The Nuclear Magnetic Resonance Spectra of Fluoroaromatics. Part V.[1] The ^{13}C Spectra of Some Fluorobenzenes and Fluorobenzofurans

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The natural abundance ^{13}C spectra of some 1-substituted 2,3-difluorobenzenes and of some 6-substituted 3-ethoxycarbonyl-4,5,7-trifluoro-2-methylbenzofurans have been obtained. The spectra have been assigned by use of ^{1}H and ^{19}F decoupling techniques, together with a consideration of the ^{13}C substituent chemical shifts, and of ^{13}C—^{19}F coupling constants. Comparison of ^{13}C substituent chemical shifts in substituted benzenes and benzofurans suggests that these parameters can be safely transferred from one aromatic system to another. Substituent effects on ^{13}C—^{19}F coupling constants have been evaluated, and the effects of *ortho*-substituents on ^{1}J couplings shown to occur *via* a π-bond mechanism.

THE ^{13}C n.m.r. spectra of a number of substituted benzenes have been recorded and analysed, and the substituent effects on the ^{13}C chemical shifts considered in detail.[2-8] These are of considerable importance both theoretically and experimentally as they give a direct indication of the variation of electron density in the aromatic ring with substitution.[8-10] Further since these substituent chemical shifts are additive,[3,4,11,12] they can be used to predict the positions of multi-substituents in the benzene ring. Deviations of >2 p.p.m. from additivity between observed and calculated ^{13}C shifts for simple substituted benzenes have been interpreted as evidence of steric interaction between adjacent substituents [4-7] or signifying possible across-ring conjugation between *para*-substituents.[4,8]

Studies of the ^{13}C spectra of fluorobenzenes are a special case as there is extensive ^{13}C–^{19}F coupling.[13,14] This results in complex spectra but also assists in assigning the shifts. The range of the couplings observed in fluorobenzenes [14] were $^{1}J_{CF}$ -230 to -270 Hz; $^{2}J_{CF}$ $|8|$ to $|26|$ Hz; $^{3}J_{CF}$ and $^{4}J_{CF} < |12|$ but no general interpretation of the substituent effects on these couplings was found.

There are few systematic data on the ^{13}C spectra of fused heteroaromatic compounds though the spectra of indole and the methylindoles have been assigned.[15]

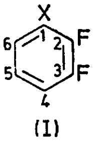
In previous Parts the ^{19}F spectra of some fluorobenzenes [16] and fluorobenzofurans [1] have been given and the effects of substituents on chemical shifts and coupling constants discussed. Thus it was of interest to extend these studies of substituent effects to the ^{13}C parameters in these compounds. We present here the complete assignments of the ^{13}C spectra of some 1-substituted 2,3-difluorobenzenes (I) and some 6-substituted 3-ethoxycarbonyl-4,5,7-trifluoro-2-methylbenzofurans (II). A preliminary account has been given.[17]

EXPERIMENTAL

The ^{13}C spectra were measured on a Varian HA 100 instrument operating at 25·1 MHz in the CW mode with proton noise decoupling and spectrum accumulation with a Varian CAT 1024 accessory. The difluorobenzenes were measured as neat liquids with external ^{13}C enriched methyl iodide as the lock signal and a small amount of dioxan added as internal reference. The benzofurans were measured in dioxan solvent which served as both lock signal and internal reference.

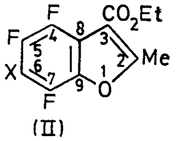
Resolution of the instrument was *ca.* 2 Hz and couplings are considered accurate to ±0·5 Hz and chemical shifts to 0·2 p.p.m.

The ^{13}C spectra of the fluorobenzofurans were also measured on a JEOL PS100 n.m.r. spectrometer in the FT mode, equipped with both ^{1}H and ^{19}F noise decoupling. Deuteriochloroform served as both solvent and lock signal. Internal tetramethylsilane was used as reference.



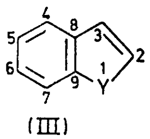
(I)

X = H,NH$_2$,NO$_2$
Br or OH



(II)

X = H,CN,Cl or F



(III)

We use the following relationships to convert experimental and literature data to the tetramethylsilane ^{13}C chemical shift scale: $\delta_{TMS} = \delta_{dioxan} + 67{\cdot}7$ p.p.m. in dioxan solution; $\delta_{TMS} = \delta_{benzene} + 129{\cdot}2$ p.p.m. in dioxan solution; $\delta_{TMS} = \delta_{CS_2} + 194{\cdot}0$ p.p.m. (from reported data for $\delta_{benzene} = \delta_{CS_2} - 64{\cdot}8$ p.p.m. in benzene solution [18]).

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[1] Part IV, R. J. Abraham, G. R. Bedford, D. Greatbanks, and D. F. Wileman, *Org. Magnetic Resonance*, 1972, **4**, 343.

[2] H. Spiesecke and W. G. Schneider, *J. Chem. Phys.*, 1961, **35**, 731.

[3] P. C. Lauterbur, *J. Amer. Chem. Soc.*, 1961, **83**, 1838.

[4] P. C. Lauterbur, *J. Amer. Chem. Soc.*, 1961, **83**, 1846.

[5] P. C. Lauterbur, *J. Chem. Phys.*, 1963, **38**, 1406.

[6] P. C. Lauterbur, *J. Chem. Phys.*, 1963, **38**, 1415.

[7] P. C. Lauterbur, *J. Chem. Phys.*, 1963, **38**, 1432.

[8] G. E. Maciel and J. J. Natterstad, *J. Chem. Phys.*, 1965, **42**, 2427.

[9] P. C. Lauterbur, *Tetrahedron Letters*, 1961, **8**, 274.

[10] T. D. Alger, D. M. Grant, and E. G. Paul, *J. Amer. Chem. Soc.*, 1966, **88**, 5397.

[11] G. B. Savitsky, *J. Phys. Chem.*, 1963, **67**, 2723.

[12] A. R. Tarpley, jun., and J. H. Goldstein, *J. Mol. Spectroscopy*, 1971, **37**, 432.

[13] T. F. Page, jun., *Mol. Phys.*, 1967, **13**, 523.

[14] F. J. Weigert and J. D. Roberts, *J. Amer. Chem. Soc.*, 1971, **93**, 2361.

[15] R. G. Parker and J. D. Roberts, *J. Org. Chem.*, 1970, **35**, 996.

[16] Part III, R. J. Abraham and M. A. Cooper, *J. Chem. Soc.* (*B*), 1968, 1094.

[17] Presented at the Annual Meeting of the Chemical Society, Autumn, 1970.

[18] T. F. Page, T. Alger, and D. M. Grant, *J. Amer. Chem. Soc.*, 1965, **87**, 5333.

All ^{13}C shifts are therefore expressed in p.p.m. downfield from tetramethylsilane reference.

Analysis.—Assignments. Difluorobenzenes (I). A typical ^{1}H noise-decoupled ^{13}C spectrum is that of (I; X = Br) shown in Figure 1. The main features of the spectrum are the large (*ca.* 250 Hz) one-bond ^{13}C–^{19}F coupling to C(2) and C(3), the much smaller two-bond coupling (8—26 Hz) to C(1) and C(4), and the very small (<2 Hz) coupling to C(5) and C(6). The assignments of the spectra started from such considerations. Then the substituent chemical shift values obtained from the monosubstituted benzenes [2,8] were used directly to calculate the ^{13}C chemical shifts, additive effects being assumed. The assignments based on these calculated values and the agreement between the observed and calculated shifts are in Table 2. In only one case [C(2) and C(3) for the bromo-compound] does the assignment differ from the calculated order. This was made by consideration of the substituent effects on the couplings (see later).

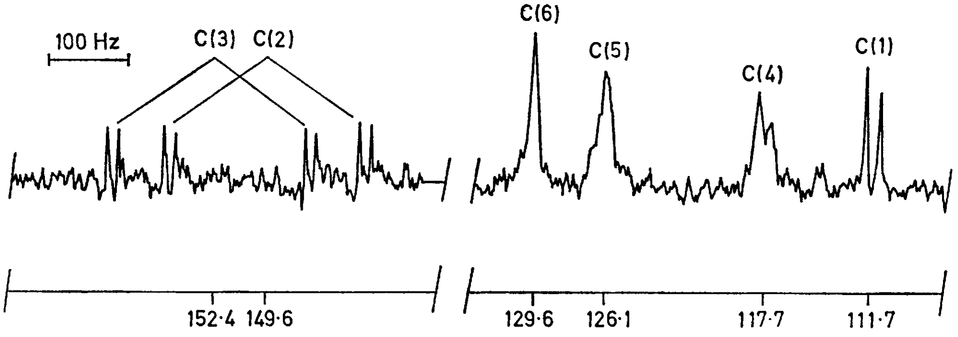

FIGURE 1 The ^{1}H noise-decoupled ^{13}C spectrum of (I; X = Br) at 25·1 MHz (chemical shifts: p.p.m. downfield from tetramethylsilane)

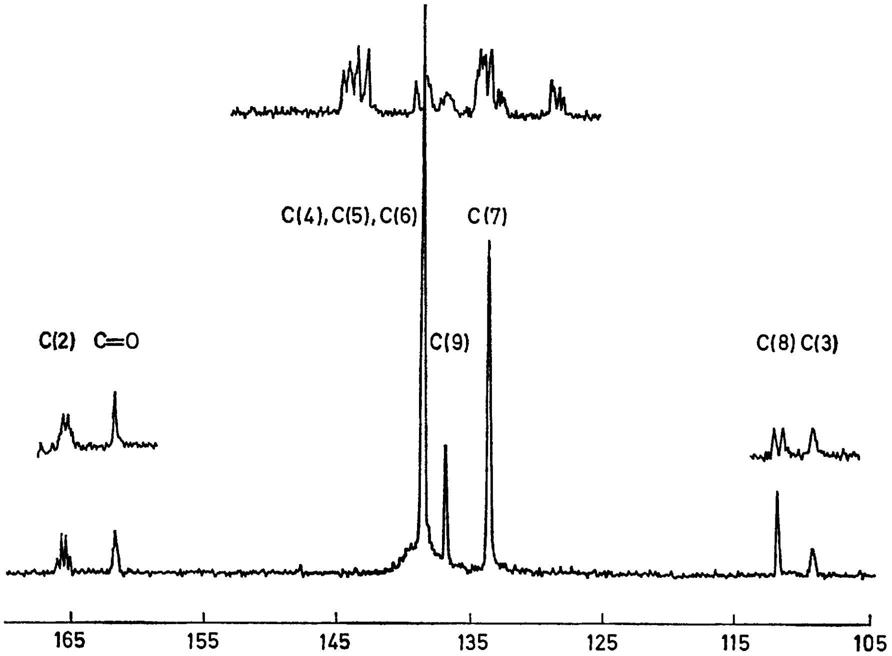

FIGURE 2 The ^{19}F noise-decoupled, and the undecoupled (insets) spectra of the low-field ^{13}C resonances of (II; X = F) at 25·1 MHz (scale: p.p.m. downfield from tetramethylsilane)

Fluorobenzofurans (II). The ^{1}H noise-decoupled ^{13}C spectra of the fluorobenzofurans (II; X = H, CN, or Cl) were assigned initially by the magnitudes of the ^{13}C–^{19}F couplings. In general C(4), C(5), and C(7) all showed the large (*ca.* 250 Hz) directly bonded ^{13}C–^{19}F coupling; C(6) appeared as a triplet coupled to two *ortho*-fluorines ($^{2}J_{\rm CF}$ *ca.* 18 Hz); C(8) and C(9) were each coupled to one *ortho*-fluorine and were basically doublets ($^{2}J_{\rm CF}$ *ca.* 18 and 12 Hz). The other resonances C(2), C(3), and C=O were resolved as single peaks under normal sweep-widths (500 Hz). Further in (II; X = CN) C(4) and C(5) could be distinguished from C(7) by the *ortho*-^{13}C–^{19}F coupling (*ca.* 15 Hz). In (II; X = H or Cl) second-order effects made the assignment of C(4) C(5), and C(7) less reliable.

These partial assignments were later confirmed by a study of the ^{13}C spectra under conditions of fluorine-noise decoupling. In these spectra C(4), C(5), and C(7) are observed as sharp singlets with large nuclear Overhauser enhancements, and in the case of (II; X = H) these peaks show small coupling to H(6). As expected, C(6) is a singlet except in (II; X = H) where coupling to H(6) gives a large doublet ($^{1}J_{\rm CH}$ *ca.* 168 Hz). C(8) and C(9) are singlets as are C(3) and C=O. C(2), however, is a quartet showing coupling to the methyl hydrogens ($^2J_{CH}$ *ca.* 7 Hz). These spectra also give high-field ^{13}C resonances which were not run in the initial study. These were observed as a triplet ($^1J_{CH}$ *ca.* 148 Hz) from the methylene of the ethoxycarbonyl group and two almost superimposed quartets ($^1J_{CH}$ *ca.* 130 Hz) from the 2-methyl and ethoxycarbonyl methyl groups.

The use of fluorine-noise decoupling also enabled an assignment of the very complex ^{13}C spectrum of the tetrafluorobenzofuran (II; X = F) to be made. The ^{19}F-decoupled spectrum of the low-field region of this compound is shown in Figure 2, together with the undecoupled spectrum (inset). The resonances at 165·8, 162·3, and 109·3 p.p.m. are assigned to C(2), C=O, and C(3) respectively, which show no resolvable coupling to any fluorine.

The peak at 111·9 p.p.m. has a typical *ortho*-fluorine coupling ($^2J_{CF}$ *ca.* 14 Hz; inset) and can thus be assigned to a bridgehead carbon. The peak at 136·8 p.p.m. appears to have a similar peak height to that at 111·9 p.p.m. and as both bridgehead carbons should have the same nuclear Overhauser enhancement it can be assumed to be the other bridgehead carbon. By elimination the two remaining peaks at 138·8 and 133·5 p.p.m. must be due to C(4), C(5), C(6), and C(7). These carbon atoms have a directly bonded fluorine atom and show large nuclear Overhauser enhancements. From the relative intensities of the two peaks, three carbons are assigned to the peak at 138·8 p.p.m. whilst only one carbon to that of 133·5 p.p.m. Further, from inspection of the undecoupled spectrum (inset), the ^{13}C resonance centred on 133·5 p.p.m. shows couplings of *ca.* 250 Hz (*i.e.*, $^1J_{CF}$) and 15 Hz (*i.e.*, one *ortho*-fluorine). On this basis the resonance is assigned to either C(4) or C(7).

These preliminary assignments were confirmed by calculations of substituent chemical shift effects in these systems (see later).

Benzofuran (III). The ^{13}C spectrum of benzofuran in dioxan was run with complete ^{1}H noise decoupling to give eight singlet resonances. In order to characterise the shifts of the two quaternary carbon atoms the spectrum was also recorded with coherent noise decoupling of the dioxan protons and with use of the dioxan ^{13}C as a lock signal as before. As the proton resonance frequencies of benzofuran are *ca.* 3—4 p.p.m.[19] to low field of the decoupling frequency centred on the dioxan protons, they experience only a partial decoupling. This results in a reduction of the ^{13}C–^{1}H couplings. The observed ^{13}C spectrum of benzofuran under these conditions contained six doublet resonances, having couplings of *ca.* 90 Hz corresponding to a reduced $^1J_{CH}$ (true value *ca.* 180 Hz), and two singlet resonances. The latter have no directly bonded protons and must be the bridgehead carbons C(8) and C(9). The shift difference between the bridgehead carbons was *ca.* 27 p.p.m. and therefore the carbon bonded directly to the electronegative oxygen [*i.e.* C(9)] could be safely assigned to the lower field shift of the two. Similarly the lowest field shift (at 145·9 p.p.m.) of the remaining six resonances was assigned to C(2) which is also bonded to the oxygen in benzofuran.

The remaining ^{13}C resonances were assigned by analogy with the ^{13}C shifts of indole (III; Y = NH)[15] and are shown in Table 1. Change of substituent Y from –NH– to –O– gives a 1·5 p.p.m. downfield change in the shift of C(8). C(7) Is in the same orientation (*ortho*) to substituent Y and a similar change in shift assigns the resonance at 112·1 p.p.m. to this carbon. The C(3), C(4), C(5), and C(6) resonances were assigned by direct analogy since the electronegativity effect of the change of heteroatom is likely only slightly to perturb these resonance positions. Thus the assignment of C(4), C(5), and C(6) is not unambiguous but the shifts are so close that this will not affect the later conclusions.

TABLE 1

Comparison of ^{13}C chemical shifts of indole (III; Y = NH)[a] and benzofuran (III; Y = O)

Substnt.	^{13}C Chemical shifts							
Y	2	3	4	5	6	7	8	9
NH	126·4	103·8	122·5	123·5	121·5	113·0	130·0	137·3
O	145·9	107·3	123·6	125·1	122·0	112·1	128·5	155·9

[a] From ref. 15.

Analysis of ^{13}C–^{19}F *couplings*. Difluorobenzenes (I). The ^{19}F spectra have been previously reported[16,20] and the fluorine chemical shifts of (I; X = NH_2, NO_2, or OH) are sufficiently separated to give first-order couplings in the ^{13}C spectra. In (I; X = Br) small second-order effects occur and the measured couplings were refined by use of LAOCN3[21] iterative computer analysis. For *o*-difluorobenzene the observed one-bond ^{13}C–^{19}F couplings to C(2)[C(3)] were corrected for second-order effects by LAOCN3 by use of the differential isotope shift (*ca.* 8 Hz) and the value of J_{FF} of −20·6 Hz found by Cooper, Weber, and Manatt.[22] The other couplings to C(1)[C(4)] and C(5)[C(6)] form deceptively simple spectra and only the sums of the couplings are obtained. The first-order values of J_{22} and J_{23} quoted previously[14] differ by *ca.* 2 Hz from these corrected values.

Fluorobenzofurans (II). The ^{19}F spectra of these compounds have been reported.[1] The ^{13}C–^{19}F couplings were only measured for (II; X = CN) which had small second-order effects and no extensive signal overlapping. The couplings to C(4), C(5), and C(7) were similarly refined by LAOCN3.

RESULTS AND DISCUSSION

Chemical Shifts.—The observed and calculated ^{13}C shifts in the difluorobenzenes (I) are shown in Table 2.

TABLE 2

^{13}C Chemical shifts observed in 1-substituted 2,3-difluorobenzenes (I), with calculated values in parentheses

Substnt.	^{13}C Chemical shifts					
	1	2	3	4	5	6
H	118·5	152·2	152·2	118·5	125·9	125·9
	(115·8)	(150·0)	(150·0)	(115·8)	(125·7)	(125·7)
NO_2	140·1	146·4	152·9	124·3	125·8	122·4
	(135·4)	(144·7)	(150·8)	(121·8)	(126·5)	(120·4)
NH_2	138·6	141·7	152·8	107·3	125·5	113·8
	(135·0)	(137·6)	(151·3)	(106·3)	(127·0)	(113·3)
Br	111·7	149·6	152·4	117·7	126·1	129·6
	(110·4)	(153·3)	(152·2)	(114·8)	(127·9)	(129·0)
OH	146·6	141·8	152·6	109·6	124·8	114·3
	(142·7)	(137·7)	(151·7)	(108·5)	(127·4)	(113·4)

Parameters for the calculated shifts were taken from substituent chemical shift data by Spiesecke and

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[19] P. J. Black and M. L. Heffernam, *Austral. J. Chem.*, 1965, **18**, 353.

[20] J. Busby, M.Sc. Thesis, University of Liverpool, 1969.

[21] S. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, 1964, **41**, 3863.

[22] M. A. Cooper, H. E. Weber, and S. L. Manatt, *J. Amer. Chem. Soc.*, 1971, **93**, 2369.

Schneider[2] except for the substituent hydroxy-group.[8] The overall agreement is very good and leads to an unambiguous assignment without reference to $^{13}C-^{19}F$ couplings in all cases but one. The ambiguity arises for C(2) and C(3) in (I; X = Br) and these have been assigned from the effect of substituents on $^{13}C-^{19}F$ couplings (see later).

The majority of calculated shifts of C(1), C(2), C(3), and C(4) are *ca.* 2 p.p.m. too small and Table 1 shows that better agreement can be obtained if the calculated shifts are obtained by use of the X substituent chemical shift values on the experimental shifts of *o*-difluorobenzene. This suggests some small interaction between *ortho*-fluorines. However, the C(2) shift of (I; X = Br) is inconsistent in that the *ortho*-Br effect is −2·6 p.p.m. relative to (I; X = H) whereas in bromobenzene it is +3·3 p.p.m.,[2] and this could be due to a bromine–fluorine interaction. From the relative good overall agreement obtained for the other shifts we conclude that fluorine gives approximately additive effects on ^{13}C shifts even when *ortho* to some fairly bulky groups (*e.g.*, NO_2, NH_2).

TABLE 3

^{13}C Chemical shifts in fluorobenzofurans (II) with calculated values in parentheses

		^{13}C Chemical shifts										
Substnt. X	Solvent	2	3	4	5	6	7	8	9	C=O	CH_2O	CH_3,CH_3
H	$CDCl_3$	165·8	109·8	139·5	146·8	101·2	142·4	117·8	137·4	162·7	61·3	14·2, 14·2
	Dioxan	166·7	108·7	140·1	147·3	101·6	143·1	115·9	138·3	162·8		
				(140·1)	(146·8)	(94·3)	(143·7)	(116·5)	(138·1)			
CN	$CDCl_3$	169·0	108·6	139·6	147·2	88·8	143·8	122·8	137·0	161·5	61·8	14·2, 14·7
	Dioxan	170·1	109·1	140·2	147·9	89·5	144·5	123·1	137·7	162·0		
				(140·9)	(150·5)	(84·5)	(147·4)	(120·3)	(138·9)			
Cl	$CDCl_3$	166·1	109·7	139·7	144·6	107·8	140·4	115·8	138·6	162·4	61·6	14·4, 14·6
	Dioxan	167·0	110·2	140·2	145·3	107·9	141·1	116·5	138·2	162·4		
				(141·1)	(147·0)	(100·7)	(143·9)	(114·0)	(139·1)			
F	$CDCl_3$	165·8	109·3	138·8	138·8	138·8	133·5	111·9	136·8	162·3	61·4	14·2, 14·2
				(141·0)	(132·5)	(129·4)	(129·5)	(111·4)	(139·0)			

TABLE 4

$^{13}C-^{19}F$ Coupling constants/Hz in 1-substituted 2,3-difluorobenzenes (I)[a]

	$^1J_{CF}$[e]		$^2J_{CF}$				$^3J_{CF}$				$^4J_{CF}$	
Substnt. X	J_{22}	J_{33}	J_{12}	J_{32}	J_{23}	J_{43}	J_{13}	J_{42}	J_{62}	J_{53}	J_{52}	J_{63}
H	−246·9	−246·9	(17·5)[b]	12·6	12·6	(17·5)	(−1·0)	(−1·0)	(5·7)	(5·7)	(3·5)	(3·5)
NO_2	−265·8	−250·9	*c*	11·6	15·8	17·8	*c*	*d*	*d*	6·3	6·3	*d*
NH_2	−237·1	−243·0	9·5	11·0	14·8	18·0	2·2	*d*	*d*	8·0	4·4	*d*
Br	−248·2	−251·7	17·7	13·3	14·0	17·8	*d*	*d*	*d*	5·7	5·7	*d*
OH	−240·6	−245·5	9·9	10·6	14·6	16·9	2·7	*d*	*d*	9·2	4·9	*d*

[a] Note the nomenclature used. The carbon nucleus is always listed first, *e.g.*, $J_{23} = J$[C(2)–F(3)]. [b] Values in parentheses estimated from substituent contributions; see text. [c] Quadruple broadened. [d] Not resolved. [e] Assumed negative.[14]

The additive effects of fluorine as a substituent were extended to the calculation of the ^{13}C shift of the benzenoid ring carbons of the fluorobenzofurans (II). Benzofuran (III) was taken as the parent ring system for these calculations which introduced two major assumptions. These were (*a*) the ambiguity in the shifts of C(4), C(5), and C(6) of benzofuran (see Table 1). Fortunately these shifts are close enough not to produce large errors in the calculated shifts owing to wrong assignments. (*b*) The substituent effects of the 2-methyl and 3-ethoxycarbonyl groups on the ^{13}C shifts of the benzenoid carbons are unknown.

The effects on C(8) and C(9) were assumed to be similar to 2-methyl substitution in furan (1·3 and −1·5 p.p.m. respectively)[18] and methoxycarbonyl substitution in benzene (*ortho* 0·2; *meta* 0·2 p.p.m.).[23] The effects on C(4), C(5), C(6), and C(7) were neglected since inter-ring effects in methylindoles have been found to be <2 p.p.m. at these positions.[15] These substituent values are all small enough to induce only marginal errors in the calculated shifts. Therefore the ^{13}C shifts of the benzenoid ring carbons in the fluorobenzofuran (II) were calculated from the shifts of benzofuran itself, by use of substituent chemical shift values for F, Cl,[2] and CN.[24]

The final assignments of the ambiguous groups of resonances, *i.e.*, C(4), C(5), and C(7), and C(8) and C(9), were made by comparison with the calculated shifts and are given in Table 3. Further confirmation that these are the correct assignments is furnished by the experimental shifts of C(4) and C(9) which are relatively constant to change in *meta*-substituent X(6). This is in agreement with the small *meta*-^{13}C substituent chemical shift in benzenes.[2] Also as C(5) and C(7) can be assigned individually in (II; X = CN) (see analysis) the shifts of these carbons in the other fluorobenzofurans should parallel those for the cyano-compound. This also is in line with the assignments given in Table 3.

The agreement between observed and calculated chemical shifts for the benzenoid carbons is very good especially for C(4), C(8), and C(9) in all the compounds. However, C(6) deviates consistently (*i.e.*, 5—9 p.p.m. to lower field than predicted). This occurs possibly as a

[23] J. B. Stothers, *Canad. J. Chem.*, 1967, **45**, 233.

[24] Unpublished results.

result of the effect of two *ortho*-fluorines which also would explain the low-field shift of C(5) in (II; X = F) which is also *ca.* 6 p.p.m. to lower field than predicted.

Table 3 shows that the use of these additive substituent effects can given an unambiguous assignment for almost all the ^{13}C benzenoid resonances in this heteroaromatic system. This produces further confirmation of the structure of these compounds.[1] Table 3 also shows the small solvent effect on the ^{13}C shifts (<1 p.p.m.) between dioxan to $CDCl_3$ solutions. Also the relative insensitivity of the shifts of the carbon atoms remote from the substituent X can be seen from the constancy of the shifts of C(2) and C(3), *i.e.*, inter-ring effects are small.

^{13}C–^{19}F *Coupling Constants.*—*1-Substituted 2,3-difluorobenzenes.* The ^{13}C–^{19}F couplings found in the 1-substituted 2,3-difluorobenzenes (I) are given in Table 4. We use the convention that J_{ij} is the coupling between $^{13}C_i$ and $^{19}F_j$ giving the carbon number i first. The ranges of these couplings are consistent with those found in the monosubstituted fluorobenzenes studied by Weigert and Roberts.[14] Further it can be seen that our difluorobenzenes (I; X = H, NH_2, NO_2, Br, or OH) differ from the *ortho*- and *meta*-substituted fluorobenzenes by one extra fluorine atom. Thus a direct comparison of the couplings given in Table 4 with those found by Weigert and Roberts gives the effect of the introduction of this second fluorine atom on the ^{13}C–^{19}F couplings. These values were found to be independent of substituent X and are given in Table 5 together with r.m.s. errors. Because some couplings were not resolved (*i.e.*, < ±2 Hz) in our compounds certain entries remain undetermined. The r.m.s. errors show that only the coupling J_{52} was found to deviate appreciably which may indicate a breakdown of additivity for four-bond couplings. However, the good overall agreement does suggest that fluorine gives constant effects on the other couplings.

TABLE 5

The *ortho*-substituent contribution/Hz of fluorine to the ^{13}C–^{19}F coupling constants in substituted benzenes (I)

^{13}C coupling [a]		Fluorine substituent contribution/Hz to ^{13}C–^{19}F couplings	
to F_2	to F_3	Position 3	Position 2
J_{12}		−3·3 ± 0·4	
	J_{13}		−8·7 ± 0·1
J_{22}		−1·1 ± 0·9	
	J_{23}		−9·9 ± 0·9
J_{32}		−8·2 ± 0·7	
	J_{33}		−1·2 ± 0·4
J_{42}			
	J_{43}		−3·7 ± 0·5
J_{52}		2·0 ± 1·2	
	J_{53}		−2·0 ± 0·7
J_{62}			
	J_{63}		

[a] See Table 4 for nomenclature.

We used these additivity relationships to assign the C(2) and C(3) shifts of (I; X = Br) which remained ambiguous when substituent chemical shift calculations were used (Table 2). The one-bond couplings are −248·2 and −251·7 Hz which when assigned to C(2) and C(3) respectively and matched to the analogous couplings in *o*- and *m*-bromofluorobenzenes (−247·0 and −250·4 Hz respectively)[14] give consistent changes with those predicted from Table 5. Similarly, the two-bond couplings to C(2) and C(3) were found to agree. This provides a useful additional means of assignment.

The two sets of values in Table 5 both correspond to the introduction of an *ortho*-fluorine and therefore both sets of values can be combined. For example, the fluorine effect on J_{12} and J_{43} should be the same and this agrees with the values in Table 5 of −3·3 and −3·7 Hz respectively. Further we can estimate the couplings for X = H, *i.e.*, *o*-difluorobenzene in which deceptively simple spectra for C(1)[C(4)] and C(5)[C(6)] limit the information obtained by direct observation to just the sum of two couplings, *i.e.*, $\Sigma J_{12} + J_{13}$ and $\Sigma J_{52} + J_{53}$. The individual couplings J_{12}, J_{13}, and J_{53} can be derived from the average contributions in Table 5 and the couplings found by Weigert and Roberts for monofluorobenzene.[14] We find therefore that J_{12} is calculated to be 17·5 Hz (−3·5 Hz fluorine contribution to a J_{12} of 21·0 Hz in monofluorobenzene) and J_{13} is −1·0 Hz (−8·7 Hz fluorine contribution to a J_{13} of 7·7 Hz in monofluorobenzene). The sum of these two predicted couplings (16·5 Hz) agrees very well with the experimental sum of 16·6 Hz. These values differ from those calculated by Weigert and Roberts from the line intensities of the ^{13}C spectrum (20·1 and −3·0 Hz). Our values, however, are obtained by separate consistent estimates and should be more accurate. Similarly we estimate J_{53} in *o*-difluorobenzene to be 5·7 Hz (−2·0 Hz fluorine contribution to a J_{53} of 7·7 Hz in monofluorobenzene). As J_{52} cannot be predicted accurately we have estimated it from the experimental sum of J_{52} and J_{53} of ±9·2 Hz which gives J_{52} as 3·5 or −14·9 Hz. The former value is consistent with four-bond ^{13}C–^{19}F couplings in *o*-fluorobenzenes (3—4 Hz)[14] and is taken as the predicted value. All these calculated couplings are included in Table 4 in parentheses.

In the light of our values of the *ortho*-fluorine effects on ^{13}C–^{19}F couplings in Table 5 we re-examined the *ortho*-substituent effects found by Weigert and Roberts[14] to see whether these new data would afford an explanation of the effects. Weigert and Roberts found that the variation of the one-bond ^{13}C–^{19}F couplings in the *para*-substituted fluorobenzenes correlated well with the fluorine chemical shift, and regarded this as indicative of a π-resonance mechanism. However, the correlation was much poorer for the *meta*-derivatives and broke down completely for the *ortho*-derivatives. ^{19}F Chemical shifts of *ortho*-substituted fluorobenzenes are known to be subject to steric as well as resonance effects.[25] Thus we have plotted the change in the one-bond ^{13}C–^{19}F coupling (relative to fluorobenzene) in *ortho*-substituted fluorobenzenes against Hammett's σ_p[26] (Figure 3)

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[25] J. W. Emsley and L. Phillips, ' Progress in N.M.R. Spectroscopy,' vol. 7, eds. J. W. Emsley, J. Feeney, and L. H. Sutcliffe, Pergamon Press, Oxford, 1971.

[26] D. H. McDaniel and H. C. Brown, *J. Org. Chem.*, 1958, **23**, 420.

using the fluorine substituent effect value of —1·1 Hz (Table 5). A good correlation is obtained, which indicates that the resonance interaction still dominates the *ortho*-substituent effect on this coupling.

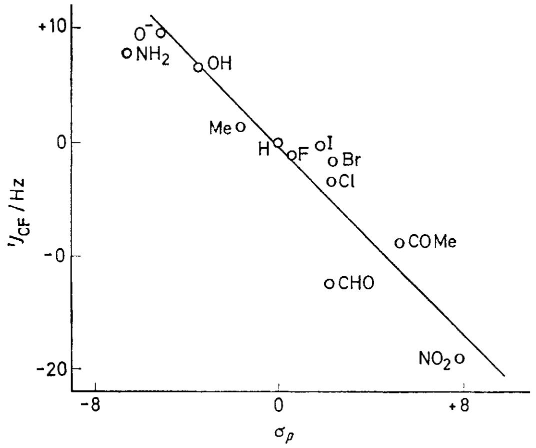

FIGURE 3 The variation of $^1J_{CF}$ (relative to H) in *ortho*-substituted fluorobenzenes against σ_p of substituent

For the other couplings, however, the use of our more accurate values for *o*-difluorobenzene still does not result in a clearer understanding of the factors affecting the couplings.

6-*Cyano*-3-*ethoxycarbonyl*-4,5,7-*trifluoro*-2-*methylbenzofuran* (II; X = CN). The couplings found in this fluorobenzofuran, for which the best resolved and most first-order spectra were obtained, are shown in Table 6. The couplings are assigned by their characteristic magnitudes, *i.e.*, $^1J_{CF} \gg {}^2J_{CF} > {}^3J_{CF} \approx {}^4J_{CF}$. The *meta*- and *para*-couplings may also be of either sign and in some instances reversed. Couplings to C(4), C(5), and C(7) have been refined for second-order effects whilst the other couplings were measured directly from the spectra. The couplings to C(7) therefore show that this carbon atom can be distinguished from C(4) and C(5) by virtue of the small couplings which must be from *meta*- and *para*-fluorines. Similarly the other couplings for the carbons are in accord with the relative positions of the fluorines. The coupling to C(3) has been assigned to F(4), but it is possible that this is due to F(7) *via* a planar zig-zag pathway, similar to that between the proton on C(3) and F(7) in these benzofurans.[1]

TABLE 6

The $^{13}C-^{19}F$ couplings in 6-cyano-3-ethoxycarbonyl-4,5,7-trifluoro-2-methylbenzofuran (II; X = CN)

	$^{13}C-^{19}F$ Couplings/Hz		
Carbon no.	F(4)	F(5) [a]	F(7)
3	3·1	nr [a]	nr
4	−258·2	14·6	4·0
5	15·5	−250·5	3·1
6	nr	*ca.* 18	*ca.* 18
7	3·8	4·08	−261·4
8	*ca.* 17	nr	nr
9	7·7	2·2	11·8

[a] nr = Not resolved.

We thank Dr. P. Beynon and Dr. R. Dean of JEOLCO (U.K.) Ltd., for obtaining the FT spectra, and the S.R.C. for a maintenance award (to D. F. W.).

[2/427 *Received*, 24*th February*, 1972]