*4.1.9. Z-4,4,5,6,6-Pentafluoro-2-iodohexa-2, 5-dienyl acetate (**2h**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 6.60 (t, *J* = 12.60 Hz, 1H), 4.82 (s, 2H), 2.08 (s, 3H). ^{19}F NMR (282 MHz, $CDCl_3$) δ: −94.4 to −94.1 (m, 3F), −106.3 to −105.5 (m, 1F), −186.6 to −185.9 (m, 1F). IR: 2988, 1785, 1751, 1653, 1430, 1347, 1296, 1213, 1161, 1048, 998 cm^{-1}. MS *m/z*: 229 (46), 131 (25), 119 (10), 43 (100). Anal. Calcd. for $C_8H_6O_2F_5I$: C, 26.69; H, 1.69, found: C, 26.97; H, 1.85.

*4.1.10. 1,1,2,3,3-Pentafluoro-5-iodo-4-propylocta-1, 4-diene (**2i**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 2.69 (t, *J* = 7.50 Hz, 1H), 2.62 (t, *J* = 7.8 Hz, 1H), 2.24–2.34 (m, 1H), 2.30–2.25 (m, 1H), 1.71–1.48 (m, 4H), 1.22–0.91 (m, 6H). ^{19}F NMR (282 MHz) δ: −91.3 (m, 2F), −94.6 (m, 1F), −106.6 (m, 1F), −184.8 (m, 1F). IR: 2966, 1782, 1618, 1466, 1342, 1289 cm^{-1}. MS *m/z*: 368 (M^+, 24), 127 (24), 109 (100), 81 (55), 79 (41), 55 (63), 41 (82). Anal. Calcd. for $C_{11}H_{14}F_5I$: C, 35.89; H, 3.83, found: C, 35.61; H, 3.83.

*4.2. General procedure for the cross-coupling of **2** with with aryl boronic acid **3***

Under nitrogen atmosphere, a mixture of **2** (0.5 mmol), aryl boronic acid **3** (0.8 mmol), $PdCl_2(PPh_3)_2$ (0.015 mmol), $KF.2H_2O$ (1.0 mmol) and toluene (2 mL) was stirred at 80 °C for 16 h. Then ether (20 mL) was added to the reaction mixture. The mixture was washed with water and brine. After removal of the solvent, the residue was purified by flash column chromatography (silica gel, eluting with hexane) to give **4**.

*4.2.1. 1,1,2,3,3-Pentafluoro-5-phenyldeca-1,4-diene (**4a**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.36–7.12 (m, 5H), 5.73 (t, *J* = 13.5 Hz, 1H), 2.61 (d, *J* = 7.5 Hz, 1.6H), 2.38 (d, *J* = 6.3 Hz, 0.4H), 1.62–1.17 (m, 6H), 0.89–0.8 (t, *J* = 7.60 Hz, 3H). ^{19}F NMR (282 MHz) δ: −88.3 (m, 0.4F), −91.5 (m, 1.6F), −95.5 (m, 0.8F), −96.4 (m, 0.2F), −107.3 (m, 1F), −183.0 (m, 1F). IR: 2962, 1784, 1646, 1344, 1293 cm^{-1}. MS *m/z*: 305 (M^+ + 1, 14), 248 (100), 197 (45), 179 (62), 159 (37), 115 (40), 77 (23). Anal. Calcd. For $C_{16}H_{17}F_5$: C, 63.15; H, 5.63, found: C, 62.99; H, 5.61.

*4.2.2. 1,1,2,3,3-Pentafluoro-5,5-diphenylpenta-1,4-diene (**4b**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.65–6.24 (m, 10H), 6.27 (t, *J* = 10.50 Hz, 1H). ^{19}F NMR (282 MHz) δ: −87.6 (m, 2F), −95.8 (q, *J* = 35.80 Hz, 1F), −107.2 (m, 1F), −183.5 (m, 1F). IR: 3062, 3034, 1786, 1633, 1494, 1347, 1304 cm^{-1}. MS *m/z*: 311 (M^+ + 1, 4), 310 (M^+, 22), 197 (100), 165 (36), 77 (44), 51 (56). HRMS. Calcd. for $C_{17}H_{11}F_5$: 310.2659, found: 310.0766.

*4.2.3. 1,1,2,3,3-Pentafluoro-5-(4-methyphenyl)deca-1,4-diene (**4c**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.35–7.01 (m, 4H), 5.73 (t, *J* = 13.20 Hz, 1H), 2.62–2.59 (m, 2H), 2.38 (s, 1.4H), 2.36 (s, 0.6H), 1.35–1.26 (m, 4H), 0.9–0.79 (m, 6H). ^{19}F NMR (282 MHz) δ: −88.3 (t, *J* = 22.84 Hz, 0.4F), −91.5 (m, 1.6F), −95.7 (m, 0.8F), −96.8 (m, 0.2F), −107.6 (m, 1F), −183.4 (m, 0.8F), −185.4 (m, 0.8F). IR: 3030, 2961, 1784, 1646, 1468, 1376, 1344, 1293 cm^{-1}. MS *m/z*: 318 (M^+, 9), 262 (100), 247 (48), 211 (13), 91 (11). HRMS. Calcd. for $C_{17}H_{19}F_5$: 318.3291, found: 318.1421.

*4.2.4. 1,1,2,3,3-Pentafluoro-5-(4-methylphenyl)5-phenylpenta–1,4-diene (**4d**)*

^{1}H NMR (300MHz, $CDCl_3$) δ: 7.35–7.11 (m, 9H), 6.18 (t, *J* = 10.50 Hz, 1H), 2.36 (s, 0.8H), 2.32 (s, 2.2H). ^{19}F NMR (282 MHz) δ: −87.1 (m, 2F), −95.8 (m, 1F), −107.1 (m, 1F), −183.1 (m, 1F). IR: 3029, 1680, 1609, 1494 cm^{-1}. MS *m/z*: 325 (M^+ + 1, 9), 324 (M^+, 46), 255 (100), 240 (55), 220 (45). HRMS. Calcd. for $C_{18}H_{13}F_5$: 324.2927, found: 324.0950.

*4.2.5. 1,1,2,3,3-Pentafluoro-5-pentyltrideca-1,4,6-triene (**4e**)*

Under nitrogen atmosphere, a mixture of **2a** (0.5 mmol), alkenyl boronic acid **3d** (0.8 mmol), $Pd(PPh_3)_4$ (0.015 mmol), $NaHCO_3$ (1.0 mmol) and toluene (2 mL) was stirred at 80 °C for 14 h. Then ether (20 mL) was added to the reaction mixture. The mixture was washed with water and brine. After removal of the solvent, the residue was purified by flash column chromatography (silica gel, eluting with hexane) to give **4e**. ^{1}H NMR (300MHz, $CDCl_3$) δ: 6.39 (td, *J* = 12.6 Hz, 0.9 Hz, 2.25H), 6.25 (t, *J* = 10.56 Hz, 0.75H). 2.62–2.53 (m, 4H), 1.61–1.28 (m, 14H), 0.93–0.88 (m, 6H). ^{19}F NMR (282MHz) δ: −92.6 (m, 1.5F), −93.0 (m, 0.5F), −94.2 (m, 0.75F), −094.5 (m, 0.25F), −106.8 (m, 1F), −186.1 (m, 1F). IR: 2961, 2933, 1784, 1468, 1347 cm^{-1}. MS *m/z*: 339 (M^+ + 1, 2), 338 (M^+, 11), 71 (72), 55 (91), 43 (100). HRMS. Calcd. for $C_{18}H_{27}F_5$: 338.4033, found: 338.1987.

*4.2.6. 1,1,2,3,3-Pentafluoro-5-phenylundeca-1,4-diene (**4f**)*

Under nitrogen atmosphere, a mixture of E-**2b** (0.5 mmol), alkyl boronic acid **3e** (0.8 mmol), $Pd(dppf)Cl_2$ (0.025 mmol), $NaHCO_3$ (1.0 mmol), Ag_2O (1.0 mmol) and THF (2 mL) was stirred at 50 °C for 18 h. Then ether (20 mL) was added to the reaction mixture. The mixture was washed with water and brine. After removal of the solvent, the residue was purified by flash column chromatography (silica gel, eluting with hexane) to give **4f**. ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.37–7.12 (m, 5H), 5.73 (t, *J* = 9.9 Hz,

1H), 2.42 (d, J = 7.5 Hz, 2H), 1.42–1.32 (m, 4H), 0.90 (t, J = 6.6 Hz, 3H). ^{19}F NMR (282 MHz) δ: −88.2 (m, 2F), −96.3 (m, 1F), −107.4 (m, 1F), −183.2 (m, 1F). IR: 2962, 1784, 1646, 1344, 1293 cm^{-1}. MS *m/z*: 291 (M^+ + 1, 2), 290 (M^+, 3), 248 (89), 177 (100), 57 (89). HRMS. Calcd. for $C_{15}H_{15}F_5$: 290.2755, found: 290.1111.

*4.3. General procedure for the cross-coupling of **2** with terminal alkyne **1***

Under nitrogen atmosphere, a mixture of **2** (0.5 mmol), alkyne **1** (0.8 mmol), $Pd(PPh_3)_4$ (0.015 mmol), CuI (0.1 mmol) and Et_3N (2 mL) was stirred at 50 °C for 16 h. After removal of the solvent in vacuo, the residue was purified by flash column chromatography (silica gel, eluting with hexane) to give **5**.

*4.3.1. 5,5,6,7,7-Pentafluoro-3-pentyl-1-phenylhepta-3, 6-dien-1-yne (**5a**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.49–7.27 (m, 5H), 6.26 (t, J = 10.8 Hz, 0.2H), 6.00 (t, J = 13.5 Hz, 0.8H), 2.38 (t, J = 7.8 Hz, 2H), 1.69–1.28 (m, 6H), 0.92 (t, J = 5.7 Hz, 3H). ^{19}F NMR (282 MHz) δ: −92.7 (m, 1.6F), −93.5 (m, 0.4F), −95.1 (m, 1F), −107.3 (m, 1F), −186.0 (m, 1F). IR: 1784, 1627, 1492 cm^{-1}. MS *m/z*: 328 (M^+, 6), 272 (97), 201 (100), 183 (87), 127 (84), 91 (50). HRMS. Calcd. for $C_{18}H_{17}F_5$: 328.3243, found: 328.1210.

*4.3.2. 6,6,7,8,8-Pentafluoro-4-pentyl-1-phenoxyocta-4, 7-dien-2-yne (**5b**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.32–6.96 (m, 5H), 5.89 (t, J = 13.5 Hz, 1H), 4.83 (s, 2H), 2.34 (t, J = 3.6 Hz, 2H), 1.56–1.21 (m, 6H), 0.87 (t, J = 6.9 Hz, 3H). ^{19}F NMR (282 MHz) δ: −92.8 (m, 2F), −94.5 (m, 1F), −106.8 (m, 1F), −185.8 (m, 1F). IR: 3067, 1784, 1633, 1496, 1346 cm^{-1}. MS *m/z*: 358 (M^+, 5), 302 (100), 94 (46), 77 (34), 55 (54). Anal. Calcd. for $C_{19}H_{19}F_5O$: C: 63.68; H, 5.34, found: C, 63.71; H, 5.33.

*4.3.3. 1-Benzyloxy-6,6,7,8,8-pentafluoro-4-pentylocta-4, 7-dien-2-yne (**5c**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.39–7.28 (m, 5H), 5.92 (t, J = 13.50 Hz, 1H), 4.61 (s, 2H), 4.33 (s, 2H), 2.30 (t, J = 8.1 Hz, 2H), 1.62–1.30 (m, 6H), 0.91 (t, J = 6.9 Hz, 3H). ^{19}F NMR (282 MHz) δ: −92.9 (m, 2F), −94.8 (m, 1F), −107.1 (m, 1F), −185.9 (m, 1F). IR: 3034, 1784, 1631, 1456 cm^{-1}. MS *m/z*: 135 (27), 91 (100), 77 (22). Anal. Calcd. for $C_{20}H_{21}F_5O$: C, 64.51; H, 5.68, found: C, 64.20; H, 6.06.

*4.3.4. 1,1,2,3,3-Pentafluoro-5-pentyldedeca-1, 4-dien-6-yne (**5d**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 5.80 (t, J = 13.8 Hz, 1H), 2.33 (t, J = 6.9 Hz, 2H), 2.24 (t, J = 8.1 Hz, 2H), 1.61–1.26 (m, 12H), 0.93–0.88 (m, 6H). ^{19}F NMR (282 MHz) δ: −92.1 (m, 2F), −95.1 (m, 1F), −107.1 (m, 1F), −185.4 (m, 1F). IR: 2225, 1784, 1630, 1468 cm^{-1}. MS *m/z*: 322 (M^+), 238 (38), 91 (42), 55 (87), 41 (100). HRMS. Calcd. for $C_{17}H_{23}F_5$: 322.3607, found: 322.1672.

*4.3.5. 1,1,2,3,3-Pentafluoro-5-phenylpentadeaca-1, 4-dien-6-yne (**5e**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.36–7.25 (m, 5H), 6.12 (t, J = 10.8 Hz, 1H), 2.34 (t, J = 6.9 Hz, 2H), 1.56–1.27 (m, 12H), 0.88 (t, J = 6.3 Hz, 3H). ^{19}F NMR (282 MHz) δ: −88.2 (m, 2F), −95.3 (m, 1F), −106.5 (m, 1F), −183.8 (m, 1F). IR: 2220, 1786, 1618, 1495 cm^{-1}. MS *m/z*: 272 (100), 251 (59), 201 (91), 183 (53). HRMS. Calcd. for $C_{21}H_{23}F_5$: 370.4047, found: 370.1695.

*4.3.6. 1,1,2,3,3-Pentafluoro-5-phenyldedeca-1, 4-dien-6-yne (**5f**)*

^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.37 (t, J = 3.6 Hz, 5H), 6.14 (t, J = 11.1 Hz, 1H), 2.36 (t, J = 6.9 Hz, 2H), 1.59–1.32 (m, 6H), 0.89 (t, J = 6.9 Hz, 3H). ^{19}F NMR (282 MHz) δ: −88.5 (m, 2F), −95.7 (m, 1F), −107.0 (m, 1F), −184.1 (m, 1F). IR: 3087, 2220, 1786, 1618, 1495 cm^{-1}. MS *m/z*: 251 (39), 201 (59), 41 (100). HRMS. Calcd. for $C_{18}H_{17}F_5$: 328.3243, found: 328.1278.

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