(5) D. M. Grant, R. J. Pugmire, E. P. Black, and K. A. Christensen, *J. Amer. Chem. Soc.*, **95**, 8465 (1973).

(6) J. P. Kintzinger and J. M. Lehn, *Mol. Phys.*, **27**, 491 (1974).

(7) S. Berger, F. R. Kreissl, and J. D. Roberts, *J. Amer. Chem. Soc.*, **96**, 4348 (1974).

(8) (a) J. A. Nelder and R. Mead, *Comput. J.*, **7**, 308 (1964). (b) We would like to thank A. F. Chang (Caltech Computing Center) for making a corresponding routine available to us and for many helpful discussions.

(9) W. C. Hamilton in "Statistics in Physical Science," Ronald Press, New York, N.Y., 1964, pp 121-128.

(10) R. S. Becker, S. Berger, D. K. Dalling, D. M. Grant, and R. J. Pugmore, *J. Amer. Chem. Soc.*, submitted for publication.

(11) R. Freeman, H. D. W. Hill, and R. Kaptein, *J. Magn. Resonance*, **7**, 82 (1972).

(12) D. L. Hawkins and J. D. Roberts, *Proc. Nat. Sci. U. S.*, **70**, 1027 (1973).

(13) I. M. Armitage, H. Huber, D. Live, H. Pearson, and J. D. Roberts, *J. Magn. Resonance*, in press.

(14) K. F. Kuhlmann and D. M. Grant, *J. Chem. Phys.*, **55**, 1998 (1971).

(15) M. J. S. Dewar, Quantum Chemistry Program Exchange, Program No. 136, Indiana University, 1970.

(16) (a) "Table of Interatomic Distances and Configuration in Molecules and Ions," *Chem. Soc., Spec. Publ.*, **No. 18** (1965); (b) R. Pasternak and A. Y. Meyer, *J. Mol. Struct.*, **20**, 351 (1974); (c) R. M. Moriorty, *Top. Stereochem.*, **8**, 271 (1973); (d) W. J. Adams, H. J. Geise, and L. S. Bartell, *J. Amer. Chem. Soc.*, **92**, 5013 (1970); (e) H. J. Geise, H. R. Buys, and F. C. Mihlhoff, *J. Mol. Struct.*, **9**, 447 (1971); (f) J. B. Hendrickson, *J. Amer. Chem. Soc.*, **83**, 4537 (1961); (g) R. Bucourt, *Top. Stereochem.*, **8**, 159 (1973); (h) R. Skrinavasan and T. Skrinavasan, *Tetrahedron*, **27**, 1009 (1971).

(17) It should be noted that the molecular geometries used for the calculations were slightly asymmetric. The average of the calculated values for equivalent carbon atoms is given in Table II.

Fluoropyridines. Carbon-13 Chemical Shifts and Carbon–Fluorine Coupling Constants

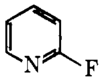
Robert L. Lichter*[1a] and Roderick E. Wasylishen*[1b]

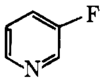
Contribution from the Department of Chemistry, Hunter College of the City University of New York, New York, New York 10021, and the National Institute of Arthritis, Metabolism, and Digestive Diseases, Bethesda, Maryland 20014.

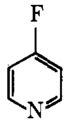
Received May 16, 1974

Abstract: Carbon-13 chemical shifts and all ^{13}C–F coupling constants have been determined for 2-, 3-, and 4-fluoropyridine and pyridinium ions. With the exception of C_2 in the 2-fluoro compounds, chemical shifts are derived additively from those of the corresponding carbons in pyridine, pyridinium ion, and fluorobenzene. $^1J_{CF}$ in 2-fluoropyridine is algebraically more positive than $^1J_{CF}$ in 3- and 4-fluoropyridine, consistent with a positive contribution associated with the presence of a proximate lone pair orbital. Protonation induces increases in the one-bond couplings of 2- and 4-fluoropyridine, while that of 3-fluoropyridine is unaffected. Many of the detailed trends exhibited by the coupling constants are paralleled by values of J_{CH} in pyridine and fluorobenzene, as well as some other heterocycles, although only crude overall correlations exist. A better correlation exists between corresponding values in the fluoronitrobenzenes vs. the fluoropyridinium ions. Most of the experimental coupling trends are reproduced by values calculated using finite perturbation theory in the INDO MO approximation assuming only the Fermi contact mechanism.

Our current interest in carbon-13 magnetic resonance parameters of unsaturated nitrogen compounds[2] has led us to examine a series of fluorinated pyridines. These are of interest because of the possibility that geometry-dependent interactions involving the lone-pair orbitals may affect chemical shifts and coupling constants. It has already been amply documented that nitrogen lone-pair orientation markedly affects coupling constants to nitrogen[2,3] and coupling between nuclei with different relative spatial proximity to the lone pair.[4] We report here ^{13}C magnetic resonance data on 2-, 3-, and 4-fluoropyridine (**1–3**) and the pyridinium ions.


1


2


3

The carbon magnetic resonance parameters of these compounds display systematic variations which allow comparison with structurally related compounds and with semiempirical MO calculations. The latter have been carried out in order to determine the extent to which the Fermi contact term can account for the observed coupling constants. Earlier published work[5] did not include **2** and **3** because of their unavailability; indeed only recently has **3** been described.[6]

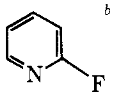
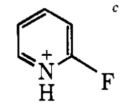
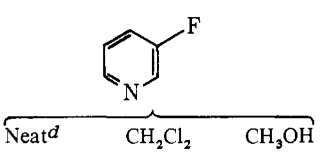
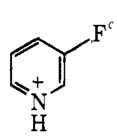
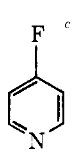
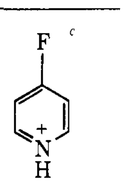
Experimental Section

Materials. 2-Fluoropyridine was obtained from Aldrich Chemical Co., while 3-fluoropyridine and 4-fluoropyridine hydrochloride were gifts from Olin Chemical. The hydrochlorides of **1** and **2** were precipitated upon passage of HCl gas through solutions of **1** and **2** in dry ether. 4-Fluoropyridine was obtained from the hydrochloride by addition of ice water to a cold suspension of the salt and potassium carbonate in dichloromethane, into which the free base was immediately extracted. The dried (K_2CO_3) solution was used directly for the NMR study.

NMR Spectra. Compounds **1** and **2** were run as neat liquids; **2** was also run as dilute (~10%) solutions in dichloromethane and in methanol; a small solvent effect is apparent. 4-Fluoropyridine and all the hydrochlorides were run as solutions in dichloromethane. Spectra were obtained in Fourier transform mode on a JEOL PS/PFT-100 spectrometer with the JEOL EC-100 data system. Chemical shifts were measured with respect to solvent resonances and converted to the TMS scale with the following factors:[7] δ (TMS) = δ (CH_2Cl_2) + 54.0; δ (TMS) = δ (CH_3OH) + 44.3. Resonance positions were determined using a 5-kHz range and 16K words of memory, giving a digital resolution of 0.6 Hz. Coupling constants were measured from 2-kHz spectra and 16K words of memory, with a digital resolution of 0.24 Hz. The line broadening induced by exponential smoothing of the free induction decay amounted to 0.22 Hz. The deuterium internal lock was derived from a deuteriobenzene capillary.

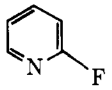
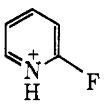
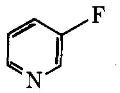
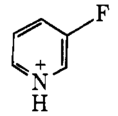
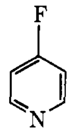
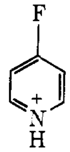
Method of Calculation. Coupling constants were calculated on an IBM-360/165 computer using the finite perturbation theory of Pople[8] in the INDO approximation. The geometry of 2-fluoropyridine was taken from a microwave study,[9] while those of 3- and 4-fluoropyridine were assumed the same as that of pyridine.[10] The C–F bond length of 2-fluoropyridine (1.354 Å) was used in all six calculations. The geometry of the fluoropyridinium ions was assumed to be that of pyridinium hydrochloride.[11]

Table I. ^{13}C Chemical Shifts and C-F Coupling Constants of Fluoropyridines and Pyridinium Ions[a]

	 [b]	 [c]	 Neat[d]	CH_2Cl_2	CH_3OH	 [c]	 [c]	 [c]
δ_{C_2}	164.6 185.0[f]	159.2 (−5.4)[e] 177.2 [−7.8][g]	138.1 137.2	138.3	137.9	130.5 (−7.8) 129.4 [−7.8]	152.5 151.6	145.8 (−6.7) 143.8 [−7.8]
δ_{C_3}	110.5 100.9	112.0 (1.5) 116.0 [5.0]	159.6 158.7	159.8	160.5	159.4 (−0.4) 163.8 [5.0]	111.8 110.0	116.0 (4.2) 116.0 [5.0]
δ_{C_4}	141.8 137.3	148.1 (6.3) 149.7 [12.4]	122.4 122.9	122.7	124.0	133.3 (10.6) 135.3 [12.4]	168.7 170.7	173.0 (4.3) 183.1 [12.4]
δ_{C_5}	122.1 119.4	123.0 (0.9) 124.5 [5.0]	124.4 125.3	124.5	125.7	129.0 (4.5) 130.4 [5.0]		
δ_{C_6}	148.3 151.6	141.5 (−6.8) 143.8 [−7.8]	145.7 145.7	145.9	145.7	138.0 (−7.8) 137.5 [−7.8]		
J_{2F}	236.3	263.4 (27.1)[h]	22.5	22.6	23.2	34.6 (12.0)	6.4	12.2 (5.8)
J_{3F}	37.6	24.4 (−13.2)	255.4	255.1	254.6	255.3 (−0.2)	16.1	21.4 (5.3)
J_{4F}	7.5	9.8 (2.3)	18.1	17.7	18.3	18.3 (0.6)	261.8	280.2 (18.4)
J_{5F}	4.2	3.8 (−0.8)	4.3	3.7	4.2	7.0 (3.3)		
J_{6F}	14.9	1.5 (−13.4)	2.9	3.7	3.9	3.7 (0)		

[a] Chemical shifts in ppm from TMS, coupling constants in Hz. Estimated errors = ±0.1 ppm and 0.2 Hz, respectively. [b] Chemical shifts from ref 5b. [c] CH_2Cl_2 solvent. [d] Contained ~10% CH_2Cl_2. [e] Numbers in parentheses are the protonation shifts: $\Delta\delta = \delta_{ion} - \delta_{base}$ (CH_2Cl_2 solvent). [f] Numbers underlined are calculated shifts (see text). [g] Numbers in brackets are protonation shifts for pyridine (ref 12). [h] Numbers in parentheses are protonation induced changes in J_{CF}: $\Delta J = J_{ion} - J_{base}$.

Table II. Nitrogen Substituent Effect on ^{13}C Chemical Shifts and Coupling Constants of Fluorobenzene[a]

						
$\Delta\delta C_2$	1.7 (21.9)[b]	−3.7 (14.1)	23.2 (21.9)	15.4 (14.1)	2.25 (21.9)	18.8 (14.1)
$\Delta\delta C_3$	−4.6 (−4.4)	−3.1 (0.6)	−3.1 (−4.4)	−3.5 (0.6)	−3.3 (−4.4)	0.9 (0.6)
$\Delta\delta C_4$	11.8 (7.6)	18.1 (20.0)	7.6 (7.6)	18.2 (20.0)	5.8 (7.6)	10.0 (20.0)
$\Delta\delta C_5$	−2.0 (−4.4)	−1.1 (0.6)	−5.5 (−4.4)	−1.0 (0.6)		
$\Delta\delta C_6$	18.3 (21.9)	11.5 (14.1)	21.8 (21.9)	13.9 (14.1)		
$\Delta J_2 F$	−9.0	18.1	1.6	13.6	−1.3	4.5
$\Delta J_3 F$	16.6	3.4	9.8	10.0	−4.9	0.4
$\Delta J_4 F$	−0.2	2.1	−3.3	−2.7	16.5	34.9
$\Delta J_5 F$	0.9	0.5	−4.0	−0.7		
$\Delta J_6 F$	7.2	−6.2	0.4	0.4		

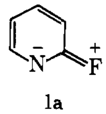
[a] Relative to fluorobenzene (ref 13); positive values denote downfield shifts or larger coupling constants. [b] Numbers in parentheses give corresponding nitrogen substituent effects in pyridine and pyridinium ion relative to benzene.

Results

Carbon-13 chemical shifts and C-F coupling constants for **1**–**3** and their hydrochlorides are given in Table I. The protonation shifts are given explicitly as are, for comparison, the corresponding protonation shifts for pyridine.[12] The substituted carbons were recognizable from the large C-F coupling constants; remaining carbons in 2-fluoropyridine have been reported earlier.[5c,e] Each carbon in both free and protonated compounds was assigned by comparing the measured shift with that calculated on the assumption that the fluorine substituent effect in fluorobenzene relative to benzene[13] could be added to the shift of the given carbon in pyridine or pyridinium ion.[12] For each compound excellent correlations were obtained ($r > 0.99$) except for C_2 of **1** and its hydrochloride (**1**-H$^+$). The measured and calculated shifts are compared in Figure 1, where $r = 0.992$. The only ambiguity arose in the assignments of C_2 and C_5 of **2**-H$^+$, where a better fit is obtained if the chemical shifts given in Table I are reversed. In that case, however, the associated C-F coupling constants are inconsistent with the trends observed for the remaining fluoropyridines and other fluoroaromatics.[14] To facilitate discussion, the data are also given with respect to fluorobenzene (Table II) and pyridine or pyridinium ion (Table III). These correspond to the nitrogen and fluorine substituent effects on fluorobenzene and pyridine, respectively. The calculated coupling constants are given in Table V.

Discussion

Chemical Shifts. The correlation in Figure 1 demonstrates that fluorine substituent effects are additive over a fairly large range of ring positions. The largest deviations might be expected in those cases where extensive conjugative interaction between fluorine and nitrogen is possible, i.e., C_2 and C_4 of **1** and **3**, respectively, because interactions of the type represented by **1a** and **3a** would tend to change


1a

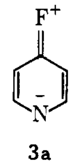
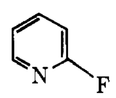
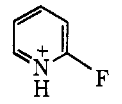
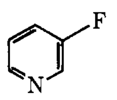
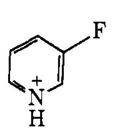
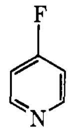
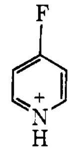

3a

Table III. Fluorine Substituent Effect on ^{13}C Chemical Shifts of Pyridines[a]

						
$\Delta\delta C_2$	14.2 (34.4)[b]	16.6 (34.4)	−12.1 (−13.4)	−12.1 (−13.4)	2.1 (1.5)	3.2 (1.5)
$\Delta\delta C_3$	−13.6 (−13.4)	−17.1 (−13.4)	35.7 (34.4)	30.3 (34.4)	−12.3 (−13.4)	−13.1 (−13.4)
$\Delta\delta C_4$	5.7 (1.5)	−0.4 (1.5)	−13.4 (−13.4)	−15.2 (−13.4)	32.6 (34.4)	24.5 (34.4)
$\Delta\delta C_5$	−2.0 (−4.4)	−6.1 (−4.4)	0.4 (1.5)	−0.1 (1.5)		
$\Delta\delta C_6$	−2.1 (1.5)	−1.1 (1.5)	−0.5 (−4.4)	−4.6 (−4.4)		

[a] Relative to pyridine and pyridinium ion, respectively (ref 12). Positive values denote downfield shifts. [b] Numbers in parentheses are the corresponding substituent effect for fluorobenzene relative to benzene (ref 14).

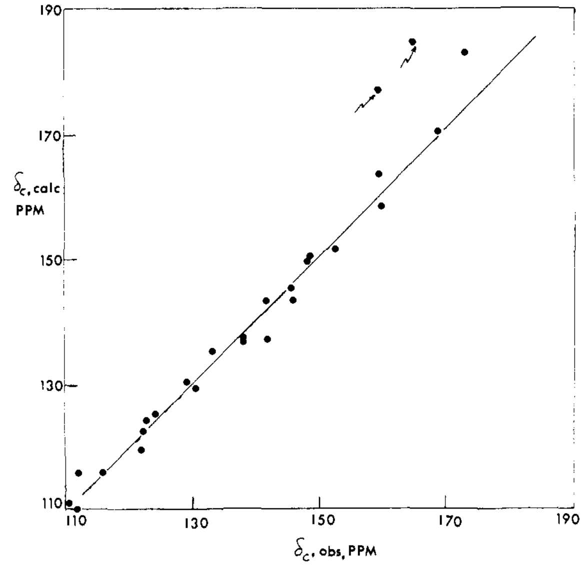


Figure 1. Plot of experimental vs. calculated ^{13}C chemical shifts of fluoropyridines. The indicated points were excluded from the calculation of the least-squares line shown.

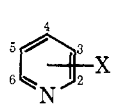
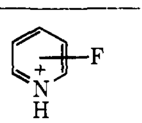
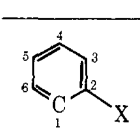
the C–N π bond orders and the molecular electron distributions in a manner not reflected by substituent parameter additivity. Indeed, C_2 in both the free and protonated forms of **1** shows the largest deviation and is not included in the calculation of the least-squares line in Figure 1. However, C_4 in **3**-H$^+$ shows a smaller deviation, while the corresponding position in **3** falls on the correlation line. Retcofsky and Friedel[5b] have discussed the effect of substitution at the 2 position within the theoretical framework for nitrogen heterocycle carbon shieldings given by Pugmire and Grant,[15] in which substantial charge removal by inductively electron-withdrawing groups can induce upfield shifts of carbon resonance positions. The action of both nitrogen and fluorine on C_2 of **1** and **1**-H$^+$ would then be expected to induce the largest deviation, as is observed. Within this framework, the smaller but substantial (10 ppm) upfield deviation of C-4 in **3**-H$^+$ relative to the calculated value suggests that the inductive effect, while attenuated, nevertheless dominates the chemical shifts.

Examination of the explicit substituent effects in Tables II and III suggests alternative ways to view the data. In both tables, **2** and **2**-H$^+$ display substituent effects which correspond most closely to those observed for pyridine and fluorobenzene relative to benzene. Large deviations from these values are exhibited by C_2 of **1** and C_4 of **3**. From Table II, a smaller downfield shift is induced at C_2 (C_1 of fluorobenzene) by incorporation of nitrogen compared to the corresponding shift arising when nitrogen is incorporated into the benzene ring. Alternatively (Table III), C_2 of pyridine experiences a smaller downfield shift upon substitution with fluorine than does the carbon of benzene; similar descriptions hold for C_4 of **3**-H$^+$. Thus, the effect of a second electronegative substituent at a carbon is attenuated by the presence of the first, an observation consistent with the Pugmire-Grant hypothesis[15] for C_2 and apparent in the 2-substituted pyridines reported by Retcofsky.[5] The same effect is discernible in polyhalomethanes.[16]

The protonation shifts (Table I) merit brief comment. In all cases the values are smaller than in pyridine itself; indeed, essentially no change is induced at C_3 of **2**. Presumably, for the reasons discussed above, electron withdrawal by the positive nitrogen is attenuated by competition from the electronegative fluorine, although the expected enhanced conjugative donation in **1** and **3** evidently compensates in part.

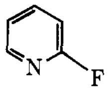
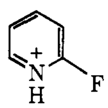
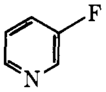
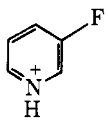
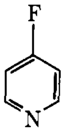
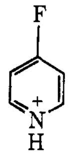
Coupling Constants. $^1J_{CF}$. Weigert and Roberts have measured a series of C–F coupling constants in substituted fluorobenzenes.[14] Resonance effects on $^1J_{CF}$ appeared to be important for para-substituted fluorobenzenes, but were increasingly less so for the meta and ortho compounds. If 3-fluoropyridine is taken as a model for the absence of conjugative N–F interaction, the nitrogen appears to act inductively to increase $^1J_{CF}$ relative to fluorobenzene (245.3 Hz)[14] in the manner expected for an electronegative substituent. In 4-fluoropyridine the inductive effect is smaller, but back-donation of the fluorine π electrons (**3a**) increases the C–F bond order which would increase $^1J_{CF}$.[17] This supposition is lent some support by the constancy on protonation of $^1J_{CF}$ and δ_{C3} of **2** where conjugative interaction is absent; on the other hand, $^1J_{CF}$ in **3** increases by 18.4 Hz,

Table IV. Comparison of Carbon–Fluorine and Carbon–Hydrogen Coupling Constants

					
	X = H[a]	X = F		X = H[b]	X = F[c]
$J_{C_2X_2}$	177.63	−236.3	−263.4	157.5	−245.3
$J_{C_3X_2}$	8.47	37.6	24.4	1.1	21.0
$J_{C_4X_2}$	6.34	±7.5	±9.8	7.6	±7.7
$J_{C_5X_2}$	−1.65	±4.2	±3.4	−1.2	±3.3
$J_{C_6X_2}$	11.16	±14.9	±1.5	7.6	±7.7
$J_{C_2X_3}$	3.12	22.6	34.6		
$J_{C_3X_3}$	163.04	−255.1	−255.3		
$J_{C_4X_3}$	0.70	17.7	18.3		
$J_{C_5X_3}$	6.56	±3.7	±7.0		
$J_{C_6X_3}$	−0.92	±3.7	±3.7		
$J_{C_2X_4}$	6.85	±6.4	±12.2		
$J_{C_3X_4}$	0.84	16.1	21.4		
$J_{C_4X_4}$	162.41	−261.8	−280.2		

[a] Reference 18. [b] Reference 13b. [c] Reference 14.

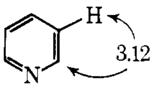
Table V. Calculated Fermi Contact Contributions to J_{CF} in Fluoropyridines and Fluoropyridinium Ions

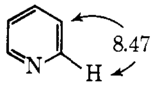
	 J_{CF}, Hz	 J_{CF}, Hz	ΔJ, Hz[a]	 J_{CF}, Hz	 J_{CF}, Hz	ΔJ, Hz[a]	 J_{CF}, Hz	 J_{CF}, Hz	ΔJ, Hz[a]
C_2	−200.6	−340.4	−139.8	−3.3	5.6	8.9	10.0	13.5	3.5
C_3	11.9	4.6	−7.3	−239.2	−338.2	−99.0	−4.1	2.6	6.7
C_4	14.2	7.2	−7.0	−2.7	−0.4	2.3	−236.4	−281.4	−45.0
C_5	−1.3	0.7	2.0	8.0	2.5	−5.5	−4.1	2.6	6.7
C_6	19.1	−4.4	−23.5	−1.0	1.8	2.8	10.0	13.5	3.5

[a] Calculated protonation effect: $\Delta J = J_{\text{ion}} - J_{\text{base}}$.

which may be interpreted by the greater conjugative electron withdrawal in the pyridinium ion. From both these viewpoints, $^1J_{CF}$ in **2** is expected to be larger than in fluorobenzene, contrary to observation. Clearly some other effect must operate and one possibility is that the proximate lone pair plays a role in transmitting spin information. The nitrogen lone-pair orbital is known to induce variations in $^1J_{CH}$[3b,4] such that coupling is larger (more positive) to that hydrogen which is closer in space. In this context it is of interest to compare $^1J_{CF}$ in the fluoropyridines with $^1J_{CH}$ in pyridine itself;[18] these values are included in Table IV together with corresponding C–H and C–F values in benzene and fluorobenzene. $^1J_{C_2H_2}$ is larger than the other one-bond $^1J_{CH}$ values, in accord with the suggestion that the lone pair makes a positive contribution to the coupling. Since $^1J_{CF}$ is known to be negative,[19] it is likely that its smaller magnitude in **1** (algebraically more positive value) owes to a similar type of positive contribution. Indeed, removal of the lone pair by protonation induces a larger relative change than that experienced by either of the other $^1J_{CF}$ values. This point is discussed further in connection with the MO calculations below.

$^2J_{CF}$. Because the magnitudes of $^2J_{CF}$ are in the range observed for substituted fluorobenzenes,[14] the sign is expected to be positive, as is the case for fluorobenzene itself. It should be noted that the value in **2** is approximately 15.1 Hz less than that in **1**. A similar trend is observed in pyridine, where $^2J_{C_2H_3}$ is ~5.4 Hz less than $^2J_{C_3H_2}$.





$^3J_{CF}$. Based on the similarity of the values in Table I to those of corresponding three-bond coupling constants in fluorobenzenes,[14] it is likely that these also are positive. The larger value which arises when an unprotonated nitrogen intervenes in the coupling path is observed for J_{CH} in other heterocycles. For example, $^3J_{C_2H_6}$ in pyridine is ~3-4 Hz greater than other three-bond values in pyridine or in benzene. Similar enhancements have been observed in thiazole[20] and in *N*-benzylidenemethylamine.[21a] The value of $^3J_{C_6F_2}$ in 2-fluoropyridine is the largest three-bond C–F coupling reported.[21b]

If the nitrogen lone pair affects the couplings, its removal should reveal more general trends comparable to those in structurally and electronically similar molecules. Indeed J_{CF} in the ions displays a moderate overall correlation with values in fluorobenzene, but none with J_{CH} in benzene. On examination of substituted fluorobenzenes[14] it is apparent that values of J_{CF} in the nitrofluorobenzenes correlate very well with those of the fluoropyridinium ions (r = 0.998, Figure 2). The similarity of the substituent effects is illustrated in a comparison of $^3J_{CF}$ in both sets of compounds, where the changes parallel each other very closely. This does not hold as well for $^2J_{CF}$, but it is interesting to note that in both 3-fluoropyridinium ion and 3-fluoronitrobenzene $^2J_{C_4F_3}$ is smaller than $^2J_{C_2F_3}$.

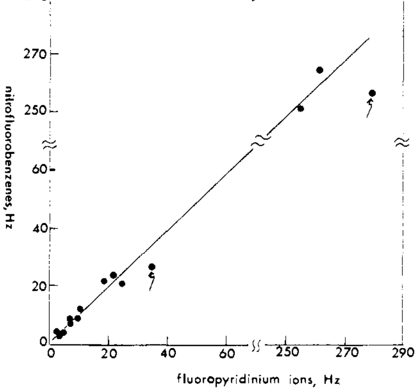
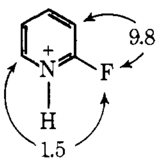
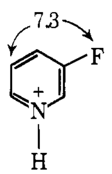


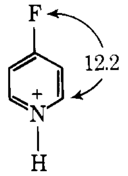
Figure 2. Plot of C–F coupling constants of nitrofluorobenzenes vs. fluoropyridinium ions. The indicated points ($^1J_{C_4F_4}$ and $^2J_{C_2F_3}$) were excluded from the calculation of the least-squares line shown.



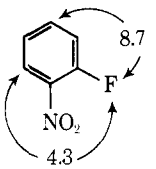
1-H$^+$



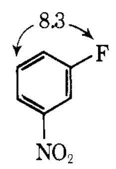
2-H$^+$



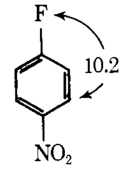
3-H$^+$



4

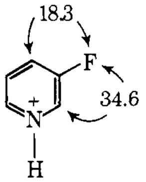


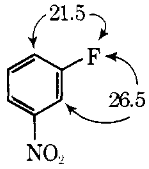
5



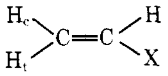
6

The largest deviations in Figure 2 are in $^1J_{C_4F_4}$ and $^2J_{C_2F_3}$, both higher in the pyridinium ions than anticipated. While no obvious rationalization exists for the former value, the immediately adjacent positive nitrogen in **2**-H$^+$ may inductively enhance $^2J_{C_2F_3}$ to a greater extent than the more remote nitro group does in **5**.





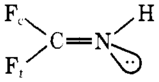
Calculated Fermi Contact Contributions to J_{CF}. $^1J_{CF}$. Our calculations (Table V) predict $^1J_{CF}$ to be much more positive in 2-fluoropyridine than in 3- or 4-fluoropyridine, in agreement with experiment. In order to examine the origin of this difference we have calculated ${}^1J_{CF}$ in the hypothetical molecule 7 using Pople and Gordon's standard geometrical model.[22] The calculated values, ${}^1J_{CF_c} = -262.9$ Hz and ${}^1J_{CF_t} = -184.8$ Hz demonstrate the sensitivity to lone-pair orientation, which makes a positive contribution to the coupling of the proximate fluorine. The calculated results are consistent with the qualitative arguments presented above. As we have noted, ${}^1J_{CH}$ for a C–H bond syn to a nitrogen lone pair is more positive than that for an anti C–H bond, a trend which is reproduced by INDO calculations.[3b,23]



8

Calculations on the protonated fluoropyridines predict larger changes than are actually observed: −140, −99, and −45 Hz for 2-, 3-, and 4-fluoropyridine, respectively. Possible reasons for this are discussed later.

${}^2J_{CF}$. Before considering the calculated values, it is appropriate to note that ${}^2J_{CH}$ values calculated by this method are in general too negative.[8b] For example, ${}^2J_{CH}$ for ethylene is calculated to be −11.6 Hz, while the observed value is −2.4 Hz.[8b] Similarly, for vinyl fluoride (**8**, X = F), we calculate ${}^2J_{C_1H_c} = -3.27$ Hz and ${}^2J_{C_1H_t} = -13.75$ Hz.[24] These values are to be compared to the experimental ones in vinyl chloride (**8**, X = Cl): ${}^2J_{CH_t} = -8.3$ Hz, ${}^2J_{CH_c} = +7.1$ Hz. Similar values obtain for vinyl bromide; the observed difference of 15 Hz is paralleled by the calculated difference of 10 Hz. Thus, although agreement between theory and experiment is far from quantitative, the calculated ${}^2J_{CH}$ values certainly reproduce the experimental trend. Two-bond couplings also have been treated more generally within the Pople–Santry formalism, which led to a qualitative discussion of the influence of substituent orientation and electronegativity on ${}^2J_{CH}$ and ${}^2J_{NH}$.[25]



7

In a similar manner, the INDO calculations predict values of ${}^2J_{CF}$ in fluorobenzene and the fluoropyridines which are more negative than the observed values. Using published atomic coordinates[26] for fluorobenzene ${}^2J_{CF}$ is predicted to be −2.4 Hz, while the observed value is +21.0 Hz.[14] The fluoropyridine values are also more negative by comparable amounts.

Protonation-induced changes in ${}^2J_{CF}$ are reproduced in the calculations. Thus, ${}^2J_{CF}$ in 2-fluoropyridine is predicted to decrease, ${}^2J_{C_4F}$ in 3-fluoropyridine and ${}^2J_{CF}$ in 4-fluoropyridine to increase, and ${}^2J_{C_4F}$ in 3-fluoropyridine to undergo a relatively small change. These are all verified experimentally in a qualitative fashion.

${}^3J_{CF}$. Again, the experimental trends exhibited by the three-bond couplings are reproduced by the calculations. The large protonation-induced change (13.4 or 16.4 Hz, depending on the sign of the experimental pyridinium value) is paralleled by a predicted 23.5 Hz increase. While the calculations fail to predict the apparent increase observed for ${}^3J_{C_4F_2}$ and ${}^3J_{C_5F_3}$ in 2- and 3-fluoropyridine, respectively, on protonation, they correctly predict the increase in ${}^3J_{C_2F_4}$ observed for 4-fluoropyridine on protonation.

J_{CF} values were also calculated for 2-, 3-, and 4-nitrofluorobenzene to determine whether any relationship exists between these calculated values and those obtained for the protonated fluoropyridines. Although a good correlation is not observed, it is of interest to point out that the calculations predict ${}^3J_{C_5F}$ to be significantly greater (5.6 Hz) than ${}^3J_{C_3F}$ in 2-nitrofluorobenzene.

Table VI. Calculated π Bond Orders in Fluoropyridines and Fluoropyridinium Ions

Compound	π	Compound	π
1	0.2320	2-H$^+$	0.2368
1-H$^+$	0.2678	3	0.2311
2	0.2065	3-H$^+$	0.2830

Conclusions Concerning the SCF–FPT–INDO Calculations. Numerical agreement between calculated and observed coupling constants is not good, but in fact exact agreement should not be expected using semiempirical MO methods, because these depend heavily on the choice of parameters used to approximate integrals which are either ignored or whose evaluation is too time consuming to carry out. Nevertheless, from the present results it appears that the Fermi contact mechanism is sufficient to qualitatively account for most of the experimental trends. While agreement between experiment and theory may be improved if contributions from dipolar and orbital interactions are also taken into account[27] a variety of other factors may be important also. For example, solvent effects could cause significant perturbations to the coupling constants, especially in the case of the fluoropyridinium ions.[28] The geometries assumed for the molecules under consideration here may also account for some of the discrepancies between theory and experiment. Finally, $s_C{}^2(0)$ and $s_F{}^2(0)$, the valence-shell s-orbital electron densities for carbon and fluorine, were assumed fixed constants, 4.0318 and 21.3126 au, respectively, in all calculations. This is not a good assumption when one is comparing charged molecules with uncharged species.

No direct correlation between one-bond coupling constants and π bond orders appears to exist (Table VI), although, as anticipated qualitatively, the calculated increase upon protonation of **1** and **3** is reflected in the coupling constants. However, because no single factor is expected to dominate the magnitudes of the couplings, we have not attempted to analyze the density matrix further.

Acknowledgments. This work was supported by the City University of New York Faculty Research Award Program. Funds for the spectrometer were provided in part by the National Science Foundation through Instrumentation Grant No. GP-37025. We are grateful to Mr. William Moloney and Dr. M. M. Boudakian of Olin Chemical for providing samples of the fluoropyridines. R.W. thanks the National Research Council of Canada for a Postdoctoral Fellowship, and Dr. E. D. Becker for his support and encouragement.

References and Notes

(1) (a) Hunter College. (b) National Institute of Arthritis, Metabolism, and Digestive Diseases. Address correspondence to this author at the Department of Chemistry, University of Winnipeg, Winnipeg, Canada, R3B 2E9.

(2) R. L. Lichter, D. E. Dorman, and R. Wasylishen, *J. Am. Chem. Soc.*, **96**, 930 (1974).

(3) (a) R. L. Lichter in "Determination of Organic Structures by Physical Methods", F. C. Nachod and J. J. Zuckerman, Ed., Academic Press, New York, N.Y., 1971, p 195; (b) R. Wasylishen in "Nuclear Magnetic Resonance Spectroscopy of Nuclei other than Protons", T. Axenrod and G. A. Webb, Ed., Wiley, New York, N.Y., 1974, p 105. (c) In discussions of this type the lone-pair electrons are treated conveniently in terms of a simple hybridization picture. Within this model the resulting orbital may be considered as a localized bond with directional character; it thus provides a convenient reference coordinate on which to base a discussion of geometric effects. See also F. G. Riddell and J. M. Lehn, *J. Chem. Soc. B*, 1224 (1968).

(4) (a) T. Yonezawa and I. Morishima, *J. Mol. Spectrosc.*, **27**, 210 (1968); (b) R. Wasylishen and T. Schaefer, *Can. J. Chem.*, **50**, 2989 (1972).

(5) H. L. Retcofsky and R. A. Friedel, (a) *J. Phys. Chem.*, 71, 3592 (1967); (b) *ibid.*, **72**, 290 (1968); (c) *ibid.*, **72**, 2619 (1968); (d) H. L. Retcofsky and F. R. McDonald, *Tetrahedron Lett.*, 2575 (1968); (e) G. Miyajima, Y. Sasaki, and M. Suzuki, *Chem. Pharm. Bull.*, **20**, 429 (1972).

(6) (a) J. L. Lyle and R. W. Taft, *J. Heterocycl. Chem.*, **9**, 745 (1972); (b) P. B. Desai, *J. Chem. Soc., Perkin Trans. 1*, 1865 (1973); (c) M. M. Boudakian, U.S. Patent 3,703,521, Nov 1972.
(7) G. C. Levy and G. L. Nelson, "Carbon-13 Nuclear Magnetic Resonance for Organic Chemists", Wiley, New York, N.Y., 1972, p 23.
(8) (a) G. E. Maciel, J. W. McIver, Jr., N. S. Ostlund, and J. A. Pople, *J. Am. Chem. Soc.*, **92**, 11 (1970), and references therein; (b) J. A. Pople, J. W. McIver, Jr., and N. S. Ostlund, *J. Chem. Phys.*, **49**, 2960 (1968).
(9) S. D. Sharma and S. Doraiswamy, *Curr. Sci.*, **41**, 475 (1970).
(10) B. Bak, L. H. Nygaard, and J. R. Anderson, *J. Mol. Spectrosc.*, **2**, 361 (1958).
(11) P. C. Rerat, *Acta Crystallogr.* **15**, 427 (1962).
(12) A. J. Jones, D. M. Grant, J. G. Russell, and G. Fraenkel, *J. Phys. Chem.*, **73**, 1624 (1969).
(13) (a) T. F. Page, Jr., *Mol. Phys.*, **13**, 523 (1967); (b) A. R. Tarpley, Jr., and J. H. Goldstein, *J. Phys. Chem.*, **76**, 515 (1972).
(14) F. J. Weigert and J. D. Roberts, *J. Am. Chem. Soc.*, **93**, 2361 (1971).
(15) R. J. Pugmire and D. M. Grant, *J. Am. Chem. Soc.*, **90**, 697 (1968).
(16) W. M. Litchman and D. M. Grant, *J. Am. Chem. Soc.*, **90**, 1400 (1968).
(17) (a) N. Muller and D. T. Carr, *J. Phys. Chem.*, **67**, 112 (1963); (b) D. Doddrell, D. Jordan, N. V. Riggs, and P. R. Wells, *J. Chem. Soc., Chem Commun.*, 1158 (1972).
(18) M. Hansen and H. J. Jakobsen, *J. Magn. Reson.*, **10**, 74 (1973).
(19) R. A. Bernheim and B. J. Lavery, *J. Am. Chem. Soc.*, **89**, 1279 (1967).
(20) I. N. Bojesen, J. H. Hog, J. T. Nielsen, I. B. Petersen, and K. Schaumberg, *Acta Chem. Scand.*, **25**, 2739 (1971).
(21) (a) V. M. S. Gil and A. C. P. Alves, *Mol. Phys.*, **16**, 527 (1969); (b) NOTE ADDED IN PROOF: After acceptance of this manuscript, Thorpe et al. (*J. Magn. Reson.*, **15**, 98 (1975)) reported C-F coupling constants in some fluorinated purines. Their results are substantially consistent with ours.
(22) J. A. Pople and M. Gordon, *J. Am. Chem. Soc.*, **89**, 4254 (1967).
(23) G. E. Maciel, J. W. McIver, Jr., N. S. Ostlund, and J. A. Pople, *J. Am. Chem. Soc.*, **92**, 1 (1970).
(24) The geometry was taken from C. Leibovici, *J. Mol. Struct.*, **6**, 158 (1970).
(25) C. J. Jameson and M. C. Damasco, *Mol. Phys.*, **18**, 491 (1970).
(26) L. Nygaard, I. Bojesen, T. Pedersen, and J. Rastrup-Andersen, *J. Mol. Struct.*, **2**, 209 (1968).
(27) A. C. Blizzard and D. P. Santry, *J. Chem. Phys.*, **55**, 950 (1971); **58**, 4714 (1973).
(28) (a) C. S. Giam and J. L. Lyle, *J. Chem. Soc. B*, 1516 (1970); (b) C. L. Bell and S. S. Danyluk, *J. Am. Chem. Soc.*, **88**, 2344 (1966).

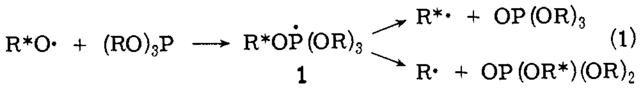
Kinetic Applications of Electron Paramagnetic Resonance Spectroscopy. XVII. Secondary Deuterium Isotope Effect and the Absence of a "Memory" in the β Scission of a Tetra-*tert*-butoxyphosphoranyl[1]

D. Griller[2] and K. U. Ingold*

Contribution from the Division of Chemistry, National Research Council, Ottawa, Ontario, Canada, K1A0R9.
Received September 11, 1974

Abstract: The reaction of tri-*tert*-butyl phosphite with *tert*-butoxy radicals yields the phosphate and a *tert*-butyl radical via an intermediate tetra-*tert*-butoxyphosphoranyl radical. Using EPR spectroscopy and deuterium labeling, it has been shown that, at temperatures from 78 to −100°, this reaction occurs without any "memory" as to which *tert*-butoxy attacked the phosphite. However, the β scission of the phosphoranyl to phosphate and *tert*-butoxy exhibits a significant secondary β-deuterium isotope effect. After correction for the isotope effect involved in the disproportionation of *tert*-butyls ($k_d^{(CH_3)_3C}/k_d^{(CD_3)_3C} = 1.4 \pm 0.2$ from 80 to −20°, it being assumed that the combination rate constants $k_c^{(CH_3)_3C}$ and $k_c^{(CD)_3C}$ are equal), the isotope effect *per deuterium* for decay of the phosphoranyl can be represented by $\log (k_\beta^H/k_\beta^D) = -0.029 + 0.063/\theta$ where $\theta = 2.3RT$ kcal/mol. These isotope effects are discussed in relation to isotope effects in analogous reactions, and the advantages in terms of sensitivity and available temperature range of our procedure are pointed out.

Trialkyl phosphites are oxidized to trialkyl phosphates by alkoxy radicals. Tetraalkoxyphosphoranyl radicals (**1**) were



$$\mathrm{R^*O\cdot} + \mathrm{(RO)_3P} \longrightarrow \underset{\mathbf{1}}{\mathrm{R^*O\dot{P}(OR)_3}} \begin{cases} \rightarrow \mathrm{R^*\cdot} + \mathrm{OP(OR)_3} \\ \rightarrow \mathrm{R\cdot} + \mathrm{OP(OR^*)(OR)_2} \end{cases} \qquad (1)$$

proposed as intermediates in this reaction many years ago,[3] and several such species have now been detected by EPR spectroscopy.[4-7]

The question as to whether the overall reaction has any "memory" when the attacking radical, R*O·, and the alkoxy groups of the phosphite, RO, are identical has attracted considerable attention.[4,6,8,9] The only important experimental observations are due to Bentrude and coworkers.[8,9] At 65° with $R = (CH_3)_3C$ and $R^* = (CH_3)_3{}^{14}C$, the ^{14}C label was completely scrambled in the phosphate.[8] At the same temperature with $R = C_6H_5CH_2$ and $R^* = p\text{-}CH_3C_6H_4CH_2$ (and vice versa) the incoming benzyloxy transferred its oxygen 1.2 times as readily as the benzyloxys of the phosphite.[9] We have reinvestigated the reaction of *tert*-butoxy with tri-*tert*-butyl phosphite over a temperature range from 78 to −100° using deuterium labeling. The results show that while there is no "memory" effect, there exists a substantial deuterium isotope effect on the β scission of this phosphoranyl.

Experimental Section

The EPR apparatus, methods of sample preparation, and measurements of radical concentration have been described previously.[6,10] Tri-*tert*-butyl phosphite and its per deuterated analog were prepared by the method of Mark and Van Wazer.[11] Perdeuteriodi-*tert*-butyl peroxide was prepared from the deuterated alcohol[12] and was purified by chromatography through an alumina column, (>98% purity by VPC). All other materials were commercially available and were purified before use.

EPR samples were prepared from the deuterated phosphite, di-*tert*-butyl peroxide, and a solvent (1:1:4 v/v). Cyclopropane was used as a solvent in experiments below room temperature, and isooctane was used in the remainder. Samples were photolyzed directly in the cavity of the EPR spectrometer, and measurements of the ratio of the normal and deuterated *tert*-butyl radical concentrations, $[(CH_3)_3C\cdot]/[(CD_3)_3C\cdot]$, were made over a range of temperature. In a second set of experiments, the labeling was reversed so that the samples contained tri-*tert*-butyl phosphite and deuterated di-*tert*-butyl peroxide. Samples were photolyzed only for a short period of time in order to avoid any complications resulting from the buildup of products. Photolysis of solutions of the respective phosphites in the absence of di-*tert*-butyl peroxide did not give rise to any EPR signals.