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Fluorine Hyperfine Splittings in the Electron Spin Resonance (ESR) Spectra of Aromatic Radicals. An Experimental and Theoretical Investigation

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This article reports our experimental and theoretical investigations of fluorine hyperfine coupling constants (hfcc's) in the anion and cation radicals of a number of fluorinated benzenes, naphthalenes, and anthracenes. We have obtained electron spin resonance (ESR) spectra and hfcc's for the electrolytically generated anion radicals of 1,2,3,4-tetrafluoronaphthalene, 1,2,3,4-tetrafluoroanthracene, and 9,10-perfluoroanthraquinone. The experimental values of the hfcc's of these radicals, along with the hfcc's of several cation radicals of fluorinated benzenes and naphthalenes currently available in the literature, have been compared to our theoretical predictions using the UB3LYP density functional method in conjunction with a variety of basis sets. The EPR-III basis set usually gave the best agreement between theory and experiment for the fluorine splittings with an average relative error of 15%. We also find that it is possible to correlate the experimental fluorine hfcc's with the calculated π- and total electron spin populations ρ on the fluorine atom, the adjacent carbon atom, and the carbon−fluorine bond, thus providing some chemical insight into the origin of the interactions. The best correlation is obtained with a two-parameter equation of the form $A_F = Q_{CF}\rho_C^{\pi} + Q_{FC}\rho_F^{\pi}$. The fit to 21 fluorine splittings using the EPR-III basis set and Mulliken π-electron spin populations gives an average error of only 9%. The average error obtained with EPR-II and NBO π-electron spin populations is 8%. Roughly 80% of the fluorine hfcc can be attributed to π-electron spin population on the fluorine atom. Our results indicate that conjugation of the fluorine atom with the ring is the primary source of the unpaired electron density on fluorine and that the often-assumed separability of σ- and π-electrons in aromatic systems is justified in these radicals as well.

Introduction

The hyperfine coupling constants (hfcc's) obtained from electron spin resonance (ESR) spectroscopy provide important information about the electronic structure and properties of organic radicals. This is a result of the direct proportionality that exists between the isotropic hyperfine splitting constant A_X due to an atom X and the spin density at the atom nucleus in the radical. Hence, the ability of a theoretical calculation to reproduce the experimentally determined hfcc's provides a critical test of methods of calculation used to describe the electronic structure of the molecule.

One of the simplest and most basic sets of radicals in which to compare experimental and calculated values of hfcc's are the radicals formed from the series of planar polycyclic aromatic hydrocarbons (PAHs). However, experimental ESR data on fluorinated anion radicals of PAHs are lacking in the literature, and to this date, there has not been a systematic theoretical study of fluorine hfcc's in radicals of this size, either anions or cations, using modern methods of electronic structure calculation. The hfcc's of a number of cation radicals of fluorinated benzenes and naphthalenes are known from previous studies,[1−3] but no experimental data are currently available in the literature on anion radicals of these compounds, nor are there any data at all on either cations or anions of fluorinated anthracenes.

The McConnell relation,[4,5]

$$A_H = Q_{CH}\rho_C^{\pi} \tag{1}$$

where A_H is the proton hyperfine constant, ρ_C^{π} is the π-electron spin population (often loosely called spin density) on the adjacent ring carbon atom, and Q_{CH} is a constant of proportionality, has been shown to be consistent with the experimental values of the isotropic proton hyperfine splittings in planar even-alternant aromatic radicals in solution.[6] In planar aromatic radicals, the unpaired electron is thought to reside primarily in the π-electron orbitals of the aromatic rings, which have no spin density in the plane of the molecule where the hydrogen nucleus resides. The existence of the proton hfcc is then explained as arising from the well-known spin polarization mechanism,[4] and Q_{CH} is called the proton spin-polarization constant.

Even the most elementary methods of calculation of ρ_C^{π}, such as those based on simple Hückel molecular orbitals, yield rather good agreement with the experimental values of the isotropic proton splittings in these kinds of systems. Both theory and experiment suggest Q_{CH} to have the value -25 ± 3 G.[6] In odd-alternant systems, in which negative spin densities can arise, an extension of the Hückel method due to McLachlan,[7] which mimics the results of a Hartree−Fock (HF) self-consistent field calculation, works quite well for proton splittings. Higher level all-electron methods calculate A_X directly from the Fermi contact interaction between unpaired electrons and the nucleus of atom X. A relation similar to eq 1 holds for this interaction but now involving the spin density $\rho(r_X)$ at the position of the nucleus X; it is given by

$$A_X = \left(\frac{\mu_0}{4\pi}\right)\left(\frac{8\pi}{3}\right)\left(\frac{g_e\beta_e g_X\beta_n}{hr_b^{\ 3}}\right)\rho(r_X) \tag{2}$$

where A_X is the hyperfine splitting constant in hertz, g_e and g_X

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are the free electron and nuclear g values, β_e and β_n are the electron and nuclear magnetons, respectively, μ_0 is the vacuum permeability, h is the Plank constant, and r_b is the Bohr radius. The factor $(\mu_0/4\pi)$ is the conversion factor between the cgs Gaussian and SI system of units. To the extent that eq 1 holds when X = H, the ratio of the spin density $\rho(r_H)$ to the spin population ρ_C^{π} on the adjacent carbon atom should be a constant, and this expectation is supported by the experimental findings.

Semiempirical Hartree–Fock (HF) methods, such as intermediate neglect of differential overlap (INDO)[8] give reasonable predictions of proton splitting constants (though usually worse than those calculated by the simpler Hückel–McLachlan method) but do not perform very well with other nuclei. Literature results[9,10] indicate that ab initio HF calculations generally fail to produce results close to the experimental values even for proton splittings. Any method capable of reliable hfcc predictions must explicitly include the effects of electron correlation. In some cases, Møller–Plesset second-order perturbation theory (MP2), the most economical post-HF approach, is in better agreement with experiment[11] but has to be used with great care.[10,12] More sophisticated techniques, such as multireference configuration interaction (MRCI) and quadratic configuration interaction with single and double excitation (QCISD), consistently give very good results but are computationally prohibitively expensive for all but the smallest radicals.[9,12,13] However, inclusion of the electron correlation in the density functional methods, which have witnessed a dramatic increase in popularity over the past decade,[14] leads to only a modest increase in computer time over the conventional HF calculations. Application of those methods to computing the ESR parameters of various types of radicals has been fruitful, and in many cases density functional calculations represent the only practical approach to the problem. Out of a multitude of functionals investigated to date, the B3LYP scheme of Becke[15] in many cases provided the highest accuracy of the calculated hfcc's.[9,10,16] The success of this functional appears to be related to the inclusion of the exact exchange term in the overall expression for the exchange–correlation energy.

An important practical aspect of any quantum-mechanical calculation is the choice of a basis set. It was observed rather early[17] that the presence in the basis set of very "tight" s-type functions with large exponents leads to a significant improvement in the results. Along those lines, Barone et al. have developed two basis sets, EPR-II[18] and EPR-III,[19] specifically tailored to the calculation of magnetic properties of radicals. These basis sets, in conjunction with the B3LYP functional, have been shown to closely reproduce the experimental splittings of ^{1}H, ^{13}C, and ^{14}N in a number of small-[19] and medium-sized[20] radicals, although for hydrogen in some cases there is no gain in accuracy over a smaller 6-31G(d) basis set of Pople.[21] Other authors advocate the use of basis sets augmented with diffuse functions.[12]

The isotropic hfcc's such as those of interest in this study are typically measured for radicals in solution at room temperature, while quantum mechanical calculations are usually performed on static molecules in a vacuum at 0 K. The coupling constants are somewhat temperature-dependent, which is attributed to the changes in the populations of the vibrational levels. The latter can be estimated by solving the corresponding one-dimensional vibrational Schrödinger equation. The hfcc at a given temperature is calculated by performing averaging over the available vibrational energy levels assuming a Boltzmann distribution of the populations. To our knowledge, to date there have been no studies of the effect of vibrational averaging on the fluorine splittings in the systems of interest. However, with the use of the above method it was shown[22,23] that hyperfine interaction parameters of the ring protons in aromatic radicals are subject to a very small ($<3 \times 10^{-4}$ G/K) temperature dependence owing to the rigidity of these planar structures. Therefore, it is not unreasonable to expect that in our systems the temperature correction to the fluorine hfcc's calculated at 0 K will be 0.1 G or less.

The dielectric constant of aprotic solvents has very little effect on the experimentally observed fluorine splittings as was shown by Hudson and Lewis[24] in the case of tetrafluoro-p-benzoquionone radical generated in THF and acetone. However, the same authors observed 3-fold lowering of A_F in 2-propanol, which is apparently due to the hydrogen bond formation between fluorine and hydrogen of the hydroxyl group. Accordingly, quantum-mechanical studies in which common aprotic solvents were represented by a dielectric continuum have registered only a small effect on the calculated splittings due to changing the dielectric constant of the medium around the radical.[23,25] Among the systems in which interaction with the solvent cannot be neglected are nitroxide radicals, radicals derived from DNA bases, and amino acid radicals.[26]

Methods

The parent compounds were synthesized by Prof. R. Filler's group at the Illinois Institute of Technology.[27,28] The NMR spectra taken to confirm their structure indicated that the compounds were 99% pure, except for the sample of 1,2,3,4-tetrafluoroanthracene, which is a 7/1 molar ratio of itself with its photodimer 9,10-dehydrodi(1,2,3,4-tetrafluoroanthracene). All radicals were generated in situ using a two-electrode electrochemical cell (Wilmad WG-810) placed within the EPR cavity. The cell was filled with N_2-purged solution containing 10^{-3}–10^{-2} M parent compound and 0.1 M n-tetrabutylammonium chloride or perchlorate in dimethylformamide. Although the solvent was initially anhydrous, all solutions were prepared and the cell was filled in the open air; therefore, trace amounts of water and oxygen were present. The cathode was Hg or Pt; the anode was Pt. A voltage of 3–13 V was applied by means of a DC power supply. Because a reference electrode was not used, accurate determination of the cathode potential was not possible. ESR spectra were recorded at room temperature on a Bruker EMX 300 spectrometer with a modulation frequency of 100 kHz. The microwave power was kept at 2 mW. The experimental coupling constants were obtained with the use of the software package PEST, version 0.96 (Public ESR Software Tools by Dave Duling at the National Institute of Environmental Health Sciences), which performs a least-squares fit to the experimental spectra. We estimate the precision of the coupling constants generated by this procedure to be ±0.02 G.

The hyperfine coupling constants (hfcc's) were computed with the Gaussian 98[29] suite of programs. All calculations in this work were performed for vacuum using the UB3LYP density functional method. A variety of basis sets were employed for the geometry optimizations and single-point calculations (Table 1): (1) Pople-style triple-ζ split valence basis sets augmented with polarization and diffuse functions;[30,31] (2) double- and triple-ζ Dunning's correlation-consistent basis sets;[32,33] (3) EPR-II and EPR-III basis sets of Barone.[18,19]

Experimental Results

The range of stability of the measured radicals varied from several minutes to several hours and was potential-dependent. The solutions exhibited yellow to dark red coloration. Spectra

TABLE 1: The Average Accuracy of hfcc's for the Radicals under Investigation Calculated with the UB3LYP Density Functional Method Using Different Basis Sets

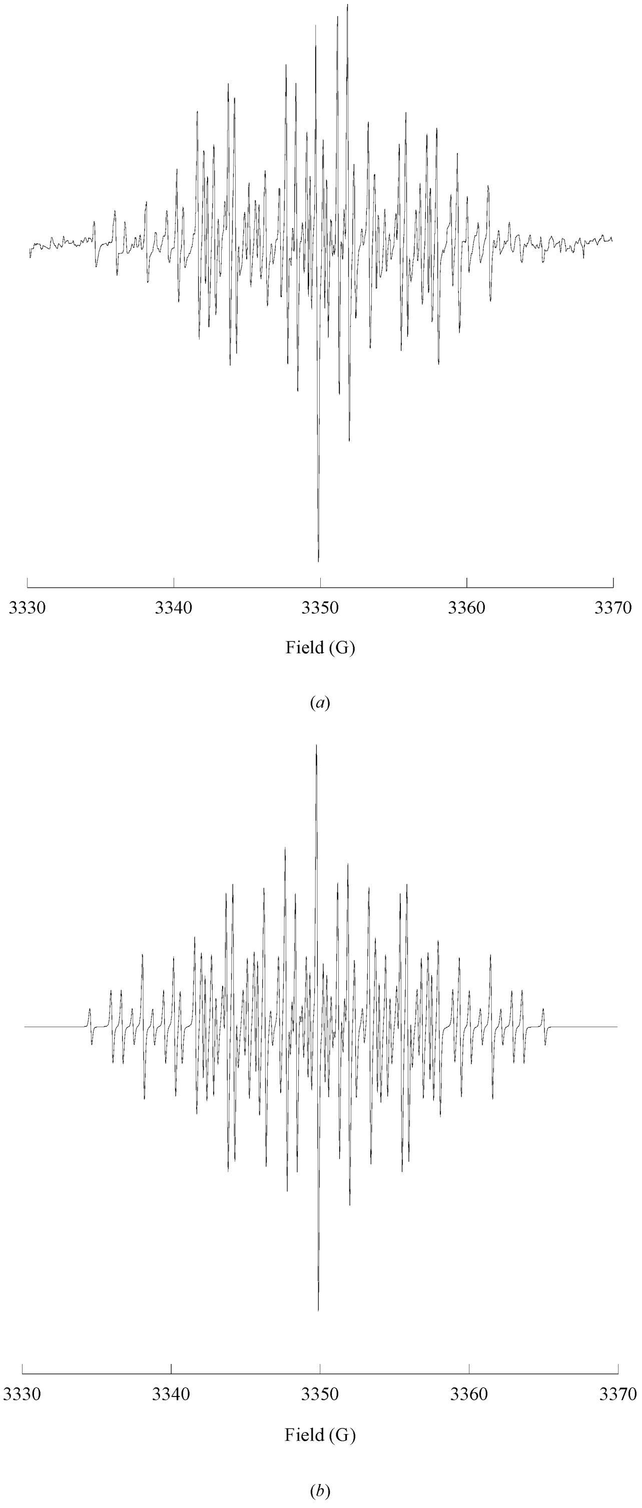
	F		H	
level of calculation	error (G)	% error	error (G)	% error
cc-PVDZ//cc-PVDZ	4.7	36	1.2	47
cc-PVTZ//cc-PVDZ	5.0	33	1.2	47
6-311G(d,p)//6-311G(d,p)	3.9	27	1.2	47
6-311+G(d,p)//6-311G(d,p)	4.0	27	1.2	50
6-311G(df,pd)//6-311G(d,p)	3.5	24	1.2	45
6-311+G(df,pd)//6-311G(d,p)	3.7	25	1.2	47
6-311G(2df,2pd)//6-311G(2df,2pd)	3.4	24	1.2	46
6-311+G(2df,2pd)//6-311G(2df,2pd)	3.5	24	1.2	47
EPR-II//EPR-II	2.5	19	1.3	50
EPR-III/EPR-II	1.7	15	1.2	48

obtained upon cathodic reduction of 1,2,3,4-tetrafluoronaphthalene (Figure 1) and 1,2,3,4-tetrafluoroanthracene (Figure 2) solutions were consistent with the formation of simple monoanion radicals of the parent compounds. All lines in the spectrum of Figure 2a can be accounted for as arising from the 1,2,3,4-tetrafluoroanthracene radical anion alone, which indicates that no radical formed from its photodimer was present. The electrolysis of perfluoroanthracene solution generated a radical with a very narrow (<10 G) spectrum (Figure 3) that is consistent with two sets of four equivalent splittings, whereas the parent compound structure necessitates an additional set of two equivalent splittings. The radical was subsequently identified as the anion of 9,10-perfluoroanthraquinone (see the Discussion section).

Computational Results

Table 1 compares the average percent errors between the calculated Fermi contact and experimental values for the 21 experimental fluorine hfcc's of the radicals in Table 2 using 10 common basis sets in our UB3LYP calculations. The EPR-III//EPR-II level of calculation is superior to all others employed with a very acceptable average percent error of 15% and an average absolute error of 1.7 G, which comprises 13% of 13.4 G, the average absolute value for the 21 F-hfcc's. These results may be compared to the fluorine hfcc's calculated with the largest Pople style basis set examined, at the 6-311+G(2df,2dp)//6-311G(2df,2dp) level, which gave an average error of 24%. Figure 4 is a plot of the EPR-III//EPR-II calculated fluorine hfcc's against the experimental values. The points cluster closely around the line of unit slope passing through the origin.

In addition to the 21 fluorine hfcc's of the 9 compounds in Table 2, there are 14 hydrogen hfcc's. However, the experimental values for three of them are indistinguishable from zero. The average error associated with the calculation of the hydrogen splittings (excluding those with zero values) at the EPR-III//EPR-II level is 48%. But even after the zero values are eliminated, this is a misleading average due to the large percent errors computed for some of the small hydrogen constants. For the hydrogen splittings, a better measure of agreement between the calculated and experimental values is the average absolute error, which is 1.2 G or 39% of 3.1 G, the average hydrogen splitting. This is still not nearly as good a percent agreement as that for the fluorine splittings, though the absolute error is less. At the same time, EPR-III//EPR-II calculations predict hydrogen splittings with 10% accuracy in cation and anion radicals of naphthalene and anthracene. So far, we have no ready explanation for this observation.

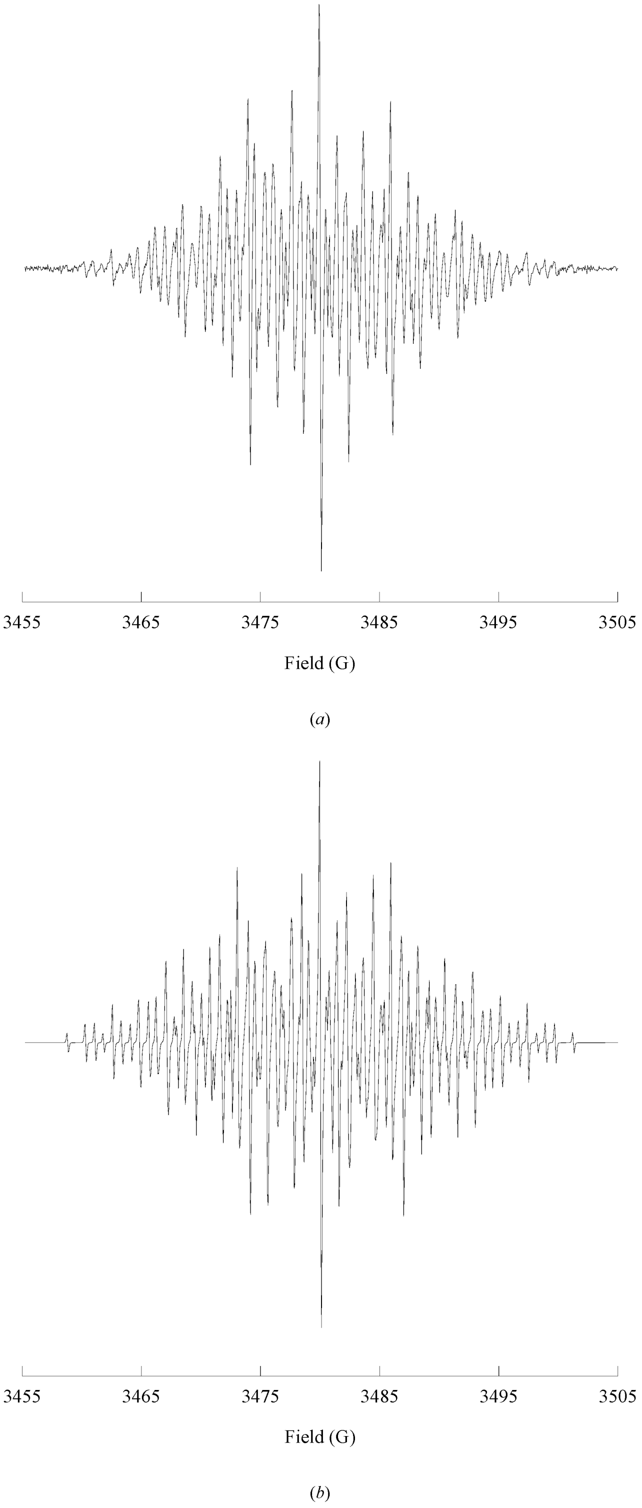


(*a*)

(*b*)

Figure 1. ESR spectrum of the radical formed upon reduction of 1,2,3,4-tetrafluoronaphthalene: (a) experiment; (b) simulation (four sets of two equivalent splittings; $A_1 = 1.42$ G, $A_2 = 2.11$ G, $A_3 = 5.61$ G, $A_4 = 6.06$ G; Lorentzian/Gaussian = 1.80; line width = 0.07 G).

The ESR experiment alone does not provide the signs of the hfcc's. However, the signs of fluorine hfcc's have been determined by NMR[34,35] and other methods[36−38] in other aromatic radicals and for the type of radicals studied here have always yielded positive values. Our calculated fluorine hfcc's are all positive and hence consistent with those studies, with one exception. At position 1 in pentafluorobenzene, the calculated value is −6.19 G. The experimental absolute value is 4.8 G. However, there is no fundamental reason that all fluorine splittings must be positive. This point is discussed further below.



(*a*)

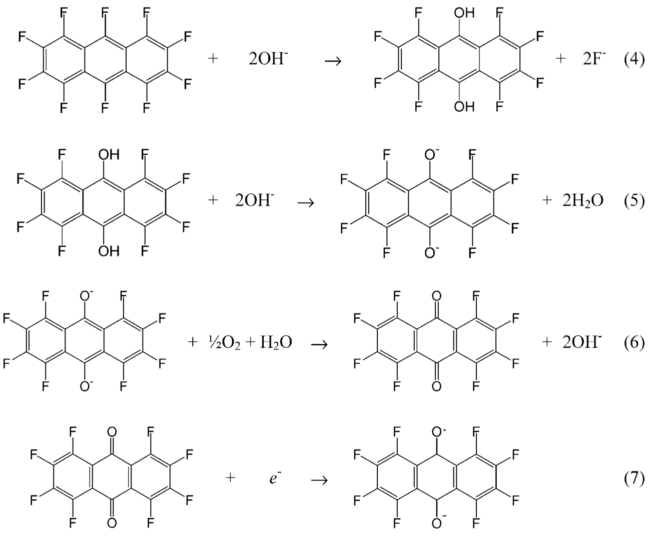
(*b*)

Figure 2. ESR spectrum of the radical formed upon reduction of 1,2,3,4-tetrafluoroanthracene: (a) experiment; (b) simulation (five sets of two equivalent splittings; $A_1 = 1.51$ G, $A_2 = 2.30$ G, $A_3 = 4.52$ G, $A_4 = 5.95$ G, $A_5 = 6.92$ G; Lorentzian/Gaussian = 0.862; line width = 0.06 G).

Discussion

The unexpected narrowness of the spectrum obtained upon cathodic reduction of perfluoroanthracene solution suggests that the radical formed should contain oxygen, which is most likely due to the presence of trace amounts of H_2O and O_2 in our experimental procedure. The experimental spectrum can be simulated by two sets of four equivalent splittings, indicating that the substitution is symmetric and occurs at the 9 and 10 positions producing 9,10-perfluoroanthraquinone. We have previously observed the formation of 9,10-anthraquinone anion radical from anthracene and 9,10-dihydro-9,10-ethenoanthracene (dibenzobarrelene) under similar experimental conditions. The following mechanism for the formation of 9,10-perfluoroanthraquinone anion radical is proposed:

$$H_2O + e^- \rightarrow \tfrac{1}{2}H_2 + OH^- \qquad (3)$$



Although 9,10-perfluoroanthraquinone is different from the type of compounds in Table 2, we have used the same EPR-III//EPR-II approach to calculate $A_{1,4,5,8}(\mathrm{F}) = -0.45$ G and $A_{2,3,6,7}(\mathrm{F}) = 2.12$ G. Considering their relatively small magnitude, these values are in a reasonable agreement with the experimental splittings of (−)0.10 and 2.71 G.

The isotropic hyperfine coupling constants as calculated from eq 2 with spin densities obtained from quantum chemical methods such as the UB3LYP/EPR-III//UB3LYP/EPR-II approach used here are the fundamental theoretical result to be compared with experiment. However, these calculations alone yield little insight into the physicochemical origin of the hyperfine interaction. It is desirable to explain the origin and magnitude of the interaction through the atomic and molecular properties of the system. For example, in the case of hydrogen hfcc's in aromatic radicals, the interaction is rationalized in terms of a spin polarization mechanism that invokes the Pauli principle and Hund's rule[6] and is proportional to the π-electron spin population on the carbon atom to which the hydrogen is attached. This mechanism is summarized by McConnell's relation (eq 1) and fits the experimental data quite well.

Similar explanations of fluorine hfcc's in aromatic systems would also be desirable, but the mechanism of the interaction in the case of fluorine is likely to be more complex. Fluorine has low-lying p-orbitals, which can participate in the bonding with the carbon atoms of the aromatic ring. Therefore, one can expect that in addition to the spin population on the adjacent carbon atom, the hfcc of fluorine will also be a function of the spin population on the fluorine atom itself, and, possibly, of the overlap population between the two atoms. There have been many attempts[1,39−42] over the years to represent fluorine hfcc's in aromatic radicals through parametric equations based on spin populations calculated by a variety of methods, mostly semiempirical. However, efforts at the interpretation of fluorine hfcc's in terms of these contributions have been hampered by the unavailability of accurately calculated spin populations, some-

TABLE 2: Experimental and Calculated hfcc's for the Radicals Studied in This Work

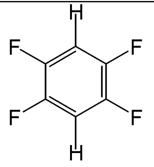
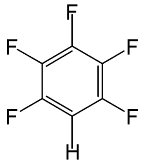
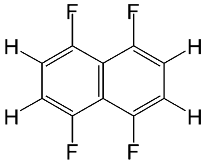
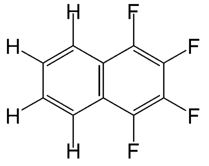
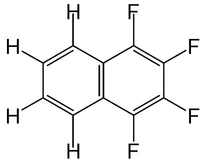
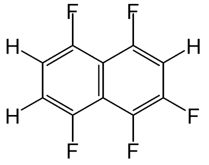
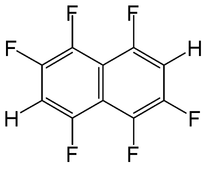
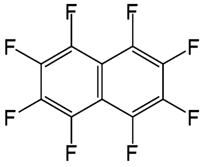
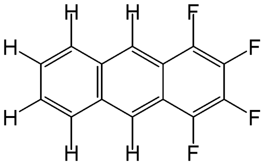
Name of parent compound	Radical structure	Experimental hfccs	Reference	6-311+G(2df,2pd)// 6-311G(2df,2pd)	% error	EPR-III// EPR-II	% error
2,3,5,6-tetrrafluoro-benzene	 (+)	25.8 (F)	1	18.1	30	21.9	15
		~ 0 (H)		1.34	—	1.49	—
pentafluoro-benzene	 (+)	(−)4.8 (F_1)	1	−5.35	12	−6.19	29
		25.8 ($F_{2,6}$)		18.5	28	21.4	17
		25.8 ($F_{3,5}$)		17.3	33	22.8	12
		~ 0 (H_4)		1.16	—	1.28	—
1,4,5,8-tetrafluoro-naphthalene	 (+)	16.2 (F)	3	13.1	19	15.9	2
		(−)4.04 (H)		−1.73	57	−1.91	53
1,2,3,4-tetrafluoro-naphthalene	 (+)	19.5 ($F_{1,4}$)	3	15.5	21	18.8	4
		6.51 ($F_{2,3}$)		3.14	52	4.00	39
		(−)2.37 ($H_{5,8}$)		−4.28	81	−4.70	98
		(−)0.59 ($H_{6,7}$)		−1.08	83	−1.19	100
1,2,3,4-tetrafluoro-naphthalene	 (-)	6.06 ($F_{1,4}$)	this work	6.07	0.2	6.37	5
		2.11 ($F_{2,3}$)		2.27	7.6	2.69	28
		(−)5.61 ($H_{5,8}$)		−6.14	9.5	−6.61	18
		(−)1.42 ($H_{6,7}$)		−1.86	31	−1.98	39
2,6,7H-pentafluoro-naphthalene	 (+)	16.1 (F_1)	3	11.2	30	13.6	16
		7.1 (F_3)		4.85	32	5.97	16
		16.1 (F_4)		14.2	12	17.3	8
		16.8 (F_5)		14.7	13	17.9	7
		16.1 (F_8)		11.8	27	14.1	12
		~0 (H_2)		−0.63	-	−0.69	-
		(−)2.1 (H_6)		−0.95	55	−1.05	50
		(−)4.2 (H_7)		−2.63	37	−2.90	31
2,6H-hexafluoro-naphthalene	 (+)	17.9 ($F_{1,5}$)	3	12.4	31	15.1	16
		10.3 ($F_{3,7}$)		7.15	31	8.73	15
		17.9 ($F_{4,8}$)		12.7	29	15.5	13
		0.29 ($H_{2,6}$)		0.06	79	0.08	72

TABLE 2 (Continued)

Name of parent compound	Radical structure	Experimental hfccs	Reference	6-311+G(2df,2pd)// 6-311G(2df,2pd)	% error	EPR-III// EPR-II	% error
perfluoro-naphthalene	 (+)	19.0 ($F_{1,4,5,8}$)	3	13.4	30	16.4	14
		4.78 ($F_{2,3,6,7}$)		2.65	45	3.30	31
1,2,3,4-tetrafluoro-anthracene	 (-)	4.52 ($F_{1,4}$)	this work	3.53	22	4.18	8
		2.30 ($F_{2,3}$)		2.15	7	2.52	7
		(−)6.92 ($H_{9,10}$)		−5.68	18	−6.16	11
		(−)5.95 ($H_{5,8}$)		−2.78	53	−3.00	50
		(−)1.51 ($H_{6,7}$)		−1.33	12	−1.43	5

times leading to contradictory conclusions.[41−43] Using the quantum-mechanical approach described above, we have fitted the experimental fluorine hfcc's to one-, two-, and three-parameter equations involving spin populations on the carbon atom, the fluorine atom, and the bond in the C−F fragment.

Figure 5 is a plot of the values of A_F calculated from the eq 8 against the experimental A_F's.

$$A_F = Q_{CF}\rho_C^{\pi} \tag{8}$$

where ρ_C^{π} is the p_z-electron spin population on the carbon atom of the C−F fragment and Q_{CF} is a constant of proportionality. The spin populations are calculated with the widely used Mulliken[44] and NBO[45] schemes and are listed in Table 3. The average percent errors in the fit of 21 fluorine hfcc's are 33% and 35%, respectively, with Q_{CF} values of 96.6 and 96.8 G. We judge these results to be an unsatisfactory fit to the data and ascribe no significance to the calculated Q values.

Here and below the Mulliken populations were calculated at the EPR-III//EPR-II level, while the NBO values refer to spin densities calculated at the EPR-II//EPR-II level because EPR-III is a linearly dependent basis set and not amenable to NBO analysis. However, judging from the literature[45] and our own experience with these calculations, NBO electron populations change little with the basis set employed; therefore, we feel that in this case direct comparison of the two population analyses is justified.

Figure 6 is a plot similar to Figure 5 but with A_F values calculated from

$$A_F = Q_{FF}\rho_F^{\pi} \tag{9}$$

where ρ_F^{π} is the p_z spin population on the fluorine atom calculated by the two approaches mentioned above. The calculated p_z electron spin populations on the fluorine atoms are smaller than their values on the ring carbon atoms, but this is not a surprising result. The fluorine substituent is not expected to conjugate as strongly with ring carbon atoms as the latter do with each other, and the majority of the unpaired spin population is expected to reside in the aromatic rings. The scatter of the data points around the line of unit slope in Figure 6 is considerably less than that seen in Figure 5. The average percent errors are only 13% and 10% with the Q_{FF} values of 484 and 411 G for the Mulliken and NBO approaches, respectively. Hence, we might conclude that unpaired spin population on the fluorine atom, though smaller than the spin population on carbon, provides the principal mechanism for the origin of the fluorine hfcc's in aromatic systems.

A check on this inference can be done by fitting the experimental hfcc's values to those calculated from the two-parameter equation

$$A_F = Q_{CF}\rho_C^{\pi} + Q_{FF}\rho_F^{\pi} \tag{10}$$

Figure 7 shows the plot of experimental against calculated hfcc's for this case. There is some improvement of the fit over the fit to eq 9. The average percent errors are now 9% and 8% for the Mulliken and the NBO spin populations, respectively. The values of the parameters are $Q_{CF} = 20.6$ G and $Q_{FF} = 394$ G with Mulliken and $Q_{CF} = 9.12$ G and $Q_{FF} = 378$ G with NBO populations, respectively. As discussed above, the NBO spin populations are considered to be the more reliable, hence these latter Q-values may be the more accurate values of the interaction parameters.

Analyzing the contribution to the overall hfcc's from p_z electron spin population on fluorine for all cations and anions studied indicates that it is on average 75% in the Mulliken scheme and 89% in the NBO scheme. But there is some notable difference between anions and cations in the proportions of the two contributions. For the anions with the Mulliken approach, the percent contributions to the hfcc's from fluorine and carbon spin populations are roughly 50/50, whereas for cations it is about 80/20. With NBO, these proportions are 80/20 for anions and 95/5 for cations. For the cations, using either Mulliken or NBO schemes, the principal contribution is due to spin population on fluorine. For the anions, the more reliable NBO spin populations show this to be true as well but to a lesser extent than for the cations. In the case of 1,2,3,4-tetrafluoronaphthalene, the differences in the hfcc's for the anion and cation radicals can be correlated to the differences in the corresponding carbon−fluorine bond. In these two radicals, the C−F bond distances are strongly affected by the charge. Geometry optimization using the EPR-II basis set yields 1.377 Å for the C_1−F_1 bond in the anion but 1.314 Å in the cation. It is tempting to conclude that longer bond distances result in smaller fluorine hfcc's and that this is due mainly to weakening

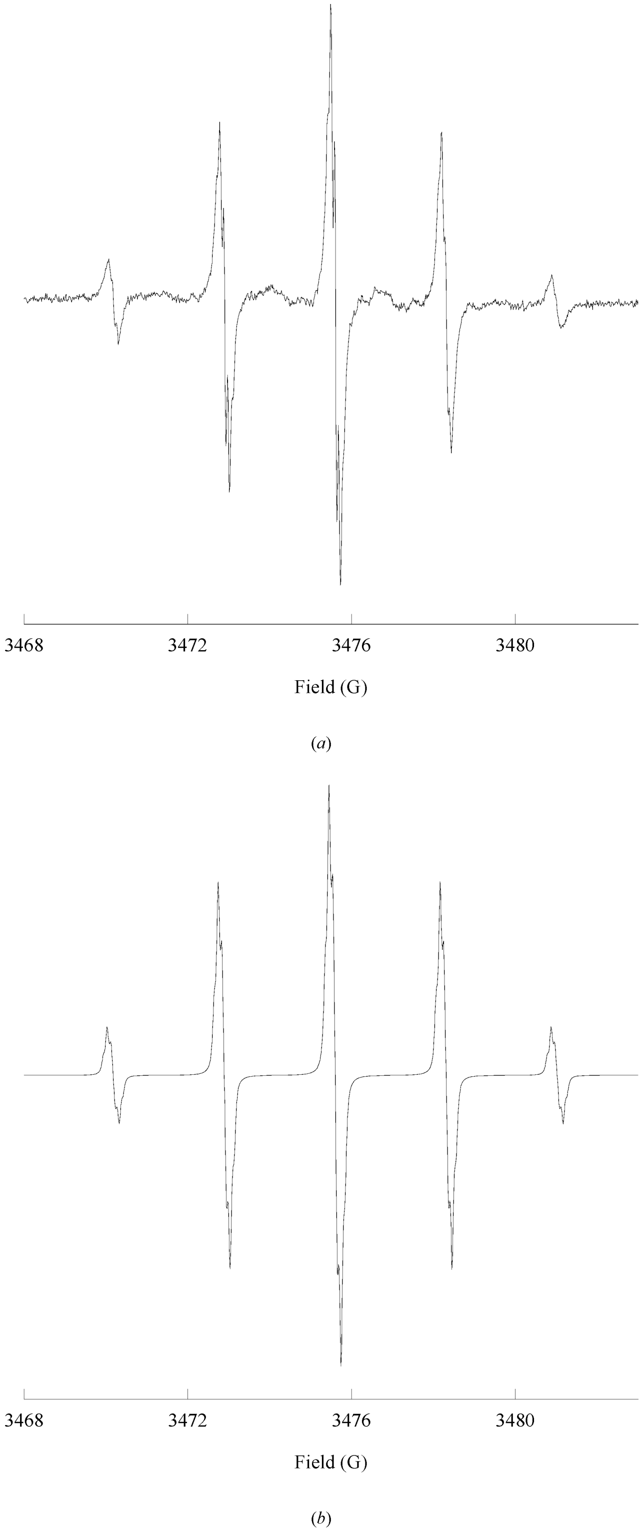


Figure 3. ESR spectrum of the radical formed upon reduction of perfluoroanthracene: (a) experiment; (b) simulation (two sets of four equivalent splittings; $A_1 = 0.10$ G, $A_2 = 2.71$ G; Lorentzian/Gaussian = 9.72; line width = 0.04 G).

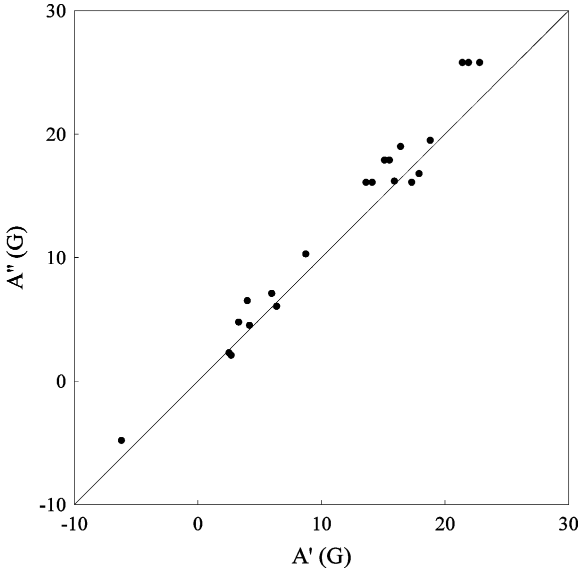


Figure 4. Plot of the experimental fluorine hfcc's A'' vs Fermi contact couplings A'. The line has the slope of unity and passes through the origin.

of the contribution from fluorine. The π-electron conjugation with the ring might be expected to be greatly weakened in the anion relative to the cation because of its greater C−F bond length. Unfortunately, we are not in a position to make a similar comparison between the anion and cation of 1,2,3,4-tetrafluoroanthracene because data for the cation are not available. Likewise, for the rest of the cation radicals in Table 2, the corresponding anion data are not available, so no general conclusion on the correlation of the hfcc's with C−F bond lengths can be reached. However, for the whole series of 21 fluorine hfcc's, including both cations and anions, we may conclude that the principal contribution to hfcc's is due to spin population on fluorine and this is the reason for the surprisingly good fit obtained with use of the one-parameter equation, eq 9.

When one compares the total spin population on fluorine to the spin population in its π-type orbitals, there is often little difference, though the difference does vary from position to position and radical to radical. On average for the 21 hfcc's studied, the difference between the total and π-type populations is only 7%. The same small percentage difference holds for the comparison between the total spin populations on the carbon atoms and their π-type spin populations. Our results confirm what might have been expected for aromatic radicals, namely, that most of the unpaired spin population resides in π-orbitals. Consequently, we expect that a fit of the experimental hfcc values to a two-parameter equation employing calculated total spin populations will result in a quality of the fit and Q-values not much different from what was obtained using π-type orbitals alone, and indeed, that is true. The fit of the hfcc's to the two-parameter equation using total Mulliken spin populations yields interaction parameters $Q_{CF} = 20.4$ G and $Q_{FF} = 370$ G, values not much different from those obtained with π-type spin populations. The average error is 10%, close to the 8% and 9% found with the π-type spin populations. This result again confirms the common notion among organic chemists that the properties of aromatic radicals are largely determined by the π-electron system.

Three-parameter equations have also been used previously by others[43,46] to explain fluorine hfcc's in aromatic compounds. Spin population in the C−F bond can contribute to the interaction. Consequently, we have fitted the experimental hfcc's to the three-parameter equation

$$A_F = Q_{CF}\rho_C^{tot} + Q_{(CF)F}\rho_{CF}^{tot} + Q_F\rho_F^{tot} \qquad (11)$$

Figure 8 shows the quality of the fit using total spin populations calculated from the Mulliken method. The points cluster closely along the line of unit slope, but the three-parameter equation does not provide an overall better fit to the data (10% average

TABLE 3: Spin Populations in the Radicals

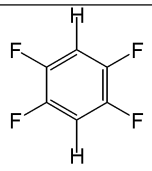
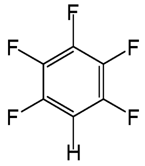
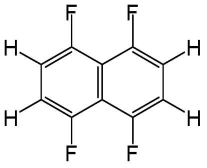
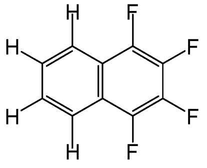
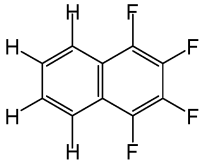
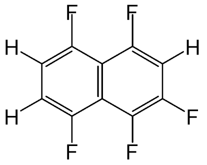
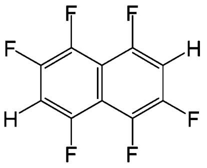
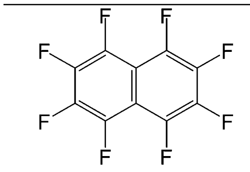
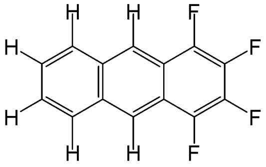
Radical	Experimental fluorine hfccs	Mulliken spin populations, ρ_F^π, ρ_C^π	Two parameter fit to Mulliken populations	% error	NBO spin populations, ρ_F^π, ρ_C^π	Two parameter fit to NBO populations	% error
 (+)	25.8 (F)	0.0548, 0.224	26.2	2	0.0681, 0.217	27.8	8
 (+)	(−)4.8 (F_1)	−0.0074, −0.0612	−4.17	13	−0.0098, −0.0684	−4.33	10
	25.8 ($F_{2,6}$)	0.0569, 0.231	27.2	5	0.0649, 0.230	26.7	3
	25.8 ($F_{3,5}$)	0.0548, 0.214	26.0	0.7	0.0628, 0.214	25.7	0.3
 (+)	16.2 (F)	0.0344, 0.176	17.2	6	0.0404, 0.174	16.9	4
 (+)	19.5 ($F_{1,4}$)	0.0404, 0.226	20.6	6	0.0473, 0.222	19.9	2
	6.51 ($F_{2,3}$)	0.0119, 0.0304	5.31	18	0.0138, 0.0417	5.60	14
 (-)	6.06 ($F_{1,4}$)	0.0097, 0.163	7.17	18	0.0156, 0.170	7.45	23
	2.11 ($F_{2,3}$)	0.0025, 0.0423	1.87	11	0.0045, 0.0447	2.10	0.7
 (+)	16.1 (F_1)	0.0292, 0.149	14.6	10	0.0341, 0.174	14.5	10
	7.1 (F_3)	0.0163, 0.0674	7.81	10	0.0190, 0.0702	7.83	10
	16.1 (F_4)	0.0371, 0.199	18.7	16	0.0432, 0.198	18.2	13
	16.8 (F_5)	0.0379, 0.202	19.1	14	0.0449, 0.199	18.8	12
	16.1 (F_8)	0.0318, 0.156	15.7	2	0.0375, 0.156	15.6	3
 (+)	17.9 ($F_{1,5}$)	0.0317, 0.170	16.0	11	0.0373, 0.167	15.6	13
	10.3 ($F_{3,7}$)	0.0215, 0.0987	10.5	2	0.0252, 0.0997	10.5	1
	17.9 ($F_{4,8}$)	0.0334, 0.177	16.8	6	0.0396, 0.147	16.3	9

TABLE 3 (Continued)

Radical	Experimental fluorine hfccs	Mulliken spin populations, ρ_F^π, ρ_C^π	Two parameter fit to Mulliken populations	% error	NBO spin populations, ρ_F^π, ρ_C^π	Two parameter fit to NBO populations	% error
 (+)	19.0 ($F_{1,4,5,8}$)	0.0350, 0.186	17.6	7	0.0411, 0183	17.2	9
	4.78 ($F_{2,3,6,7}$)	0.0100, 0.0320	4.60	4	0.0116, 0.0348	4.71	2
 (-)	4.52 ($F_{1,4}$)	0.0062, 0.0978	4.47	1	0.0084, 0.106	4.15	8
	2.30 ($F_{2,3}$)	0.0029, 0.0370	1.89	18	0.0038, 0.0383	1.80	22

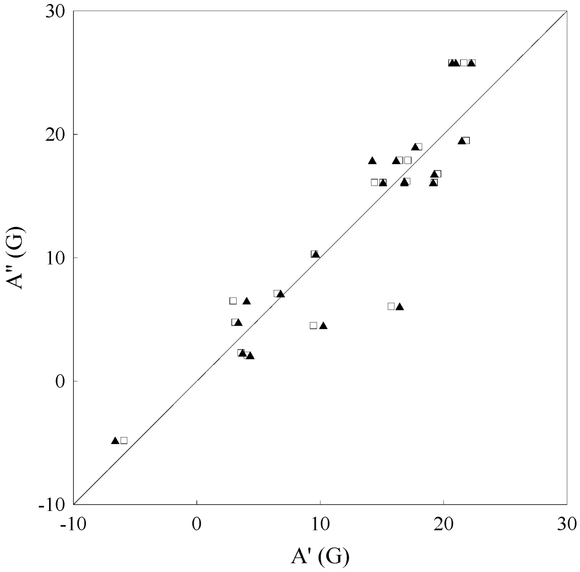


Figure 5. Plot of the experimental fluorine hfcc's A'' vs A' calculated with eq 8 using p_z-electron spin population: (☐) Mulliken; (▲) NBO. The line has the slope of unity and passes through the origin.

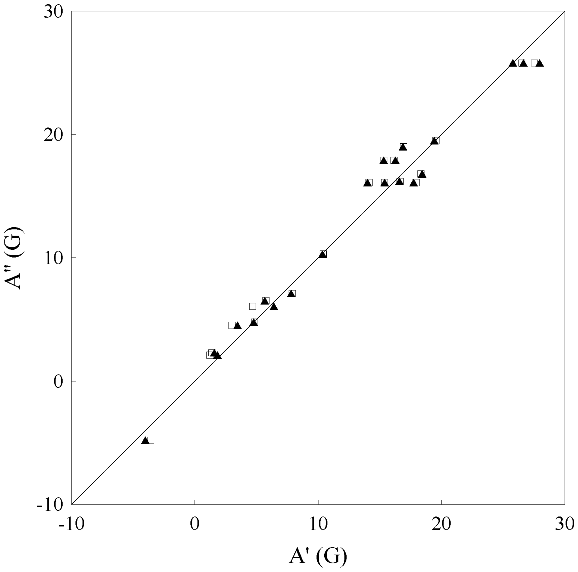


Figure 6. Plot of the experimental fluorine hfcc's A'' vs A' calculated with eq 9 using p_z-electron spin populations: (☐) Mulliken; (▲) NBO. The line has the slope of unity and passes through the origin.

error). This is explained by the fact that the ratio $\rho_{CF}^{tot}/\rho_C^{tot}$ is quite constant at almost every position at 0.14 ± 0.01. Only a few of the 21 ratios are outside of that range. The interaction parameters obtained through the fitting process are $Q_{CF} = 23.0$ G, $Q_{FF} = 362$ G, and $Q_{(CF)F} = 200$ G. The major contribution to the interaction is again the spin population on fluorine, and the contributions from carbon and carbon−fluorine spin populations tend to cancel each other because the C−F spin population is negative. We hesitate to place too much significance on conclusions based on the less-reliable Mulliken overlap spin populations. Unfortunately, the NBO scheme implemented in the Gaussian 98 package does not provide bond spin populations.

In summary, the two-parameter equation, eq 10, provides an excellent fit to the fluorine hfcc's and a reasonable interpretation of their origin. The three-parameter equation provides little additional insight into the mechanism of the interaction. The signs of the parameters Q_{CF} and Q_{FF} in both eq 10 and eq 11 emerge as positive. One might expect that Q_{CF}, which arises from a spin polarization mechanism similar to the mechanism that is the origin of the McConnell parameter Q_{CH} and which is known to work well in the description of hydrogen hfcc's, should have the same sign as the negative Q_{CH}. However, some previous studies[47,48] of fluorine hfcc's dating to the early 1970s have indicated that positive values might occur, though there has been no uniformity in the literature on this point. Our results seem quite unambiguous on this matter and the question then arises as to why the spin polarization mechanism could lead to a positive contribution to fluorine hfcc's. First, there is little doubt that almost all fluorine hfcc's in aromatic systems are positive. The sign has been established experimentally through NMR and other studies.[34−38] In terms of the two-parameter equation, a positive fluorine hfcc could arise in two ways: either both Q_{CF} and Q_{FF} are positive or one is positive and the contribution from that term overrides the negative contribution from the other term. Our work indicates that both are positive.

TABLE 4: Experimental and Calculated hfcc's of Fluorinated Benzenes

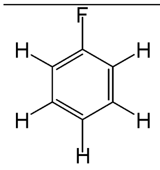
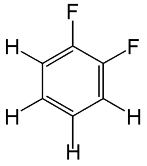
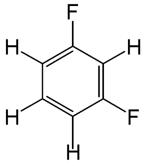
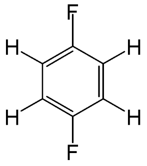
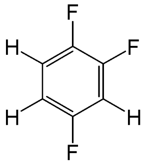
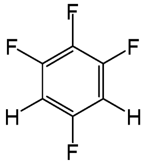
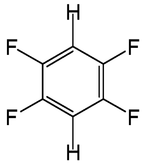
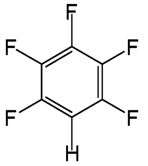
Radical	Experimental hfccs	Reference	INDO//UHF/3-21G	UB3LYP/EPR-III// UB3LYP/EPR-III
 (+)	57 (F$_1$) [CCl$_3$F]*	2	126	33 (F$_1$)
	(–)11 (H$_4$) [CCl$_3$F]		−9.1	−11
	47 (F$_1$) [c-C$_6$F$_{12}$]			
	(–)11 (H$_4$) [c-C$_6$F$_{12}$]			
 (+)	42 (F$_{1,2}$) [CCl$_3$F]	2	90	26
	(–)5 (H$_{4,5}$) [CCl$_3$F]		−4.9	−6.6
 (+)	37 (F$_{1,3}$) [CCl$_3$F]	2	63	20
	(–)3 (H$_{4,6}$) [CCl$_3$F]		−8.2	−9.6
	36 (F$_{1,3}$) [c-C$_6$F$_{12}$]			
	(–)3 (H$_{4,6}$) [c-C$_6$F$_{12}$]			
 (+)	54 (F$_{1,4}$) [CCl$_3$F]	2	99	32
	(–)2 (H$_{2,3,5,6}$) [CCl$_3$F]		−1.3	−1.9
 (+)	55 (F$_1$) [c-C$_6$F$_{12}$]	2	99	32
	26 (F$_2$) [c-C$_6$F$_{12}$]		45	13
	47 (F$_4$) [c-C$_6$F$_{12}$]		67	26
	(–)6 (H$_5$) [c-C$_6$F$_{12}$]		−4.0	−5.3
 (+)	58 (F$_1$) [c-C$_6$F$_{12}$]	2	134	37
	11 (F$_{2,6}$) [c-C$_6$F$_{12}$]		18	3.5
	44 (F$_4$) [c-C$_6$F$_{12}$]		67	27
	(–)1 (H$_{3,5}$) [c-C$_6$F$_{12}$]		−0.8	−1.6
 (+)	38 (F$_{2,3,5,6}$) [c-C$_6$F$_{12}$]	2	63	22
	2 (H$_{4,6}$) [c-C$_6$F$_{12}$]		1.9	1.5
	25.8 (F$_{2,3,5,6}$)	1		
	~0 (H$_{4,6}$)			

TABLE 4 (Continued)

Radical	Experimental hfccs	Reference	INDO//UHF/3-21G	UB3LYP/EPR-III//UB3LYP/EPR-III
	(–)6 (F_1) [c-C_6F_{12}]	2	−13.4	−6.2
	45 ($F_{2,6}$) [c-C_6F_{12}]		67	23
	43 ($F_{3,5}$) [c-C_6F_{12}]		63	21
	~0 (H_4) [c-C_6F_{12}]		1.5	1.3
(+)				
	(–)4.8 (F_1)	1		
	25.8 ($F_{2,6}$)			
	25.8 ($F_{3,5}$)			
	~0 (H_4)			

[a] Chemical formula in brackets is the matrix substance.

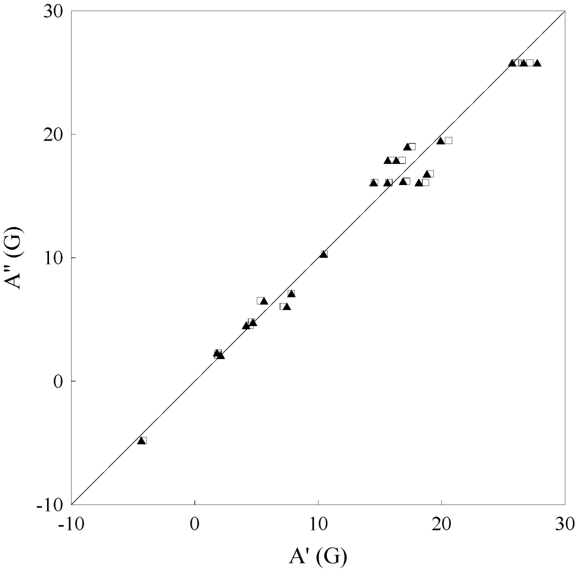


Figure 7. Plot of the experimental fluorine hfcc's A'' vs A' calculated with eq 10 using p_z-electron spin populations: (□) Mulliken; (▲) NBO. The line has the slope of unity and passes through the origin.

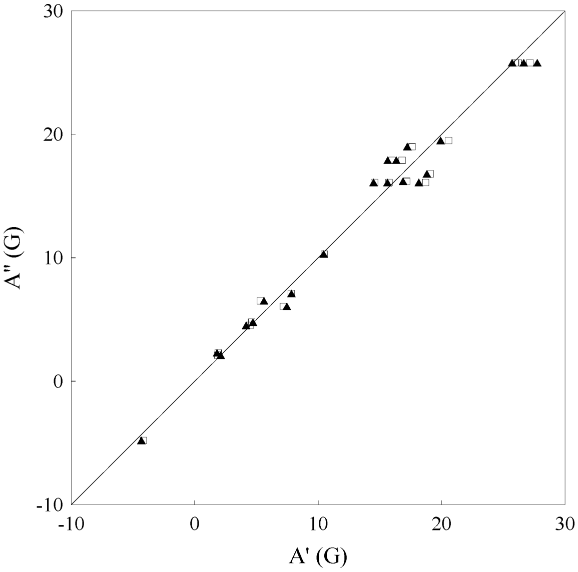


Figure 8. Plot of the experimental fluorine hfcc's A'' vs A' calculated with eq 11 using total Mulliken spin populations. The line has the slope of unity and passes through the origin.

The negative sign for Q_{CH} is usually explained as arising from the operation of Hund's rule that aligns the spins parallel in the π- and σ-orbitals of carbon in the C−H fragment. This is followed by an antiparallel alignment of spins in the σ-orbital of carbon and the s-orbital of hydrogen in the C−H bond, resulting in an overall negative hfcc. However, Hund's rule of maximum spin is a qualitative rule that holds in many but not all cases;[49] hence, there is no fundamental reason for Q_{CF} to be negative.

Hasegawa et al.[2] have performed experimental and theoretical studies of a number of fluorinated benzene radicals. Two of those radicals, the cations of 2,3,5,6-tetrafluorobenzene and pentafluorobenzene, are among the radicals studied here. It is of interest to compare their experimental results and INDO//UHF/3-21G calculations to the experimental data of Schastnev and Zhidomirov[1] and to our calculated hfcc values for these radicals as shown in Table 4. Because these are all one-ring structures and many of them are highly symmetric, all geometry optimizations in this case were performed with the more computationally expensive EPR-III basis. First, comparing the isotropic fluorine splittings obtained by Hasegawa et al. in halocarbon solid matrixes at low temperatures to Schastnev and Zhidomirov's room-temperature data in liquid solution we see that the former values are about 50−60% higher. Our calculated fluorine hfcc's correspond closely to Schastnev and Zhidomirov's values. There are two possible explanations for the discrepancy. The first is that Hasegawa et al. did not directly determine the isotropic hfcc's from the spectra but obtained them from the values of $A_{\|}$ and $A_{\perp}$, which in turn were not derived directly from the positions of individual lines in the spectra but instead by simulating the overall line shape of the powder-like spectra. The second is that the halocarbon matrix may influence the values of the hfcc's as indicated by the data in Table 1 of ref 2. The difference in temperature may also play a small role.

The INDO//UHF/3-21G predictions[2] are 50% higher than the low-temperature data and 2−3 times higher compared to the solution data of Schastnev and Zhidomirov. This overestimation of fluorine hfcc's by INDO has been noted before.[16,50] In contrast, our theoretical UB3LYP/EPR-III//UB3LYP/EPR-III values of the isotropic hfcc's for fluorine match closely the experimental values in solution (see Table 4).

Conclusions

We have obtained and assigned the new ESR spectra of the anion radicals of 1,2,3,4-tetrafluoronaphthalene, 1,2,3,4-tetrafluoroanthracene, and 9,10-perfluoroanthraquinone not previously reported in the literature. Application of the UB3LYP density functional method in conjunction with the EPR-III basis set of Barone to the calculation of the Fermi contact hyperfine splitting constants in these and the other fluorinated aromatic ion radicals studied yields values of the constants to within 15% of the experimental ones. This level of agreement between theory and experiment matches or exceeds the best correlations found with the older semiempirical and approximate UHF calculations, such as the Hückel−McLachlan and UHF−INDO methods, and our study provides the best results obtained to date on larger aromatic radicals using modern methods of electronic structure calculation.

We find that fluorine hfcc's in the radicals in question can be adequately represented to less than 10% average error with a simple two-parameter equation, which is a function of the spin populations on the fluorine atom and the ring carbon atom to which it is bonded. Our results support the common notions of the separability of the σ- and π-electron systems in these aromatic compounds and that their properties are largely a result of the π-electron contribution.

In this article, we focused our attention on fluorinated radicals of the first three members of the series of PAHs: benzene, naphthalene, and anthracene. In the future, we hope to extend the methods developed here to investigate a series of radicals formed from fluorine- and methyl-substituted benzanthracenes. The carcinogenicity of these compounds is known to depend strongly on the positions of the fluorine and methyl substituents,[51−53] and consequently, the information gained about the electronic structure of their radicals is of considerable interest.

Acknowledgment. The authors thank Dr. G. R. Pack and Dr. G. Lamm of the University of Louisville Chemistry Department, as well as the University of Louisville Dahlem Supercomputer Center, for providing the computational resources for this work. A.R. was supported by Grant GM29079 from the National Institutes of Health to G.R.P. The parent compounds for the study were kindly provided to us by Prof. R. Filler at the Illinois Institute of Technology.

References and Notes

(1) Schastnev, P. V.; Zhidomirov, G. M. *Zh. Strukt. Khim.* **1969**, *10*, 998.
(2) Hasegawa, A.; Itagaki, Y.; Shiotani, M. *J. Chem. Soc., Perkin Trans. 2* **1997**, 1631.
(3) Thomson, C.; McCulloch, W. J. *Mol. Phys.* **1970**, *19*, 817.
(4) McConnell, H. M. *J. Chem. Phys.* **1956**, *24*, 764.
(5) McConnell, H. M.; Chesnut, D. B. *J. Chem. Phys.* **1958**, *28*, 107.
(6) Weil, J. A.; Bolton J. R.; Wertz, J. E. *Electron Paramagnetic Resonance. Elementary Theory and Practical Applications*; John Wiley & Sons: New York, 1994.
(7) McLachlan, A. D. *Mol. Phys.* **1960**, *3*, 233.
(8) Pople, J. A.; Beveridge, D. L. *Approximate Molecular Orbital Theory*; McGraw-Hill: New York, 1970.
(9) Cohen, M. J.; Chong, D. P. *Chem. Phys. Lett.* **1995**, *234*, 405.
(10) Barone, V. *Theor. Chim. Acta* **1995**, *91*, 113.
(11) Hou, X.-J.; Huang, M.-B. *J. Phys. Chem. A* **2002**, *106*, 10655.
(12) Gauld, J. W.; Eriksson, L. A.; Radom, L. *J. Phys. Chem. A* **1997**, *101*, 1352.
(13) Schreckenbach, G.; Ziegler, T. *Theor. Chem. Acc.* **1998**, *99*, 71.
(14) Koch, W.; Holthausen, M. C. *A Chemist's Guide to Density Functional Theory*, 2 ed.; Wiley-VCH: Weinheim, Germany, 2001.
(15) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648.
(16) Batra, B.; Giese, B.; Spichty, M.; Gescheidt, G.; Houk, K. N. *J. Phys. Chem.* **1996**, *100*, 18371.
(17) Morokuma, K.; Konishi, H. *Chem. Phys. Lett.* **1971**, *12*, 408.
(18) Barone, V. *Recent Advances in Density Functional Methods*; World Scientific: Singapore, 1995; Part 1, p 287.
(19) Rega, N.; Cossi, M.; Barone, V. *J. Chem. Phys.* **1996**, *105*, 11060.
(20) Mattar, S. M.; Emwas, A. H.; Stephens, A. D. *Chem. Phys. Lett.* **2002**, *363*, 152.
(21) Lahorte, P.; De Proft, F.; Callens, F.; Geerlings, P.; Mondelaers, W. *J. Phys. Chem. A* **1999**, *103*, 11130.
(22) Eloranta, J.; Suontamo, R.; Vuolle, M *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 3313.
(23) Adamo, C.; Subra, R.; Di Matteo, A.; Barone, V. *J. Chem. Phys.* **1998**, *109*, 10244.
(24) Hudson, A.; Lewis, J. W. *J. Chem. Soc. B* **1969**, 531.
(25) Vatanen, V.; Eloranta, J. M.; Vuolle, M. *Magn. Reson. Chem.* **1999**, *37*, 774.
(26) Barone, V.; Crescenzi, O.; Improta, R. *Quant. Struct.-Act. Relat.* **2002**, *21*, 105.
(27) Cantrell, G. L.; Filler, R. *J. Org. Chem.* **1984**, *49*, 3406.
(28) Cantrell, G. L.; Filler, R. *J. Fluorine Chem.* **1985**, *29*, 417.
(29) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.7; Gaussian, Inc.: Pittsburgh, PA, 1998.
(30) Krishnan, R.; Blinkley, J. S.; Seeger, R.; Pople, J. A. *J. Chem. Phys.* **1980**, *72*, 650.
(31) Frisch, M. J.; Pople, J. A.; Blinkley, J. S. *J. Chem. Phys.* **1984**, *80*, 3265.
(32) Dunning, T. H., Jr. *J. Chem. Phys.* **1989**, *90*, 1007.
(33) Wilson, A. K.; van Mourik, T.; Dunning, T. H., Jr. *J. Mol. Struct.* **1996**, *388*, 339.
(34) Eaton, D. R.; Josey, A. D.; Benson, R. E.; Phillips, W. D.; Cairns, T. L. *J. Am. Chem. Soc.* **1962**, *84*, 4100.
(35) Icli, S.; Kreilick, R. W. *J. Phys. Chem.* **1971**, *75*, 3462.
(36) Bolton, J. R.; Fraenkel, G. K. *J. Chem. Phys.* **1964**, *40*, 3307.
(37) Brinkman, M. R.; Bethell, D.; Hayes, J. *J. Chem. Phys.* **1973**, *59*, 3431.
(38) Bargon, J.; Seifert, K.-G. *J. Phys. Chem.* **1973**, *77*, 2877.
(39) Kaplan, M.; Bolton, J. R.; Fraenkel, G. K. *J. Chem. Phys.* **1965**, *42*, 955.
(40) Brown, J. K.; Williams, W. G. *Trans. Faraday Soc. 2* **1968**, *64*, 298.
(41) Hinchcliffe, A.; Murrell, J. N. *Mol. Phys.* **1968**, *14*, 147.
(42) Kulkarni, S. V.; Trapp, C. *J. Am. Chem. Soc.* **1970**, *92*, 4801.
(43) Fischer, P. H. H.; Colpa, J. P. *Z. Naturforsch. A* **1969**, *24*, 1980.
(44) Mulliken, R. S. *J. Chem. Phys.* **1955**, *23*, 1833.
(45) Reed, A. E.; Weinstock, R. B.; Weinhold, F. *J. Chem. Phys.* **1985**, *83*, 735.
(46) Schastnev, P. V.; Zhidomirov, G. M. *Zh. Strukt. Khim.* **1964**, *5*, 839.
(47) Konishi, H.; Morokuma, K. *J. Am. Chem. Soc.* **1972**, *94*, 5603.
(48) Kumari, U.; Ray, N. K. *Int. J. Quantum Chem.* **1973**, *7*, 215.
(49) Cowan, R. D. *The Theory of Atomic Structure and Spectra*; University of California Press, Ltd.: Berkeley, CA, 1981; p 124.
(50) Benson, H. G.; Hudson, A.; Lewis, J. W. E. *Mol. Phys.* **1971**, *21*, 935.
(51) Miller, E. C.; Miller, J. A. *Cancer Res.* **1960**, *20*, 133.
(52) Bergmann, E. D.; Blum, J.; Haddow, A. *Nature* **1963**, *200*, 480.
(53) Dunning, W. F.; Curtis, M. R. *J. Natl. Cancer Inst.* **1960**, *25*, 387.