J = 8, 1.4 Hz), 7.63 (2 H, d, J = 9 Hz), 7.45–7.55 (3 H, m), 2.62 (3 H, s); IR (KBr) ν_{max} 3080 (w), 2960 (w), 2940 (w), 2820 (w), 1680 (s), 1590 (s), 1570 (s), 1480 (s), 1440 (s), 1285 (m), 1250 (s), 1235 (m), 1045 (s), 1020 (m), 860 (m), 780 (m), 750 (s) cm^{-1}; mass spectrum m/z 230 (M^+ + 2 - 28, 1), 229 (M^+ + 1 - 28, 4), 228 (M^+ - 28, 23), 220 (11), 219 (16), 218 (100), 213 (30), 185 (22), 154 (27), 147 (15), 119 (30), 109 (67), 91 (20), 77 (14), 65 (12). Anal. Calcd for $C_{14}H_{12}N_2OS$: C, 65.60; H, 4.72; N, 10.93; S, 12.51. Found: C, 65.80; H, 4.88; N, 10.94; S, 12.57.

(4-*n*-Butylphenyl)diazo phenyl sulfide (3b): ^1H NMR δ 7.66 (2 H, d, J = 7 Hz), 7.49 (2 H, d, J = Hz), 7.37–7.45 (3 H, m), 7.19 (2 H, d, J = 8 Hz), 2.59 (2 H, t, J = 8 Hz), 1.57 (2 H, m), 1.32 (2 H, m), 0.90 (3 H, t, J = 7 Hz); IR (neat) ν_{max} 3030 (w), 2955 (m), 2920 (m), 2850 (w), 1580 (m), 1475 (s), 1440 (m), 1020 (m), 830 (w), 740 (m) cm^{-1}; mass spectrum m/z 244 (M^+ + 2 - 28, 4), 243 (M^+ + 1 - 28, 11), 242 (M^+ - 28, 56), 220 (10), 219 (15), 218 (100), 199 (83), 185 (16), 154 (24), 109 (69), 91 (22), 65 (8). Anal. Calcd for $C_{16}H_{18}N_2S$: C, 71.07; H, 6.71; S, 11.86. Found: C, 71.17; H, 6.51; S, 12.20.

(4-Methoxyphenyl)diazo phenyl sulfide (3c): ^1H NMR δ 7.65 (2 H, d, J = 7 Hz), 7.55 (2 H, d, J = 9 Hz), 7.35–7.45 (3 H, m), 6.88 (2 H, d, J = 9 Hz), 3.76 (3 H, s); IR (neat) ν_{max} 3060 (m), 3010 (m), 2970 (w), 2930 (w), 2830 (w), 1590 (m), 1580 (s), 1490 (s), 1475 (s), 1440 (s), 1250 (s), 1170 (m), 1020 (m), 830 (m), 800 (w) cm^{-1}. Anal. Calcd for $C_{13}H_{12}N_2OS$: C, 63.91; H, 4.95; N, 11.47; S, 13.12. Found: C, 64.12; H, 5.08; N, 11.25; S, 13.16.

(3-Methoxyphenyl)diazo phenyl sulfide (3d): ^1H NMR δ 7.44 (2 H, d, J = 8.9 Hz), 7.34 (1 H, d, J = 8.2 Hz), 6.92–7.30 (5 H, m), 6.71 (1 H, dd, J = 8.4, 1.7 Hz), 3.63 (3 H, s); IR (neat) ν_{max} 3080 (w), 3000 (w), 1960 (w), 2940 (w), 2830 (w), 1590 (s), 1575 (s), 1480 (s), 1440 (s), 1285 (m), 1250 (s), 1045 (s), 860 (m), 780 (m), 750 (s), 710 (w) cm^{-1}. Anal. Calcd for $C_{13}H_{12}ON_2S$: C, 63.91; H, 4.95; N, 11.47; S, 13.12. Found: C, 63.85; H, 4.96; N, 11.42; S, 13.17.

(2-Methoxyphenyl)diazo Phenyl Sulfide (3e). After purification, the orange oil was taken up in ether/petroleum ether, and then the solvent was evaporated. Upon refrigeration the orange oil solidified to a light orange solid: mp 31–33 °C; ^1H NMR δ 7.49 (2 H, d, J = 8.9 Hz), 7.31 (1 H, dd, J = 8.3, 2.4 Hz), 7.07–7.24 (5 H, m), 6.78 (1 H, dd, J = 8.3, 2.5 Hz), 3.71 (3 H, s); IR (neat) ν_{max} 3060 (w), 3010 (w), 2960 (w), 2930 (w), 2830 (w), 1580 (m), 1480 (s), 1440 (m), 1250 (s), 1170 (m), 1025 (s), 750 (s), 705 (m) cm^{-1}. Anal. Calcd for $C_{13}H_{12}ON_2S$: C, 63.91; H, 4.95; N, 11.47; S, 13.12. Found: C, 64.28; H, 5.14; N, 11.16; S, 12.88.

General Procedure for Fluorination Reaction. A portion (100 μmol) of diazo sulfide and a precise amount of *n*-dodecane (internal standard) was weighed in a polyethylene vial. Toluene was added (0.75 mL), and the solution was cooled in an ice bath. Stirring was initiated, and HF–pyridine then was added. When a 20- or 5-fold excess of HF was used, it was added as neat pyridinium poly(hydrogen fluoride); for lower stoichiometries, a freshly prepared 0.5 or 0.2 M solution in THF was used. Immediately thereafter, 6–10 equiv of $AgNO_3$ was added, and the vial was sealed with a Teflon-lined screw cap and gradually warmed to 90 °C for 30 min with continued stirring. The reaction mixture was then cooled and filtered through a small silica gel column, eluting with acetone.

Product yields were determined through GC analysis of the eluate. This was achieved with the aid of a calibration curve which related the response factors of the product with the response factors of the internal standard, *n*-dodecane. The fluorinated products were identified by GC–MS and by coinjection on the GC with authentic samples. Byproducts were determined either by GC–MS and coinjection or by ^1H NMR and mass spectra analysis.

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Registry No. **1a**, 99-92-3; **1b**, 104-13-2; **1c**, 104-94-9; **1d**, 536-90-3; **1e**, 90-04-0; **3a**, 111278-45-6; **3b**, 134705-05-8; **3c**, 114650-58-7; **3d**, 114650-57-6; **3e**, 107046-27-5; **4a**, 403-42-9; **4b**, 20651-65-4; **4c**, 459-60-9; **5a**, 98-86-2; **5b**, 104-51-8; **5c**, 100-66-3; **8**, 108-98-5; **10a**, 87261-60-7; **10b**, 77153-60-7; **10c**, 74148-29-1; silver ion, 14701-21-4.

A Facile Synthesis of α,ω-Dicarboxylic Acids Containing Perfluoroalkylene Groups

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Introduction

A variety of fluorine-containing polymers have been used as gas-permeable membranes, contact lenses, optical fiber sheathing materials, photoresistors, or biomedical materials.[1] They display the characteristic virtues of water and oil repellency, low surface energy, high affinity for oxygen, high chemical and light resistance, and bioinactivity. Fluorinated difunctional monomers like polyfluorinated α,ω-dicarboxylic acids and α,ω-diisocyanates are among the most promising starting materials for the synthesis of a new class of such polymers via condensation polymerization and addition polymerization. Two types of these fluorinated monomers have been described: type A diacids of the formula $HO_2CCH_2(CF_2)_nCH_2CO_2H$ (n = 2, 4, 6)[2,3] and type B diacids of the formula $HO_2CCH_2CH_2(CF_2)_nCH_2CH_2CO_2H$ (n = 3, 4).[4,5] In type A diacids, the α-hydrogen atoms are strongly acidic, and elimination of HF takes place easily under basic conditions. In type B acids, the α-hydrogen atoms are less acidic, which should make the chemical stability of polymers derived from such acids superior to that of polymers derived from type A diacids. However, the known methods for the synthesis of type B diacids are not straightforward. Obviously, an industrially feasible synthesis of such compounds is highly desirable. We recently described the perfluoroalkylation of carbon–carbon multiple bonds[6] and of aromatic rings,[7] and the carbonylation[8] of perfluoroalkyl-substituted organic compounds, both catalyzed by transition-metal complexes. The polyfluorinated organic compounds so obtained are expected to be versatile building blocks for

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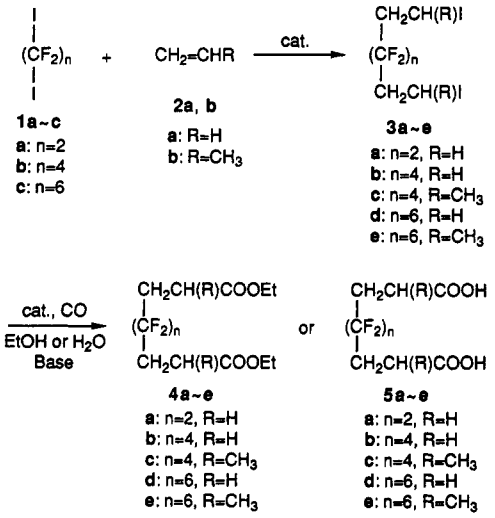
Table I. Metal Carbonyl Catalyzed Insertions of Terminal Olefins (2) into 1[a]

entry	$I(CF_2)_nI$, n =	olefin CH_2=CHR, R (equiv)	catalyst[b] (mol %)	cocatalyst (mol %)	reaction temp (°C)	reaction time (h)	isolated yield of product (%)
1	4	H (10 atm)	Fe_3 (6)	none	100	4	90
2	4	H (10 atm)	Fe (10)	EA[c] (40)	100	3	78
3	4	H (10 atm)	Co (9)	EA[c] (32)	100	3	70
4	4	H (10 atm)	Ru (5)	EA[c] (32)	100	3	60
5	4	CH_3 (5)	Fe_3 (5)	none	100	24	62
6	4	$SiMe_3$ (3)[d]	Fe_3 (4)	none	70	1	88
7	6	H (10 atm)	Fe_3 (5)	none	100	12	91
8	6	CH_3 (5)	Fe_3 (5)	none	100	24	89

[a] All reactions were performed in a stainless steel autoclave in the absence of solvent unless otherwise noted. [b] Fe = $Fe(CO)_5$, Fe_3 = $Fe_3(CO)_{12}$, Co = $Co_2(CO)_8$, Ru = $Ru_3(CO)_{12}$. [c] EA = ethanolamine. [d] The reaction carried out in a sealed glass tube.

Scheme I



employment in the synthesis of other useful organofluorine compounds.[9] Here we describe a facile synthesis of type B diacids from α,ω-diiodoperfluoroalkanes (1, $I(CF_2)_nI$; n = 2, 4, 6), one that also employs transition-metal catalysts.

Results and Discussion

As a first step toward the desired compounds, the insertion of terminal olefins (2) into both C–I bonds of α,ω-diiodoperfluoroalkanes $I(CF_2)_nI$ (**1a**, n = 2; **1b**, n = 4; **1c**, n = 6) was attempted. No reaction took place with **1c** was treated with ethylene (**2a**, 60 atm) in the absence of a catalyst at 100 °C for 12 h in a stainless steel autoclave. However, insertion proceeded smoothly when a mixture of **1c**, **2a** (10 atm), and a catalytic amount (5 mol %) of $Fe_3(CO)_{12}$ was heated at 100 °C for 12 h to give 1,10-diiodo-3,3,4,4,5,5,6,6,7,7,8,8-dodecafluorodecane (**3d**) in 91% isolated yield. No 1,8-diiodo-1,1,2,2-tetrahydroperfluorooctane ($I(CF_2)_6CH_2CH_2I$) was produced under these conditions. Cobalt and ruthenium carbonyl complexes are also proved to be effective catalysts. The presence of a small amount (10–40 mol %) of ethanolamine, triethylamine, or pyridine along with the $Co_2(CO)_8$ or $Ru_3(CO)_{12}$ catalyst led to larger yields. Both 1-propene (**2b**) and trimethylvinylsilane could also be inserted under similar mild conditions to give the expected products in good yield. Representative results are shown in Table I.

On the other hand, attempts to insert ethylene (**2a**) into 1,2-diiodotetrafluoroethane (**1a**) failed, and the desired product (**3a**) was not obtained. Instead, tetrafluoroethylene and diiodo transition-metal compounds (Met-I_2) may have been formed by the reaction of **1a** and the catalyst. Therefore, 1,6-diiodo-3,3,4,4-tetrafluorohexane (**3a**) was prepared by a known method[10a] in 75% yield.

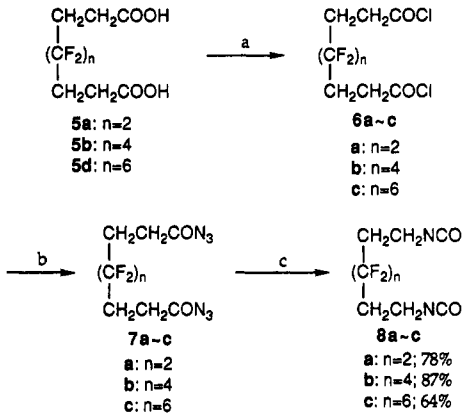
Next, the carbonylation of compound **3** was investigated. Treatment of ethanol solution of compounds **3** with CO (50 atm) in the presence of a base like triethylamine (2 equiv) or potassium fluoride (4 equiv) and a catalytic amount (10 mol %) of a transition metal complex at 100 °C for 24 h gave the diethyl esters **4** (Table II). Among

Table II. Carbonylation of 3 Catalyzed by Co or Pd Complexes[a]

entry	substrate	catalyst[b] (mol %)	HY	base[c]	product	isolated yield (%)
1	**3a**	Co (10)	EtOH	Et_3N	**4a**	86
2	**3b**	Pd (10)	EtOH	KF	**4b**	64
3	**3c**	Pd (10)	EtOH	KF	**4c**	81
4	**3d**	Pd (10)	EtOH	Et_3N	**4d**	67
5	**3e**	Pd (10)	EtOH	KF	**4e**	77
6	**3a**	Co (10)	H_2O	KF	**5a**	97
7	**3b**	Pd (10)	H_2O	KF	**5b**	93
8	**3c**	Co (20)	H_2O	KF	**5c**	69
9	**3d**	Co (20)	H_2O	KF	**5d**	94
10	**3e**	Co (20)	H_2O	KF	**5e**	67

[a] All reactions were performed in a stainless steel autoclave at 100 °C for 24 h (entries 1–5) or at 80 °C for 48 h (entries 6–10) under 50 atm of CO pressure. [b] Co = $Co_2(CO)_8$, Pd = $(Ph_3P)_2PdCl_2$. [c] A theoretical amount of base was added in all reactions: Et_3N = 2 equiv.; KF = 4 equiv.

Scheme II[a]



[a] (a) $SOCl_2$, reflux, 1–2 h; (b) HN_3·py, 0 °C, 15 min; (c) 95–100 °C, toluene, 1 h.

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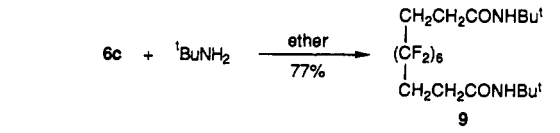
Scheme III



the group VIII transition-metal complexes that were evaluated as catalysts, $Co_2(CO)_8$ and $(Ph_3P)_2PdCl_2$ were highly effective.[11] For example, the Pd-catalyzed carbonylation of **3b** gave diester **4b** in 67% yield.

The reaction of compound **3** with CO (50 atm) in the presence of a Co or Pd catalyst (10–20 mol %), water (20 equiv), and potassium fluoride (4 equiv), in *t*-BuOH solution at 80 °C for 48 h gave the corresponding diacids **5a–e** directly, in moderate to excellent yields. The use of potassium fluoride as the base resulted in higher yield of diacids than did the use of triethylamine. As Table II shows, the Pd- or Co-catalyzed carbonylation of **3** gave **4** or **5** in moderate to high yield, regardless of the number of difluoromethylene units present in the parent compound.

The type B diacids so obtained could be easily converted into the corresponding α,ω-diisocyanates (**8**) in overall yields of 64–87% (Scheme II). The refluxing of solution of diacids **5** and thionyl chloride afforded dichlorides **6**. The reaction of dichlorides **6** with the HN_3–pyridine complex in toluene solution at 0 °C for 15 min gave the corresponding azides **7**. Although compounds **7a–c** were not isolated, their presence was inferred from the IR spectra of the toluene solutions, which showed two absorption bands, at ca. 2150 and at ca. 1720 cm^{-1}, attributable to N_3 and C=O stretching vibrations, respectively. Curtius rearrangement of **7** (95–100 °C, toluene, 1 h) produced the corresponding α,ω-diisocyanates **8**. Products **8** are potential precursors of the antithrombogenic polyurethanes described by Kato et al.[1]

In conclusion, a facile synthesis of α,ω-dicarboxylic acid and α,ω-diisocyanates containing perfluoroalkylene groups from α,ω-diiodoperfluoroalkanes has been described. The products are promising precursors of fluorine-containing polymers that possess unusual properties.

Experimental Section

Melting points were determined with a Yanagimoto micro melting point apparatus and are uncorrected. IR spectra were recorded with a JASCO A-202 spectrometer. ^1H NMR spectra were recorded with Hitachi R-90H (90 MHz) or Bruker AM-400 (400 MHz) instruments. Chemical shifts are reported in ppm downfield from internal TMS. ^{19}F NMR spectra were recorded with a Varian XL-100-15A (94.1 MHz) spectrometer. Chemical shifts are reported in ppm downfield from internal $CFCl_3$. Mass spectra were recorded with a Hitachi RMU-6MG spectrometer that was operated at an ionization voltage of 70 eV. Refractive indices were determined with an Atago Abbe refractometer at 20 °C. Elemental analyses were performed at the Sagami Chemical Research Center.

α,ω-Diiodoperfluoroalkanes ($I(CF_2)_nI$; n = 2, 4, and 6) were purchased from Japan Halon Co., Ltd., and were used without further purification.

Et_2O was distillted under dry Ar from benzophenone ketyl immediately before use. Other solvents and reagents were used as received.

1,10-Diiodo-3,3,4,4,5,5,6,6,7,7,8,8-dodecafluorodecane (3d). A mixture of 1,6-diiodoperfluorohexane (**1c**, 2.79 g, 5.03 mmol) and $Fe_3(CO)_{12}$ (125 mg, 0.25 mmol) under 10 atm of ethylene in a 30-mL stainless steel autoclave was heated at 100 °C for 12 h. To the cooled mixture was added aqueous $Na_2S_2O_3$. The mixture was then extracted with Et_2O. The extract was dried ($MgSO_4$) and concentrated in vacuo. The residue was recrystallized (hexane) to provide 1,10-diiodo-3,3,4,4,5,5,6,6,7,7,8,8-dodecafluorodecane (**3d**) in 91% yield (2.79 g): mp 91 °C; ^1H NMR ($CDCl_3$) δ 2.35–3.10 (m, 4 H), 3.10–3.45 (m, 4 H); ^{19}F NMR ($CDCl_3$) δ −114.2 (br, 4 F), −121.1 (br, 4 F), −123.5 (br, 4 F); IR (KBr) 1218, 1170, 1135, 1062, 690, 515 cm^{-1}; MS m/e 610 (M^+, 100), 463 (24), 155 (16), 141 (43), 127 (61), 65 (42), 51 (18), 27 (19). Anal. Calcd for $C_{10}H_8F_{12}I_2$: C, 19.69; H, 1.32. Found: C, 19.94; H, 1.33.

1,6-Diiodo-3,3,4,4-tetrafluorohexane (3a) was prepared by a known method[10] in 75% yield: ^1H NMR ($CDCl_3$) δ 2.30–3.00 (m, 4 H), 3.25 (t, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −114.8 (br, 4 F); IR (KBr) 1439, 1350, 1308, 1185, 1158, 1050, 915 cm^{-1}; MS m/e 410 (M^+, 57), 283 (100), 141 (25), 77 (97). Anal. Calcd for $C_6H_8F_4I_2$: C, 17.58; H, 1.97. Found: C, 17.60; H, 1.87.

1,8-Diiodo-3,3,4,4,5,5,6,6-octafluorooctane (3b): mp 93.5 °C; ^1H NMR ($CDCl_3$) δ 2.46–3.06 (m, 4 H), 3.06–3.40 (m, 4 H); ^{19}F NMR ($CDCl_3$) δ −114.4 (br, 4 F), −123.0 (br, 4 F); IR (KBr) 1360, 1196, 1170, 1112, 1064, 722, 512 cm^{-1}; MS m/e 510 (M^+, 58), 383 (55), 141 (67), 77 (100), 65 (72), 51 (25), 27 (35). Anal. Calcd for $C_8H_8F_8I_2$: C, 18.84; H, 1.58. Found: C, 18.92; H, 1.51.

2,9-Diiodo-4,4,5,5,6,6,7,7-octafluorodecane (3c): mp 35.0–35.5 °C; ^1H NMR ($CDCl_3$) δ 2.04 (d, J = 7 Hz, 6 H), 2.20–3.30 (m, 4 H), 4.45 (tq, J = 7 and 7 Hz, 2 H); ^{19}F NMR ($CDCl_3$) δ −114.2 (br, 4 F), −124.0 (br, 4 F); IR (KBr) 1365, 1268, 1208, 1165, 1118, 1032, 868, 715, 502 cm^{-1}; MS m/e 538 (M^+, 2), 410 (4), 283 (29), 155 (12), 91 (22), 77 (11), 65 (18), 47 (100), 41 (25). Anal. Calcd for $C_{10}H_{12}F_8I_2$: C, 22.33; H, 2.25. Found: C, 22.46; H, 2.22.

2,11-Diiodo-4,4,5,5,6,6,7,7,8,8,9,9-dodecafluorododecane (3e): mp 53 °C; ^1H NMR ($CDCl_3$) δ 2.04 (d, J = 7 Hz, 6 H), 2.30–3.30 (m, 4 H), 4.45 (tq, J = 7 and 7 Hz, 2 H); ^{19}F NMR ($CDCl_3$) δ −114.1 (br, 4 F), −122.1 (br, 4 F), −124.0 (br, 4 F); IR (KBr) 1455, 1368, 1272, 1202, 1170, 1140, 1019, 689, 660, 508 cm^{-1}; MS m/e 638 (M^+, 1), 384 (15), 91 (9), 65 (12), 47 (100), 43 (41). Anal. Calcd for $C_{12}H_{12}F_{12}I_2$: C, 22.59; H, 1.90. Found: C, 22.22; H, 1.74.

Diethyl 4,4,5,5,6,6,7,7,8,8,9,9-Dodecafluorododecanedioate (4d). A mixture of $(Ph_3P)_2PdCl_2$ (17.5 mg, 0.025 mmol), **3d** (152 mg, 0.25 mmol), Et_3N (0.07 mL, 0.5 mmol), and EtOH (1 mL) was stirred at 100 °C for 24 h under 50 atm of CO pressure. The cooled mixture was extracted with Et_2O. The extract was washed with water and dried ($MgSO_4$). Silica gel column chromatography gave **4d** in 67% yield: n^{20}_D 1.3870; ^1H NMR ($CDCl_3$) δ 1.26 (t, J = 7 Hz, 6 H), 2.10–2.90 (m, 8 H), 4.18 (q, J = 7 Hz, 4 H); ^{19}F NMR (acetone-d_6) δ −115.2 (br 4 F), −122.4 (br, 4 F), −124.1 (br, 4 F); IR (neat) 1738 (ν(C=O)) cm^{-1}; MS m/e 502 (M^+, 16), 457 (100), 429 (99), 402 (21), 129 (26), 123 (22), 77 (24), 55 (48), 45 (20), 29 (93). Anal. Calcd for $C_{16}H_{18}F_{12}O_4$: C, 38.26; H, 3.61. Found: C, 38.15; H, 3.54.

Diethyl 4,4,5,5-tetrafluorooctanedioate (4a): n^{20}_D 1.4050; ^1H NMR ($CDCl_3$) δ 1.26 (t, J = 7 Hz, 6 H), 2.00–2.80 (m, 8 H), 4.18 (q, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −137.7 (br, 4 F); IR (neat) 1740 (ν(C=O)) cm^{-1}; MS m/e 302 (M^+, 8), 257 (47), 229 (15), 209 (15), 55 (60), 29 (100). Anal. Calcd for $C_{12}H_{18}F_4O_4$: C, 47.68; H, 6.00. Found: C, 47.40; H, 6.02.

Diethyl 4,4,5,5,6,6,7,7-octafluorodecanedioate (4b): n^{20}_D 1.3880; ^1H NMR ($CDCl_3$) δ 1.27 (t, J = 7 Hz, 6 H), 2.10–2.95 (m, 8 H), 4.18 (q, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −113.9 (br, 4 F), −122.7 (br, 4 F); IR (neat) 1738 (ν(C=O)) cm^{-1}; MS m/e 402 (M^+, 6), 357 (60), 329 (31), 284 (5), 55 (53), 45 (16), 29 (100). Anal. Calcd for $C_{14}H_{18}F_8O_4$: C, 41.80; H, 4.51. Found: C, 41.66; H, 4.58.

Diethyl 2,9-dimethyl-4,4,5,5,6,6,7,7-octafluorodecanedioate (4c): n^{20}_D 1.3930; ^1H NMR ($CDCl_3$) δ 1.25 (t, J = 7 Hz, 6 H), 1.30 (d, J = 7 Hz, 6 H), 1.90–3.10 (m, 6 H), 4.17 (q, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −119.9 (br, 4 F), −126.1 (br, 4 F); IR (neat) 1740 (ν(C=O)) cm^{-1}; MS m/e 430 (M^+, 14), 385 (36), 357 (36), 269 (24), 91 (35), 47 (34), 29 (100). Anal. Calcd for $C_{14}H_{22}F_8O_4$: C, 44.66; H, 5.15. Found: C, 44.38; H, 5.11.

Diethyl 2,11-dimethyl-4,4,5,5,6,6,7,7,8,8,9,9-dodecafluorododecanedioate (4e): n^{20}_D 1.3818; ^1H NMR ($CDCl_3$) δ 1.25 (t, J = 7 Hz, 6 H), 1.30 (d, J = 7 Hz, 6 H), 1.85–3.10 (m, 6 H), 4.18 (q, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −115.3 (br, 4 F), −123.6 (br, 4 F), −125.7 (br, 4 F); IR (neat) 1740 (ν(C=O)) cm^{-1}; MS m/e 530 (M^+, 10), 485 (26), 457 (30), 429 (21), 91 (28), 73 (15), 47 (62),

(11) The carbonylation of **3b** (EtOH solution, 50 atm of CO, 100 °C, 24 h) was also catalyzed by other transition-metal complexes. The yields of **4b** as a function of the catalyst were 53%, $Co_2(CO)_8$ (10 mol%); 9%, $Rh_6(CO)_{16}$ (1.7 mol %); 1%, $Ru_3(CO)_{12}$ (3.3 mol %); 1%, $PtCl_2(PPh_3)_2$ (10 mol %).

29 (100). Anal. Calcd for $C_{16}H_{22}F_{12}O_4$: C, 40.77; H, 4.18. Found: C, 40.87; H, 4.10.

4,4,5,5,6,6,7,7,8,8,9,9-Dodecafluoro-1,12-dodecanedioic Acid (5d). A mixture of $Co_2(CO)_8$ (1.64 g, 4.8 mmol), **3d** (14.64 g, 24 mmol), water (8.8 mL, 488 mmol), KF (5.58 g, 96.3 mmol), and *t*-BuOH (120 ml) in a 200-mL stainless steel autoclave was stirred at 80 °C under 50 atm of carbon monoxide pressure. To the cooled mixture was added concentrated aqueous HCl. The mixture was extracted with Et_2O. The extract was washed with water, dried ($MgSO_4$), and concentrated in vacuo. The residue was recrystallized (Et_2O/hexane) to give **5d** in 94% (10.1 g) yield: mp 182 °C; ^1H NMR (acetone-d_6) δ 2.40 (m, 4 H), 2.7 (m, 4 H), 9.0 (br, 2 H); ^{19}F NMR (acetone-d_6) δ −114.1 (br, 4 F), −121.3 (br, 4 F), −123.2 (br, 4 F); IR (KBr) 3300–2800 (ν(OH)), 1710 (δ(C=O)) cm^{-1}; MS *m/e* 429 (M^+ − 17, 20), 402 (41), 139 (52), 131 (37), 123 (33), 109 (47), 103 (100), 77 (62), 59 (64), 55 (80), 47 (44), 45 (40). Anal. Calcd for $C_{12}H_{10}F_{12}O_4$: C, 32.30; H, 2.26. Found: C, 32.44; H, 2.29.

4,4,5,5-Tetrafluoro-1,8-octanedioic acid (5a): mp 204 °C; ^1H NMR (acetone-d_6) δ 2.10–3.00 (m, 8 H); ^{19}F NMR (acetone-d_6) δ −115.9 (br, 4 F); IR (KBr) 3450–3200 (ν(OH)), 1710 (ν(C=O)) cm^{-1}; MS *m/e* 229 (M^+ − 17, 7), 208 (8), 161 (10), 123 (37), 103 (100), 77 (40), 73 (40), 60 (58), 55 (78), 47 (47), 42 (42), 28 (34). Anal. Calcd for $C_{12}H_{10}F_{12}O_4$: C, 32.30; H, 2.26. Found: C, 32.44; H, 2.29.

4,4,5,5,6,6,7,7-Octafluoro-1,10-decanedioic acid (5b): mp 187–187.5 °C; ^1H NMR (acetone-d_6) δ 2.15–2.90 (m, 8 H), 11.0 (br, 2 H); ^{19}F NMR (acetone-d_6) δ −114.4 (br, 4 F), −123.3 (br, 4 F); IR (KBr) 3300–2800 (ν(OH)), 1720 (ν(C=O)) cm^{-1}; MS *m/e* 329 (M^+ − 17, 11), 302 (8), 123 (23), 109 (31), 103 (86), 77 (56), 73 (41), 59 (48), 55 (100), 47 (51), 45 (41). Anal. Calcd for $C_{10}H_{10}F_8O_4$: C, 34.70; H, 2.91. Found: C, 34.53; H, 2.85.

2,9-Dimethyl-4,4,5,5,6,6,7,7-octafluoro-1,10-decanedioic acid (5c): mp 1660168 °C; ^1H NMR (acetone-d_6) δ 1.33 (d, J = 8 Hz, 6 H), 1.60–3.10 (m, 6 H), 10.8 (br, 2 H); ^{19}F NMR (acetone-d_6) δ −113.4 (br, 4 F), −123.7 (br, 4 F); IR (KBr) 3300–2800 (ν(OH)), 1715 (ν(C=O)) cm^{-1}; MS *m/e* 357 (M^+ − 17, 3), 330 (7), 153 (27), 137 (17), 111 (23), 103 (16), 99 (17), 95 (18), 91 (67), 89 (52), 87 (34), 77 (24), 73 (68), 69 (41), 61 (27), 59 (22), 47 (65), 45 (45), 28 (60), 18 (100). Anal. Calcd for $C_{12}H_{14}F_8O_4$: C, 38.51; H, 3.77. Found: C, 38.38; H, 3.69.

2,11-Dimethyl-4,4,5,5,6,6,7,7,8,8,9,9-dodecafluoro-1,12-dodecanedioic acid (5e): mp 149.5–151 °C; ^1H NMR (acetone-d_6) δ 1.33 (d, J = 8 Hz, 6 H), 1.60–3.10 (m, 6 H), 11.0 (br, 2 H); ^{19}F NMR (acetone-d_6) δ −113.2 (br, 4 F), −121.6 (br, 4 F), −123.7 (br, 4 F); IR (KBr) 3300–2800 (ν(OH)), 1710 (ν(C=O)) cm^{-1}; MS *m/e* 457 (M^+ − 17, 2), 430 (14), 163 (21), 153 (22), 133 (22), 121 (32), 91 (60), 87 (30), 73 (75), 47 (100), 45 (37), 28 (34). Anal. Calcd for $C_{14}H_{14}F_{12}O_4$: C, 35.46; H, 2.98. Found: C, 35.56; H, 2.99.

3,3,4,4,5,5,6,6,7,7,8,8-Dodecafluoro-1,10-diisocyanatodecane (8c). A solution of **5d** (0.892 g, 2 mmol) and $SOCl_2$ (2 mL) was refluxed for 2 h under Ar. Excess $SOCl_2$ was then evaporated in vacuo to provide 4,4,5,5,6,6,7,7,8,8,9,9-dodecafluoro-1,12-dodecanedioyl dichloride (**6c**) in quantitative yield. To a toluene (2 mL) solution of **6c** was added a mixture of HN_3 (1.3 M, 3.1 mL, 4 mmol) and pyridine (0.33 mL, 4 mmol) in toluene (3 mL) at 0 °C. The solution was stirred for 15 min at 0 °C. The pyridine hydrochloride that precipitated was removed by filtration. Excess HN_3 was evaporated from the filtrate in vacuo (20 mmHg) over 1 h to give a toluene (~5 mL) solution of 4,4,5,5,6,6,7,7,8,8,9,9-dodecafluoro-1,12-dodecanedioyl diazide (**7c**). The toluene solution so obtained was heated at 95 °C for 1 h. After evaporation of the toluene, **8c** was obtained in 64% overall yield (0.565 g).

6c: ^1H NMR ($CDCl_3$) δ 2.45 (tt, J = 18 and 7 Hz, 4 H), 3.24 (t, J = 7 Hz, 4 H); IR (KBr) 1785 (ν(C=O)) cm^{-1}.

7c: IR (KBr fixed cell, toluene) 2145 ($\nu(N_3)$) and 1722 (ν(C=O)) cm^{-1}.

8c: ^1H NMR ($CDCl_3$) δ 2.40 (tt, J = 18 and 7 Hz, 4 H), 3.65 (t, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −114.7 (br, 4 F), −122.2 (br, 4 F), −124.1 (br 4 F); IR (KBr) 2270 (ν(N=C=O)) cm^{-1}; MS *m/e* 441 (M^+ + 1, 1), 384 (2), 56 (100). Anal. Calcd for $C_{12}H_8F_{12}N_2O_2$: C, 32.74; H, 1.83; N, 6.36. Found: C, 32.74; H, 1.83; N, 6.56.

3,3,4,4-Tetrafluoro-1,6-diisocyanatohexane(8a): ^1H NMR ($CDCl_3$) δ 2.37 (tt, J = 18 and 7 Hz, 4 H), 3.64 (t, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −115.2 (br, 4 F); IR (KBr) 2275 (ν(N=C=O)) cm^{-1}; MS *m/e* 241 (M^+ + 1, 1), 184 (16), 56 (100). Anal. Calcd for $C_8H_8F_4N_2O_2$: C, 40.01; H, 3.36; N, 11.66. Found: C, 40.19; H, 3.27; N, 11.36.

3,3,4,4,5,5,6,6-Octafluoro-1,8-diisocyanatooctane (8b): ^1H NMR ($CDCl_3$) δ 2.41 (tt, J = 18 and 7 Hz, 4 H), 3.66 (t, J = 7 Hz, 4 H); ^{19}F NMR ($CDCl_3$) δ −114.9 (br, 4 F), −124.1 (br, 4 F); IR (KBr) 2280 (ν(N=C=O)) cm^{-1}; MS *m/e* 341 (M^+ + 1, 1), 284 (2), 56 (100). Anal. Calcd for $C_{10}H_8F_8N_2O_2$: C, 35.31; H, 2.37; N, 8.24. Found: C, 34.95; H, 2.44; N, 8.63.

4,4,5,5,6,6,7,7,8,8,9,9-Dodecafluoro-*N*,*N*′-di-*tert*-butyl-1,12-dodecanediamide (9). To an Et_2O (4 mL) solution of **6c** (483 mg, 1 mmol) was added *t*-$BuNH_2$ (4 equiv). The solution was stirred for 30 min at room temperature. The solution was then washed with water and dried ($MgSO_4$). Purification by silica gel column chromatography ($CHCl_3$/EtOAc, 1:1) provided **9** in 77% yield: mp 163 °C; ^1H NMR ($CDCl_3$) δ 1.35 (s, 18 H), 2.10–2.70 (m, 8 H), 5.25 (br, 2 H); ^{19}F NMR ($CDCl_3$) δ −114.8 (br, 4 F), −122.3 (br, 4 F), −124.1 (br, 4 F); IR (KBr) 3340 (ν(NH)), 1650 (ν(C=O)) cm^{-1}; MS *m/e* 556 (M^+, 3), 485 (2), 58 (100), 57 (18). Anal. Calcd for $C_{20}H_{28}F_{12}N_2O_2$: C, 43.17; H, 5.07; N, 5.03. Found: C, 43.15; H, 5.16; N, 4.95.

Methanolysis of Phosphoramidates with Boron Trifluoride–Methanol Complex

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The synthesis of novel organophosphorus compounds remains important owing to their widespread use as agrichemicals,[1] biochemicals,[2] antisense oligonucleotides,[3] chemical reagents, and transition-state analogues.[4] Yet, the labile nature of certain functional groups appended to the phosphorus atom makes several classes of organophosphorus compounds difficult to prepare.

Phosphorothiolates **2** (Figure 1) are impurities that are found in commercial thiophosphoryl insecticides **1**.[5] Phosphorothiolates were found to be far more potent inhibitors of acetylcholinesterases than the parent phosphorothionates,[6] suggesting these materials could pose a risk to public health. A reliable and flexible synthesis of these impurities is needed to aid in the overall evaluation of their toxic action. Moreover, a method that would permit the preparation of chiral phosphorothiolates would be a worthy secondary aim. Several chiral phosphorus ester syntheses have been reported.[7]

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