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Liquid-phase photofluorination with elemental fluorine. Part III. Synthesis of perfluorocycloalkyl ethers with/without a chlorine substituent

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Abstract

Liquid-phase photofluorination (LPPF) of 2-phenyl-2-methoxyhexafluoropropane **1** gave the desired *F*-2-cyclohexyl-2-methoxypropane, **2**, in 21% yield. An unusual rearranged product, *F*-2-cyclohexylmethyl isopropyl ether, **4**, and a degradation product, *F*-2-cyclohexylpropane, **3**, were also produced in 10 and 20% yields, respectively. A plausible reaction mechanism for the formation of the rearranged product **4** was presented. The Cl-containing ethers with cyclic structures, 2-chlorohexafluorocyclopentenyl cyclopentyl ether, and 2-chlorohexafluorocyclopentenyl 2,2,3,3,4,4,5,5-octafluoro-*n*-pentyl ether were also perfluorinated by the LPPF method to give the corresponding Cl-containing *F*-ethers in fair yields. The total retention of the chlorine atom through perfluorination and the ability to have a benzene substituent on the substrate are benificial features of this novel perfluorinating method.

Keywords: Liquid-phase photofluorination; Perfluorocycloalkyl ethers; GC-MS; ^{19}F-NMR

1. Introduction

Perfluorochemicals are becoming increasingly important in the fine chemical industry [1]. Fluosol-DA®, which is an emulsion of a mixture comprising perfluorodecalin and perfluorotri-*n*-propylamine, has been used as a treatment for coronary artery surgery (PTCA) [2]. Perfluorooctylbromide is now in an advanced stage of development as a gastrointestinal imaging agent [3]. These fine applications spur the development of a new perfluorinating method which enables tailor-made synthesis of perfluorochemicals having specifically designed structures. In this connection we have developed a novel perfluorinating method which we call liquid-phase photofluorination. Previous reports have shown that this method is useful for preparing highly branched perfluoro-ethers and -tertiary amines [4]. In order to gain further insights we carried out LPPF of partially fluorinated ethers having a phenyl or a chlorine substituent, neither of which is tolerated in the electrochemical fluorination (ECF) process.

It was found in our laboratory that if one bromine atom is incorporated into the perfluorochemical structures, the critical solution temperature (c.s.t.) decreases remarkably. This bromine's lipophilic effect on *F*-chemicals is desirable for an oxygen carrier from the viewpoint of excretion rate, but a bromine substituent also incorporates lability towards some chemicals, e.g. conc. H_2SO_4 and $LiAlH_4$. This chemical lability raises concerns as to whether these perfluorobromides will meet the high level of chemical inertness required for medicinal use [5]. Although chlorine may be less effective than bromine in lowering the c.s.t., it still has a substantial effect. This is illustrated by the fact that c-$C_8Cl_3F_{13}O$ is miscible with benzene, while c-$C_8F_{16}O$ is only slightly soluble [6].

In contrast to bromine, a chlorine substituent embedded in the perfluoro-framework is so inert that even replacement with a fluorine atom under cobalt trifluoride fluorination conditions is difficult [7]. Further, the stability of the chlorine substituent was investigated as part of the Manhattan Project and it was concluded in its voluminous report that monochloropentadecafluoroheptane is inert enough for use in the gas-diffusion method of separating uranium isotopes as well as perfluoroheptane [8].

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We surmised from the above discussion that chlorine-containing perfluoroethers with cyclic structures may have desirable properties as oxygen carriers.

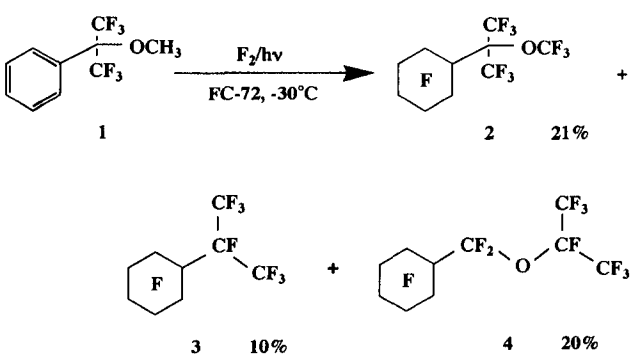
The present work was carried out in 1982–1984 and its original concept has already been reported in a patent [9]. This paper describes a part of the work in detail.

2. Results and discussion

The ether **1** was prepared by the Friedel–Crafts reaction of hexafluoroacetone with benzene followed by methylation with dimethylsulfate [10]. The LPPF technique is, in general, carried out by introducing the substrate dissolved in an inert solvent into an inert reaction medium saturated with undiluted fluorine gas under UV irradiation. The LPPF of the compound **1** proceeded smoothly at ca. −31 °C and the corresponding perfluoroether, **2**, was isolated by preparative GLC in 21% yield, together with the fragmented product, **3**, and the rearranged product **4** in 10 and 20% yields, respectively (Scheme 1). We also carried out ECF of the same substrate for comparison, but only a messy mixture containing primarily compounds **3** and **4** was obtained in ca. 14% yield. What is worse, the cathode surface was totally covered by polymerized films which were rather difficult to remove. A recent paper refers to observed difficulties during the electrochemical fluorination of compounds having a phenyl group as a substituent [11]. Therefore, LPPF is superior to ECF in toleration of the phenyl substituent.

The products were isolated by preparative-scale GLC and characterized by GC-MS (positive electron impact and negative chemical ionization) and ^{19}F-NMR. ^{19}F-NMR data of **2–4** are summarized in Table 1. The compound **3** is already known [5a], but its ^{19}F-NMR data are included in the table, because no such data are available in the literature. As may be expected, the CF_2 groups of the *F*-cyclohexane rings are split into AB type quartets by the locked conformation imposed by bulky substituents.

The positive EI MS of **2** showed $M-F^+$ with the intensity of 0.2. A couple of fragment ions diagnostic to the structure of **2** arose from α- and β-scissions of the molecular oxonium radical (Table 2). Since the compound **4** was totally unexpected and formed through rather unusual consecutive rearrangements, a negative CI MS was also measured to ascertain the structure. In the negative ion spectrum, the molecular ion, which was not observed in the positive EI spectrum, was observed. The base peak of $OCF(CF_3)_2^-$ at m/z 185 is a further proof of the structure of **4**. The other diagnostic fragment anions of **4** are summarized in Table 3.



Scheme 1.

The low yield of **2** may be caused by the large steric hindrance in the C(tert)–C(quart) bond and the lability of the C(tert)–O bond. We cannot show a clear picture of the mechanism owing to the many reaction sites, and so we drew a simplified scheme by keeping the phenyl group intact (Scheme 2). We believe that even such an oversimplified scheme is helpful to understand the essence of the mechanism. The rapid conversion of the intermediate radical **I** to the stable radical **IV** is a plausible mechanism for the formation of **3**. This kind of bond lability was found in the case of the photofluorination of 2-propoxy-*F*-2-methylpentane [4].

Compound **4** was probably formed through the ring closure at the methoxy group as in structure **II** followed by a successive ring opening reaction caused by the large steric hindrance.

The weakness of the C–C bond caused by the steric hindrance of the highly-branched *F*-compounds has not been investigated well. Tatlow et al. reported that the pyrolysis of *F*-dicyclohexyl which had a C(tert)–C(tert) congested bond required temperatures over 600 °C [5]. We accidentally found before that highly branched *F*-alkanes such as *F*-3-ethyl-2,3,4-trimethylpentane were thermolabile even at ca. 100 °C (unpublished results). Recently Tonelli et al. reported first-order kinetics on the thermolysis of highly branched *F*-alkanes, in which they said *F*-2,3,3,4-tetramethylpentane pyrolyzed through a C(tert)–C(quart) bond homolysis at the rate of 6.5×10^{-5} at 181 °C [12]. This is the fastest figure among the various structures they investigated and corresponds to a half-life of ca. 18 min at 181 °C. Our process uses reaction temperatures as low as −30 °C, which is seemingly in conflict with the bond-scission mechanism presented (vide supra). Of course there is really no conflict at all. The pyrolysis process starts from the rate-limiting C–C bond homolysis at the most strained position, forming a pair of perfluoroalkyl radicals, and this is then followed by rapid beta scissions. On the other hand, the C–C bond breaking occurring in the photofluorination process is the result of a beta scission initiated by hydrogen atom abstraction with F_2 or an F atom. Therefore, the C–C bond breaks through this beta scission even at −30 °C in the photofluorination process. The observed formation of rearranged product **4** strongly suggests that this intramolecular beta scission reaction is more rapid than or at least of a comparable rate to the F-alkyl radical plus F or F-alkyl radical plus F_2 reaction.

The thermolability and chemical stability of highly congested *F*-compounds is now under investigation. Such investigations are expected to provide fundamental knowledge about the nature of chemical bonds in strained *F*-compounds and also help to establish some criteria for the molecular

Table 1
^{19}F NMR spectra of compounds **2**, **3**, and **4**

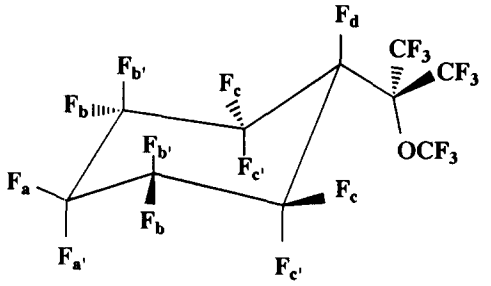
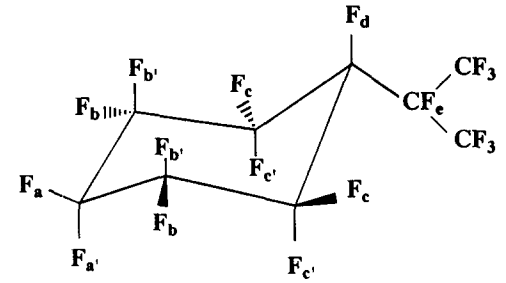
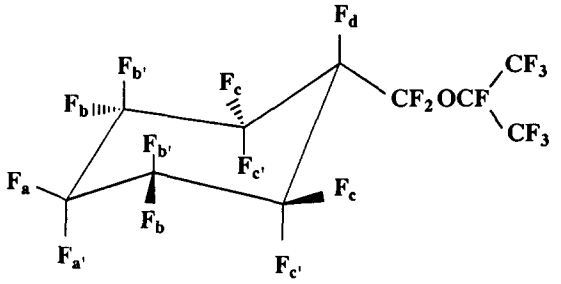
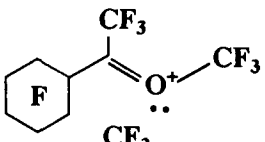
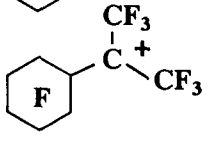
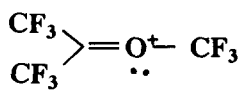
Compound	Formula	Chemical shifts		Coupling constants (Hz)
2		$-C(CF_3)_2$	−66.65	
		$-OCF_3$	−52.55	
		$F_{a,a'}$	−142.2, −124.2	$J_{aa'}$ = 284 Hz
		$F_{b,b'}$	−138.1, −121.8	$J_{bb'}$ = 282 Hz
		$F_{c,c'}$	−127.0, −115.4	$J_{cc'}$ = 294 Hz
		F_d	−179.3	
3		$CF_3F_{a,a'}$	−70.9	$J_{aa'} = J_{b,b'}$ = 288 Hz
		$F_{a,a'}$	−142.2, −124.3	$J_{cc'}$ = 297 Hz
		$F_{b,b'}$	−138.6, −121.9	$J_{eb'}$ = 28.4 Hz
		$F_{c,c'}$	−128.3, −116.7	$J_{de} = J_{eCF3} = J_{ce} = J_{c'e}$ = 16.6 Hz
		F_d	−180.8	
		F_e	−181.9	
4		$-CF(CF_3)_2$	−146.0	
		$-CF_3$	−81.28	
		$-CF_2O-$	−69.16	
		$F_{a,a'}$	−142.41, −124.53	$J_{aa'}$ = 288.1 Hz
		$F_{b,b'}$	−140.30, −122.75	$J_{bb'}$ = 286.0
		$F_{c,c'}$	−131.79, −119.76	$J_{cc'}$ = 297.7
		F_d	−187.4	

Table 2
Diagnostic fragment ions for the structure of **2**

m/z	Relative intensities	Fragment ions
497	0.2	$M\text{-}F^+$
447	0.1	
431	4.0	
235	3.3	

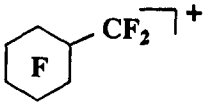
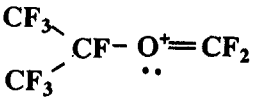
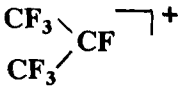
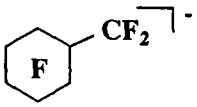
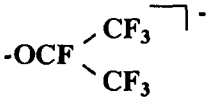
design of the *F*-componds suitable for oxygen transport. *F*-compounds that are too hindered must be toxic, because of the degradation products formed during the emulsification or sterilization processes. The toxicity of *F*-2-ethyl-2,3,4,5-tetramethylfuran found in our laboratory may be an example (unpublished results).

2.1. Synthesis of chlorine-containing F-cyclic ethers; F-(2-chlorocyclopentyl cyclopentyl) ether 7 and F-(2-chlorocyclopentyl n-pentyl) ether 8

The compounds **5** and **6** were prepared by Williamson synthesis in 80 and 50% yield, respectively (Scheme 3). Anello et al. reported that a similar reaction of 1,2-dichlorohexafluorocyclopentene with methoxide or ethoxide gave the corresponding adducts in 85 and 51% yields, respectively [13].

Molecular ions (*m/z* 294, 296) and key fragment ions of $\overline{CF_2(CF_2)_2CCl{=}C}^+$ (*m/z* 209, 301) and $\overline{CH_2(CH_2)_3CH}^+$ (*m/z* 69) were found in the MS of **5** with relative intensities

Table 3
Diagnostic fragment ions for the structure of 4

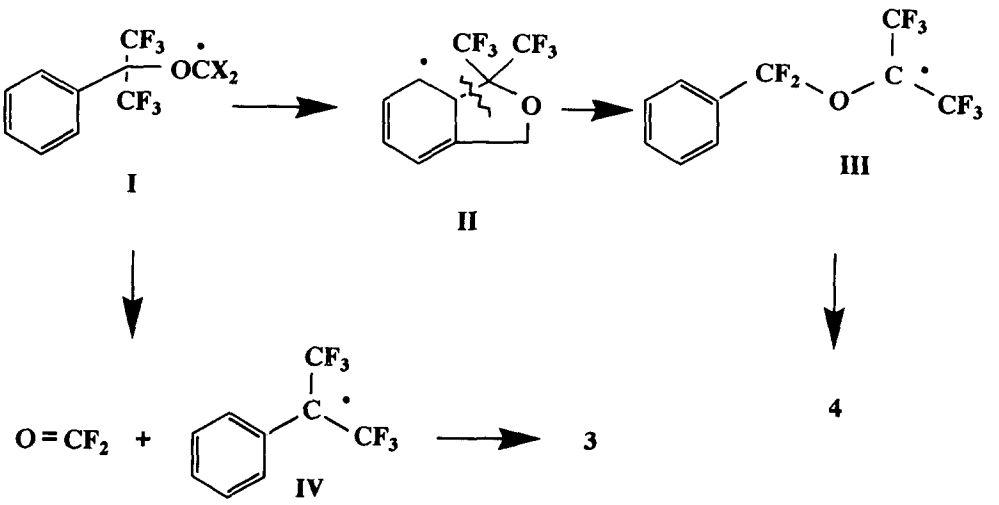
Positive ion		
331	10.5	
281	9.3	
235	1.7	
169	8.50	
Negative ion		
516	0.3	
331	6.2	
185	100.0	

of 0.1, 1.1, and 100, respectively. (Isotope peaks for the chlorine element were observed in consistent abundances, but only the data on ^{35}Cl was included for its convenience.) These ions are consistent with the structure of **5**. The relative intensities of the latter two species reflect the relative stability of those cationic species. To make a brief comment here on the assignment of $\overline{CH_2(CH_2)_3CH}^+$ might be necessary, because the quadrupolar MS cannot differentiate those two species of CF_3^+ and $\overline{CH_2(CH_2)_3CH}^+$, which have a common m/z 69, and further because the CF_3^+ always accompanies the MS of poly- or per-fluorocompounds in relatively high intensities by fluorine atom scrambling even though no CF_3 group is included in the structures. The contribution of the CF_3^+ ion to the population of the m/z 69 was estimated to be very low because the MS of 1,2-dichlorohexafluorocyclopentene yielded fragment ions having m/z 244 (M^+), 209 ($\overline{CF_2(CF_2)_2CCl=C}^+$) and 69 ($CF_3^+$) in relative intensities of 100, 33.9 and 10.8, respectively. A fragmentation pathway for **6** is illustrated in Scheme 4.

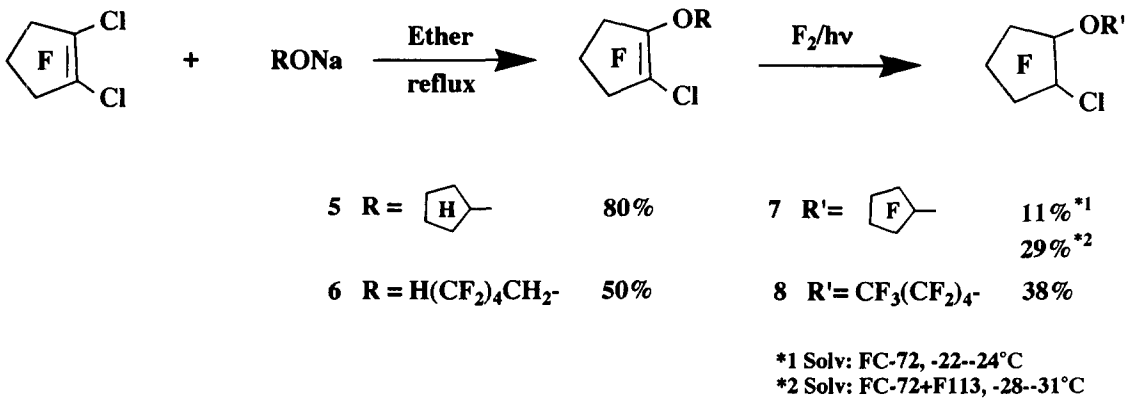
FC-72 (nominal chemical structure is not released by the manufacturer, but FC-72 appears to be *F*-hexane, as a dominant component, by both its ^{19}F-NMR spectrum and observed physical properties) was employed for the LPPF of **5** as both the solvent for the substrate and the reaction medium. Several explosions (not so detrimental as to stop the reaction) occurred throughout the fluorination in this case, resulting in a poor yield of the desired **7** (11% by GLC). A poor solubility of the substrate **5** at the low temperature used (−22 to −24 °C) might be the cause of the explosion. To circumvent the solubility problem, a mixture of F113 and FC-72 (1:5 by volume) was used as the solvent for the substrate. No explosions occurred this time and the fluorination proceeded smoothly to give a better yield (29% by GLC).

The reaction mixture was analyzed by GC-MS. Many minor peaks were observed in both cases, but the major peak seemed to be the desired compound by observations of the diagnostic ions such as $^+\overline{CF(CF_2)_3CF^{35}Cl}$ (m/z 247, 11.1), $^+\overline{CF(CF_2)_3CF^{37}Cl}$ (m/z 249, 3.7), and $^+\overline{CF(CF_2)_3CF_2}$ (m/z 231, 12.0).

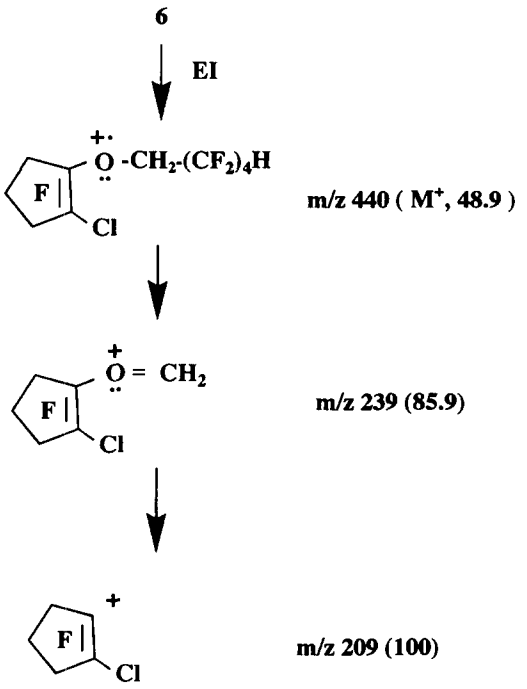
The product peak (by GC-MS) was isolated by preparative GLC as described in the experimental. Its ^{19}F-NMR spectrum showed very many complex signals between −115.8 and −138.5 ppm, suggesting that the collected peak was a diastereomixture because of the three chiral centers. No further attempt to isolate the stereoisomers was made.



Scheme 2.



Scheme 3.



Scheme 4.

Table 4
Relative intensities of a series of diagnostic fragment ions for the ring structure of **7**

n	C_nF_{2n+1}		C_nF_{2n}		C_nF_{2n-1}	C_nF_{2n-2}	C_nF_{2n-3}
5	–	<	0.2	<	5.4	0.5	1.3
4	–	<	0.2	<	31.4	6.4	4.1
3	0.2	<	1.2	<	79.7	2.6	13.1
2	5.1	<	12.1		1.5	0.4	–
1	25.8		0.7		–		

NCI-GC-MS of **7** was measured to obtain a further structural confirmation. No molecular ion was observed again, but four characteristic ions found at m/z 247 (100), 249 (0.3), 263 (31.4) and 265 (9.3) support the structural assignment. For m/z 247 there are two possibilities, which are $\overline{CF_2(CF_2)_2CFCl}\overline{CF}^-$ and $\overline{CF_2(CF_2)_3}\overline{CFO}^-$, but it is clear that the latter anion is responsible because of the low abundance of m/z 249. The fragment anion with the structure $\overline{CF_2(CF_2)_2CFCl}\overline{CFO}^-$ is responsible for m/z 263 and 265. Combining these two fragment structures leads unequivocally to the structure **7**.

An *F*-cyclic alkane structure is characterized by the fragment ion series of C_nF_{2n+1}, C_nF_{2n}, C_nF_{2n-1}, C_nF_{2n-2}, and C_nF_{2n-3}, the relative intensities of which increase in this order if compared in the same n number [14]. This rule works rather well for larger n values. The relative intensities for the series in the MS of **7** support the ring structure (Table 4). The relative intensities of the Cl-containing congeners in Table 5 also support a ring structure.

The fluorination of **6** was carried out in the same manner except that 1,1,2-trichloro-1,2,2-trifluoroethane (F113) was used as the solvent and as the reaction medium. The products obtained were unexpectedly complex, but the major peak was estimated by MS in both the positive and negative modes. Yield estimated by GLC was 48%.

Molecular and M−F ions were not observed in either mode, but the fragment ions with m/z 313 and 315 ($\overline{CF_2(CF_2)_2CFCl}\overline{CFO}^+{=}CF_2$) which arise from the same fragmentaion pathway as **6** and C_nF_{2n+1} (n = 1–5) were diag-

Table 5
Relative intensities of a series of diagnostic fragment ions for the Cl-containing ring structure of **7**

n	$C_nF_{2n}Cl$		$C_nF_{2n-1}Cl$		$C_nF_{2n-2}Cl$	$C_nF_{2n-3}Cl$	$C_nF_{2n-4}Cl$
5	–		–	<	12.8	0.2	0.2
4	–		–	<	15.9	1.0	0.9
3	–		–	<	100.0	0.4	2.8
2	0.8	<	2.2	>	0.9	0.2	–
1	4.6		0.4		–		

Table 6
Relative intensities of a series of diagnostic fragment ions for the ring structure of **8**

n	C_nF_{2n+1}		C_nF_{2n}		C_nF_{2n-1}	C_nF_{2n-2}	C_nF_{2n-3}
5	18.5	>	0.5	>	–	–	0.7
4	0.3	>	0.2	>	19.3	2.7	1.9
3	3.2	>	1.1	<	34.2	1.2	5.9
2	51.1	>	18.9	>	1.0	0.3	–
1	100.0	>	0.5		–		

Table 7
Relative intensities of a series of diagnostic fragment ions for the Cl-containing ring structure of **8**

n	$C_nF_{2n}Cl$	$C_nF_{2n-1}Cl$	$C_nF_{2n-2}Cl$	$C_nF_{2n-3}Cl$	$C_nF_{2n-4}Cl$
5	–	–	< 23.7	–	–
4	0.8	–	< 14.1	0.7	0.4
3	–	–	< 44.4	–	1.7
2	0.5	< 4.8	> 0.5	–	–
1	3.1	0.3	–		

nostic of the ring structure of **8** (Tables 6 and 7). Negative mode MS yielded the characteristic fragment ions, which is similar to the case of **7**. Thus the diagnostic fragment anions of m/z 263 (26.9), 265 (8.7) and 285 (68.1) which correspond to the structures of $\overline{CF_2(CF_2)_2CFCl}\overline{CFO}^-$ and $C_5F_{11}O^-$ confirmed the structure of **8**.

Relative abundances of C_nF_{2n+1} and C_nF_{2n} ($n = 1$–5) supported the existence of a C_5F_{11} moiety in the structure (Table 6). Cl-containing fragment ion series shown in Table 7 suggested the chlorine atom was on the ring moiety.

The LPPF of **5** and **6** showed that the chlorine substituents were retained in the LPPF process. The toleration of the chlorine substituent is beneficial, compared to the ECF process, which is known to be too drastic to retain the chlorine substituent [15].

3. Experimental

All usual safety precautions should be taken when handling undiluted fluorine. Hexafluoroacetone was a gift from Daikin Industries Ltd. and used as received. Elemental fluorine (98% technical grade) was purchased from Air Products and Chemicals Inc. and used after purification through sodium fluoride pellets. 1,2-Dichlorohexafluorocyclopentene and 1*H*,1*H*,5*H*-*F*-pentanol were purchased from PCR Research Chemicals, Inc. and used as received. FC-72 (3M Co.) was used as the solvent after refining by distillation (b.p. 55–57 °C).

IR spectra were obtained on a Perkin-Elmer 281 spectrometer. Mass spectra (MS) were run on a Hewlet-Packard (HP) 5985B quadrupole mass spectrometer system using 4.8 × 0.32 cm columns packed with 10% OV-202 on 100–200 mesh Gas Chrom RZ. Negative chemical ionization (NCI) mass spectra were recorded on the same instrument retrofitted with HP accessory 18962A (NCI packages). Argon gas was used as the reagent gas. MS data on the chlorine-containing ions are given only for the ^{35}Cl isotope for convenience. ^1H- and ^{19}F-NMR spectra were measured with a Varian T-60 (56.4 MHz) in neat liquids. ^{19}F-NMR of **2** and **3** were recorded on an IBM-Brucker WP-270SY NMR spectrometer operated at 254.18 MHz. Chemical shifts of ^{19}F-NMR are reported on the δ scale, with $CFCl_3$ as an internal standard and positive shifts to high frequency of the reference; those of ^1H-NMR are expressed on the δ scale using TMS as an external standard.

Experimental details on the liquid-phase photofluorination were given in the previous report [4].

3.1. 2-Phenyl-2-methoxyhexafluoropropane 1

Into a solution of (2-hydroxyhexafluoro-2-propyl)-benzene (170 g, 0.7 mole) in dry THF (1000 ml) was added metal sodium (17.5 g, 0.76 mole). After refluxing overnight, dimethylsulfate (71 g, 0.56 mole) was added, and then refluxed overnight again. Into the reaction mixture was added methanol (10 ml) at room temperature. The reaction mixture was poured into ca. 500 ml of iced water. The organic layer was separated, dried over sodium sulfate, and distilled under atmospheric pressure. Yield 91% (163 g), b.p. 166–172 °C; MS, ^1H- and ^{19}F-NMR data are consistent with those reported [6b].

3.2. F-2-Cyclohexyl-2-methoxypropane 2 (nc), F-2-cyclohexylpropane 3, and F-2-cyclohexylmethyl isopropyl ether 4 (nc)

A solution of **1** (12 g, 46.5 mmol) in 170 ml of FC-72 was pumped at a rate of 6.2 ml h^{-1} (1.7 mmol h^{-1}) into a well-stirred FC-72 solution that had been saturated with undiluted fluorine under UV irradiation. Undiluted fluorine gas was bubbled into the reaction mixture to maintain the saturation throughout the fluorination. The reaction temperature was controlled at -30 ± 1 °C. After the organic addition was complete, fluorine addition was continued by bubbling undiluted fluorine gas through the reaction mixture for 6 h at a temperature of -15 to -10 °C. The fraction boiling at 120–131 °C (18.2 g) was analyzed using a nickel column (1/8 in × 18 ft) packed with 29.4% Fomblin® (on Gas Chrom RZ 100–120 mesh); injection, 160 °C, oven, 80 °C, detector (TCD), 150°C. Three major components, **2**, **3** and **4**, were eluted in this order with the area ratio of 3.5:1:2. Each component was isolated by a preparative-scale GLC, using a copper column (1/4 in × 16 ft) packed with 19.6% Fomblin® (on Gas Chrom RZ 100–120 mesh). Yields for **2**, **3** and **4** were 21, 10, and 20%, respectively. Anal. Calcd. for $C_{10}F_{20}O$ (**2** and **4**): C, 23.27, F, 73.63; Found for **2**: C, 23.50, F, 73.45; Found for **4**: C, 23.55, F, 73.33.

3.3. 2-Chlorohexafluorocyclopenten-1-yl cyclopentyl ether 5 (nc)

Cyclopentanol (23 g, 0.27 mole) and sodium metal (5.6 g, 0.24 mole) were placed in a 100 ml flask containing 25 ml of dry THF. The mixture was refluxed overnight. The alkoxide solution obtained was diluted with 200 ml of dry ether and added to a solution of 1,2-dichlorohexafluorocyclopentene (49 g, 0.2 mole) in 100 ml of dry ether at room temperature over 20 min. After refluxing for 2 h, the reaction mixture was poured into iced water (ca. 150 ml). The organic layer was separated and the water layer was extracted with ether (100 ml × 2). The combined organic layer was dried over

$CaCl_2$. The solvent was distilled off at atmospheric pressure, then distilled under reduced pressure to give 46.6 g of **5**, b.p. 58–60 °C at 2 mmHg; yield 79%, ^{19}F-NMR (neat), −106.1 (s, 2F), −111.1 (s, 2F), −125.5 (s, 2F), MS, 294 (M^+, 0.1), 209 ($\overline{CF_2(CF_2)_2CF{=}CCl}$, 1.1).

3.4. 2-Chlorohexafluorocyclopentenyl 2,2,3,3,4,4,5,5-octafluoro-n-pentyl ether 6 (nc)

2,2,3,3,4,4,5,5-Octafluoro-*n*-pentanol (11.6 g, 0.05 mole) and sodium metal (1.4 g, 0.05 mole) in 100 ml of dry ether were stirred overnight at room temperature. The resultant solution was added into a solution of 1,2-dichlorohexafluorocyclopentene (12.3 g, 0.05 mole) in 100 ml of dry ether with vigorous stirring. After stirring for 1 h at room temperature, the reaction mixture was poured into iced water (ca. 150 ml). The organic layer was separated and dried over sodium sulfate. The solvent was distilled off at atmospheric pressure and then distilled under reduced pressure to give 11.2 g of **6** (b.p. 80–88 °C at 14 mmHg, 50% yield). ^{19}F-NMR (neat), −108.3 (2F), −110.5 (2F), −126.1 (2F), these are ring CF_2s, −117.2 (2F), −121.3 (2F), −126.1 (2F), −134.5 (2F), ^{1}H-NMR (neat), 5.69 (tt, J = 52.0, 5.4 Hz, 2H), 4.59 (t, J = 12.4 Hz, 1H), MS; 440 (M^+, 48.9), 421 ($M-F^+$, 18.0), 239 ($\overline{CF_2(CF_2)_2C(O^+{=}CH_2){=}CCl}$, 85.9), 209 ($\overline{CF_2(CF_2)_2CF{=}CCl}^+$, 100).

3.5. F-2-Chlorocyclopentyl cyclopentyl ether 7 (nc)

A solution (ca. 8 w/v %) of **5** (8 g, 27.2 mmole) dissolved in 100 ml of a mixture of FC-72 and F113 (5:1 by volume) was pumped into the reaction medium (FC-72) saturated with undiluted fluorine gas under UV irradiation at a rate of 7.2–28.5 ml h^{-1} at −28 to −31 °C. After the feeding of the substrate solution was completed, the introduction of the fluorine gas was maintained for 12 h to finish the exhaustive fluorination. The reaction mixture was washed with aq.$NaHCO_3$ and water, then dried over $CaCl_2$. The resultant liquid was distilled to give two fractions; Fr1 (69–119 °C, 6.3 g containing 55.8% of **7**) and Fr2 (119–142 °C, 8.0 g, 65.4% purity by GLC) and the residue (5.0 g). Yield by GLC was 29%. The compound **7** was isolated by preparative-scale GLC using a nickel column (1/4 in × 16 ft) packed with 16.4% Fomblin® (on Gas Chrom RZ 100–120 mesh) and its ^{19}F-NMR (254.18 MHz) was measured by using $CFCl_3$ as both a solvent and an internal standard. All signals but one signal (singlet at ca. −143 ppm) were found between −115.8 and −138.5 ppm. The signals were too complex to assign owing to the stereoisomers. EI-MS (70 eV); 297 ($\overline{CF_2(CF_2)_3CFO}^+{=}CF_2$, 0.3), 247 ($\overline{CF_2(CF_2)2CFClCF}^+$, 12.8). NCI-MS; 263 ($\overline{CF_2(CF_2)_2CFClCFO}^-$, 31.4), 247 ($\overline{CF_2(CF_2)_3CFO}^-$, 100), 212 (95.8), Anal. Calcd. for $C_{10}ClF_{17}O$: C, 24.29, F, 65.31, Found: C, 24.35, F, 65.40.

3.6. F-2-Chlorocyclopentyl n-pentyl ether 8 (nc)

The fluorination of **6** (11 g, 25 mmol) was carried out in a similar manner as for **5**. F113 was used not only as the solvent for the substrate but also as the reaction medium instead of FC-72. When the reaction mixture was poured onto cracked ice, a fuming reaction occurred (but not so vigorously) and a yellow color developed immediately in the F113 layer. The yellow substance was extractable with water (its partition coefficient to the water layer seems to be low judging from the extent of the coloration) and was discolored easily by aqueous sodium thiosulfate (3 g in 100 ml). The organic layer separated was dried over $CaCl_2$. The solvent was distilled out and the resultant liquid was distilled using a silver-coated vacuum-jacketed column (9 in long) packed with a spiral of stainless gauze to give two fractions, Fr1 (b.p. 83–141 °C, 1.0 g, 56% purity by GLC), and Fr2 (b.p. 141–147 °C, 4.8 g, 85% purity by GLC) and the residue (2.9 g). Yield by GLC was 42%. ^{19}F-NMR data were not easy to interpret owing to the isolation problem. EI-MS (70 eV); 313 ($\overline{CF_2(CF_2)_3CFO}^+{=}CF_2$). NCI-MS; 285 ($C_5F_{11}O^-$, 68.1), 263 ($\overline{CF_2(CF_2)_2CFClCFO}^-$, 26.9), 212 (100).

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