Perfluorinated Stellanes: The Synthesis of Perfluorinated Bisnoradamantane. Long-Range ^{19}F NMR Virtual Coupling

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A three-step synthesis of perfluorinated bisnoradamantane, *F*-tricyclo[3.3.0.0^{3,7}]octane, the smallest unsubstituted perfluorinated cage compound yet reported in the literature, is described. Oleum oxidation of adamantane to adamantane-2,6-dione followed by aerosol fluorination to *F*-adamantane-2,6-dione which is then photodecarbonylated in near-quantitative yields produces the perfluorinated stellane. ^{19}F NMR spectra of these perfluorinated cage compounds, which exhibit long-range fluorine−fluorine virtual coupling, are described. The highly symmetric *F*-bisnoradamantane structure results in a highly symmetrical splitting pattern which is readily interpretable.

Introduction

In recent years, our interest in the syntheses of perfluorinated cage compounds has led to the syntheses of perfluorinated adamantane,[1] diamantane,[2] [2.2.2]-bicyclooctane,[3] etc. These three molecules are notable in that the smallest ring in each system is a six-membered ring. Because the diamondoid six-membered ring has very low strain energy, aerosol direct fluorination has proven to be a very successful method for the perfluorination of these compounds. However, for those cage compounds that have a relatively high ring strain energy, such as cubane or [1.1.1]propellane, ring opening occurs during the direct fluorinations.[4] To avoid this problem, we have sought alternative methods leading to the smaller ring perfluorinated cage compounds.

Tricyclo[3.3.0.0^{3,7}]octane (**1**) (bisnoradamantane) is the most symmetrical of the all-five-membered-ring cage homologs. Literature syntheses of **1** have always involved multiple step procedures, no less than five steps, to our knowledge.[5] Although bisnoradamantane (**1**) has an all-five-membered-ring structure, it consists of two twist-boat cyclohexanes.

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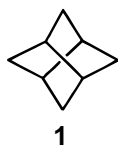
The strain energy is therefore large compared to those for the adamantane derivatives. Therefore, after consideration of the potential for ring opening, instead of following the multistep procedure of synthesizing structure **1** and then perfluorinating it, which is the most direct method for the synthesis of perfluorinated compounds from hydrocarbon precursors, we sought an alternative synthetic approach to perfluorinated bisnoradamantane.

Results and Discussion

In contrast to the "direct" method which would require a minimum of six steps, we wish to report a three-step "indirect" synthesis leading to perfluorinated bisnoradamantane from adamantane. In earlier work we found that perfluorinated cage ketones easily extrude CO to form a carbon−carbon bond. Perfluorinated adamantanone under UV irradiation eliminates CO to form *F*-noradamantane (eq 1).[6] If, we reasoned, perfluorinated adamantane-2,6-dione could eliminate two CO molecules, a two-step synthesis of perfluorinated bisnoradamantane will have been achieved starting from the corresponding hydrocarbon adamantane-2,6-dione (eq 2).
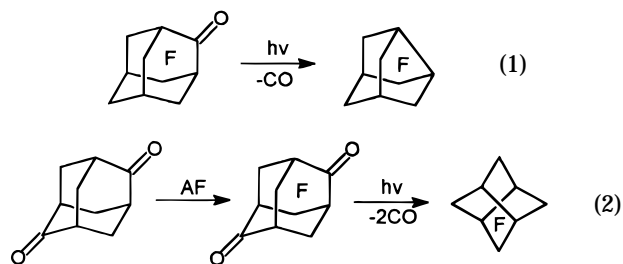
Two one-step methods for the synthesis of adamantane-2,6-dione are found in the literature. The Morat and Rassat method,[7] using CrO$_3$/Ac$_2$O to oxidize adamantanone to form adamantane-2,6-dione (20%) and 5-acetoxyadamantan-2-one (36%), did not give the reported result in our hands; 5-acetoxyadamantan-2-one was the dominant product, and 2,6-adamantanedione occurred only in trace amounts. However, the method of Geluk and Schlatmann, which starts with adamantane and 20% oleum, easily produced the reported result in 5.7% yield (lit.[8] 5.9%).

A DSC analysis of an unsealed adamantane-2,6-dione sample shows that sublimation begins at about 140 °C. To obtain good stoichiometric control of the solid adamantane-2,6-dione during fluorination, 1,2,3-trichloropropane (bp 157 °C) was chosen as a compatible co-fluorinating solvent enabling liquid injection of the dione into the aerosol reactor by syringe pump.

The four bridgehead hydrogen atoms in adamantane-2,6-dione are severely deactivated by the two carbonyl

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(6) Adcock, J. L.; Luo, H. *J. Org. Chem.* **1992**, *57*, 4297.

(7) Morat, C.; Rassat, A. *Tetrahedron Lett.* **1979**, *45*, 4409.

(8) Geluk, H. W.; Schlatmann, J. L. M. A. *Rec. Trav. Chim. Pays-Bas* **1971**, *90*, 516.

groups. As a result, these bridgehead hydrogen atoms are harder to substitute with fluorine atoms. In an aerosol fluorination run under conditions normally sufficient to perfluorinate adamantanes (C−H to F_2 ratio of 1:2−3), the major products isolated were 1,3- and 1,5-dihydryl-*F*-adamantane-2,6-dione. However, when the fluorine input is doubled, the major product is *F*-adamantane-2,6-dione (**2**).

The UV irradiation of *F*-adamantane-2,6-dione in CFCl$_3$ solution results in the elimination of two CO molecules. The irradiation reaction was monitored by ^{19}F NMR. Both compounds **2** and **3** are highly symmetrical and exhibit only two chemical shifts in their respective ^{19}F NMR spectra. In an earlier paper, we reported that *F*-adamantanone eliminates CO to form *F*-noradamantane under UV irradiation (eq 1); the formation of *F*-noradamantane could be observed in as little as 10 min.[6] During the photochemical reaction of *F*-adamantane-2,6-dione, the formation of *F*-bisnoradamantane could also be observed by ^{19}F NMR after only 10 min irradiation; after 2 h irradiation, no *F*-adamantane-2,6-dione could be observed.

3

The photochemical reaction of *F*-adamantane-2,6-dione is very clean and almost quantitative. Despite the fact that two twist-boat configurations exist in the bisnoradamantane structure, the elimination of two CO molecules from *F*-adamantane-2,6-dione is as uncomplicated as the elimination of one CO molecule from *F*-adamantanone. The most plausible reason is that the four bridgehead carbon atoms are rigidly held in the proper positions to effect rapid closure. After elimination of CO (and the formation of a singlet diradical) carbon−carbon bond formation is inevitable.

F-Bisnoradamantane and its precursor, *F*-adamantane-2,6-dione, display some interesting virtual spin−spin coupling in their ^{19}F NMR spectra. Virtual long-range spin−spin coupling was first used to describe proton−proton long-range coupling.[9] Later it was also used to explain fluorine−fluorine long-range coupling in perfluorinated chain compounds.[10] In the ^{19}F NMR spectrum of the highly symmetric *F*-adamantane,[1] long-range fluorine−fluorine virtual coupling resulted in symmetrical splitting patterns; the simpler and highly symmetric *F*-bisnoradamantane produces results which are better resolved and more easily interpretable (Figure 1). This simplicity of interpretation is rarely seen even in other only slightly less symmetrical perfluorinated compounds, e.g., *F*-adamantane-2,6-dione (Figure 2).

The ^{19}F NMR spectrum of *F*-bisnoradamantane has a unique, *deceptively simple*, splitting pattern (Figure 1). The bridgehead fluorine peak has a multiplicity of 9, and the methylene fluorine peak has a multiplicity of 5 with peak separations of 2.8 Hz. In perfluorinated bisnoradamantane all the bridgehead fluorines are chemically equivalent and have the same chemical shift but they are not *magnetically equivalent*. The same is true of the eight difluoromethylene fluorines. The observed phenomena, an effective A_4X_8 spin system, can only be
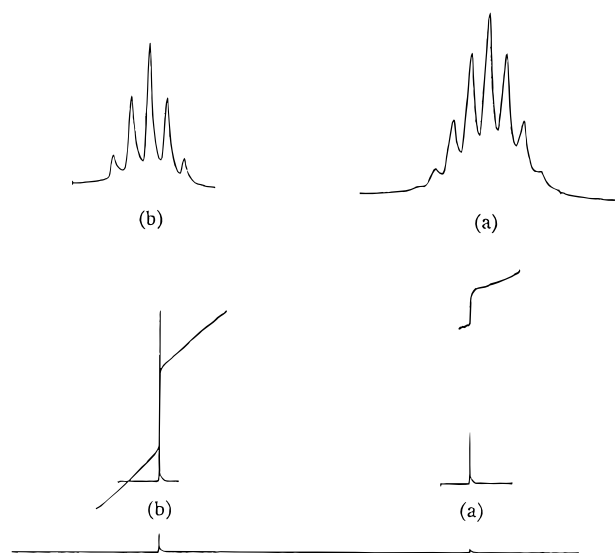
(9) Musher, J. I.; Corey, E. J. *Tetrahedron* **1962**, *18*, 791.
(10) Bovey, F. A. *Nuclear Magnetic Resonance Spectroscopy*; Academic Press: San Diego, 1988; p 441.

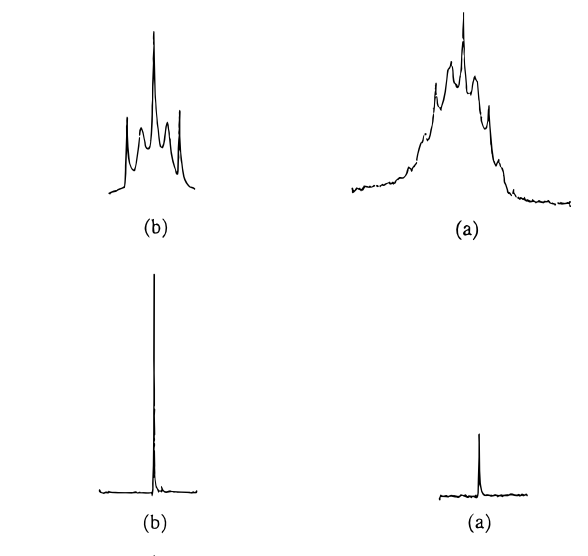**Figure 1.** 84.3 MHz ^{19}F FTNMR of *F*-bisnoradamantane.

Figure 2. 84.3 MHz ^{19}F FTNMR of *F*-adamantane-2,6-dione.

explained as a result of virtual long-range spin−spin coupling, the relative magnitudes of coupling constants, and chemical shift differences coupled with the D$_{2d}$ symmetry of the molecule. To paraphrase Abraham and Bernstein,[11] *The system ABC ... XYZ...will be expected to give a simple spectrum when the terms of the type J_{AB}, J_{XY} are large compared to the chemical shift differences δ_{AB}, δ_{XY} plus terms of the form $J_{AX}-J_{AY}$, etc. and in this case the spectrum will be a simple first-order A_mX_n spectrum in which the separation of the lines in each group of the spectrum is given by the average of the coupling constants J_{AX}, J_{AY}, etc. This statement has to be modified when the system has some elements of symmetry. ... This is due to the fact that the element of symmetry in the A_2X_2 case [vs. ABXY case] causes all the matrix elements in the calculation to appear as sums or differences of the actual coupling constants involved. However, the form of [the] eqs. ... is very similar and thus the same type of statement will be true in the symmetric case, but sums and differences of the actual coupling constants may be involved.*

(11) Abraham, R. J.; Bernstein, H. J. *Can. J. Chem.* **1961**, *39*, 216−230 see pp 228−229.

In polyfluorinated or perfluorinated compounds $^4J_{F-F}$ and $^5J_{F-F}$ coupling constants are usually larger than $^3J_{F-F}$ coupling constants. The vicinal fluorine coupling constant, ^3J, usually is near zero.[12] It has been assumed that the near-zero coupling of vicinal fluorines is caused by the restricted rotation of the carbon−carbon bond.[13] $^2J_{F-F}$ coupling where the geminal fluorines are *diastereotopic* may have chemical shift differences of several ppm and coupling constants of between 250 and 400 Hz.[14]

In *F*-bisnoradamantane, all the ^3J coupling between the bridgehead fluorines and the methylene fluorines on adjacent carbons ($^3J_{Fa-Fb}$ and $^3J_{Fa'-Fa''}$) can reasonably be expected to have near-zero coupling due to the rigid "cage" structure **3a**. However, all of the four-bond

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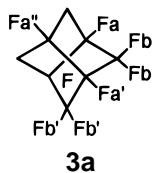
fluorine−fluorine couplings (including the coupling between Fb−Fa″, Fb−Fb′, and Fa−Fa′) are expected to be greater than 5 Hz. In general, if two nuclei have the same chemical shift, no matter how strongly they are coupled to each other, no coupling constant will be observed since the necessary transitions for their observation are forbidden by appropriate selection rules.[15] In this structure, all the methylene fluorine atoms, which are separated by two or four bonds, are chemically equivalent and thus have the same chemical shift. Therefore, although they may be strongly coupled to each other, the coupling constants $^2J_{Fb-Fb}$ and $^4J_{Fb-Fb'}$ cannot be observed. The same reasoning can be applied to the unobserved $^4J_{Fa-Fa'}$ coupling constants. However, instead of coupling as separate nuclei, the eight methylene fluorine nuclei behave as a magnetically equivalent group. The bridgehead methine nuclei "see" a magnetically equivalent set of eight spin $^1/_2$ nuclei resulting in the observed nonet. Likewise, the eight methylene fluorine nuclei appear coupled to a magnetically equivalent group of four spin $^1/_2$ nuclei giving rise to the observed quintet. The experimental spacing of the quintet is 2.8 Hz; accordingly, this spacing should be equal to $^1/_2(^3J_{Fa-Fb} + {}^4J_{Fb-Fa''})$.[9,10] Since $^3J_{Fa-Fb}$ is likely near-zero, $^4J_{Fb-Fa''}$ should be therefore be 5.6 Hz.

Compared to the *F*-bisnoradamantane, *F*-adamantane-2,6-dione is a less symmetric structure. The ^{19}F NMR spectrum of the dione has a similar splitting pattern to that of *F*-bisnoradamantane (Figure 2). However, *F*-adamantane-2,6-dione exhibits a considerably more complicated spectrum.

No virtual coupling was observed in the ^{13}C NMR spectrum of *F*-bisnoradamantane. The bridgehead carbon atoms appear as doublets with unresolved peaks, and the methylene carbon atoms appear as triplets with unresolved peaks.

Experimental Section

The perfluorinations were carried out on an improved aerosol fluorination reactor, and detailed operating procedures have been described elsewhere.[16] Photochemical reactions were carried out using a 550-W medium-pressure mercury lamp (Ace-Hanovia) in a water-cooled quartz immersion well. The fluorinated products were manipulated on a vacuum line; some purifications were achieved by trap to trap fractionation using slush baths, and gas chromatography was used for final purification: Bendix Model 2300, subambient multicontroller, equipped with a QF-1 column, 7 m × 3/8 in. 13% fluorosilicone QF-1 (Analabs) stationary phase on 60−80 mesh, acid-washed chromosorb P conditioned at 225 °C (12 h). The purity of some of the compounds was monitored on a SP 2100 (Supelco) 60 m × 0.25 mm i.d. fused silica capillary column (Hewlett-Packard 5890A). The products were characterized by vapor phase infrared spectra recorded on a Bio-Rad Spc 3200 spectrometer. The negative chemical ionization (electron attachment) mass spectrum was recorded on a VG.ZAB-EQ mass spectrometer. Samples were introduced into the source via the reference inlet to a pressure of 10^{-6} Torr and diluted with nitrogen gas to $10^{-5}-10^{-4}$ Torr and bombarded with 70 eV electrons. ^{19}F NMR spectra were determined on a JEOL FX90Q FTNMR spectrometer (omniprobe, operating at 84.3 MHZ) in CFCl$_3$ as both solvent and internal standard. Elemental analyses were performed by E+R Microanalytical Laboratory, Inc., Corona, NY.

Adamantane-2,6-dione was prepared according to the procedure in the literature[8] and purified by column chromatography using ether as the eluant and silica gel as the stationary phase.

Aerosol Fluorination of Adamantane-2,6-dione. A solution of adamantane-2,6-dione (1.0 g, 6.1 mmol) in CH$_2$ClCHClCH$_2$Cl (3.1 mL, 29 mmol) was injected into the reactor at a rate of 1.0 mL/h by a syringe pump. Specific fluorination conditions are tabulated in the supporting information.

Following the general procedure, the major products were collected in a −22 °C trap. Compound **2** was separated by gas chromatography on a fluorosilicone QF-1 column (7 m × 3/8 in.) as major product. The column temperature was 120 °C, and the retention time was 10 min. The yield was 26%. Characterization of **2**: MS *m/z* (intensity, identification) 380 (2.8, C$_{10}$F$_{12}$O$_2$), 352 (1.8, C$_9$F$_{12}$O), 314 (2.0, C$_9$F$_{10}$O), 295 (89, C$_9$F$_9$O), 267 (85, C$_8$F$_9$), 248 (100, C$_8$F$_8$); ^{19}F NMR (ppm vs CFCl$_3$) −123.8 (irr quintet, ^5J = 12.8 Hz, 8F), −215.9 (irr. nonet, ^5J = 12.8 Hz, 4F); IR (vapor) νCO 1817 cm^{-1} (s).

Synthesis of *F*-Bisnoradamantane. Following an example from the literature,[6] *F*-adamantane-2,6-dione (0.102 g, 0.268 mmol) was dissolved in CFCl$_3$ (0.701) in a 5-mm NMR tube. The NMR tube was sealed on the vacuum line and irradiated using a mercury lamp for 2 h. After irradiation, the NMR tube was connected to the vacuum line. The reaction mixture was separated on the vacuum line by trap-to-trap fractionation. A white solid of 0.085 g was collected in the −22 °C trap (98% yield) and further purified by gas chromatography on the Fluorosilicone QF-1 column. The column temperature was 60 °C, and the retention time was 9.2 min. Characterization of **3**: MS *m/z* (intensity, identification) 324 (70, C$_8$F$_{12}$), 305 (27, C$_8$F$_{11}$), 255 (53, C$_7$F$_9$), 205 (100, C$_6$F$_7$); ^{19}F NMR (ppm vs CFCl$_3$) −118.1 (quintet, $^4J_{CF_2-CF}$ ≈ 5.6 Hz, 8F), −206.0 (nonet, $^4J_{CF_2-CF}$ ≈ 5.6 Hz, 4F); the IR spectrum exhibits no C=O absorption. Anal. Calcd for C$_8$F$_{12}$: C, 29.65; F, 70.35. Found: C, 29.76; F, 70.13.

Supporting Information Available: Table of aerosol fluorination parameters (1 page). This material is contained in 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.

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