Chem. Pharm. Bull.
32(11)4382—4387(1984)

Studies on Organic Fluorine Compounds. XLI.[1] The Friedel–Crafts Reaction of Trifluoropropene

YOSHIRO KOBAYASHI,*,[a] TAKABUMI NAGAI,[b] ITSUMARO KUMADAKI,*,[b]
MASAAKI TAKAHASHI,[c] and TAKASHI YAMAUCHI[c]

Tokyo College of Pharmacy,[a] Horinouchi, Hachioji, Tokyo 192-03, Japan,
Faculty of Pharmaceutical Sciences, Setsunan University,[b]
Nagaotoge-cho, Hirakata, Osaka 573-01, Japan, and
Kureha Chemical Industry, Co., Ltd.,[c]
Nishikimachi, Iwaki 974, Japan

(Received March 15, 1984)

The Friedel–Crafts reaction of 1,1,1-trifluoropropene with benzene and its derivatives was accomplished in the presence of fluorine-containing acid catalysts. The reaction proceeded at the terminal carbon atom of the olefin to give 3,3,3-trifluoropropylated aromatic compounds. The scope and limitations of this reaction were examined. This substituent was found to be *ortho*- and *para*-directing.

Keywords——Friedel–Crafts reaction; trifluoropropene; trifluoropropyl; Nafion-H; hydrogen fluoride; boron trifluoride; tetrafluoroboric acid; benzene; trifluoropropylation

Nowadays, organic fluorine compounds have found many applications, and some exhibit useful biological activities.[2] For example, the trifluoromethyl group enhances the lipophilicity of the mother compounds, and this effect is believed to be partly responsible for the biological activity of many trifluoromethylated compounds. A trifluoromethyl group is very commonly introduced into biologically active substances in the process of drug design. However, the trifluoromethyl group is a very stable substituent and trifluoromethylated compounds are very slowly decomposed in biological systems. Great stability and high lipophilicity are not necessarily desirable characteristics, as is clear from the example of polychlorobiphenyl. Therefore, we tried to find a new fluoroalkyl substituent which would retain the advantages of fluorine compounds but would be rather more easily metabolized by bioorganisms.

For this purpose, we chose the 3,3,3-trifluoro-1-propyl group, since a linearly alkylated compound is degraded more easily than a branched one. To introduce this group, the Friedel–Crafts reaction of 3,3,3-trifluoro-1-propene was used. The Friedel–Crafts reaction of trifluoropropene has not been reported previously. The unsubstituted propene is known to react at the central carbon atom, but the electronic effect of the trifluoromethyl group should make the terminal carbon reactive and a linearly substituted compound should be produced. Menger and Mandell mentioned in their textbook[3] that the formation of a secondary carbonium ion was prevented by the electronic effect of the trifluoromethyl group, but did not discuss the possibility of terminal carbonium ion formation. Therefore, to clarify the reactivity of trifluoropropene, its reaction with benzene was examined in the presence of several kinds of catalysts.

In this report, our search for good catalysts for the trifluoropropylation of benzene will be described first and the scope and limitations of this reaction will be discussed later.

First, trifluoropropene (**1**) was bubbled into a suspension of aluminum chloride in benzene at room temperature. The reaction mixture was treated with water and analyzed by gas chromatography-mass spectroscopy (GC-MS). Most of the benzene was recovered and formation of 1,1-difluoroindane together with a trace of 1-chloro-1-fluoroindane was observed. This may be due to the attack of aluminum chloride on not the π-electrons of **1** but a fluorine atom of the trifluoromethyl group leading to the formation of an allyldifluorocarbonium ion followed by cyclization of the difluoroallylbenzene, as shown in Chart 1. The possibility of the formation of (3,3,3-trifluoropropyl)benzene (**2**) followed by cyclization was excluded, since **2** was found not to give indanes on treatment with aluminum chloride.

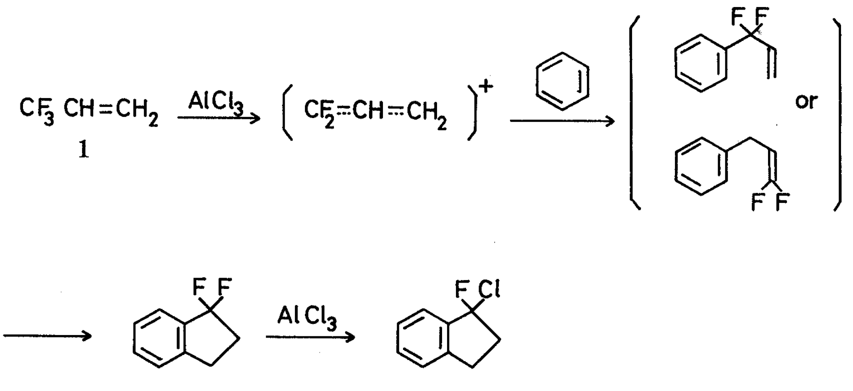

Chart 1

To avoid this cyclization, preliminary formation of an adduct of **1** with a protonic acid seemed to be favorable, since the adduct would yield the trifuloropropyl cation if it lost the conjugate base of the acid, as shown in Chart 2. A sulfonic acid was expected to be suitable.

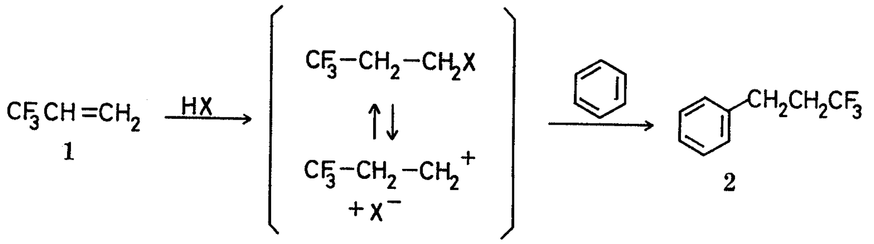

Chart 2

First, we used Nafion-H[4)] for this purpose, since it is a strong sulfonic acid. Further, it is solid and much easier to deal with than any other sulfonic acid catalyst.

Heating of **1** with benzene in the presence of Nafion-H in a sealed tube gave 14.3% (3,3,3-trifluoropropyl)benzene (**2**) and 3.1% bis(3,3,3-trifluoropropyl)benzene with recovery of 81.6% of the starting benzene.

The structure of **2** was determined from the spectral data. For example, the ^{19}F-nuclear magnetic resonance (NMR) showed a triplet coupled with methylene protons. This means that the trifluoromethyl group is in the terminal position. A mixture of the bis-substituted compounds was obtained as an oil by distillation. The bulk of this oil solidified on standing, and the solid was recrystallized from methanol. This compound was found to be 1,4-bis(3,3,3-trifluoropropyl)benzene (**3**) from its spectral data. The main component of the unsolidified part seemed to be the *ortho* isomer. These results show that the Friedel–Crafts reaction of **1** occurs at the terminal position of the double bond and that the trifluoropropyl group is *ortho*- and *para*-directing.

Nafion-H could be used as a catalyst, but the conversion was low. To improve the conversion, the reaction in the presence of hydrogen fluoride was examined. Heating of **1** and benzene with hydrogen fluoride gave **2** in a yield of 26.4%, with recovery of 62.7% of the benzene. The yield of polysubstituted products was less than 3%. In an attempt to further improve the yield, we tried this reaction in the presence of tetrafluoroboric acid. To obtain an anhydrous catalyst, hydrogen fluoride and boron trifluoride were introduced into a reaction vessel. When the reaction was carried out at 100 °C, almost all the trifluoropropene was consumed, but 27.9% of the benzene was recovered and the yield of **2** was only 35.0%, while bis- and tris-substituted compounds were formed in yields of 21.5 and 8.3%, respectively. This result shows that these conditions are too drastic for selective substitution to occur. Thus, the amount of boron trifluoride was reduced and the reaction was carried out at room temperature. In this case, a 59% yield of **2** was obtained, but bis-substituted compounds were still formed in 29% yield. These results suggest that the reactivity of **2** is nearly the same as that of benzene, and that this reaction is reversible, since at high temperature bis compounds were formed at the expense of the mono compound.

Finally, we tried the reaction in the presence of boron trifluoride, though this is not a protonic acid, but a strong Lewis acid. In the presence of an equimolar amount of boron trifluoride, 58% **2** was obtained with 24% bis compounds, while only 34% **2** was formed after 22 h with recovery of 65% of the benzene when 0.2 eq of the catalyst was used. This indicates that boron trifluoride forms a complex with benzene and a nearly equimolar amount is necessary.

Next, the applicability of this reaction to several benzene derivatives was examined. Some electron-rich and electron-deficient derivatives were treated with **1** under acidic conditions. First, phenol was treated in the presence of hydrogen fluoride and boron trifluoride. Mono (20.4%) and bis trifluoropropylated compounds (4.8%) were obtained together with considerable amounts of dihydrocoumarin derivatives (10.3%), which might be produced by the intramolecular reaction of 2-(trifluoropropyl)phenol (**4**) and trifluoropropylation. The mono isomers were found to be a mixture of 2- (**4**) and 4-(trifluoropropyl)phenol (**5**). This result suggested that phenol was very reactive and the conditions were too drastic. Thus, hydrogen fluoride alone was used as the catalyst. The yield of mono-substituted compounds was not changed (18%) and that of bis isomers was suppressed to 0.14%, but the amount of coumarin derivatives and other unidentified by-products was not decreased.

Next, the reaction of anisole was examined in the presence of hydrogen fluoride. Surprisingly, this compound did not give trifluoropropyl compounds at all. The use of hydrogen fluoride and boron trifluoride resulted in the formation of phenolic substances, and no trifluoropropyl compound was detected. This may be due to the higher basicity of anisole compared with trifluoropropenes.

The reaction of chlorobenzene in the presence of hydrogen fluoride and boron trifluoride gave 42.5% mono-substituted compounds, 2-(**6**) and 4-isomer (**7**), 8.4% 2,4-bis(trifluoropropyl)chlorobenzene (**8**), 1.9% 2,4,6-tris(trifluoropropyl)chlorobenzene (**9**), and 0.6% tetra-substituted compound.

Heating of benzotrifluoride with **1** in the presence of hydrogen fluoride and boron trifluoride at 165 °C gave 12.6% 3-(trifluoropropyl)benzotrifluoride (**10**) and 19.8% 3,5-bis(trifluoropropyl)benzotrifluoride (**11**) with recovery of the starting material. Lowering the reaction temperature to 100 °C did not improve the yield of **10** significantly. These results show that the introduction of a trifluoropropyl group into benzotrifluoride makes the product more reactive than the starting material.

Many attempts to trifluoropropylate nitrobenzene by means of this reaction were all unsuccessful. The results for substituted benzenes are summarized in Chart 3.

In conclusion, the Friedel–Crafts reaction of trifluoropropene (**1**) with usual Lewis acid catalysts was unsuccessful, but it was accomplished by the use of protonic and/or fluorine-

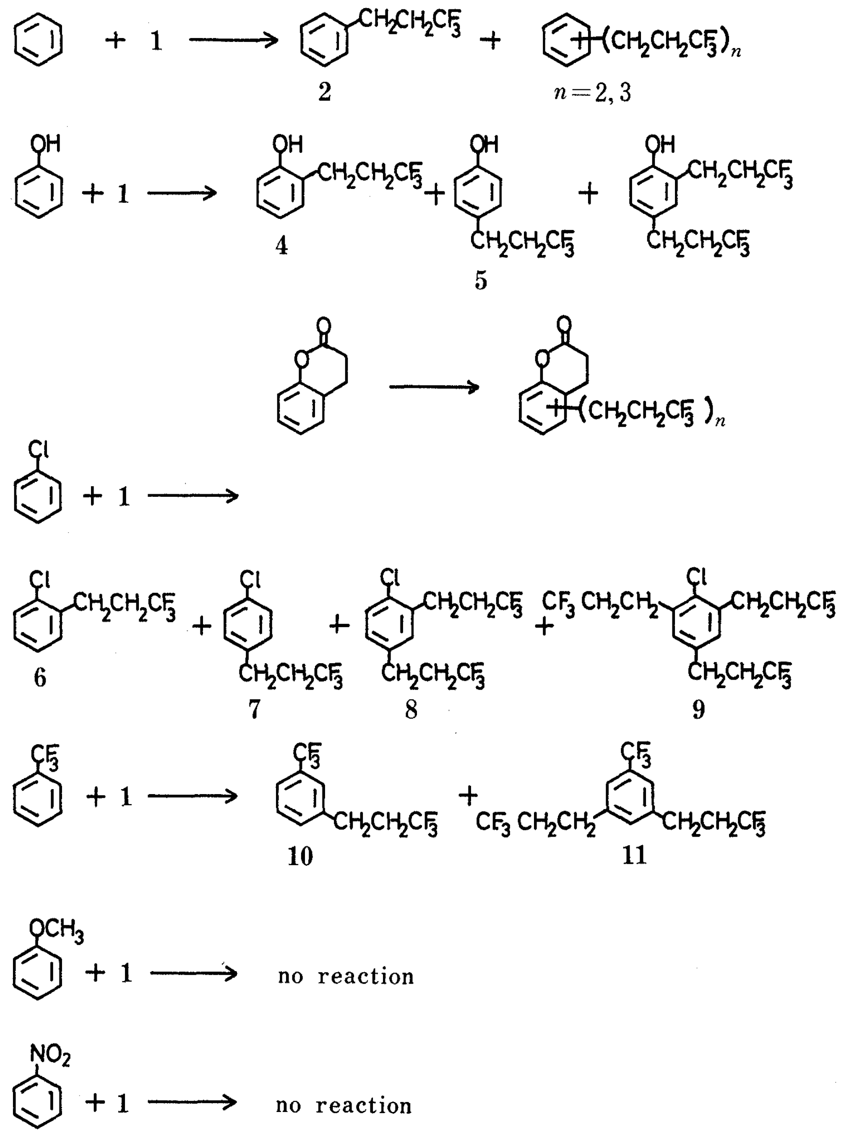

Chart 3

containing catalysts. Compound **1** reacts at the terminal position to give 3,3,3-trifluoropropyl compounds. This reaction should be applicable to the syntheses of many trifluoropropyl compounds. Some applications will be reported in separate papers.

Experimental

Melting points were determined on a Yanaco MP apparatus and are uncorrected. ^{1}H-NMR spectra were obtained with Varian EM-360L and EM-390L NMR spectrometers. ^{19}F-NMR spectra were determined with the EM-360L spectrometer using benzotrifluoride as an internal standard (upper field taken as plus). ^{13}C-NMR spectra were determined on a JEOL FX-100 spectrometer. Spectral patterns are designated as follows: s, singlet; d, doublet; t, triplet; m, multiplet. Mass spectra (MS) were determined with a Hitachi M-80 double-focusing mass spectrometer. Analytical and preparative GC were performed on a Hitachi 163 gas chromatograph.

Reaction in the Presence of Aluminum Chloride——**1** (10 g) was slowly bubbled into a suspension of aluminum chloride (1 g) in benzene (10 g) at room temperature under stirring. The reaction mixture was treated with ice-water. The organic layer was dried and analyzed by GC-MS. Formation of 1,1-difluoroindane (8%, *m/e* 154, M$^+$) together with a trace of 1-chloro-1-fluoroindane (*m/e* 170, M$^+$) was observed.

Reaction in the Presence of Nafion-H——**1** (5 g) was passed into a stainless steel tube containing benzene (5 g) and Nafion-H (1 g) through a vacuum line, and the tube was shaken at 150 °C for 20 h. The tube was opened at room temperature. Nafion-H was filtered off and washed with CH_2Cl_2. The combined organic layer was washed with dil.$NaHCO_3$, and analyzed by GC. From the ratio of peak areas, the yields of **1** and bis-substituted compounds were estimated to be 14.3 and 3.1%, respectively. The mixture was fractionally distilled under a vacuum to give mono- and bis-substituted products. The mono-substituted product (**2**) was obtained as a colorless oil; bp 62 °C/20 mmHg. MS *m/e* 174 (M^+); high resolution MS calcd for $C_9H_9F_3$: 174.066. Found: 174.063. ^{1}H-NMR ($CDCl_3$) δ: 2.03—2.67 (2H, m), 2.67—3.17 (2H, m), 7.35 (5H, m). ^{19}F-NMR ($CDCl_3$) δ: 3.94 (t, $J_{H\text{-}F}=10.3$ Hz). A part of the fraction boiling at 107—114 °C/20 mmHg, containing bis-substituted compounds, solidified on standing, and the solid was recrystallized from MeOH to give colorless cubes; mp 47.5—48.5 °C. MS *m/e* 270 (M^+); high resolution MS calcd for $C_{12}H_{12}F_6$: 270.084. Found: 270.081. ^{1}H-NMR ($CDCl_3$) δ: 2.08—2.70 (4H, m), 2.70—3.00 (4H, m), 7.23 (4H, s). ^{19}F-NMR ($CDCl_3$) δ: 3.93 (t, $J_{H\text{-}F}=10.3$ Hz). ^{13}C-NMR ($CDCl_3$) δ: 27.69 (q, $J_{C\text{-}F}=3.0$ Hz), 35.44 (q, $J_{C\text{-}F}=28.8$ Hz), 126.64 (q, $J_{C\text{-}F}=277.4$ Hz), 128.40, 137.32. The chemical shifts estimated by Savitsky's rule for *p*-bis-(2-bromoethyl)benzene are 129.1 and 137.8, respectively. The *para*-substituted isomer was the main component of the bis-substituted compounds. The minor product was considered to be the *ortho* isomer. The tris-substituted compounds were detected by GC-MS (M^+ 366).

Reaction in the Presence of Hydrogen Fluoride——A mixture of benzene (10 g), hydrogen fluoride (1 g) and **1** (7 g) was shaken in a stainless steel tube at 120 °C for 48 h. The reaction mixture was poured into the mixture of ice–$NaHCO_3$. The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2. The organic layer was treated as described above and found to contain benzene (71.3%), **2** (26.4%), bis-isomers (2.2%), and tris-isomers (0.1%).

Reaction in the Presence of Hydrogen Fluoride–Boron Trifluoride——(a): Boron trifluoride was added to a stainless steel tube containing benzene (10 g), **1** (10 g) and hydrogen fluoride (1 g) till the pressure reached 2 atm. The mixture was shaken at 100 °C for 40 h. The products were analyzed in the manner described above. The mixture was found to contain benzene (27.9%), **2** (35.0%), bis-substituted isomers (21.5%) and tris-isomers (8.3%).

(b): Boron trifluoride (*ca.* 0.5 g) was added to a mixture of benzene (10 g), **1** (12 g) and hydrogen fluoride (1.5 g) in a stainless steel tube. The mixture was shaken at room temperature for 4.5 h, then analyzed as described above. It was found to contain benzene (11%), **2** (59%) and bis-substituted compounds (29%).

Reaction in the Presence of Boron Trifluoride——(a): A mixture of benzene (10 g), **1** (12 g) and boron trifluoride (*ca.* 9 g) was shaken in a stainless steel tube at room temperature for 24 h. The mixture was analyzed as described above and found to contain benzene (17%), **2** (57%) and bis-substituted isomers (24%).

(b): The reaction was carried out as described above, except that the amount of boron trifluoride was *ca.* 1.8 g, giving 34% **2** and 0.4% bis-substituted isomers, with partial recovery of benzene (65%).

Reaction of Phenol——Boron trifluoride was added to a stainless steel tube containing phenol (10.7 g), **1** (12 g) and hydrogen fluoride (7 g) to give a pressure of 1 atm at −78 °C. The mixture was stirred at room temperature for 24 h. The reaction tube was opened and the content was poured onto ice–$NaHCO_3$, then extracted with CH_2Cl_2. The extract was dried over $MgSO_4$. After evaporation of the solvent, the residue was fractionally distilled under a vacuum: Fr. 1, bp 82—92 °C/15 mmHg, 1.75 g; Fr. 2, bp 74—94 °C/1 mmHg, 3.5 g; Fr. 3, bp 96—97 °C/1 mmHg, 1.0 g; Fr. 4, bp 157—164 °C/1 mmHg, 1.53 g; Fr. 5, bp 185—205 °C/1 mmHg, 4.65 g. Each fraction was analyzed by GC, and the yields were estimated from the peak areas. Mono-substituted isomers (9.6%), bis isomer (10.9%) and tris isomer (2.9%) were obtained together with unchanged starting material (19.4%) and unidentified by-products (43.8%). For identification, the fractions were further separated by prep. GC. 2-(3,3,3-Trifluoropropyl)phenol (**4**), colorless needles; mp 48—48.5 °C. MS *m/e* 190 (M^+); high resolution MS calcd for $C_9H_9F_3O$: 190.064. Found: 190.064. ^{1}H-NMR ($CDCl_3$) δ: 2.11—2.64 (2H, m), 2.64—2.94 (2H, m), 4.82 (1H, s), 6.69—7.33 (4H, m). ^{19}F-NMR ($CDCl_3$) δ: 3.51 (t, $J=10.3$ Hz). ^{13}C-NMR ($CDCl_3$, decoupled with ^{1}H) δ: 23.22 (q, $J=3.7$ Hz), 33.70 (q, $J=28.2$ Hz), 115.20, 121.09, 125.53, 126.96 (q, $J=280.8$ Hz), 127.90, 130.30, 153.25. The simulated chemical shifts of the aromatic carbon are 116.1, 121.5, 126.4, 128.6, 130.2 and 155.7. 4-(3,3,3-Trifluoropropyl)phenol (**5**), colorless oil; bp 117—125 °C/4 mmHg. MS *m/e* 190 (M^+); high resolution MS calcd for $C_9H_9F_3O$: 190.064. Found: 190.064. ^{1}H-NMR ($CDCl_3$) δ: 2.03—2.64 (2H, m), 2.64—2.93 (2H, m), 5.10 (1H, br s), 6.80 (2H, d, $J=9$ Hz), 7.07 (2H, d, $J=9$ Hz). ^{19}F-NMR ($CDCl_3$) δ: 3.47 (t, $J=10.3$ Hz). 2.4-Bis(3,3,3-trifluoropropyl)phenol, colorless oil. MS *m/e* 286 (M^+); high resolution MS calcd for $C_{12}H_{12}F_6O$: 286.079. Found: 286.080. ^{1}H-NMR ($CDCl_3$) δ: 2.03—2.63 (4H, m), 2.63—3.00 (4H, m), 5.20 (1H, s), 6.70 (1H, d, $J=9$ Hz), 7.01 (1H, d, $J=9$ Hz), 7.02 (1H, s). ^{19}F-NMR ($CDCl_3$) δ: 3.85 (t, $J=10.3$ Hz). 2,4,6-Tris(3,3,3-trifluoropropyl)phenol, colorless needles; mp 126—129 °C. MS *m/e* 382 (M^+); high resolution MS calcd for $C_{15}H_{15}F_9O$: 382.097. Found: 382.098. ^{1}H-NMR ($CDCl_3$) δ: 2.07—2.63 (6H, m), 2.63—3.03 (6H, m), 4.50 (1H, s), 6.87 (2H, s). ^{19}F-NMR ($CDCl_3$) δ: 3.69 (m, $J=10.3$ Hz). ^{13}C-NMR ($CDCl_3$) δ: 23.12 (q, $J=3.7$ Hz), 27.46 (q, $J=3.7$ Hz), 33.89 (q, $J=28.2$ Hz), 35.91 (q, $J=29.4$ Hz), 125.87, 126.77 (q, $J=278.1$ Hz), 128.40, 132.06, 150.04. The simulated chemical shifts of aromatic carbons are 127.0, 129.2, 132.4 and 154.7. The main components of the by-products were found to be dihydrocoumarin and its trifluoropropylated derivatives by GC-MS.

Reaction of Chlorobenzene——Boron trifluoride was added to a mixture of chlorobenzene (5.5 g), hydrogen fluoride (3 g) and **1** (5 g) in a stainless steel tube at −78 °C till the inner pressure reached 1 atm. The mixture was shaken at 135 °C for 40 h, then worked up as described above. The CH_2Cl_2 extract was separated into two fractions by fractional distillation. The first fraction contained mainly mono-substituted isomers, bp 76—86 °C/25 mmHg, 4.59 g; the second consisted of a mixture of poly-substituted isomers, bp 105—108 °C/8 mmHg, 1.44 g. The yields were determined from the peak areas in GC. For the identification of products, each fraction was further separated by prep. GC. 2-(3,3,3-Trifluoropropyl)chlorobenzene (**6**), colorless oil. MS *m/e* 208 (M^+); high resolution MS calcd for $C_9H_8ClF_3$: 208.027. Found: 208.029. ^1H-NMR ($CDCl_3$) δ: 2.14—2.54 (2H, m), 2.67—3.00 (2H, m), 6.94—7.37 (4H, m). ^{19}F-NMR ($CDCl_3$) δ: 3.51 (t, J=10.3 Hz). 4-(3,3,3-Trifluoropropyl)chlorobenzene (**7**), colorless oil. MS *m/e* 208 (M^+); high resolution MS calcd for $C_9H_8ClF_3$: 208.027. Found: 208.029. ^1H-NMR ($CDCl_3$) δ: 2.03—2.48 (2H, m), 2.72—2.90 (2H, m), 7.13 (2H, d, J=9 Hz), 7.27 (2H, d, J=9 Hz). ^{19}F-NMR ($CDCl_3$) δ: 3.48 (t, J=10.3 Hz). 2,4-Bis(3,3,3-trifluoropropyl)chlorobenzene (**8**), colorless oil. MS *m/e* 304 (M^+); high resolution MS calcd for $C_{12}H_{11}ClF_6$: 304.045. Found: 304.047. ^1H-NMR ($CDCl_3$) δ: 2.29—2.57 (4H, m), 2.80—3.08 (4H, m), 7.04 (1H, d, J=8 Hz), 7.07 (1H, s), 7.30 (1H, d, J=8 Hz). ^{19}F-NMR ($CDCl_3$) δ: 3.40 (t, J=10.3 Hz). 2,4,6-Tris(3,3,3-trifluoropropyl)chlorobenzene (**9**), colorless needles; mp 47—50 °C. MS *m/e* 400 (M^+); high resolution MS calcd for $C_{15}H_{14}ClF_9$: 400.064. Found: 400.064. ^1H-NMR ($CDCl_3$) δ: 2.22—2.53 (6H, m), 2.77—3.12 (6H, m), 6.99 (2H, s). ^{19}F-NMR ($CDCl_3$) δ: 3.40 (t, J=10.3 Hz). Tetrakis(3,3,3-trifluoropropyl)chlorobenzene was detected by GC-MS (M^+, 496).

Reaction of Benzotrifluoride——Boron trifluoride was added to a mixture of benzotrifluoride (13 g), hydrogen fluoride (5 g) and **1** (10 g) in a stainless steel tube till the inner pressure reached 1 atm. The mixture was shaken at 165 °C for 24 h, and the content of the tube was treated as described above. The CH_2Cl_2 extract was fractionally distilled under a vacuum. The first fraction contained mainly **10**, bp 63—68 °C/18 mmHg, 2.75 g; the second fraction contained mainly **11**, bp 88—91 °C/7 mmHg, 6.11 g; the third fraction showed bp 188—192 °C/7 mmHg, 2.58 g. The yields were estimated from the peak areas in GC. For identification, each fraction was purified by prep. GC. 3-(3,3,3-Trifluoropropyl)benzotrifluoride (**10**), colorless oil; bp 103 °C/30 mmHg. MS *m/e* 242 (M^+); high resolution MS calcd for $C_{10}H_8F_6$: 242.053. Found: 242.051. ^1H-NMR ($CDCl_3$) δ: 2.10—2.75 (2H, m), 2.76—3.10 (2H, m), 7.25—7.53 (4H, m). ^{19}F-NMR ($CDCl_3$) δ: −0.03 (3F, s), 3.83 (3F, t, J=10.3 Hz). ^{13}C-NMR ($CDCl_3$) δ: 28.24 (q, J=3.7 Hz), 35.50 (q, J=28 Hz), 118.8, 123.7 (q, J=3.7 Hz), 124.2 (q, J=278 Hz), 125.1 (q, J=3.7 Hz), 126.7 (q, J=278 Hz), 129.3, 131.8, 140.1. 3,5-Bis(3,3,3-trifluoropropyl)benzotrifluoride (**11**), colorless cubes; mp 40—42 °C. MS *m/e* 338 (M^+); high resolution MS calcd for $C_{12}H_{11}F_9$: 338.072. Found: 338.071. ^1H-NMR ($CDCl_3$) δ: 2.42—2.70 (4H, m), 2.99—3.21 (4H, m), 7.23 (1H, s), 7.33 (2H, s). ^{19}F-NMR ($CDCl_3$) δ: −0.08 (3F, s), 3.82 (6F, t, J=10.3 Hz); ^{13}C-NMR ($CDCl_3$) δ: 28.2 (q, J=3.7 Hz), 35.5 (q, J=28 Hz), 118.7, 123.6 (q, J=3.7 Hz), 124.2 (q, J=278 Hz), 126.8 (q, J=278 Hz), 131.8, 140.7.

Acknowledgement We are very grateful to the Takeda Science Foundation for a grant to I.K.

References and Notes

1) Part XL: Y. Kobayashi, T. Morikawa, and T. Taguchi, *Chem. Pharm. Bull.*, **31**, 2616 (1983).
2) R. Filler and S. M. Naqvi, "Biomedicinal Aspects of Fluorine Chemistry," ed. by R. Filler and Y. Kobayashi, Kodansha Ltd., Tokyo, 1982, p. 1.
3) F. M. Menger and L. Mandell, "Electronic Interpretation of Organic Chemistry," Plenum Press, New York, 1980, p. 10.
4) For details of Nafion-H, see M. Fieser, R. L. Danheiser, and W. Roush, "Fiesers' Reagents for Organic Synthesis," Vol. 9, John Wiley and Sons, Inc., New York, 1981.