

Synthesis and Chemistry of Perfluoro Macrocycles

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Abstract: The perfluoro macrocycles perfluoro-18-crown-6, perfluoro-12-crown-4, perfluoro-15-crown-5, perfluoro-cyclohexano-15-crown-5, perfluorodicyclohexano-18-crown-6, perfluorodicyclohexano-24-crown-8, and perfluoro-4,7,13,16,21,24-hexaoxa-1,10-diazabicyclo[8.8.8]hexacosane (perfluorocryptand [222]) have been prepared by carefully controlled elemental fluorination. Although they are much weaker bases than their hydrocarbon analogues, these perfluoromacrocycles are very stable materials which should have a number of applications. The crystal structures of perfluoro-18-crown-6 and of a perfluorodicyclohexano-18-crown-6 isomer are reported. Gas-phase studies with several perfluoro crown ethers and with the perfluorocryptand [222] have shown that such macrocycles tenaciously bind O_2^- and F^- . Perfluoro crown ethers and cryptands coordinate anions preferentially over cations. The collisionally activated mass spectra of several perfluoro macrocyclic ions are described.

Introduction

Since Pederson¹ first discovered the complexing power of crown ethers, the role of macrocycles has become more important in understanding the principles of host-guest chemistry in molecular recognition.^{2,3} Cryptands were prepared by Lehn and co-workers⁴ and have been studied extensively by Lehn and others. As is well-known, these are a very useful class of ligands which form very stable complexes with numerous metal cations. The preparation of new crown ethers is important because crown ethers have many applications in research laboratories and industry. Crown ethers not only complex with cations but also complex with neutral molecules.⁵ Many important applications derive from their complexing ability with alkali metals⁶ and their catalytic effect on chemical reactions.⁷⁻⁹ Lehn first reported the coordination of a fluoride ion in a macrocycle.¹⁰ Recently, Farnham and co-workers prepared a fluorinated macrocyclic compound complexed with a fluoride anion.¹¹ The fluoride ion is held within the chiral cavity and interacts with four ethylene (CH_2) groups. In both cases the fluoride ions are held in place by hydrogen bonding and coordinate the hydrogen atoms bound to the central ring.

Perfluoro crown ethers have been synthetically inaccessible by conventional reactions of fluorocarbons and outside the capability of synthesis using selective fluorination reagents. The first examples of this potentially useful class of macrocycles have been prepared in our laboratory. These syntheses have been accomplished using the La Mar process, a broadly applicable technique for controlling reactions of elemental fluorine.¹² All

reactions were conducted in the previously described cryogenic fluorination reactor.^{12,13} Perfluoro crown ethers were expected to be unusually stable. The reactions to produce perfluoro macrocycles are illustrated in Figure 1. Perfluoro crown ethers have applications in biomedical technology and may have applications in catalytic chemistry and perhaps as oxygen carriers.

Experimental Section

The starting hydrocarbon crown ethers were dried using a molecular sieve (4 Å) or purified by distillation or recrystallization before use. In a typical experiment of 18-crown-6, 15-crown-5, and 12-crown-4, 0.81 g of 18-crown-6 and 2.09 g of NaF were ground to a fine powder and mixed well in a drybox. We found for these experiments that several factors influenced the yield obtained: the surface area exposed to fluorine, the reaction temperatures, the reaction time, and the fluorination conditions. The surface area variable was particularly important. To increase the surface area, sodium fluoride was used as solid support upon which the starting crown ether was coated. A second function of this sodium fluoride was to react with the hydrogen fluoride produced as the reaction proceeds. It is also important to dry carefully the crown ether starting materials. If this is not done or the sodium fluoride support is not provided, the yields are drastically reduced.

The mixture was placed in a nickel boat inside a bucket reactor¹² and loaded into a fluorination system. A trap was placed after the reactor which was used to collect the volatile products. After a He purge was maintained for at least several hours, the reactor and trap were cooled to $-78^\circ C$. The fluorination reaction was started and followed conditions similar to those shown in Table 1. After the reaction, He was passed through the reactor to sweep fluorine from the system.

Volatile products or by-products produced were transferred from the $-78^\circ C$ trap to a vacuum line for fractionation. Fractions were obtained that stopped in traps at -23 and $-78^\circ C$. The $-23^\circ C$ fraction was further separated into three components using a gas chromatograph with a 25-ft \times 0.25-in., 10% QF-1, chromosorb P column. Mass spectra of 18-crown-6, 15-crown-5, and 12-crown-4 were taken with a Bell & Howell Model 21-491 low-resolution spectrometer at 70 eV at $250^\circ C$, unless otherwise specified.

Perfluoro-18-crown-6. The major component was identified as perfluoro-18-crown-6 ether. Perfluoro-18-crown-6 was a volatile colorless crystalline solid with a melting point of $34^\circ C$, obtained in 33% yield (0.71 g based on starting 18-crown-6). Elemental analyses were consistent with $C_{12}F_{24}O_6$. Calcd: C, 20.71; F, 65.60. Found: C, 20.90; F, 65.35. The vapor-phase IR spectrum exhibited bands at 1240 (vs), 1220 (vs), 1140 (vs), and 730 (m) cm^{-1} . The ^{19}F NMR (C_6F_6 solution) contained a singlet at -91.0 ppm from external $CFCl_3$. The ^{13}C NMR (C_6F_6 solution) also contained a singlet which was observed at 114.9 ppm from

(13) Huang, H. N.; Lagow, R. J. *Bull. Soc. Chim. Fr.* **1986**, 6, 993.

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 (1) Pederson, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 2495.
 (2) (a) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 89. (b) Cram, D. *Science* **1988**, *240*, 760.
 (3) (a) Hiroaka, M. *Crown Compounds*; Kodansha Scientific: Tokyo, 1978.
 (b) Izatt, R. M.; Christensen, J. S. *Progress in Macrocyclic Chemistry*; Wiley: New York, 1979; Vol. 1.
 (4) (a) Dietrich, B.; Lehn, J. M.; Sauvage, J. P. *Tetrahedron Lett.* **1969**, *34*, 2855. (b) Lehn, J.-M.; Sauvage, J. P.; Dietrich, B. *J. Am. Chem. Soc.* **1970**, *92*, 2916. (c) Lehn, J.-M. *Angew. Chem.* **1988**, *100* (1), 91.
 (5) Vogtle, F.; Muller, W. M. *J. Inclusion Phenom.* **1984**, *1*, 369.
 (6) Pederson, C. J. *J. Am. Chem. Soc.* **1970**, *92*, 391.
 (7) Feton, D. E. *Chem. Soc. Rev.* **1977**, *6*, 325.
 (8) Dockex, J. *Synthesis* **1973**, 441.
 (9) Gokel, G. W.; Durst, H. D. *Synthesis* **1976**, 168.
 (10) Graf, E.; Lehn, J.-M. *J. Am. Chem. Soc.* **1976**, *98*, 6403.
 (11) Farnham, W. B.; Roe, D. C.; Dixon, D. A.; Calabrese, J. C.; Harlow, R. L. *J. Am. Chem. Soc.* **1990**, *112*, 7707.
 (12) Margrave, J. L.; Lagow, R. J. *Prog. Inorg. Chem.* **1979**, *26*, 161.

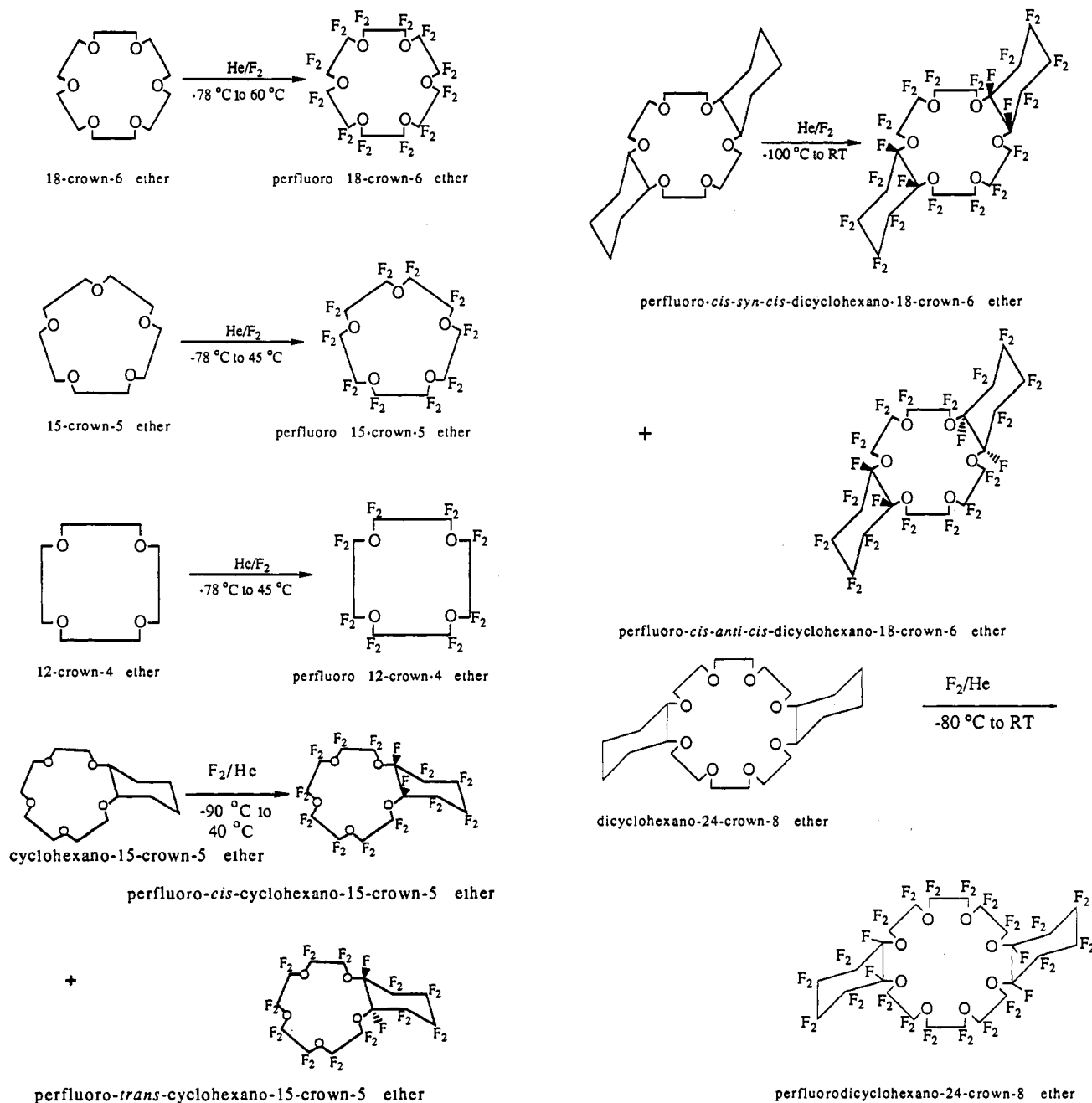


Figure 1. Reaction scheme for all compounds.

Table 1. Fluorination Parameters for 18-Crown-6

<i>t</i> , h	He, cm ³ /min	F ₂ , cm ³ /min	<i>T</i> , °C
16	60	0	-78
23	40	1.0	-78
24	20	1.0	-78
24	10	1.0	-78
24	10	3.0	-78
24	0	1.0	-78
36	0	2.0	-78
29	0	2.0	RT ^a
24	0	2.0	45
47	0	2.0	60
24	60	0	60

^a RT = room temperature.

external TMS. The mass spectrum (with the spectrometer cooled to ambient temperature) gave no parent peak, but instead, a peak at *m/e* 677 was observed which corresponded to the molecular ion minus one fluorine. Other prominent peaks included *m/e* 630 (C₁₁F₂₂O₅⁺), 564 (C₁₀F₂₀O₄⁺), 445 (C₈F₁₅O₄⁺), 332 (C₆F₁₂O₂⁺), 313 (C₆F₁₁O₂⁺), 213 (C₄F₇O₂⁺), 185 (C₃F₇O⁺), 119 (C₂F₅⁺, base peak), 100 (C₂F₄⁺), 69 (CF₃⁺), and 50 (CF₂⁺). The remaining two fractions from the GC

separation were identified as CF₃O(CF₂CF₂O)₄CF₃ (40 mg) and CF₃-CF₂O(CF₂CF₂O)₄CF₃ (22 mg) (see Table 2). These are reaction by-products, straight chain perfluoropolyethers, resulting from the ring system cleavage. The separations of 15-crown-5 and 12-crown-4 were performed in a similar manner.

Perfluoro-15-crown-5 Ether. A 17.9% yield (0.503 g) of perfluoro-15-crown-5 was obtained from the reaction of 1.06 g of 15-crown-5, accompanied by three major fragment products (see Table 2). Perfluoro-15-crown-5 has a boiling point of 146 °C and a freezing point of -11.5 °C (Calcd for C₁₀F₂₀O₅: C, 20.71; F, 65.50. Found: C, 20.90; F, 65.04). The IR spectrum gave bands at 1250 (s, sh), 1228 (vs, sh), 1158 (vs, sh), and 745 (m) cm⁻¹. The ¹⁹F NMR showed a singlet at -91.8 ppm from CFC₃. The ¹³C NMR consisted of a singlet at 114.9 ppm from TMS. The mass spectrum contained the following peaks: *m/e* 580 (C₁₀F₂₀O₅⁺, P), 561 (C₁₀F₁₉O₅⁺, P - F), 448 (C₈F₁₆O₃⁺), 329 (C₆F₁₁O₃⁺), 215 (C₄F₈O⁺), 213 (C₄F₇O₂⁺), 185 (C₃F₇O⁺), 119 (C₂F₅⁺, base peak), 100 (C₂F₄⁺), 97 (C₃F₇O⁺), 85 (CF₃O⁺), 69 (CF₃⁺), 50 (CF₂⁺), 47 (CFO⁺).

Perfluoro-12-crown-4 Ether. A 0.93 g of 12-crown-4 reacting with elemental fluorine yielded 0.88 g of perfluoro-12-crown-4. The reaction yield was 35%. The principal by-products isolated were CF₃O(CF₂CF₂O)₂CF₃ and CF₃CF₂O(CF₂CF₂O)₂CF₃ (see Table 2). Perfluoro-12-crown-4 has a boiling point of 118 °C, and the freezing point is -64

Table 2. Characterizations of Straight Chain Perfluoropolyethers

compound (highest <i>m/e</i> in mass spectrum)	assigned ¹⁹ F chemical shift, ppm (vs ext. CFC1 ₃)	relative intensities	
		obsd	theor
1. CF ₃ OCF ₂ CF ₂ OCF ₂ CF ₂ OCF ₃ a b c c b a 367 (C ₆ F ₁₃ O ₃ , P-F)	a = -58.5 b = -93.2 c = -91.1	1.5 1.1 1.0	1.5 1.0 1.0
2. CF ₃ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ OCF ₃ a b c c c c d 417 (C ₇ F ₁₅ O ₃ , P-F)	a = -58.3 b = -93.0 c = -91.0 d = -89.7	1.4 1.0 4.4 1.5	1.5 1.0 4.0 1.5
3. CF ₃ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₃ a b b b b b a 467 (C ₈ F ₁₇ O ₃ , P-F)	a = -89.9 b = -91.0	1.0 2.1	1.0 2.0
4. CF ₃ O[CF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ O]CF ₃ a b c c c c b a 483 (C ₈ F ₁₇ O ₄ , P-F)	a = -58.1 b = -92.0 c = -90.9	1.5 1.0 2.2	1.5 1.0 2.0
5. CF ₃ CF ₂ O[CF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ O]CF ₃ a b c c c c c c d (533 (C ₉ F ₁₉ O ₃ , P-F)	a = -58.0 b = -92.7 c = -90.8 d = -89.6	1.2 1.0 5.2 1.2	1.5 1.0 6.0 1.5
6. CF ₃ O[CF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ O]CF ₃ a b c c c c c c b a 599 (C ₁₀ F ₂₁ O ₅ , P-F)	a = -58.3 b = -93.0 c = -91.0	1.5 1.0 2.9	1.5 1.0 3.0
7. CF ₃ CF ₂ O[CF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ OCF ₂ CF ₂ O]CF ₃ a b c c c c c c c d 599 (C ₁₀ F ₂₁ O ₅ , P-CF ₃)	a = -58.0 b = -92.7 c = -90.6 d = -89.4	1.4 1.0 8.0 1.3	1.5 1.0 8.0 1.5

°C (Calcd for C₈F₁₆O₄: C, 20.71; F, 65.50. Found: C, 20.99; F, 65.18). The IR spectrum showed bands at 1260 (vs, sh), 1212 (vs, sh), 1188 (vs, sh), 1160 (vs, sh), 1080 (m), 825 (w), and 745 (w, br) cm⁻¹. The ¹⁹F NMR gave a singlet at -90.0 ppm from external CFC1₃, and ¹³C NMR gave a singlet at 114.9 ppm from TMS. The mass spectrum consisted of the following peaks: *m/e* 445 (C₈F₁₅O₄⁺, P-F), 213 (C₄F₇O₂⁺), 185 (C₃F₇O⁺), 2131 (C₃F₅⁺), 119 (C₂F₅⁺, base peak), 100 (C₂F₄⁺), 97 (C₂F₃O⁺), 85 (CF₃O⁺), 69 (CF₃⁺), 50 (CF₂⁺), 47 (CFO⁺).

Perfluorocyclohexano-15-crown-5 Ether, Trans- and Cis-Isomers. After the fluorination was finished, the white powder containing products and sodium fluoride from the disk reactor¹³ was collected and placed under vacuum. The volatiles were transferred into an acetone/dry ice trap. The GC assay of the volatile liquid on a 15% Kel-F column (Chromosorb A 60/80, 10 ft × 0.25 in., isothermal at 120 °C, helium carrier gas flow at 45 mL/min) gave two major peaks with a ratio of 1.0:0.82, based on peak area integration. The retention times were 13.4 and 15.0 min for cis- and trans-isomers, respectively. The hydrocarbon starting material, 15-crown-5 ether, purchased from PCR Inc., was dried over a 4-Å molecular sieve (Aldrich Chemical Co.) before use. The trans- and cis-isomers were analyzed by mass spectra, ¹⁹F NMR, high-resolution mass spectra, and IR. Both isomers gave strong *m/e* of 742 and M - C₆F₁₁ = 461 with similar ion fragmentation patterns. There are two tertiary fluorines in the expected perfluoro structure which lead to two possible isomers: trans and cis. The ¹⁹F NMR clearly established the structure differences between the two isomers. The first major peak collected from GC was the cis-isomer and the second was the trans. All cyclohexano groups are in chair form in solution. Due to the fluxional character of the perfluorocyclohexyl groups bound to the ether ring, positive assignments of ¹⁹F signals of ether ring fluorines are difficult. However, assignment of their configuration was based on the chemical shifts of perfluorodecalin published in the literature.¹⁴

¹⁹F NMR chemical shift (δ CFC1₃) for the trans-isomer: -86.7 to -93 ppm (complex), -121.35 ppm (d, *J*_{F-F} = 309.17 Hz, 2F), -125.61 ppm (d, *J*_{F-F} = 290.48 Hz, 2F), -135.23 ppm (s, 2F), -136.82 ppm (d, *J*_{F-F} = 309.17 Hz, 2F), -143.64 ppm (d, *J*_{F-F} = 290.48 Hz, 2F). ¹⁹F NMR chemical shift for the cis-isomer: -87 to -95 ppm (complex), -131.3 ppm (br, 4F), -134.0 ppm (br, 4F), -150.07 ppm (br, 2F). This illustrates the fluxional character of the cyclohexyl group on the NMR time scale. The infrared spectrum shows typical perfluoro ether absorptions below 1500 cm⁻¹. Data for the trans-isomer: 633 (w), 647 (w), 692 (w), 722

(w), 751 (w), 969 (s), 984 (m), 1048 (m), 1189 (s, br), 1193 (s, br), 1317 (m) cm⁻¹. Data for the cis-isomer: 633 (w), 661 (w), 714 (w), 720 (w), 762 (w), 972 (s), 1046 (m), 1146 (s, br), 1193 (s, br), 1266 (m, br), 1314 (m) cm⁻¹. Elemental compositions were studied with high-resolution mass spectroscopy, chemical ionization negative mode. Calcd: 741.9330. Found (trans): 741.9306, mDa = 2.4; the Found (cis): 741.9336, mDa = -0.6. Both isomers are clear, volatile oils. The boiling point of the trans-isomer is 199-200 °C, and that of the cis-isomer is 200-201 °C. The melting points for both isomers are between -44 and -46 °C. The melting point of the starting material is below 26 °C.¹⁵ The boiling point of the trans-isomer starting material is 110 °C (0.001 Torr, molecular distillation).¹⁶ The total yield of trans- and cis-isomers is 18.5% for 1 g of starting material. The yields are not optimized.

Perfluorodicyclohexano-18-crown-6 Ether, Cis-Syn-Cis- and Cis-Anti-Cis-Isomers. After the fluorination was finished, a white powder was collected from the disk reactor and extracted with a 100 mL of Freon 113 (1,1,2-trichlorotrifluoroethane) twice. This solution was washed with 100 mL of 0.5 M sodium hydroxide solution three times. The Freon 113 was removed by distillation, leaving a viscous oil. This oil was distilled under vacuum (0.5 mm, 125 °C). The distillate was further separated using gas chromatography (25% Fomblin Z, 0.25-in. × 10-ft column, isothermal at 200 °C, helium flow rate of 45 mL/min). The retention times were 31.2 and 34.5 min for the cis-syn-cis- and cis-anti-cis-isomers, respectively.

The two perfluoro isomers were identified primarily by GC/CIMS. Both isomers gave intense parent peaks at *m/e* = 1020. All cyclohexano groups in both isomers are in the chair form in the solid state, but in solution, both isomers are fluxional. Therefore, the assignments of the ¹⁹F resonances of the ether rings and cyclohexano groups are difficult. Infrared spectra of both isomers were taken as neat liquids, and they were virtually identical. The infrared spectra exhibited bands at 1192 (vs, br), 1042 (m), 974 (vs), 709 (w), 632 (w), and 485 cm⁻¹ (w). The ¹⁹F NMR spectra of both isomers show complex patterns at -80 to -95 ppm (δ CFC1₃), which correspond to the resonances of fluorine atoms of the ether ring, and -120 to -150 ppm (δ CFC1₃), which correspond to fluorines attached to the cyclohexano groups. The low-temperature ¹⁹F NMR spectra were studied and were not helpful in assigning the structures. Both isomers are colorless crystalline solids obtained in a total of 8.2-12.3% yield based on 1 g of starting material. The approximate ratio of

(15) Pederson, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.(16) Ikeda, I.; Yamamura, S.; Nakatsuji, Y.; Okahara, M. *J. Org. Chem.* **1980**, *45*, 5355.(14) Homer, J.; Thomas, L. E. *Proc. Chem. Soc.* **1961**, 139.

the syn-isomer to the anti-isomer is 53.54% based on GC assay. The syn-isomer has a melting point of 54–55 °C, and the anti-isomer, 49–50 °C.

Perfluorodicyclohexano-24-crown-8 Ether. This reaction was run on 1-g scale. After 8 days following conditions similar to those shown in Table 1, the disk reactor was purged again with helium at 150 °C and fluorocarbon liquids were collected in a room temperature trap and in a -78 °C trap. The room temperature liquid contains most of the desired product. Final purification was performed using gas chromatography (15% SE-30, 3/8-in. × 10-ft column, isothermal at 180 °C, helium flow rate of 45 mL/min). The retention time was 24.1 min. The desired product was identified primarily by the mass spectrum and high-resolution mass spectrum. Mass spectrum, chemical ionization negative mode (methane, 2×10^{-5} Torr, 130 °C): m/e 1252 (M^-), 1214 ($M - 2F^-$), 1020 ($M - C_4F_8O_2^-$), 971 ($M - C_6F_{11}^-$), 959 ($M - C_7F_{11}^-$), 877 ($M - C_8F_{13}O_2^-$), 827 ($M - C_9F_{15}O_2^-$), 761 ($M - C_{10}F_{17}O_3^-$), 711 ($M - C_{12}F_{21}O_3^-$), 645 ($M - C_{12}F_{21}O_4^-$), 633 ($M - C_{13}F_{21}O_4^-$), 595 ($M - C_{13}F_{23}O_4^-$), 529 ($M - C_{14}F_{25}O_5^-$), 479 ($M - C_{15}F_{27}O_5^-$), 367 ($M - C_{18}F_{31}O_5^-$), 317 ($M - C_{19}F_{33}O_5^-$), 251 ($M - C_{20}F_{35}O_6^-$), 201 ($M - C_{21}F_{37}O_6^-$). The elemental composition was studied by high-resolution mass spectrometry using a chemical ionization negative mode. Calcd: 1251.8891. Found: 1251.8874, $mDa = 1.6$. The infrared spectrum was taken as a neat liquid. The infrared spectrum exhibits bands at 1220 (vs, br), 1150 (m), 950 (vs), 900 (w), 750 (m), 740 (m), 730 (m), 560 (w), and 475 cm^{-1} (w). In solution, fluxional structures, as expected, and again the assignments of ^{19}F resonances of the ether rings and cyclohexyl groups are difficult. The ^{19}F NMR data gave a complex pattern at -80 to -93 ppm (δ $CFCl_3$), which corresponds to the resonances of fluorine atoms of the ether ring, and at -120 to -150 ppm (δ $CFCl_3$), which corresponds to fluorines of the cyclohexyl ring. The low-temperature ^{19}F NMR spectra were studied and were not very useful in assigning the structure. The yield was 3% based on 1 g of starting material. Attempts to separate the isomers were not successful. It is probable that the large ring structure decreases the polar character expected from the tertiary fluorines.

Perfluoro-4,7,13,16,21,24-hexaoxa-1,10-diazabicyclo[8.8.8]hexacosane. A 0.99-g sample of the cryptand was dissolved in 25 mL of methylene chloride and added to 10 g of dry sodium fluoride powder. The mixture was slurried to coat the starting material on sodium fluoride particles. The solvent was removed under vacuum, and the dry material was finely ground and dispersed over the copper turnings in the reactor chamber. The disk reactor system has been previously described.¹³ The reactor was connected to the fluorination system and purged with helium to remove any air from the system. The reactor was cooled to -100 °C, and the fluorination sequence was begun.

Upon completion of the reaction sequence, the reactor was removed and the contents extracted with $CFCl_2CF_2Cl$. The solvent was removed using a rotovap. The crude product was isolated as ca. 2 mL of a cloudy light yellow oil. Purification of the material was performed by preparative gas chromatography using a 0.25-in. × 10-ft stainless steel column packed with 25% OV-101 on Chromosorb A, 60/80 mesh. With the column temperature at 150 °C and the helium carrier gas flow at 45 mL/min, the compound was eluted in 5.4 min.

Preparative gas chromatography of the crude material was used to isolate 0.75 g of a clear colorless oil for a yield of 28%. The compound was identified using ^{19}F NMR, mass spectral analysis, and elemental analysis. The ^{19}F NMR spectrum ($CFCl_3$) consisted of three signals at -81.4 (s), -87.0 (t, $J_{F-F} \sim 1$ Hz), and -88.5 ppm (t, $J_{F-F} \sim 1$ Hz). The $^{13}C\{^{19}F\}$ NMR spectrum (TMS) also shows three peaks at 113.5, 115.3, and 116.8. The melting point of perfluorocryptand [222] is 32.7 °C. The infrared analysis was performed as a thin film on KBr, showing peaks at 1276 (vs, br), 1229 (vs, br), 1211 (vs, br), 1256 (vs, br), 1131 (vs, br), 1049 (m, sh), 984 (w), 893 (m), 878 (m), 840 (w), 769 (m), 744 (m, sh), 715 (m), and 704 (m) cm^{-1} . Elemental analysis was performed by Schwarzkopf Microanalytical Laboratories, Woodside, NY. The elemental analysis agreed well with $C_{18}F_{36}N_2O_6$. Calcd: C, 21.10; F, 66.80; N, 2.74. Found: C, 21.41; F, 66.50; N, 2.39. Electron-impact mass spectral analysis of the compound, performed on a Bell and Howell Model 491 spectrometer at 70 eV, provided little structural information. The molecular ion was observed at m/e 1024 as a small peak (<1% relative abundance (R.A.)), allowing confirmation of the expected molecular weight. Electron capture negative ion (ECNI) mass spectrometry combined with collisionally induced dissociation (CID) provided more structural information and contained a large (100%) parent ion at 1024.¹⁷

Table 3. Crystallographic Data^a for $C_{12}F_{24}O_6$ (I) and $C_{20}F_{36}O_6$ (II)

	I	II
fw	696.09	1020.16
<i>a</i> , Å	9.8203(10)	27.0514(15)
<i>b</i> , Å	11.8778(20)	10.0876(10)
<i>c</i> , Å	17.8395(21)	23.5261(26)
β , deg	95.162(15)	100.920(8)
<i>V</i> , Å ³	2072.4(5)	6303.5(11)
<i>Z</i>	4	8
<i>F</i> (000)	1344	3936
cryst syst	monoclinic	monoclinic
space group	$P2_1/n$	$C2/c$
<i>T</i> , °C	-110	-75
radiation	graphite monochromatized, Mo $K\alpha$ ($\lambda = 0.71073$ Å)	
2θ range, deg	4–50	4–55
scan speed, deg/min	6	6–12
ρ_{calc} , g/cm ³	2.23	2.15
no. of reflns measd	3 855	13 623
no. of unique reflns	0	7 649
<i>R</i> _{int}	0	0.025
μ , cm ⁻¹	2.916	2.787
transm factor ^b range	not applied	not applied
cryst size, mm	.5	0.25 × 0.44 × 0.44
no. of reflns used	2 991	3 959
no. of reflns rejected ^c	864	3 278
<i>R</i> (<i>F</i>) ^d	0.0330	0.0425
<i>R</i> _w (<i>F</i>)	0.0456	0.0449
goodness of fit	1.71	1.288
parameters	380	559
max $ \Delta /\sigma$	<0.1	<0.1
min, max peaks, e/Å ³	-0.35, 0.27	-0.28, 0.22

^a Data were collected on a Nicolet P3 diffractometer. Data for I and II were collected at reduced temperature using a Nicolet low-temperature delivery system. Lattice parameters were obtained from the least-squares refinement of 15 reflections with $28.0 < 2\theta < 29.8^\circ$ for I and 40 reflections with $22.5 < 2\theta < 29.6^\circ$ for II. ^b Absorption correction was based on measured crystal faces. ^c Unobserved reflections have $F < 4(\sigma(F))$ for II and $F < 5(\sigma(F))$ for I. ^d The function, $\sum w(|F_o| - |F_c|)^2$, was minimized, where $w = 1/(\sigma(F_o)^2 + (0.02F)^2)$.

The GC/ECNI spectrum of the compound had a base peak attributed to the molecular ion at m/e 1024. No reagent gas adducts were observed under any conditions investigated due to the high electron affinity of the compound. Ions observed at m/e 986, 908, and 792 were attributed to the loss of F_2 , C_2F_4O , and $C_4F_8O_2$, respectively. The other ions at m/e 496, 346, and 296 were the result of further ionization in the source and are not major features of the CID spectra. Stepwise or concerted multiple extrusion of neutral perfluoroethylene oxide was observed and produces the ions at m/e 908, 792, and 560. Further loss of the C_2F_4O or C_3F_6N fragment yields ions at m/e 428, 444, and 676. CID studies suggest that the cyclic structure of the perfluorinated cryptand is preserved as the fragmentation proceeds.

X-ray Experimental Studies on Perfluoro-18-crown-6, $C_{12}F_{24}O_6$ (I), and Perfluoro-*cis-syn-cis*-dicyclohexyl-18-crown-6, $C_{20}F_{36}O_6$ (II). Large, colorless, blocklike crystals were grown by sublimation. These materials sublimed readily at room temperature and at atmospheric pressure. The data were collected at reduced temperatures on a Nicolet P2₁ diffractometer for I and a P3 diffractometer for II using graphite monochromatized, Mo $K\alpha$ radiation ($\lambda = 0.7107$ Å). A Nicolet low-temperature delivery system was used to control the temperature of the data crystals. Details of the crystal data, data collection, and structure refinement are listed in Table 3. Check reflections of moderate intensity were remeasured periodically during the data collection to monitor instrument and crystal stability. A smoothed curve of the intensities of these check reflections was used to scale the data. The data were also corrected for *Lp* effects. A 1° scan range in ω was used for I and II. The molecule in II lies around a crystallographic inversion center at 0, 1/2, 0. The structures were solved by direct methods using MULTAN78 for I¹⁸ and SHELXTL-Plus for II.¹⁹ The structures were refined by full-matrix least-squares procedures with anisotropic thermal parameters using SHELX76 for I²⁰ and

(17) Maleknia, S. D.; Clark, W. D.; Lagow, R. J. Presented at the 36th ASMS Conference on Mass Spectrometry and Allied Topics, San Francisco, CA, June 1988.

(18) Main, P.; Hull, S. E.; Lessinger, L.; Germain, G.; DeClercq, J.-P.; Woolfson, M. M. MULTAN78. A system of Computer Programs for the Automatic Solution of Crystal Structures from X-ray Diffraction Data; Universities of York, England, and Louvain, Belgium, 1978.

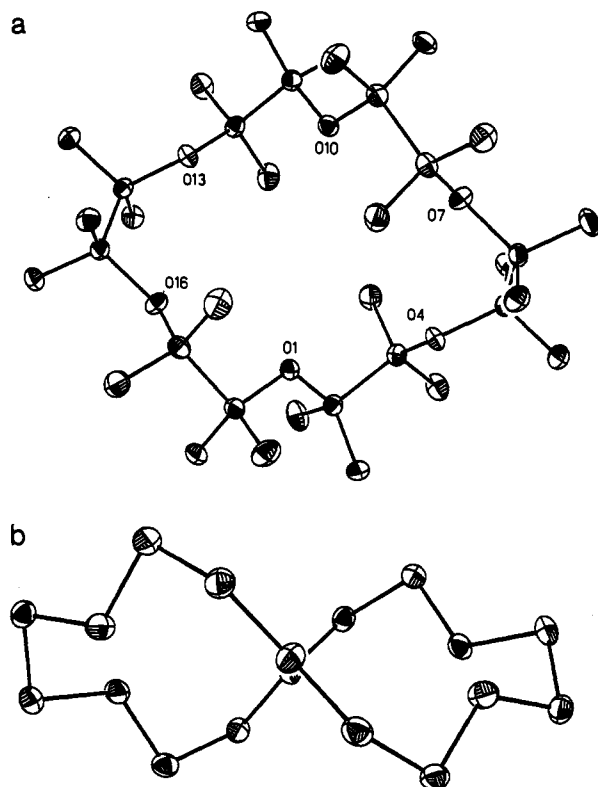


Figure 2. View of the thermal ellipsoid representations of perfluoro-18-crown-6 (I). Ellipsoids are scaled to the 30% probability level. (a) View approximately normal to the plane through the six oxygen atoms (O₆ plane). All atoms are shown. (b) Side view of the crown illustrating a twisted conformation. The F atoms are omitted for clarity.

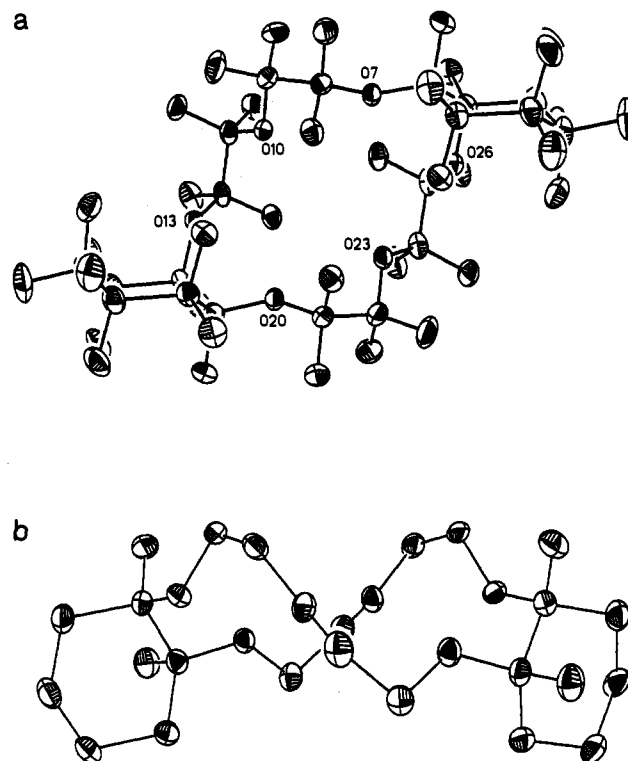


Figure 3. View of the thermal ellipsoid representations of perfluoro-*cis-syn-cis*-dicyclohexyl-18-crown-6 (II). Ellipsoids are scaled to the 30% probability level. (a) Usual chair conformation of the cyclohexyl ring. All atoms are shown. (b) Twisted conformation of the crown. Only F atoms at the bridgehead carbons are shown. This conformation is similar to that found for I.

SHELXTL-Plus for II¹⁹ (see Figures 2 and 3). The function, $\sum w(|F_o| - |F_c|)^2$, was minimized, where $w = 1/(\sigma(F_o))^2$ and $\sigma(F_o) = 0.5kI^{-1/2}[(\sigma(I))^2 + (0.02I)^2]^{1/2}$. The intensity, I , is given by $(I_{\text{peak}} - I_{\text{background}})(\text{scan rate})$, 0.2 is a factor to downweigh intense reflections and to account for instrument instability, and k is the correction due to Lp effects, absorption (where applied), and decay. $\sigma(I)$ was estimated from counting statistics: $\sigma(I) = [(I_{\text{peak}} + I_{\text{background}})^{1/2}(\text{scan rate})]$. The scattering factors for the non-H atoms were taken from Cromer and Mann,²¹ with anomalous-dispersion corrections taken from Cromer and Liberman.²² The linear absorption coefficient was obtained from values found in the *International Tables for X-ray Crystallography*.²³ Other computer programs are listed in ref 11 of Gadol and Davis.²⁴

Mass Spectrometric Characterization by Collisionally Activated Dissociation. The perfluoro macrocycles were further characterized by collisionally activated dissociation (CAD) mass spectrometric techniques. CAD is a method in which a mass-selected ion undergoes energetic collisions with a neutral target gas, resulting in fragmentation of the ion by structurally diagnostic pathways.²⁵ The acquisition of characteristic CAD spectra is especially important for the interpretation of the gas-phase macrocyclic complexation studies described later. For the CAD spectra discussed in this section, a Finnigan MAT TSQ-70 triple-stage quadrupole mass spectrometer was operated in both negative and positive ionization modes at a source temperature of 80 °C. For the negative ionization mode, methane or argon was introduced into the source at 1.2 Torr to aid in the production of thermal electrons to promote electron capture negative ionization.

Each of the perfluorinated crown ethers produced $(M - F)^+$ ions under positive chemical ionization conditions, likely as a result of elimination

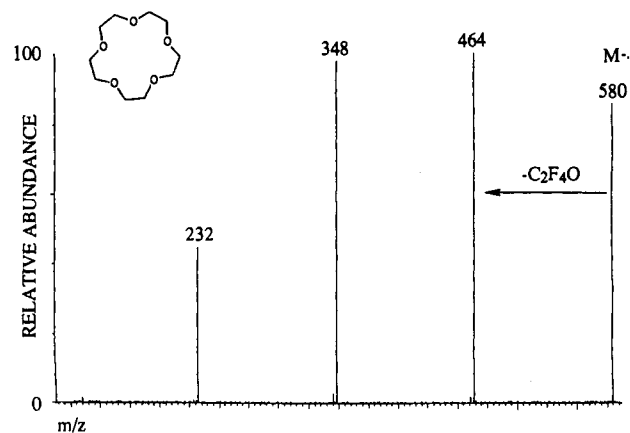


Figure 4. Collisionally activated dissociation mass spectra of the M^+ ion of perfluoro-15-crown-5 acquired with a triple-quadrupole mass spectrometer.

of FH from an initial $(M + H)^+$ ion.²⁶ These positive ions dissociate via two routes upon collisional activation. They may eliminate units of C₂F₄O, or they may eliminate $(C_2F_2O_2 + nC_2F_4O)$ where $n = 0, 1, 2, \dots$. In the negative ion mode, the perfluoro crown ethers produce abundant anions, M^- , which dissociate by a characteristic series of losses.²⁶ For example, a typical CAD spectrum for perfluoro-15-crown-5 is shown in Figure 4. In general, the molecular radical anion of each perfluoro crown ether dissociates by loss of nC_2F_4O units ($n = 1, 2, 3$).

The perfluorinated 4,7,13,16,21,24-hexaoxa-1,10-diazabicyclo[8.8.8]-hexacosane (cryptand) dissociated by several pathways that are analogous to those noted for the crown ethers: elimination of nC_2F_4O units is predominant, where $n = 1, 2, 3$, resulting in ions at m/e 908, 792, and 676.²⁶ Additionally, losses of two or three C₂F₄O units in conjunction with C₄F₉N elimination are observed as fragment ions at m/e 559 and 443. These latter fragments are evidence of cleavage at the nitrogen bridge.

(19) Sheldrick, G. M. *SHELXTL-PLUS*; Siemens Analytical X-ray Instruments, Inc.: Madison, WI, 1989.

(20) Sheldrick, G. M. *SHELX76. A Crystallographic Computing Package*; University of Cambridge, England, 1976.

(21) Cromer, D. T.; Mann, J. B. *Acta Crystallogr.* **1968**, *A24*, 321.

(22) Cromer, D. T.; Liberman, D. *J. Chem. Phys.* **1970**, *53*, 1891.

(23) *International Tables for X-ray Crystallography*; Kynoch Press; Birmingham, U.K., 1974; Vol. IV, p 55.

(24) Gadol, S. M.; Davis, R. E. *Organometallics* **1982**, *1*, 1607.

(25) Busch, K. L.; Glish, G. L.; McLuckey, S. A. *Mass Spectrometry/ Mass Spectrometry: Techniques and Applications of Tandem Mass Spectrometry*; VCH: New York, 1988.

(26) Maleknia, S.; Liou, J.; Brodbelt, J. *Org. Mass Spectrom.* **1991**, *26*, 997.

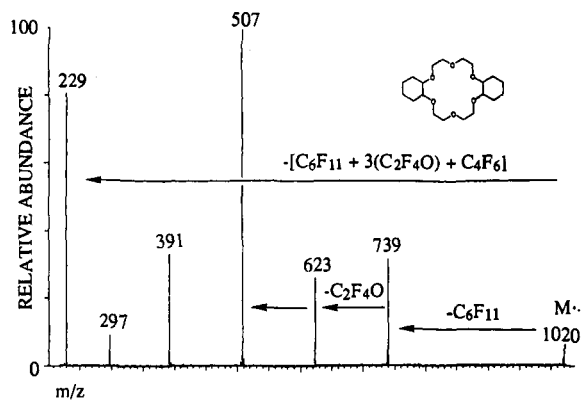


Figure 5. Collisionally activated dissociation mass spectra of the M^+ ion of perfluorodicyclohexano-18-crown-6 acquired with a triple-quadrupole mass spectrometer.

The CAD spectra of the molecular anions of two perfluorodicyclohexano crown ethers, the 18-crown-6 and 24-crown-8 ethers, also show characteristic fragmentation patterns.²⁶ The CAD spectrum for the first isomer is shown in Figure 5. For these substituted perfluoro crown ethers, the molecular anions do not dissociate via simple loss of C_2F_4O units as was observed for the other macrocycles. Instead, elimination of C_6F_{11} (cyclohexyl ring) is a predominant process and may then be coupled with losses of nC_2F_4O . The first process may be rationalized as a radical-initiated ring cleavage, followed by a fluorine transfer to the cyclohexyl ring via a four-membered transition state. The resulting fragment ion is presumably acyclic. This fragment ion then proceeds to dissociate by consecutive losses of C_2F_4O units. For the 18-crown-6 ether shown in Figure 5, losses of up to three units of C_2F_4O are observed in conjunction with loss of C_6F_{11} (formation of m/e 391, 507, 623, 739). Additionally, loss of three C_2F_4O units is observed, coupled to the loss of both C_6F_{11} , the first cyclohexyl ring, and C_4F_6 , the second cyclohexyl ring, resulting in formation of m/e 229. For the analogous 24-crown-8 system, this latter pathway (elimination of both cyclohexyl rings) is coupled instead to the loss of four C_2F_4O units.

Discussion

Perfluorinated derivatives of hydrocarbon compounds usually exhibit different properties than their hydrocarbon analogues. The perfluoro crown ethers are markedly more volatile than the hydrocarbon products. One would expect the dimensions of the pocket size to change, and both modeling and crystal structures clearly establish that the pockets are smaller and that the crown ether rings are slightly more bent. As observed in the gas-phase studies, perfluoro crown ethers and cryptands all coordinate O_2^- , F^- , and several other such anions. Although a crystal structure of an encapsulated anionic species is not yet in hand, the possibility of obtaining the formation of such a structure is being studied.

Perfluoro crown ethers and cryptands are indeed very weak bases if there is any base character at all. For the gas-phase complexes of O_2^- and F^- , it would also appear that electron density from the anion is transferred to the binding sites in the crown ether. One would suspect that the binding occurs at the oxygen. As indicated by the fragmentation thermodynamics, there is a 40–60-kcal interaction binding the anion to the macrocycle.

Whether the perfluoro macrocycles are also capable of binding cations is still not certain. Two talented collaborators on this project have not been successful in obtaining cationic complexes with the alkaline metals. One reason was that the perfluoro macrocycles are not soluble in common organic solvents. On the other hand, both organometallic compounds and organic species as well as these perfluoro macrocycles are soluble in chlorofluoro solvents such as Freon 113, $F_2ClC-CF_2Cl$. It is also quite possible that the base character in such perfluoro macrocycles is nonexistent.

The single crystal X-ray diffraction studies of 18-crown-6 ether indicate that the guest-free ring is puckered in a manner so that the oxygen sites are exposed and projected toward a possible metal coordination site. In view of the possibility of a rigid

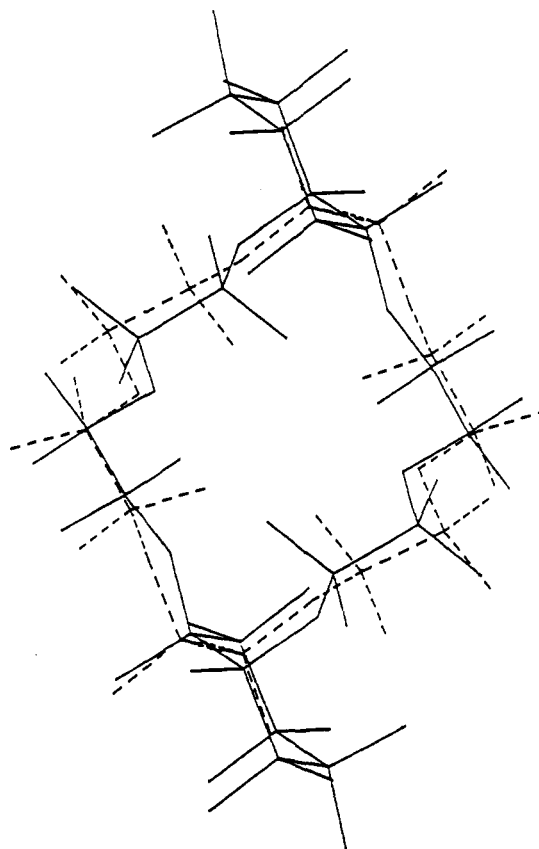


Figure 6. Superposition of the carbon and oxygen atoms of the perfluoro-*cis-syn-cis*-dicyclohexano-18-crown-6 ether (solid lines) onto the equivalent atoms of perfluoro-18-crown-6 ether (dashed lines) illustrating the similar configurations of the perfluoro ether rings of the two structures.

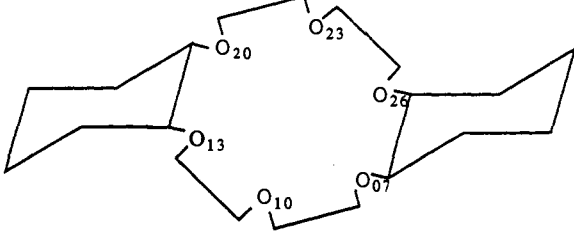
conformation existing in the solution at lower temperature, the ^{19}F spectrum of 18-crown-6 in $CFCl_3$ has been monitored at $-85^\circ C$. Only one singlet peak was observed. This observation establishes that the molecule is quite flexible in the solution. The energy barrier associated with the conformational change should be extremely low.

Two crystal structures of perfluoro crown ethers, containing the 18-crown-6 ether skeleton, are reported. Comparisons of these structures show that the perfluoro-18-crown-6 ether and the *cis-syn-cis*-isomer have similar conformations of the ether ring skeleton.²⁷ Figure 6 shows the superposition of the carbon and oxygen atoms of the perfluoro-*cis-syn-cis*-dicyclohexano-18-crown-6 ether (solid lines) onto the equivalent atoms of perfluoro-18-crown-6 ether (dashed lines). This illustrates the similar configurations of the perfluoro ether rings of the two structures. The perfluorocyclohexyl groups may not be the dominating steric factor which controls the conformation of the ether ring skeleton. Distances between oxygen atoms and the center of the molecule and between adjacent oxygen atoms in the *cis-syn-cis*-isomer are given in Tables 4. Previously, preliminary data on the structure of the *cis-anti-cis*-isomer have been reported,²⁸ but the problem of disorder in crystals grown by sublimation has not been solved.

Although perfluoro-18-crown-6 has a melting point of $34^\circ C$ in a sealed capillary, the solid compound has a substantial vapor pressure; it can be sublimed easily and moves on a vacuum line. Perfluoro-18-crown-6 has a marked propensity to form large and beautiful single crystals. Crystals weighing at least 0.5 g which have the appearance of sparkling zircons are obtained routinely. Both perfluoro-15-crown-5 and -12-crown-4 species are clear liquids with properties favorable for several biomedical applications.

(27) Lin, T.-Y.; Lynch, V. M.; Lagow, R. J. Unpublished results.

(28) Lin, T.-Y.; Lagow, R. J. *J. Chem. Soc., Chem. Commun.* **1991**, 12.

Table 4. Distances between Oxygen Atoms and the Center of the Molecule, and between Adjacent Oxygen Atoms in Perfluoro-*cis-syn-cis*-dicyclohexano-18-crown-6 Ether


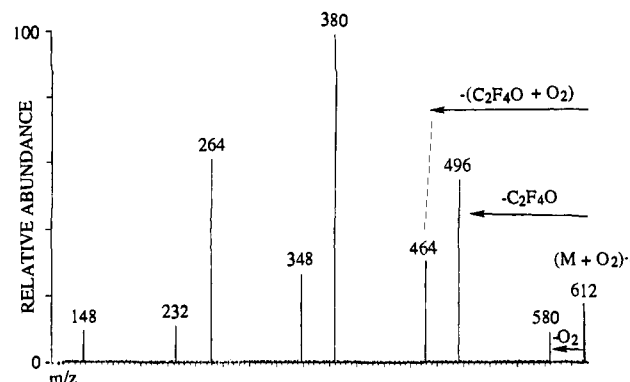
atom(s)	distance (Å)
From Atom to Center of Molecule	
O ₇	2.536
O ₁₀	2.129
O ₁₃	3.177
O ₂₀	2.543
O ₂₃	2.141
O ₂₆	3.181
Between Adjacent Oxygen Atoms	
O ₁₃ -O ₂₀	2.662
O ₂₀ -O ₂₃	2.713
O ₂₃ -O ₂₆	2.665
O ₂₆ -O ₀₇	2.667
O ₀₇ -O ₁₀	2.707
O ₁₀ -O ₁₃	2.667

Perfluoro-15-crown-5 has great potential as a ¹⁹F NMR imaging agent.²⁹ This crown ether has only one fluorine resonance, making very sharp pictures during brain scans and spinal scans of animals possible. Perfluoro-15-crown-5 has also been used successfully as an oxygen carrier in collaborative studies between our group and Dr. Leland Clark's laboratory. Toxicology work at Air Products has established that the perfluoro crown ethers are nontoxic in animals and therefore very different from hydrocarbon crown ethers. Recently over 2 kg of perfluoro-15-crown-5 has been made in very high yield by new technology.³⁰

The perfluorocryptand [222] compound is expected to have interesting applications. Aside from the possibility of acting as a perfluoro "host" for certain types of "guest" species, the perfluorocryptand [222] has shown potential as a very clean, high-mass compound for use as a mass spectral marker material.¹⁷ The compound is expected to be biologically inert (in contrast to the hydrocarbon analogue) and, as in the case of the perfluoro crown ether compounds, may be useful in fluorocarbon biological and medical applications where physiologically inert or oxygen-carrying fluids are required.

The synthetic work reported here coupled with new technology³⁰ opens the possibility of preparation of many novel crown ether systems as well as the synthesis of a series of perfluoro cryptands. Such ligands should be much less subject to chemical attack or thermal degradation.

Gas-Phase Reactions of Perfluoro Macrocycles. The coordination capabilities of perfluorinated macrocycles have generated considerable interest because of the importance of crown ethers and related macrocycles as model hosts in the field of molecular recognition.²⁻³ Numerous studies have described aspects of host-guest complexation of hydro crown ethers with a variety of model guests, including alkali metal ions and ammonium ions.⁶ Thus, the perfluorinated macrocycles provide an intriguing structural analog to the hydrogenated macrocycles. Studies of these novel model hosts may reveal new insight into the structural and thermodynamic factors which mediate selective complexation. Recently, studies of host-guest chemistry in the solvent-free environment of the gas phase have opened a new frontier for the

**Figure 7.** Collisionally activated dissociation mass spectra of the $(M + O_2)^-$ ion of perfluoro-15-crown-5 acquired with a triple-quadrupole mass spectrometer.

investigation of molecular recognition.³¹⁻³⁶ Complexation may be evaluated in the absence of solvation effects, and thus the intrinsic binding properties of model hosts can be examined. Three studies of the gas-phase ion chemistry of perfluoro macrocycles are reviewed in the following section.

The high oxygen-carrying capacity of some perfluorocarbons makes them viable as artificial blood components,³⁷ and yet to date the mechanism of oxygen binding to fluoro ethers is not well understood. Thus, it was of considerable interest to probe the ability of perfluoro macrocycles to bind molecular oxygen and other small molecules in the gas phase in order to obtain new information about the binding affinities of these compounds.³¹ For these studies, each perfluoro macrocycle was admitted into the source of a triple-quadrupole mass spectrometer. Argon was introduced into the source manifold at $2-3 \times 10^{-6}$ Torr to aid in the production of thermal electrons for electron capture negative ionization. The desired reagent gas (CO, N₂, CO₂, or air for O₂) was added to attain a total source pressure of 1-2 Torr. The ethers examined included perfluoro-12-crown-4, perfluoro-15-crown-5, perfluoro-18-crown-6, perfluorinated 4,7,13,16,21,24-hexaaxo-1,10-diazabicyclo[8,8,8]hexacosane (cryptand), their hydro crown analogs, and one acyclic perfluoro ether, perfluoro-triethylene glycol dimethyl ether.

Each perfluoro macrocycle was ionized to form M^+ then allowed to react with O₂ to successfully form $(M + O_2)^-$ adducts.³¹ Ion/molecule reactions involving *acyclic* perfluoro ethers and *hydrogenated* crown ethers were also examined to determine whether the cyclic and/or perfluoro natures of the macrocycles played a role in the formation of the $(M + O_2)^-$ adducts. *Neither* the perfluoro acyclic analogs nor any hydrogenated crown ether reacted with O₂ to form $[M + O_2]^+$ adduct ions. This result confirmed that the macrocyclic nature of the perfluoro crown ethers enhanced their ability to bind O₂.

Additionally, the abilities of the perfluoro crown ethers to form complexes with CO, N₂, CO₂, and Ar, species with sizes and some chemical and physical properties similar to those of O₂, were examined. Adducts with these species were *not* observed.³¹ Thus, the tendencies of the perfluoro crown ethers to form adducts exhibited striking selectivity for O₂ only.

Structural details of the perfluoroether adduct ions, $(M + O_2)^-$, were probed via collisionally activated dissociation of the mass-selected ions.³¹ Figure 7 illustrates the 40-eV CAD spectra of the perfluoro-15-crown-5 $(M + O_2)^-$ adduct (m/e 612), showing two series of fragment ions. One is a series of losses of $(C_2F_4O)_n$,

(31) Brodbelt, J. S.; Maleknia, S.; Liou, C.-C.; Lagow, R. J.; Lin, T.-Y. *J. Am. Chem. Soc.* **1991**, *113*, 5913.

(32) Brodbelt, J. S.; Maleknia, S.; Lagow, R. J.; Lin, T.-Y. *J. Chem. Soc., Chem. Commun.* **1991**, 1705.

(33) Maleknia, S.; Brodbelt, J. S. *J. Am. Chem. Soc.* **1992**, *114*, 4295.

(34) Liou, C.-C.; Brodbelt, J. S. *J. Am. Chem. Soc.* **1992**, *114*, 6761.

(35) Liou, C.-C.; Brodbelt, J. S. *J. Am. Soc. Mass Spectrom.* **1992**, *3*, 543.

(36) Zhang, H.; Chu, I.; Leming, S.; Dearden, D. A. *J. Am. Chem. Soc.* **1991**, *113*, 7415.

(37) Reiss, J.; LeBlanc, M. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 621.

(29) Schweighardt, F. K.; Rubertone, J. A. U.S. Patent 4 838 274, 1989.

(30) Bierschen, T. R.; Juhlke, T. J.; Kawa, H.; Lagow, R. J. U.S. Patent 5 093 432, 1992.

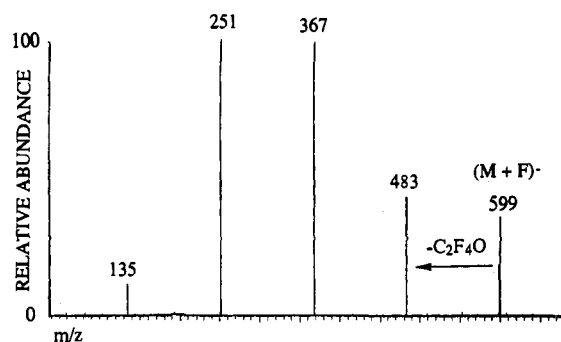


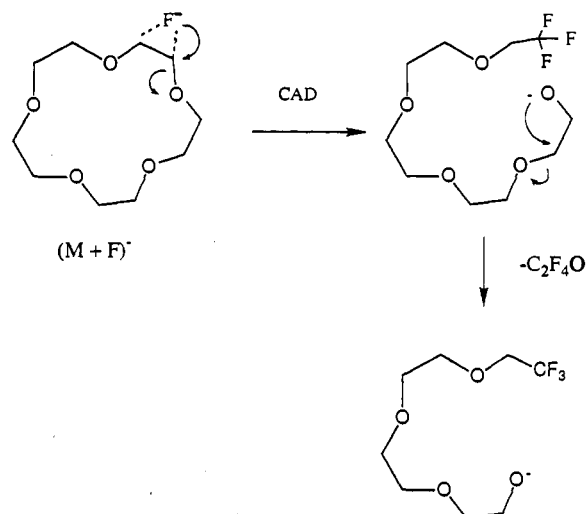
Figure 8. Collisionally activated dissociation mass spectra of the $(M + F)^-$ ion of perfluoro-15-crown-5 acquired with a triple-quadrupole mass spectrometer.

analogous to the series of losses observed from the M^- ion, resulting in fragment ions at m/e 148, 264, 380, and 496. This trend indicates that the O_2 is bound to the perfluoro crown ether strongly enough to be retained after the adduct ion is activated and implies that the binding interaction must be at least as strong as the C-C and C-O bonds that are cleaved during the competing dissociation processes in which C_2F_4O units are expelled. The C-C and C-O bond energies for these perfluoro crown ethers have been estimated as 84 and 98 kcal/mol, respectively. Additionally, a series of fragment ions corresponding to loss of $(nC_2F_4O + O_2)$ units is seen at m/e 232, 348, and 464, where $n = 3, 2, 1$, the same fragment ions produced from CAD of the noncomplexed molecular ion shown in Figure 4.

Direct loss of O_2 is not a significant dissociation channel using any collisional activation conditions (for 10–120-eV kinetic energy collisions, the percentage of the total fragment ion abundance due to O_2 loss is 0–10%). This result suggests that the O_2 -crown ether complex is not a loosely bound adduct but, instead, a species in which stronger bonding forces are involved than those associated with a single weak ion/dipole electrostatic interaction. An adduct species in which O_2 fits in the pocket of the crown ether anion is possible (enhancing multiple bonding interactions), or a structure in which the O_2 is cradled by four electronegative fluorine atoms is feasible. In general, O-F bonds are not stronger than 50 kcal/mol, so a complex containing a single F- O_2 binding interaction is not supported.

It was also timely to examine the ability of perfluoro macrocycles to react with fluoride in the gas phase.³² It has been shown recently from crystallographic studies that a fluoride ion may be held in the cavity of a fluorinated macrocyclic ether,¹¹ and thus it was of interest to investigate the possibility of forming related fluoride complexes in the gas phase. Fluoride/macrocylic adducts were successfully generated in the gas phase by ionization of a mixture of a macrocycle and a fluorinated reagent such as CHF_3 admitted simultaneously into the ion source. Moderately abundant $(M + F)^-$ adducts (relative abundance = 10% compared to M^-) are formed by reaction of F^- with the macrocyclic molecules. The CAD spectrum of the $(M + F)^-$ adduct of perfluoro-15-crown-5, shown in Figure 8, is similar to the CAD spectrum for the molecular anion M^- of perfluoro-15-crown-5, shown above in Figure 4, with the exception that each fragment ion is shifted to a higher mass by 19 amu (due to the fluorine addition). The series of ions incorporating the additional fluorine is the only type of fragment observed, indicating that the fluorine is *always* retained by the ionic portion during dissociation. The most abundant dissociation processes involve loss of two or three C_2F_4O units. The direct loss of F^- from the $(M + F)^-$ adduct is not observed. This result suggests a very strong crown ether-fluoride binding interaction. For example, the fluoride ion may

Scheme 1. Proposed Mechanism for Dissociation of the $(M + F)^-$ Adduct



attack any carbon position and promote ring opening, resulting in an acyclic structure with a covalently bound fluorine. A mechanism depicting this proposed pathway is shown in Scheme 1.

In the third gas-phase study,³⁸ a new type of polymer ion consisting of a perfluorinated macrocycle (M) associated with multiple ether molecules was generated in the source of a triple-quadrupole mass spectrometer by a novel gas-phase cationic polymerization process. The polymer ions have the general formula $(M - F + n\text{Ether})^+$, where $n = 1, 2, 3, \dots$ depending on the type of ether. The ethers which promoted the most extensive polymerization were highly strained cyclic ethers such as ethylene oxide and ethylene sulfide, whereas the perfluoro macrocycles attached only one unit of the acyclic ether analogues, such as dimethyl ether. It is proposed that the strained cyclic ethers attach to the perfluorinated ion and then undergo sequential ring-opening polymerization to form an extended polyether chain which is covalently anchored to the perfluorinated substrate. The nature of the binding interactions in these novel types of polymer assemblies is still under investigation.

The ability to form and characterize new types of macrocyclic ion complexes involving perfluoro ethers holds great promise for future studies of host-guest complexation in the gas phase. Comparisons to the gas-phase chemistry of hydrogenated macrocycles may allow further insight into the influence of thermochemical and structural properties on the binding interactions of host molecules.

Acknowledgment. We are grateful for support of this work by the Air Force Office of Scientific Research (F49620-92-J-O104) and the U.S. Department of Energy (DE-FG05-91ER12119).

Supplementary Material Available: Tables listing fractional atomic coordinates and equivalent isotropic thermal parameters, anisotropic thermal parameters, bond lengths and angles, and torsion angles, and drawings showing the atom labeling schemes and the unit cell packings for I and II (22 pages); observed and calculated structure factors (65 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(38) Brodbelt, J. S.; Liou, C.-C.; Maleknia, S.; Lin, T.-Y.; Lagow, R. J. *J. Am. Chem. Soc.* 1993, 115, 11069.