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Reactions of Nucleophiles with Perfluoro[2.2]paracyclophane

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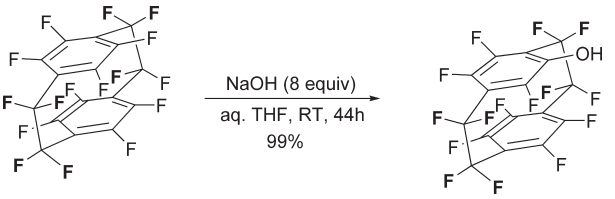


The aromatic rings of perfluoro[2.2]paracyclophane are extremely reactive with respect to nucleophilic substitution reactions. This paper emphasizes products of monosubstitution by hydroxide, alkoxide, thiolate, enolate, and amine nucleophiles. All reactions appear to proceed via S_NAr mechanisms; reactivity issues are discussed including the effect of substituents on reactivity and regiochemistry of substitution.

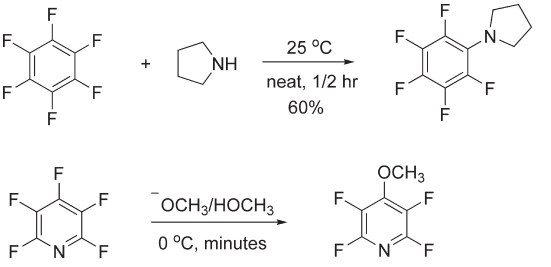
Introduction

Fluorine substituents on alkenes or aromatic rings are known to significantly enhance the electron deficiency of these unsaturated systems and as a result increase their reactivity toward nucleophiles.[1−3] Trifluoromethyl substituents, although not as effective as a nitrile group, are even more effective activating groups for such nucleophilic attack.[3−5] Such activation derives, of course, from the ability of these groups to stabilize the *carbanion* "Meisenheimer" intermediates that would be formed, for example, during a nucleophilic aromatic substitution reaction proceeding via an S_NAr mechanism. Such a process, proceeding by a carbanion intermediate, is the most common by which nucleophilic aromatic substitution reactions occur, such mechanism being facilitated by substituents that will increase the electron deficiency of the system.

Because of the presence of multiple fluorine substituents, hexafluorobenzene and pentafluoropyridine exhibit high reactivity toward nucleophiles (Scheme 1),[2,3,6,7] as do trifluoromethyl-substituted analogues, such as perfluorotoluene.[3,4,8] In a kinetic study of the reactivity of perfluoropolymethylbenzenes toward nucleophiles,[4] it was observed that, in its reaction with $^-OCH_3/HOCH_3$ at 25 °C, perfluorotoluene is 7000 times as reactive as hexafluorobenzene. Adding a second (para) trifluoromethyl group (as in perfluoro-*p*-xylene) leads to a somewhat lower reactivity, but it is still 2900 times more reactive than hexafluorobenzene.

Perfluoro[2.2]paracyclophane (**F8**) has recently been synthesized[9] and because its aromatic rings resemble those of perfluoro-*p*-xylene, it should be expected to exhibit high reactivity toward nucleophiles, although the reactivity may be somewhat diminished because of the nonplanarity of **F8**'s benzene rings.

SCHEME 1. Reactivity of Hexafluorobenzene and Pentafluoropyridine with Nucleophiles



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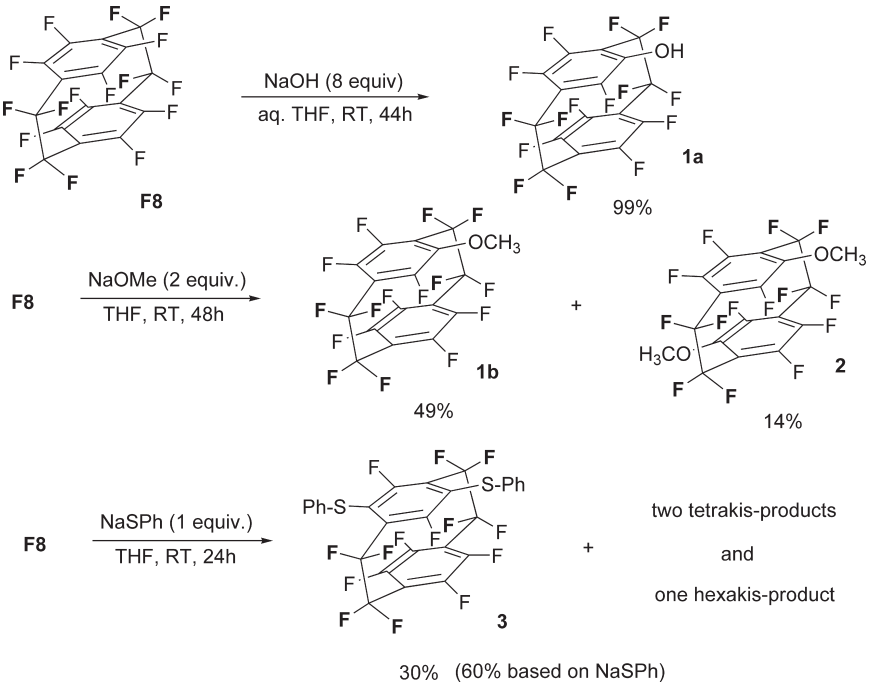
SCHEME 2. Reactions of F8 with Nucleophiles



Results and Discussion

Indeed, **F8** proved to be very reactive with a large variety of nucleophiles. In this paper, reactions that led mainly to monosubstitution will be emphasized, with discussion centered on the definition of factors that favor monosubstitution. Subsequent papers will deal with multisubstitution reactions of **F8**, the regiochemistry of multisubstitution, and characterization of the multisubstituted products, including detailed multidimensional NMR analysis of these products.

When **F8** was allowed to react at room temperature with *up to 8 equiv* of NaOH in aqueous THF a single, monohydroxy product **1a** was formed in 99% yield (Scheme 2). A similar reaction of 2.2 equiv of NaOMe in THF yielded the monosubstituted product **1b** in 49% yield along with 14% of a dimethoxy product, the pseudo-para isomer **2**. Providing further contrast, a reaction of **F8** with *1 equiv* of sodium thiophenolate yielded *no* monosubstituted product at all. Instead, the *p*-bis(phenylthio) product **3** was obtained in 30% yield along with small amounts of tetrakis- and hexakis-(phenylthio) products.

All three of the above nucleophiles were highly reactive in their respective substitution reactions with **F8**, with the reactions being complete after 2 days at room temperature for hydroxide and methoxide. The reaction with phenyl thiolate required only 1 day. The differences exhibited by these nucleophiles with respect to multiple substitution can be explained based on the variable effects of the different substituents (O^-, OMe, and SPh) of the monoadducts on their reactions with a second equivalent of nucleophile. Substitution of fluorine by hydroxide to form phenol derivative **1a** will, of course, under the reaction conditions actually form the deprotonated phenolate anion, and the O^- substituent will act as a powerful donor to the aromatic system that will strongly inhibit further reaction of a nucleophile with the ring bearing the O^-. Not only that, but the impact of the O^- must also be significantly transmitted to the other benzene ring of the paracyclophane, since a second strong hydroxide nucleophile is also not observed to add to that ring either. As a weaker donor, the methoxy substituent of **1b** appears to inhibit its reaction with a second equivalent of methoxide, but its influence is not sufficiently strong to prevent substitution of the other, unsubstituted benzene ring of **1b**. The observed result was consistent with results obtained by Tatlow and co-workers in their study of the reaction of perfluoro-*p*-xylene with methoxide ion.[8] In contrast, the results obtained from the reaction of **F8** with thiophenolate anion clearly indicate that the SPh substituent of the putative monoadduct must activate that ring toward addition of a second nucleophile. Such results are consistent with the previously observed formation of only *p*-bis-(phenylthio)-2,3,5,6-tetrafluorobenzene from the reaction of either 1 or 2 equiv of phenylthiolate anion with hexafluorobenzene.[10]

TABLE 1. Reaction of Nucleophiles with Perfluoro[2.2]paracyclophane in THF at Room Temperature

nucleophile	equiv	reaction time, h	product no. and yield (%)	color
HO^-	8	44	**1a** (99)	yellow
MeO^-	2	48	**1b** (49)	white
			2 (14)	white
$C_6H_5S^-$	1	24	**3** (30)	yellow
$4-F-C_6H_4-O^-$	1	18	**1c** (77)	white
$^-CH(CO_2Me)_2$	4	48	**1d** (73)	white
tert-butyllithium	1.1	18	**1e** (54)	white
Et_2NH	4.4	20	**1f** (91)	yellow
$(CH_2)_4NH$	2.2	24	**1g** (84)	yellow
$PhCH_2NHCH_3$	2.2	24	**1h** (68)	yellow
$(CH_3)_2NH$ (aq)	2.2	1	**1i** (70)	yellow

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TABLE 2. Reaction of Bidentate Nucleophiles with Perfluoro[2.2]paracyclophane in THF at Room Temperature

bidentate nucleophile	equiv	reaction time, h	product no. and yield (%)	color
$HOCH_2CH_2OH$	1.1 (excess NaH)	48	**1j** (50)	white
$NH_2CH_2CH_2NHCH_2Ph$	2.2	24	**1k** (58)	yellow
1,2-dihydroxybenzene	2 (excess NaH)	48	**4a** (78)	light yellow
1,2-dihydroxy-4-nitrobenzene	1.1 (excess NaH)	48	**4b** (56)	light yellow
1,2-benzene-dithiol	1.1 (excess NaH)	18	**4c** (75)	brown
$NH_2CH_2CH_2NH_2$	2.2	18	**5a** (70)	red
$EtNHCH_2CH_2NHEt$	2.2	18	**5b** (62)	red

Dimethyl malonate anion behaves much like hydroxide in its reaction with **F8**, forming only a monoadduct even when the nucleophile is present in great excess. The reason for this is much the same, since the monoadduct would become immediately deprotonated to form the highly unreactive carbanion. Other nucleophiles, generally oxygen and nitrogen nucleophiles that serve to deactivate the ring to which they become attached, have also been utilized in reaction with **F8**, with the results from all of these reactions being summarized in Table 1.

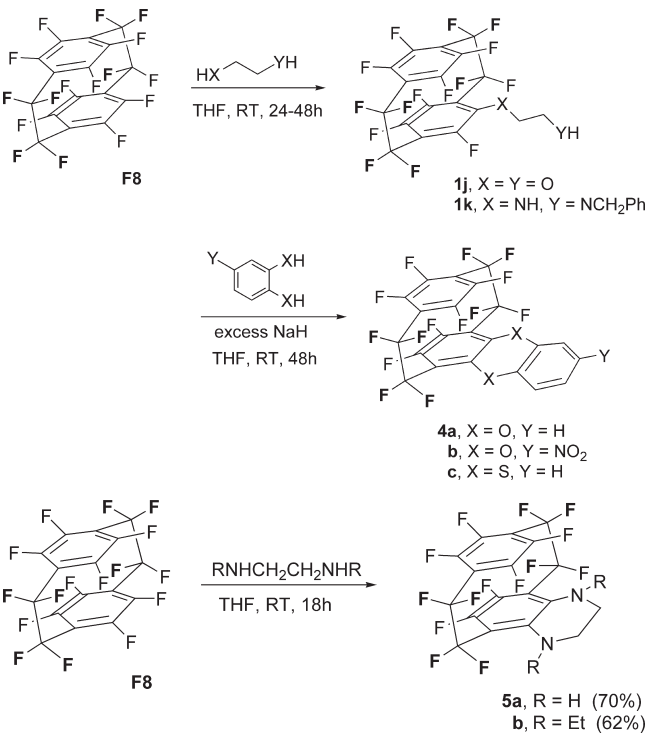
All of the above reactions were carried out preparatively for times of between 18 and 48 h, but it was later determined that the reactions with most of the nucleophiles were complete in less than an hour. Indeed, while conducting relative reactivity experiments it was determined that the reactions of methoxide with **F8**, hexafluorobenzene, and pentafluoropyridine in THF were all complete within 15 min. Under conditions of direct competition, in the presence of equal amounts of **F8** and pentafluoropyridine, methoxide reacted exclusively with pentafluoropyridine. Likewise, **F8** reacted exclusively in competition with hexafluorobenzene. Thus in reactions with nucleophiles, pentafluoropyridine is much more reactive than **F8**, which is itself much more reactive than hexafluorobenzene.

All of the reaction mixtures were observed to develop a yellow color during reaction. Among the monosubstituted products, the ether, malonate, and *tert*-butyl products were colorless, whereas the hydroxy, sulfide, and amine products were various shades of yellow. The UV−vis absorption spectra of these products show a progression toward longer wavelength absorption as the substituent becomes increasingly electron donating (see Figures SI-1a and 1b and SI-2 in the Supporting Information).

Bidentate nucleophiles were also examined to determine whether the intramolecular mode of reaction for the second nucleophile might provide sufficient kinetic advantage to observe cyclic products (Scheme 3 and Table 2). Reaction of ethylene glycol in the presence of excess NaH led simply to formation of the monoadduct **1j**. Attempts to stimulate cyclization by raising the temperature of the reaction led only to decomposition. In contrast, catechol (*o*-dihydroxybenzene) gave the cyclic diether, **4a**, resulting from consecutive nucleophilic substitution of **F8** by the *o*-phenolate anions. Likewise, reactions of the primary and secondary bis-amines, 1,2-diaminoethane and 1,2-di(ethylamino)ethane, also resulted in formation of the respective cyclic disubstituted products **5a** and **5b**. These two compounds were both red in color, with their UV bands extending past 500 nm (see Figures SI-3 and SI-4 in the Supporting Information).

Although all of the reactions of **F8** with nucleophiles can be understood within the context of the conventional S_NAr addition−elimination mechanism involving formation of a Meisenheimer (carbanion) intermediate, because of the extreme electron deficiency of the **F8** substrate and the obvious electron-transfer ability of many of the nucleophiles in Table 1, it was considered prudent to also consider the possibility that the reactions might proceed via an electron-transfer, free radical chain $S_{RN}1$ mechanism. In pursuit of evidence regarding this issue, the reduction potential of **F8** was determined via differential pulse voltammetry, and EPR studies were carried out to determine whether the **F8** radical anion might be detected, either electrochemically or during the course of any of the reactions of **F8** with the various nucleophiles.

SCHEME 3. Reaction of F8 with Bidentate Nucleophiles



Electrochemical characterizations of **F8** and nitro-AF4 were performed by cyclic voltammetry (CV) and differential pulse voltammetry (DPV) in acetonitrile with 0.1 M tetrabutylammonium hexafluorophosphate (Bu_4NPF_6) as a supporting electrolyte. The results are given in Table 3. The cyclic voltammogram of **F8** shows an irreversible reduction wave with a peak at −1.24 V (vs. SCE) (Figure 1a). The voltammogram of **F8** shows anodic current in the reverse scan, peaked at −0.80 V (vs. SCE), corresponding to the oxidation of reduced species. In addition, no change in the voltammogram was observed when scanning

TABLE 3. Summary of Electrochemical Characterization of F8 and Nitro-AF4[a]

compd	E_{pc},[b] V	E_{pa},[b] V	E_{red},[c] V
F8	−1.24	−0.80	−1.12
nitro-AF4	−1.16	−0.65	−0.94

[a]Potentials are adjusted to vs. SCE. [b]CV. [c]DPV

cycles were repeated 10 times, which suggests the chemically reversible nature of the redox process. The results suggest probable delocalization of the charge through the stacked π-system of **F8** stabilizing the intermediate radical anion species.

Because of the electrochemically irreversible nature of the redox process, the DPV technique was utilized to determine the reduction potential of **F8**. The DPV voltammogram shows a reduction peak at −1.12 V (vs. SCE) (Figure 1b). Although the presence of a possible second reduction wave was observed, the results were inconclusive due to overlapping solvent reduction waves. The reduction potential of **F8** in acetonitrile (−1.12 V vs. SCE) is virtually the same as those of nitrobenzene (−1.14 V) and *p*-fluoronitrobenzene (−1.13 V),[11] more negative than that of nitro-AF4 (the nitro derivative of the bridge-fluorinated [2.2]paracyclophane, AF4) (−0.94 V), but more positive than that of hexafluorobenzene (−2.2 V) or that reported for pentafluoropyridine (−2.3 V).[12] The reduction potential of perfluoro-*p*-xylene has not yet been reported.

Halonitroaromatics generally do not undergo substitution by the free radical chain $S_{RN}1$ mechanism, mainly because the intermediate nitro-stabilized aromatic radical anions appear to be too stable to allow dissociation of halide to form the propagating aryl radical in a kinetically competitive manner.[13,14] Moreover, fluoride has proved to be by far the worst halide leaving group for an $S_{RN}1$ reaction.[15,16] Thus, it seems unlikely that **F8**, which has a similarly stabilized radical anion and only fluoride leaving groups, would participate in a productive $S_{RN}1$ reaction.

An attempt to directly observe the **F8** radical anion by EPR under conditions of electrochemical generation failed, although the **F8** was destroyed by the potential; nor could this radical anion be detected in situ, that is during the reaction of **F8** with PhS^-Na^+ in THF. Electron transfer obviously was occurring during the electrochemical experiment; thus the lack of an observable EPR spectrum indicates that the intermediate radical anion (and any other radical species that are formed subsequently) must have been destroyed too rapidly to be observed. All that one can conclude by the lack of an EPR signal during the chemical reactions is that if the reaction proceeds via an SET process, any radical anion/radical intermediates must be too short-lived to be observed in the experiment.

The fate of the **F8** radical anion was probed by examining the reaction mixture after electrochemical reduction of **F8** in acetonitrile. No paracyclophane products could be observed

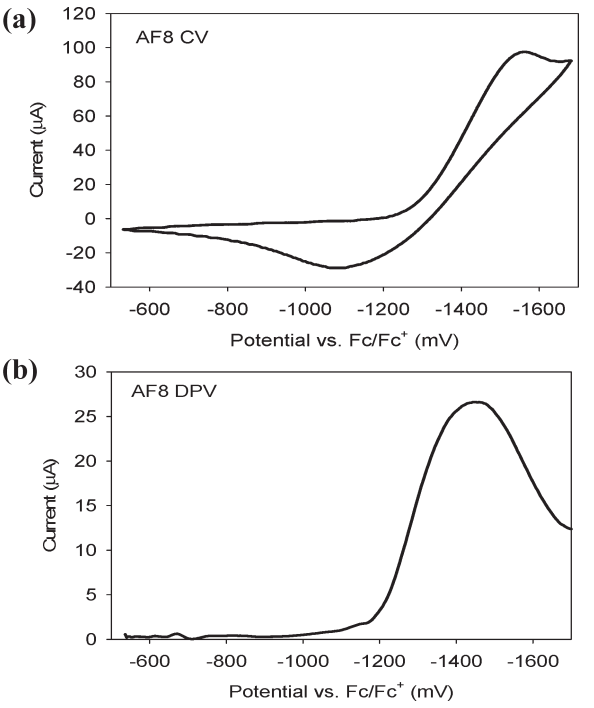


FIGURE 1. (a) Cyclic voltammogram (CV) of **F8**. (b) Differential pulse voltammogram (DPV) of **F8**.

with fluorine having been replaced on the benzene rings. The only products thus far identified derived from destruction of the paracyclophane structure, which means that when **F8**'s radical anion is formed, it prefers reactions other than loss of aromatic fluoride. Again, this result appears to preclude involvement of an $S_{RN}1$ mechanism in the reaction of **F8** with nucleophiles.

The intervention of any free radical chain mechanism was additionally tested by an experiment in which the reaction of nucleophile pyrrolidine with **F8** was carried out in the presence of 1 equiv of free radical trap, TEMPO. The reaction was not inhibited and proceeded in a normal manner. This result again speaks clearly against involvement of a free radical chain process.

Lastly, the involvement of a free radical chain process in the reaction of **F8** with *methoxide* can be specifically ruled out based on earlier work by Bunnett[17] and Saveant,[18] which indicated that methoxide's preferred reaction with aryl radicals is hydrogen atom abstraction to form the $^{\bullet}CH_2O^-$ radical anion. No such reductive reaction was observed in any of our reactions.

All of these results lead one to conclude that the reactions of **F8** with nucleophiles cannot proceed via the free radical chain $S_{RN}1$ mechanism, and that the most probable mechanism for these reactions is the S_NAr mechanism proceeding via its usual delocalized (Meisenheimer) carbanion intermediate. One cannot completely rule out electron transfer or at least formation of a charge transfer complex as the initial step of the nucleophilic substitution mechanism, since nonradical chain SET processes, where an intermediate charge

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transfer complex of radical anion and radical collapse within the solvent cage to form the Meisenheimer complex, have been proposed previously.[19]

Conclusion

The aromatic rings of perfluoro[2.2]paracyclophane are exceptionally receptive to nucleophilic substitution, and all of the observations related to **F8**'s reactivity and regiochemistry of reactions with the various nucleophiles that have been presented and discussed in this paper can be readily rationalized within the framework of the S_NAr mechanism.

Experimental Section

Perfluoro[2.2]paracyclophan-4-ol (1a). To a solution of sodium hydroxide (128 mg, 3.2 mmol) in water (0.5 mL) was added tetrahydrofuran (THF) (8 mL) and perfluoro[2.2]paracyclophane (**F8**) (198.4 mg, 0.4 mmol). The reaction mixture was homogeneous and it was stirred at room temperature (rt) for 44 h and then concentrated to dryness. The residue was purified by column chromatography (ethyl acetate) to obtain **1a** (196 mg, 99.2%) as a yellow solid: mp 192−193 °C; ^{1}H NMR (acetone-d_6) δ 3.75 (br s, 1H); ^{19}F NMR (acetone-d_6) δ −98.15 (d, J = 255.0 Hz, 1F), −99.36 (ddm, J_1 = 255.2 Hz, J_2 = 25.1 Hz, 1F), −100.79 (dd, J_1 = 247.0 Hz, J_2 = 27.1 Hz, 1F), −101.27 (ddd, J_1 = 251.0 Hz, J_2 = 26.8 Hz, J_3 = 10.4 Hz, 1F), −102.24 (J_1 = 249.0 Hz, J_2 = 62.3 Hz, 1F), −105.20 (dddd, J_1 = 244.8 Hz, J_2 = 72.7 Hz, J_3 = 16.6 Hz, J_4 = 10.4 Hz, 1F), −106.54 (dddd, J_1 = 247.0 Hz, J_2 = 68.5 Hz, J_3 = 16.6 Hz, J_4 = 10.2 Hz, 1F), −106.82 (dddd, J_1 = 251.0 Hz, J_2 = 68.5 Hz, J_3 = 18.6 Hz, J_4 = 6.5 Hz, 1F), −131.96 (m, 1F), −134.80 (d, J = 22.1 Hz, 1F), −136.44 (m, 1F), −137.98 (d, J = 8.7 Hz, 1F), −138.82 (d, J = 72.7 Hz, 1F), −144.13 (d, J = 78.9 Hz, 1F), −162.58 (br s, 1F); HRMS (CI) calcd for $C_{16}H_1F_{15}O$ 493.9788, found 493.9774.

4,7-Bis(phenylthio)perfluoro[2.2]paracyclophane (3). Following the procedure used for **1a**, a mixture of sodium benzenethiolate (29.4 mg, 0.2 mmol) and **F8** (99.2 mg, 0.2 mmol) in anhydrous THF (4 mL) was stirred at rt for 48 h. After column chromatography (hexanes) 40 mg of product **3** was obtained (30% based on **F8**, 60% based on thiolate) as a yellow solid: mp 122−124 °C; ^{1}H NMR, δ 7.75 (m, 10H); ^{19}F NMR δ −100.2 (dd, J_1 = 245 Hz, J_2 = 12 Hz, 2F), −100.7 (dd, J_1 = 251 Hz, J_2 = 43 Hz, 2F), −101.0 (d, J = 63 Hz, 2F), −102.2 (ddd, J_1 = 245 Hz, J_2 = 66 Hz, J_3 = 6.4 Hz, 2F), −103.3 (dddd, J_1 = 252 Hz, J_2 = 55 Hz, J_3 = 15 Hz, J_4 = 6 Hz, 2F), −128.5 (dd, J_1 = 43 Hz, J_2 = 11 Hz, 2F), −134.3 (dddd, J_1 = 54 Hz, J_2 = 20 Hz, J_3 = 6 Hz, J_4 = 4 Hz, 2F). Anal. Calcd for $C_{28}H_{10}F_{14}S_2$: C 49.71, H 1.49. Found: C 49.84, H 1.64.

4-(4-Fluorophenoxy)perfluoro[2.2]paracyclophane (1c). To a mixture of 4-fluorophenol (28 mg, 0.25 mmol) in anhydrous THF (10 mL) was added 60% sodium hydride (11 mg, 0.275 mmol). The resulting reaction mixture was stirred for 30 min, after which **F8** (124 mg, 0.25 mmol) was added. The mixture was stirred at rt overnight, and then it was concentrated to dryness. The residue was purified by column chromatography (hexanes) to obtain **1c** (110 mg, 76.9%) as a white solid: mp 98−99 °C; ^{1}H NMR δ 7.01 (m, 2H), 6.81 (m, 2H); ^{19}F NMR δ −99.46 (ddd, J_1 = 249.0 Hz, J_2 = 29.1 Hz, J_3 = 10.4 Hz, 1F), −100.4 (ddd, J_1 = 253 Hz, J_2 = 31 Hz, J_3 = 10 Hz, 1F), −100.6 (ddd, J_1 = 251 Hz, J_2 = 29 Hz, J_3 = 10 Hz, 1F), −101.0 (d, J = 251 Hz, 1F), −104.5 (dd, J_1 = 245 Hz, J_2 = 62 Hz, 1F), −104.9 (ddt, J_1 = 249 Hz, J_2 = 73 Hz, J_3 = 15 Hz, 1F), −105.4 (ddt, J_1 = 251 Hz, J_2 = 62 Hz, J_3 = 14 Hz, 2F), −119.0 (m, 1F), −122.0 (m, 1F), −131.7 (m, 2F), −132.3 (dd, J_1 = 56 Hz, J_2 = 10 Hz, 1F), −133.2 (dt, J_1 = 64 Hz, J_2 = 17 Hz, 1F), −134.6 (m, 1F), −135.3 (m, 1F). Anal. Calcd for $C_{22}H_4F_{16}O$: C 44.92, H 0.69. Found: C 45.24, H 0.72.

4-(Bis(carbomethoxyl)methyl)perfluoro[2.2]paracyclophane (1d). To a solution of dimethyl malonate (161.7 mg, 1.2 mmol) in anhydrous THF (10 mL) was added 60% sodium hydride (48 mg, 1.2 mmol) and the mixture was stirred at rt for 10 min. Then **F8** (148.8 mg, 0.3 mmol) was added and the reaction mixture was stirred at rt for 2 days, after which it was concentrated to dryness. The residue was purified by column chromatography (chloroform) to obtain **1d** (80 mg, 73%) as a white solid: mp 148−149 °C; ^{1}H NMR δ 5.14 (s, 1H), 3.88 (s, 3H), 3.78 (s, 3H); ^{19}F NMR δ −98.7 (ddd, J_1 = 251 Hz, J_2 = 25 Hz, J_3 = 12 Hz, 1F), −99.3 (ddd, J_1 = 251 Hz, J_2 = 21 Hz, J_3 = 8 Hz, 1F), −100.0 (ddd, J_1 = 249 Hz, J_2 = 25 Hz, J_3 = 8 Hz, 1F), −100.1 (ddd, J_1 = 249 Hz, J_2 = 33 Hz, J_3 = 8 Hz, 1F), −104.6 (dt, J_1 = 251 Hz, J_2 = 17 Hz, 1F), −105.4 (dddd, J_1 = 251 Hz, J_2 = 69 Hz, J_3 = 35 Hz, J_4 = 8 Hz, 1F), −105.7 (ddt, J_1 = 257 Hz, J_2 = 69 Hz, J_3 = 12 Hz, 1F), −106.6 (ddt, J_1 = 253 Hz, J_2 = 75 Hz, J_3 = 12 Hz), −109.5 (dd, J_1 = 73 Hz, J_2 = 10 Hz, 1F), −122.1 (m, 1F), −129.0 (m, 2F), −131.8 (m, 1F), −134.1 (m, 1F), −134.5 (m, 1F). Anal. Calcd for $C_{21}H_7F_{15}O_4$: C 41.47, H 1.16. Found: C 41.76, H 1.06.

Catechol Adduct of F8 (4a). To a solution of catechol (110 mg, 1 mmol) in anhydrous THF (10 mL) was added 60% sodium hydride (88 mg, 2.2 mmol). The resulting reaction mixture was stirred at room temperature for 10 min, after which **F8** (248 mg, 0.5 mmol) was added. The mixture was stirred at rt overnight, and then it was concentrated to dryness. The residue was purified by column chromatography (hexanes) to obtain **4a** (220 mg, 77.5%) as a light yellow solid: mp 162−163 °C; ^{1}H NMR δ 7.06 (dd, J_1 = 6.6 Hz, J_2 = 3.6 Hz, 2H), 6.93 (dd, J_1 = 6.6 Hz, J_2 = 3.6 Hz, 2H); ^{19}F NMR δ −99.6 (d, J = 249 Hz, 2F), −100.2 (ddd, J_1 = 253 Hz, J_2 = 25 Hz, J_3 = 6 Hz, 2F), −103.8 (ddq, J_1 = 249 Hz, J_2 = 74. Hz, J_3 = 10 Hz, 2F), −104.6 (dd, J_1 = 253 Hz, J_2 = 62 Hz, 2F), −131.3 (m, 2F), −136.6 (d, J = 62 Hz, 2F), −139.2 (d, J = 71 Hz, 2F). Anal. Calcd for $C_{22}H_4F_{14}O_2$: C 46.66, H 0.71. Found: C 46.35, H 0.51.

Electrochemistry. The cyclic voltammetry (CV) experiments were performed on a Bioanalytical Systems CW50 electrochemical analyzer at a sweep rate of 100 mV/s, using a platinum disk working electrode, a platinum wire auxiliary electrode, and a silver wire pseudoreference electrode. At the end of each scan, ferrocene was added as internal standard and potentials are referenced to the potential of ferrocene/ferrocenium redox couple. The differential pulse voltammetry experiments were performed with the same setup at a scan rate of 20 mV/s, a pulse amplitude of 50 mV, and a pulse period of 200 ms. Sample and pulse width were 17 and 50 ms, respectively. Solutions of samples were prepared in acetonitrile. The supporting electrolyte was 0.10 M tetrabutylammonium hexafluorophosphate ($TBAPF_6$). The experimental potentials obtained vs. ferrocene/ferrocenium redox couple were corrected to the SCE standard (correction factor of +0.328 C)

Bulk Electrolysis of F8. Bulk electrolysis of **F8** was performed on a Bioanalytical Systems CV-27 cyclic voltammograph, using a platinum gauze working electrode, a coiled platinum wire auxiliary electrode, and a silver wire pseudoreference electrode. Ferrocene was used as an internal standard for the reference electrode potential. **F8** (200 mg, 0.4 mmol) was dissolved in 20 mL of acetonitrile containing 0.10 M tetrabutylammonium hexafluorophosphate ($TBAPF_6$) as supporting electrolyte. The solution was purged with nitrogen gas for 15 min. The potential of the working electrode was kept at −1.1 V (vs. SCE) for 4 h with continuous stirring. The solution turned darker brown as the electrolysis proceeded. The current was ca. 10 mA for the duration of the experiment. The resulting solution was concentrated to dryness, then purified by column chromatography (silica gel, hexanes) to obtain two fractions. The first

(19) Bacaloglu, R.; Blasko, A.; Bunton, C.; Dorwin, E.; Ortega, F.; Zucco, C. *J. Am. Chem. Soc.* **1991**, *113*, 238−246 and references cited therein.

fraction was recovered **F8** (120 mg), whereas the second fraction was a mixture of reduced products. Both proton and fluorine NMR spectra indicated an absence of aromatic C−H bonds and the probable presence of a CH_2 group resulting from reduction of two geminal fluorines on one of the bridges of **F8** to form a CH_2-CF_2 bridge.

Reaction in the Presence of TEMPO. To a solution of pyrrolidine (20.5 mg, 0.29 mmol) and 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO, 45 mg, 0.29 mmol) in anhydrous THF was added **F8** (65.4 mg, 0.13 mmol). The resulting reaction mixture was stirred for 1 h and then concentrated to dryness and purified by column chromatography (silica gel, hexanes) to provide 4-(pyrrolidin-1-yl)perfluoro[2.2]paracyclophane (**1g**) (100% conversion, 84% isolated yield) as a yellow solid.

Competition Experiments. To a mixture of pentafluoropyridine (50 mg, 0.295 mmol) and **F8** (124 mg, 0.25 mmol) in anhydrous THF (6 mL) was added NaOMe (8 mg, 0.148 mmol). After stirring for 10 min at rt, a fluorine NMR of the mixture indicated that the methoxide anion had only reacted with the pentafluoropyridine. The **F8** was untouched.

A similar experiment designed to compare the reactivities of **F8** and hexafluorobenzene resulted in reaction of methoxide only with the **F8**.

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Supporting Information Available: General experimental information, UV−vis spectra of **1a**−**i**,**k**, and the sodium salt of **1a**, **4a**−**c**, and **5a**,**b**, proton and fluorine NMR spectra of all new compounds, and details of experimental and characterization data for compounds **1b**, **2**, **1e**, **1f**, **1g**, **1h**, **1i**, **1j**, **1k**, **4b**, **4c**, **5a**, and 5b. This material is available free of charge via the Internet at http://pubs.acs.org.