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The synthesis and application of fluorous boronates without perfluorinated solvents

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Dedicated to Professor Herbert W. Roesky on the occasion of his 70th birthday.

Abstract

The synthesis of a fluorous diol **4** bearing a perfluorodecyl chain was described. A series of boronic acid were attached to **4** by esterification. The purification of the products was fulfilled by facile filtration instead of expensive and environmental troublesome fluorous liquid–liquid extraction. The Suzuki cross-coupling reactions of the formed fluorous boronates **5** underwent smoothly and the fluorous diol **4** was recycled in good yields.

Keywords: Fluorous biphase synthesis; Fluorous boronates; Suzuki coupling reaction

1. Introduction

The solid-phase polymers and fluorous ponytails were commonly used as ''tags'' in combinatorial and parallel synthesis, which were usually designed to facilitate the isolation of products, catalysts or reagents [1,2]. Solid-phase synthesis has successfully simplified the separation to be an easy wash and filtration, but the reactivity of the supported substrates is slowed down because of unfavorable heterogeneous reaction kinetics. In addition, the inability to monitor the reaction by NMR, mass spectroscopy and TLC is another serious disadvantage for usual solid-phase synthesis [3]. Therefore, fluorous synthesis has become an excellent strategic alternative to solid-phase synthesis. Fluorous synthesis that is similar to solid-phase synthesis in concept is performed in homogeneous reactions. Many applications of fluorous methodology have been extensively developed in the last few years [4]. Fluorous compounds are usually isolable or recoverable by fluorous liquid–liquid extraction, and a large amount of perfluorinated solvents are needed. Compared with common organic solvents, the fluorous solvents are expensive and may cause the environmental persistence. Several groups reported that the fluorous solid/organic liquid separation which could be used to recycle the fluorous catalysts [5–7]. Several kinds of polymer-bound diols [8] and fluorous diols [9] were used to immobilize boronic acid and facilitate the intermediate purification steps. According to the empirical rule [10] ''longer fluorous chains cause an increase in partition coefficient coupled with a decrease in absolute solubilities in both phases'', we designed and synthesized a fluorous diol **4** bearing a perfluorodecyl chain and then used it to attach the boronic acid. The immobilization of the boronic acid via fluorous diol **4** has two essential advantages compared with the above methods. Firstly, the intermediates can be purified through facile filtration, which omitted the expensive and un-environmental perfluorinated solvent. Secondly, the reaction can be conducted homogeneously and monitored by TLC. We used the Suzuki coupling reaction of the fluorous boronates as a de-tag strategy to recycle the fluorous

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diol **4**. The intermediates and final products can be purified by simple wash and filtration.

2. Results and discussion

The fluorous diol **4** and fluorous boronates **5** were prepared as shown in Scheme 1. Dibenzoyl peroxide (DBP) initiated addition of perfluorodecyl iodide to allyl acetate afforded the adduct **2** in good yield [11]. Then reduction of **2** with zinc and acetic acid gave the fluorous alkene **3**. Dihydroxylation of **3** with *N*-methylmorpholine-*N*-oxide in the presence of osmium tetraoxide and small quantity of pyridine in aqueous acetone at 50 °C provided the desired fluorous diol **4** in 87% yield. Subsequently, the fluorous diol **4** was used to immobilize boronic acid in trifluoromethylbenzene (BTF) at 50–80 °C. Diol **4** was completely converted into fluorous boronate **5** by treatment with 1.0 equiv. or slightly excess of arylboronic acid. The immobilization reaction usually took more than 15 h to be finished. Higher reaction temperature can accelerate the reaction. The reaction could be monitored by TLC. After complete disappearance of fluorous diol **4**, the reaction mixture was concentrated in vacuo. A little ethanol was added, and the excess organic boronic acid was removed by shaking and filtration. The filtration cake was dissolved in dichloromethane at elevated temperature. After cooling at −10 °C, the white solid was re-crystallized from the solution. Then the fluorous boronates **5a–j** were obtained through rapid filtration in high purity and good yields which were fully characterized by ^{1}H NMR, ^{19}F NMR, IR, MS and elemental analysis. Fluorous boronates **5** are mostly white or pale yellow solids. Since prolonged exposure of moisture might cause the hydrolysis of fluorous boronates, they were kept in dry vessels and showed adequate storage stability for long periods of time.

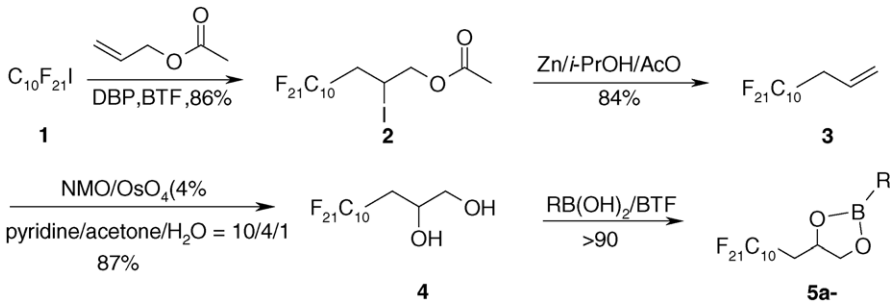
The fluorous boronates **5a–j** were then applied in Suzuki coupling reaction, which is an important tool for carbon–carbon bond formation. As shown in Scheme 2, the Suzuki coupling reaction of fluorous boronates **5** with aryl halides **6** underwent smoothly under standard Suzuki reaction conditions [12]. Although fluorous boronates were used in this case, we did not find any retarding effect for the Suzuki coupling reaction by the perfluoroalkyl chains. Biaryl **7** was obtained by filtration followed by chromatography (silica gel) in good yield. The fluorous diol **4** was recovered at high yield and purified by simple filtration which could be reused for the reaction sequence. The results were summarized in Table 1.

In conclusion, we have designed and synthesized a new fluorous diol **4**. A series of boronic acids were attached to fluorous diol **4** by esterification. The key aspect of our strategy was the application of fluorous solid/organic liquid extraction without perfluorinated solvent. The formed fluorous boronates could be purified by facile filtration. The Suzuki coupling reaction was adopted as the de-tagging strategy in synthesis, which also demonstrated the usefulness of fluorous solid/organic liquid extraction without perfluorinated solvent. In addition, the fluorous diol could be recovered in high yields and high purities.

3. Experimental

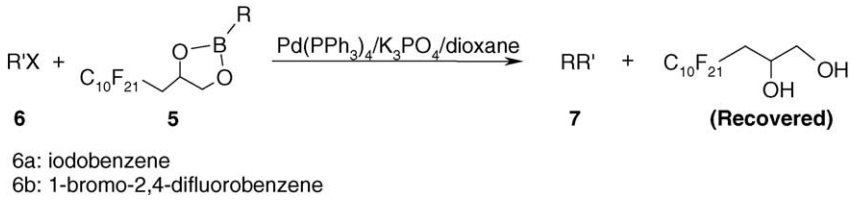
3.1. General

$CF_3C_6H_5$ (BTF) was distilled over P_2O_5. Other purchased chemicals and reagents were used as received. All reactions were carried out under a dry nitrogen atmosphere in predried glasswares. Melting points were determined on a Paike melting point apparatus and were uncorrected. The structures of all products were characterized by ^{1}H NMR and ^{19}F NMR spectroscopy (Bruker AM 300, 300 MHz for ^{1}H, 282 MHz for ^{19}F or Bruker AM 400, 400 MHz for ^{1}H, 376 MHz for ^{19}F) using TMS and $CFCl_3$ as internal standard. All chemical shifts (δ) are expressed in ppm, and



a:R=C_6H_5-
b:R=*p*-MeC_6H_4-
c:R=*p*-$MeOC_6H_4$-
d:R=*trans*-C_6H_5CH=CH-
e:R=2-thienyl-
f:R=*m*-$MeSC_6H_4$-
g:R=*p*-ClC_6H_4-
h:R=*m*-$H_2NC_6H_4$-
i:R=*o*-$OHCC_6H_4$
j:R=*n*-propyl

Scheme 1. Synthesis of fluorous diol and its application in immobilizing organic boronic acids.



Scheme 2. Suzuki coupling reaction of fluorous boronates.

coupling constants (*J*) are given in Hertz. Mass spectra were determined on a Finnigan-MAT-8430 instrument using EI ionization at 70 eV. IR spectra were recorded on a Shimadzu IR-440 spectrometer.

*3.2. 2-Iodo-3-(4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,13-henicosafluorodecyl)propyl acetate(**2**)*

1-Iodoperfluorodecane **1** (27.101 g, 42 mmol) and dibenzoyl peroxide (0.166 g, 1 mmol) were added into trifluoromethylbenzene (10 mL) under nitrogen with stirring. After the temperature was raised to 70 °C, the substrates were dissolved completely. Then allyl acetate (6.302 g, 63 mmol) was added dropwise for 1 h. The reaction mixture was stirred for 8 h at 95–100 °C. Then the reaction mixture was cooled to room temperature, a violet brown solid was obtained. Purification of the crude product by column chromatography (silica gel, petroleum ether:-ethyl acetate = 50:1) gave compound **2** as a white solid (26.893 g, 86%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.39–4.19 (m, 3H), 2.90–2.77 (m, 2H), 2.05 (s, 3H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −81.07 (s, 3F), −113.40, −114.02 (2s, 2F), −122.02 (s, 10F), −122.96 (s, 2F), −123.76 (s, 2F), −126.38 (s, 2F).

*3.3. 3-(4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,13-Henicosafluorodecyl)-propene (**3**)*

Zinc powder (2.493 g, 38 mmol) was added to a vigorously stirred solution of **2** (22.124 g, 29 mmol) in *iso*-propanol (60 mL) and the gray solution was heated. After the temperature raised to 85 °C, acetic acid (30 mL) diluted in *iso*-propanol (50 mL) was added dropwise for 1 h. Then the reaction mixture was warmed to reflux for 7 h. After the reaction mixture was cooled to room temperature, a white solid was precipitated. Poured out the upper solution and the solid was dried under vacuum. The desired product **3** was obtained as a white solid (12.401 g, 75%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.86–5.79 (m, 1H), 5.39–5.33 (m, 2H), 2.93–2.82 (m, 2H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.94 (s, 3F), −113.34 (s, 2F), −121.84 (s, 10F), −122.81 (s, 2F), −123.17 (s, 2F), −126.24 (s, 2F).

Table 1
Suzuki coupling reaction of fluorous boronates **5** and the recovery of diol **4**[a]

Entry	Fluorous boronates **5**	*R′*X	*RR′*	Yield (%)	Recovery of diol **4** (%)[b]
1	**5**a	**6**a	**7**aa	84	91
2	**5**b	**6**a	**7**ab	87	92
3	**5**e	**6**a	**7**ae	76	89
4	**5**f	**6**a	**7**af	92	94
5	**5**g	**6**a	**7**ag	89	89
6	**5**h	**6**a	**7**ah	86	76
7	**5**i	**6**a	**7**ai	82	81
8	**5**a	**6**b	**7**ba	84	90

[a] All reactions were carried out in the presence of aryl halides (0.16 mmol), fluorous boronates **5** (0.15 mmol), $Pd(PPh_3)_4$ (6 mg, 0.0052 mmol) and aqueous potassium phosphate (2 M, 15 μL, 0.3 mmol) in dioxane (3 mL).
[b] Yields were based on the fluorous boronates **5**.

*3.4. 3-(4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,13-Henicosafluorodecyl)-propane 1,2-diol (**4**)*

In a three-necked flask, NMNO (2.889 g, 22 mmol) and **3** (6.969 g, 12.4 mmol) were dissolved in a mixture of acetone (40 mL), H_2O (4 mL) and pyridine (1 mL). The mixture was cooled to 0–5 °C, and 4% aqueous solution of OsO_4 (1.2 mL) was added by syringe. After stirred for 1 h at 0 °C, the reaction mixture was warmed to 50 °C and stirred for 20 h. Aqueous sodium disulfite (20 mL) was slowly added through a dropping funnel to quench the reaction. The reaction mixture is filtered on Buchner funnel. The filtrate was extracted twice with ethyl acetate (30 mL) and the filter residue was dissolved in ethyl acetate. The combined organic layers were dried over anhydrous magnesium sulfate, filtered and concentrated to afford the crude product. Purification of the crude product by column chromatography on silica gel (petroleum ether: ethyl acetate = 4: 3) gave compound **4** as a white solid in 87% yield, mp: 136–138 °C. ^{1}H NMR (400 MHz, Methanol–d_4) δ 3.98–3.94 (m, 1H), 3.46–3.35 (m, 2H), 2.39–2.29 (m, 1H), 2.20–2.07 (m, 1H); ^{19}F NMR (376 MHz, Methanol–d_4) δ −82.32 (s, 3F), −113.40, −114.02 (m, 2F), −122.66 (s, 10F), −123.66 (s, 2F), −124.62 (s, 2F), −127.22 (s, 2F). IR(KBr) 3405, 2963, 1209, 1151, 802, 647 cm^{-1}; MS (EI, 70 ev, *m/z*) 595 (M^+ + 1,1), 594 (M^+, 1), 577 (1), 563 (100), 169 (20), 131 (39), 100 (10), 69 (59).

*3.5. General procedure for the preparation of fluorous boronates (**5**)*

To a mixture of organic boronic acid (0.300 mmol) and fluorous diol 4 (178 mg, 0.299 mmol) was added BTF

(6 mL) under nitrogen atmosphere. Then the mixture was stirred at 70 °C for about 15 h. The solvent was removed under vacuum to afford a white solid, then ethanol (1.5 mL) was added. The mixture was shaken vigorously and filtered. Then the filtration cake was dissolved in dichloromethane at elevated temperature, cooled to −10 °C and fluorous boronates **5** were obtained by rapid filtration.

*3.5.1. 2-Phenyl-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10, 11,11,11-henicosafluorodecyl-[1,3,2] dioxaborolane (**5**a)*

Yield: 191 mg (94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82–7.80 (m, 2H), 7.52–7.48 (m, 1H), 7.41–7.34 (m, 2H), 4.58 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 4.09 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 2.73–2.65 (m, 1H), 2.45–2.38 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.67 (s, 3F), −112.40 (s, 2F), −121.72 (s, 10F), −122.65 (s, 2F), −123.47 (s, 2F), −126.06 (s, 2F); IR (KBr) 2963, 2921, 1603, 1500, 1485, 1441, 1406, 1386, 1355, 1218, 1151, 1095, 1027, 884, 802, 760, 700, 648, 556, 529 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 680 (M^+, 29), 148 (10), 147 (100), 118 (28), 117 (12), 91 (32), 77 (5), 69 (9). Anal. Calcd. for $C_{19}H_{10}F_{21}BO_2$: C 33.56, H 1.48; Found: C 33.86, H 1.70.

*3.5.2. 2-p-Tolyl-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10, 10,11,11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane(**5**b)*

Yield: 195 mg (94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70(d, J = 8.0 Hz, 2H), 7.21(d, J = 8 Hz, 2H), 5.00–4.95 (m, 1H), 4.57 (dd, J_1 = 7.2 Hz, J_2 = 9.2 Hz, 1H), 4.08 (dd, J_1 = 7.2 Hz, J_2 = 9.2 Hz, 1H), 2.73–2.69 (m, 1H), 2.44–2.38 (m, 1H), 2.38 (s, 3H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.68 (s, 3F), −112.39 (s, 2F), −121.71 (s, 10F), −122.64 (s, 2F), −123.47 (s, 2F), −126.05 (s, 2F); IR(KBr) 2989, 2921, 1614, 1519, 1486, 1438, 1409, 1386, 1354, 1322, 1217, 1152, 1092, 1022, 884, 816, 647, 556, 529 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 695 (M^+ + 1,17), 694 (M^+, 80), 161 (100), 132 (44), 105 (48), 91 (28), 69 (15). Anal. Calcd for $C_{20}H_{12}F_{21}BO_2$: C 34.60, H 1.74; Found: C 34.38, H 2.15.

*3.5.3. 2-(4-Methoxyphenyl)-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8, 9,9,10,10,11,11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane (**5**c)*

Yield: 195 mg (94%) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, J = 8.0 Hz, 2H), 6.92 (d, J = 8.0 Hz, 2H), 4.99–4.93 (m, 1H), 4.56 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 4.06 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 3.84 (s, 3 H), 2.72–2.68 (m, 1H), 2.43–2.36 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.68 (s, 3 F), −112.37 (s, 2F), −121.70 (s, 10F), −122.63 (s, 2F), −123.46 (s, 2F), −126.04 (s, 2F); IR (KBr) 2962, 2934, 2839, 1608, 1569, 1486, 1454, 1439, 1413, 1386, 1355, 1296, 1215, 1151, 1095, 1031, 885, 831, 797, 646, 556, 529 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 711 (M^+ + 1, 23), 710 (M^+, 100), 177 (41), 148 (26), 121 (39), 69 (16); Anal. Calcd. for $C_{20}H_{12}F_{21}BO_3$: C 33.83, H 1.70; Found: C 33.79, H 1.70.

*3.5.4. 2-Styryl-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11, 11,11-henicosaflu-orodecyl)-[1,3,2] dioxaborolane(**5**d)*

Yield: 196 mg (94%) ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.5–7.50 (m, 2H), 7.44 (d, J = 18.3 Hz, 1H), 7.40–7.33 (m, 3H), 6.18 (d, J = 18.3 Hz, 1H), 4.95–4.86 (m, 1H), 4.54–4.48 (t, J = 9.0 Hz, 1H), 4.04–3.98 (t, J = 9.0 Hz, 1H), 2.70–2.57 (m, 1H), 2.48–2.34 (m, 1H); ^{19}F NMR (282 MHz, $CDCl_3$) δ −80.97 (s, 3F), −112.81 (s, 2F), −122.07 (s, 10F), −122.98 (s, 2F), −123.80 (s, 2F), −126.40 (s, 2F); IR(KBr) 2965, 2923, 1625, 1577, 1450, 1351, 1212, 1151, 1113, 1025, 881, 752, 695, 649, 558, 529 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 707 (M^+, 20), 706 (M^+ − 1,100), 173 (71), 143 (15), 117 (25), 116 (55), 69 (16); Anal. Calcd. for $C_{21}H_{12}F_{21}BO_2$: C 35.69, H 1.71; Found: C 35.55, H 2.01.

*3.5.5. 2-Thienyl-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11, 11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane(**5**e)*

Yield: 190 mg (94%) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, J = 4.0 Hz, 2H), 7.22(t, J = 4.0 Hz 1H), 5.02–4.95 (m, 1H), 4.60–4.56 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 4.12–4.08 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 2.76–2.71 (m, 1H), 2.45–2.39 (m, 1H); ^{19}F NMR (376 MHz) δ −80.69 (s, 3F), −112.37 (s, 2F), −121.71 (s, 10F), −122.65 (s, 2F), −123.48 (s, 2F), −126.06 (s, 2F); IR(KBr) 2997, 2926, 1524, 1438, 1428, 1360, 1303, 1208, 1151, 1062, 1020, 885, 657, 556, 529 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 687 (M^+ + 1, 12), 686 (M^+, 54), 153 (100), 124 (24), 97 (35), 69 (20); Anal. Calcd. for $C_{17}H_8F_{21}BO_2S$: C 29.76, H 1.17; Found: C 29.83, H 1.13.

*3.5.6. 2-(4-Methylthiophenyl)-4-(2,2,3,3,4,4,5,5,6,6, 7,7,8,8,9,9,10,10,11,11,11-henicosafluorodecyl)- [1,3,2]dioxaborolane(**5**f)*

Yield: 206 mg (94%) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68(s, 1H), 7.56(d, J = 8.0 Hz 1H), 7.48–7.38 (m, 1H), 7.32 (d, J = 8.0 Hz 1H), 5.00–4.97 (m, 1H), 4.58 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 4.09 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 2.79–2.64 (m, 1H), 2.50 (s, 3H), 2.53–2.30 (m, 1H); ^{19}F NMR (376 MHz) δ −80.67 (s, 3F), −112.34 (s, 2F), −121.68 (s, 10F), −122.62 (s, 2F), −123.44 (s, 2F), −126.03 (s, 2F); IR(KBr) 2983, 2920, 1631, 1592, 1440, 1353, 1209, 1152, 1017, 998, 881, 791, 701, 650, 556, 530 cm^{-1}; MS (EI, 70 ev, *m*/*z*) 728 (M^+ + 2, 7), 727 (M^+ + 1, 23), 726 (M^+, 100), 193 (23), 164 (7), 137 (27), 69 (14); Anal. Calcd. for $C_{20}H_{12}F_{21}BO_2S$: C 33.08, H 1.67; Found: C 33.05, H 2.15.

*3.5.7. 2-(4-Chlorophenyl)-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8, 9,9,10,10,11,11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane (**5**g)*

Yield: 196 mg (94%) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (d, J = 8.0 Hz, 2H), 7.39 (d, J = 8.0 Hz, 2H), 5.02–4.95 (m, 1H), 4.58 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 4.09 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 2.74–2.67 (m, 1H), 2.45–2.38 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.67 (s, 3F), −112.37 (s, 2F), −121.69 (s, 10F), −122.62 (s, 2F),

−123.43 (s, 2F), −126.03 (s, 2F); IR(KBr) 2963, 2924, 1599, 1522, 1485, 1438, 1406, 1394, 1353, 1216, 1152, 1097, 1017, 884, 794, 644, 555, 529 cm^{-1}; MS (EI, 70 ev, *m/z*) 716 (M^+ + 2, 18), 714 (M^+, 52), 183 (33), 181 (100), 154 (10), 152 (32), 127 (14), 125 (42), 69 (23); Anal. Calcd. for $C_{19}H_9F_{21}BO_2Cl$: C 31.93, H 1.26; Found: C 31.62, H 1.25.

*3.5.8. 2-(3-Aminophenyl)-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane (**5h**)*

Yield: 189 mg (94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21–7.12 (m, 3 H), 6.84–6.81 (m, 1H), 5.00–4.93 (m, 1H), 4.56 (t, *J* = 8.0 Hz, 1H), 4.07 (t, *J* = 8.0 Hz, 1H), 3.75 (br, 2H), 2.72–2.68 (m, 1H), 2.45–2.34 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.68 (s, 3F), −112.38 (s, 2F), −121.69 (s, 10F), −122.63 (s, 2F), −123.46 (s, 2F), −126.04 (s, 2F); IR(KBr) 3431, 3374, 2922, 1620, 1582, 1447, 1357, 1216, 1151, 1090, 1016, 887, 706, 665, 644, 557, 529 cm^{-1}; MS (EI, 70 ev, *m/z*) 696 (M^+ + 1, 21), 695 (M^+, 100), 694 (M^+ − 1,35), 162 (35), 131 (11), 119 (49), 106 (36), 69 (20); Anal. Calcd. for $C_{19}H_{11}F_{21}BO_2N$: C 32.83, H 1.59, N 2.01; Found: C 32.62, H 1.68, N 1.70.

*3.5.9. 2-(4-Formylphenyl)-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-henicosafluorodecyl)-[1,3,2] dioxaborolane (**5i**)*

Yield: 194 mg (94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.07 (s, 1H), 7.97 (d, *J* = 8.0 Hz, 2H), 7.89 (d, *J* = 8.0 Hz 2H), 5.06–4.99 (m, 1H), 4.63 (t, *J* = 8.0 Hz, 1H), 4.14 (t, *J* = 8.0 Hz, 1H), 2.75–2.67 (m, 1H), 2.51–2.39 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −80.70 (s, 3F), −112.35 (s, 2F), −121.69 (s, 10F), −122.63 (s, 2F), −123.43 (s, 2F), −126.04 (s, 2F); IR(KBr) 2963, 2925, 2849, 1707, 1677, 1563, 1511, 1438, 1406, 1384, 1352, 1219, 1151, 1090, 1018, 885, 828, 791, 645, 556, 529 cm^{-1}; MS (EI, 70 ev, *m/z*) 708 (M^+, 36), 707 (M^+ − 1,100), 706 (M^+ − 2,28), 175 (76), 146 (23), 119 (35), 91 (18), 69 (18); Anal. Calcd. for $C_{20}H_{10}F_{21}BO_3$: C 33.93, H 1.42; Found: C 33.83, H 1.68.

*3.5.10. 2-Propyl-4-(2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-henicosa-fluorodecyl)-[1,3,2] dioxaborolane (**5j**)*

Yield: 175 mg (94%), ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.80–4.76 (m, 1H), 4.38 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 3.89 (dd, J_1 = 8.0 Hz, J_2 = 8.0 Hz, 1H), 2.61–2.56 (m, 1H), 2.29–2.17 (m, 1H), 1.50–1.42 (m, 2H), 0.94 (t, *J* = 7.6 Hz, 3H), 0.85 (t, *J* = 7.6Hz, 3H); ^{19}F NMR(376 MHz, $CDCl_3$) δ −80.70 (s, 3F), −112.46 (s, 2F), −121.71 (s, 10F), −122.63 (s, 2F), −123.51 (s, 2F), −126.04 (s, 2F); IR(KBr) 2931, 1631, 1374, 1344, 1209, 1151, 1063, 892, 648, 557, 529 cm^{-1}; MS (EI, 70 ev, *m/z*) 645 (M^+ − 1,2), 113 (88), 69 (82), 61 (100); Anal. Calcd. for $C_{10}H_{12}F_{21}BO_2$: C 29.74, H 1.87; Found: C 29.53, H 1.79.

3.6. Experimental procedures for the fluorous Suzuki-coupling reaction

To a solution of aryl halide (0.16 mmol) in dioxane (3 mL) was added fluorous boronate **5** (0.15 mmol), Pd $(PPh_3)_4$ (6 mg, 0.0052 mmol) and aqueous potassium phosphate (2 M, 15 μL, 0.3 mmol). The reaction mixture was heated to reflux for 20 h and then extracted with ethyl acetate (3 mL) twice. The combined organic layers were filtered through a short plug of kieselguhr which was washed with ethyl acetate (2 mL). The filtrate was concentrated on a rotary evaporator, then filtered again and washed with dichloromethane (1 mL). The fluorous diol **4** was recovered as the filtration cake and dried in vacuum and characterized by ^{1}H and ^{19}F NMR. The purity of the fluorous diol attained was above 95%. Then the filtrate was concentrated by rotary evaporation. The crude product was purified by chromatography on silica gel to give the biaryl product **7**.

*3.6.1. Biphenyl (**7aa**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, *J* = 8.0 Hz, 4H), 7.44 (t, *J* = 8.0 Hz, 4H), 7.34 (t, *J* = 8.0 Hz, 2H).

*3.6.2. 4-Phenyltoluene (**7ab**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (d, *J* = 8.0 Hz, 2H), 7.49 (d, *J* = 8.0 Hz, 2H), 7.42 (t, *J* = 7.6, 2H), 7.32 (t, *J* = 7.6 Hz, 1H), 7.24 (d, *J* = 8.0 Hz, 2H).

*3.6.3. 2-Phenylthiophene (**7ae**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63–7.61 (m, 2H), 7.40–7.36 (m, 2H), 7.32–7.26 (m, 3H), 7.09–7.07 (m, 1H).

*3.6.4. 3-Methylsulfanylbiphenyl (**7af**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57–7.54 (m, 2H), 7.47–7.40 (m, 3H), 7.36–7.31 (m, 3H), 7.25–7.20 (m, 1H), 2.50 (s, 3H).

*3.6.5. 4-Chlorobiphenyl (**7ag**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58–7.50 (m, 4H), 7.46–7.33 (m, 5H).

*3.6.6. 3-Aminobiphenyl (**7ah**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57–7.55 (m, 2H), 7.44–7.33 (m, 3H), 7.26–7.24 (m, 1H), 7.02–6.72 (m, 3H), 3.89–3.55 (br, 2H).

*3.6.7. 4-Formylbiphenyl (**7ai**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 10.06 (s, 1H), 7.97–7.95 (m, 2H), 7.77–7.75(m, 2H), 7.65–7.63 (m, 2H), 7.51–7.47 (m, 3H).

*3.6.8. 2,4-Difluorobiphenyl (**7ba**)*

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70–7.68 (m, 2H), 7.60–7.41 (m, 5H), 7.05–6.95 (m, 1H); ^{19}F NMR (376 MHz, $CDCl_3$) δ −111.68 (s, 1F), −113.70 (s, 1F).

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References

[1] F.Z. Dörwald, Organic Synthesis on Solid Phase, Wiley/VCH, Weinheim, 2000.
[2] P. Kirsch, Modern Fluoroorganic Chemistry: Synthesis, Reactivity, Applications, Wiley/VCH, Weinheim, 2004.
[3] T. Miura, K. Goto, D. Hosaka, T. Inazu, Angew. Chem. Int. Ed. 42 (2003) 2047–2051.
[4] (a) S.J. Tavener, J.H. Clark, J. Fluorine Chem. 123 (2003) 31–36, Fluorous reviews;
(b) W. Zhang, Tetrahedron 59 (2003) 4475–4489;
(c) J. Yoshida, K. Itami, Chem. Rev. 102 (2002) 3693–3716;
(d) A.P. Dobbs, M.R. Kimberley, J. Fluorine Chem. 118 (2002) 3–17;
(e) D.P. Curran, Pure Appl. Chem. 72 (2000) 1649–1653;
(f) E. de Wolf, G. Van Koten, B.-J. Deelman, Chem. Soc. Rev. 28 (1999) 37–41;
(g) L.P. Barthel-Rosa, J.A. Gladysz, Coord. Chem. Rev. 190–192 (1999) 587–605;
(h) B. Betzemeier, P. Knochel, Top. Curr. Chem. 206 (1999) 61–78;
(i) R.H. Fish, Chem. Eur. J. 5 (1999) 1677–1680;
(j) M. Cavazzini, F. Montanari, G. Pozzi, S. Quici, J. Fluorine Chem. 94 (1999) 183–193;
(k) D.P. Curran, Angew. Chem. Int. Ed. 37 (1998) 1174–1196;
(l) I.T. Horváth, Acc. Chem. Res. 31 (1998) 641–650.
[5] (a) M. Wende, R. Meier, J.A. Gladysz, J. Am. Chem. Soc. 123 (2001) 11490–11491;
(b) M. Wende, J.A. Gladysz, J. Am. Chem. Soc. 125 (2003) 5861–5872.
[6] K. Isihara, S. Kondo, H. Yamamoto, Syn. Lett. (2001) 1371–1374.
[7] (a) M.W. Markowicz, R. Dembinski, Org. Lett. 4 (2002) 3785–3787;
(b) M.W. Markowicz, R. Dembinski, Synthesis (2004) 80–86.
[8] (a) D.G. Hall, J. Tailor, M. Gravel, Angew. Chem. Int. Ed. 38 (1999) 3064–3067;
(b) M. Gravel, K.A. Thompson, M. Zak, C. Berube, D.G. Hall, J. Org. Chem. 67 (2002) 3–15.
[9] (a) D. Chen, F.L. Qing, Y. Huang, Org. Lett. 4 (2002) 1003–1005;
(b) Y. Huang, D. Chen, F.L. Qing, Tetrahedron 59 (2003) 7879–7886.
[10] L.E. Kiss, I. Kövesdi, J. Rábai, J. Fluorine Chem. 108 (2001) 95–109.
[11] V. Církva, B. Améduri, B. Boutevin, O. Paleta, J. Fluorine Chem. 83 (1997) 151–158.
[12] (a) For reviews on Suzuki reaction, see S. Kotha, K. Lahiri, D. Kashinath, Tetrahedron, 58 (2002) 9633–9695;
(b) N. Miyaura, A. Suzuki, Chem. Rew. 95 (1995) 2457–2483.