

General Features of the X Part of an ABX Spin System in Isotropic and Liquid Crystalline Phases as Illustrated by the $^{13}\text{C}-\{^1\text{H}\}$ Spectra of 2,2'-Difluorobiphenyl

M. Edgar,¹ J. W. Emsley,² and M. I. C. Furby

Department of Chemistry, University of Southampton, Southampton SO17 1BJ, United Kingdom

Received April 1, 1997; revised July 22, 1997

The $^{13}\text{C}-\{^1\text{H}\}$ NMR spectra of 2,2'-difluorobiphenyl dissolved in isotropic and liquid crystalline solvents have been obtained and analyzed. They are examples of the X part of an ABX spectrum. It is shown that the spectrum of the isotropic solution yields J_{AX} , J_{BX} , J_{AB} , δ_{AB} , and δ_{X} , but only if all the transitions are detected, and that intensities as well as frequencies of the transitions are used in the analysis. It is demonstrated that for 2,2'-difluorobiphenyl this requires that for some of the carbons it is necessary to detect very weak transitions. For the spectra of liquid crystalline solutions of ABX systems it is shown that the dipolar couplings D_{AX} , D_{BX} , and D_{AB} are obtained only if these couplings are in a certain sensitive range of relative values. The sensitive range can be adjusted by using variable angle sample spinning (VASS). It is demonstrated that VASS spectra taken near the magic angle can be used to obtain the absolute signs of the scalar couplings.

© 1997 Academic Press

INTRODUCTION

The primary motivation for recording the $^{13}\text{C}-\{^1\text{H}\}$ spectra of 2,2'-difluorobiphenyl was to obtain the dipolar couplings, D_{CF} , which could then be used to investigate the structure and conformation of this molecule in a liquid phase. The procedures used to do this, however, have a wider significance. The spectra for each ^{13}C are of the type ABX, with A and B being the two fluorine nuclei, which are non-equivalent if there is an isotope shift produced by the ^{13}C nucleus. The unknown spectral parameters for a sample in a liquid crystalline solvent are scalar couplings, J_{AB} , J_{AX} , and J_{BX} , the isotope shift, δ_{AB} , and three dipolar couplings, D_{AB} , D_{AX} , and D_{BX} . To obtain all these parameters it is necessary to assume that the scalar couplings are the same in isotropic and liquid crystalline phases, and so the problem is resolved into how to analyze ABX spectra of isotropic

and anisotropic samples. There are three factors which make these seemingly straightforward tasks more complex, and more interesting.

The first factor concerns the analysis of the spectra of the isotropic samples. Thus, Weigert and Roberts (1) in 1971 described the ABX $^{13}\text{C}-\{^1\text{H}\}$ spectra given by the isotropic liquid samples of the three isomers of difluorobenzene, and showed that all the spectral parameters could be obtained from the spectra, but only if all of the six theoretically possible lines, as given in Table 1, are detected, and that both the frequencies and the intensities of the lines are used in the analysis. Some of the $^{13}\text{C}-\{^1\text{H}\}$ spectra in these compounds did not show the six lines, and so ambiguities in their analysis were unavoidable at that time. The improvements in signal-to-noise that can be obtained 26 years later means that it is now possible to observe very weak lines, and this can be crucial for obtaining the spin-spin couplings and chemical shifts in ABX spectra of samples in the isotropic liquid phase. This is demonstrated here for the $^{13}\text{C}-\{^1\text{H}\}$ spectra given by a sample of 2,2'-difluorobiphenyl dissolved in CDCl_3 .

The second factor concerns the analysis of the spectra of ABX systems when the sample is dissolved in a liquid crystalline phase. The theoretical expressions for the line positions and intensities of the X part of such a spectrum, given in Table 1, suggest that all the dipolar couplings can be obtained provided that the magnitudes and signs of the scalar couplings are known, but only when the relative magnitudes of the J_{ij} and D_{ij} fall within certain narrow ranges of values. For one particular solution of a compound in a liquid crystalline solvent it is unlikely that these sensitive ranges of values will occur. It will be demonstrated here, however, that this problem can be overcome for many of the carbon resonances in 2,2'-difluorobiphenyl by recording spectra on samples which are spinning about an axis making an angle β with the magnetic field (2, 3). In these samples the liquid crystal directors align along the spinning axis for certain ranges of values of β , and this leads to a reduction

¹ Present address: Institut für Organische Chemie, Freie Universität Berlin, Germany.

² To whom correspondence should be addressed.

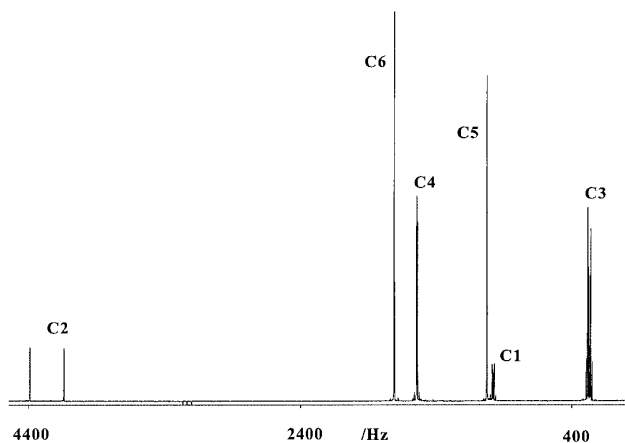


FIG. 1. The 90.5-MHz $^{13}\text{C}-\{^1\text{H}\}$ spectrum of a solution of 2,2'-difluorobiphenyl dissolved in CDCl_3 .

in the D_{ij} by a factor $(3 \cos^2\beta - 1)/2$. This can enable the $^{13}\text{C}-\{^1\text{H}\}$ spectra to be tuned into the desired sensitive range, and hence the magnitude of the D_{ij} can be obtained, and their signs relative to those of the J_{ij} .

The third factor is that the absolute signs of the J_{ij} can be obtained if, as in the present case, the absolute sign of the D_{ij} are known.

EXPERIMENTAL

2,2'-Difluorobiphenyl was purchased from Fluorochem Ltd. The $^{13}\text{C}-\{^1\text{H}\}$ spectra on a sample (6 mg) dissolved in CDCl_3 (540 mg) was obtained on a Bruker AM 360 spectrometer. The variable angle sample spinning (VASS) spectra were obtained on a sample of 2,2'-difluorobiphenyl dissolved as a 5% by weight solution in the nematic solvent ZLI 1167 (Merck) on a Bruker MSL 200 spectrometer. The liquid crystalline solvent was chosen because it does not contain aromatic carbons. The sample was contained in a glass bottle which was sealed by epoxy resin. The bottle fits

into a zirconium rotor of 7 mm o.d. for use in a VASS probe type MAS200 SB BL7. The spinning rate used must be above the threshold at which the directors align along the spinning axis, and in the present case it was convenient to use 1000 Hz. Proton decoupling was achieved on the liquid crystalline sample using the Waltz-16 pulse sequence with a 90° proton pulse of 6.7 μs .

RESULTS AND DISCUSSION

$^{13}\text{C}-\{^1\text{H}\}$ Spectra of the Isotropic Solution

The full spectrum of the aromatic region is shown in Fig. 1, and Table 1 gives the theoretical expressions for the X part of an isotropic ABX spin system by setting all the dipolar couplings to zero. Note in particular that all six lines are observed for each carbon resonance only if $\delta_{\text{AB}} \neq 0$ and $J_{\text{AX}} \neq J_{\text{BX}}$.

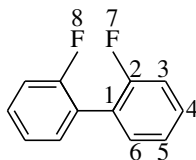
Figure 2a shows the spectrum from C1. Six lines are present, and this establishes immediately that δ_{AB} is finite and that J_{AX} and J_{BX} are not equal. The spectrum consists of three pairs of lines, each pair symmetrically disposed about the center of the multiplet. The center of the multiplet fixes the carbon chemical shift, but the three splittings are insufficient to fix J_{AX} , J_{BX} , J_{AB} , and δ_{AB} . These four parameters can be determined by taking into account the relative intensities within the multiplet, as well as their positions. This was achieved using an iterative spectral analysis program, ARCANA (4), which is based on LAOCOON (5), and which uses only the line positions. The procedure adopted was first to estimate starting values for the four parameters. Thus, a value of $|J_{\text{AB}}| = 18.2$ Hz has been obtained from a $^{19}\text{F}-\{^1\text{H}\}$ spectrum of a sample of 2,2'-difluorobiphenyl dissolved in pyridine (50%) by Cooper *et al.* (6). An estimate of $J_{\text{AX}} = 20.98$ Hz was made, this being the value for $^2J_{\text{CF}}$ in neat fluorobenzene (7). The pair of lines 2 and 5 in Fig. 2a are separated by $|J_{\text{AX}} + J_{\text{BX}}|$, and so gives an estimate for J_{BX} . At this stage in the analysis

TABLE 1
Frequencies and Intensities of the Transitions in an ABX Spin- $\frac{1}{2}$ System

Line No.	Frequency	Intensity
1	$\nu_{\text{X}} - \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} + J_{\text{BX}} + 2D_{\text{BX}})$	1
2	$\nu_{\text{X}} + (C_+ - C_-)$	$(Q_1 - Q_2)^2/(1 + Q_1^2)(1 + Q_2^2)$
3	$\nu_{\text{X}} - (C_+ + C_-)$	$(1 + Q_1Q_2)^2/(1 + Q_1^2)(1 + Q_2^2)$
4	$\nu_{\text{X}} + (C_+ + C_-)$	$(1 + Q_1Q_2)^2/(1 + Q_1^2)(1 + Q_2^2)$
5	$\nu_{\text{X}} - (C_+ - C_-)$	$(Q_1 - Q_2)^2/(1 + Q_1^2)(1 + Q_2^2)$
6	$\nu_{\text{X}} + \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} + J_{\text{BX}} + 2D_{\text{BX}})$	1

Note. $C_+ = \frac{1}{2}[(\delta_{\text{AB}} + \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} - J_{\text{BX}} - 2D_{\text{BX}}))^2 + (J_{\text{AB}} - D_{\text{AB}})^2]^{1/2}$, $C_- = \frac{1}{2}[(\delta_{\text{AB}} - \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} - J_{\text{BX}} - 2D_{\text{BX}}))^2 + (J_{\text{AB}} - D_{\text{AB}})^2]^{1/2}$ and $Q_1 = (J_{\text{AB}} - D_{\text{AB}})/[\delta_{\text{AB}} - \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} - J_{\text{BX}} - 2D_{\text{BX}}) + 2C_-]$, $Q_2 = (J_{\text{AB}} - D_{\text{AB}})/[\delta_{\text{AB}} + \frac{1}{2}(J_{\text{AX}} + 2D_{\text{AX}} - J_{\text{BX}} - 2D_{\text{BX}}) + 2C_+]$.

TABLE 2
 ^{13}C Chemical Shifts, δ_p Relative to C3, Coupling Constants, J_{ij} , and the Fluorine Isotope Shift δ_i^{FF} , Obtained from the Analysis of the Spectrum of 2,2'-Difluorobiphenyl Dissolved in CDCl_3



		Coupling constants/Hz					
i,j	1,7	1,8	2,7	2,8	3,7	3,8	
J_{ij}	16.2 ± 0.1	-1.2 ± 0.1	-248.5 ± 0.1	-0.5 ± 0.1	23.3 ± 0.1	-0.8 ± 0.1	
i,j	4,7	4,8	5,7	5,8	6,7	6,8	
J_{ij}	8.8 ± 0.1	-0.8 ± 0.1	4.0 ± 0.1	-0.4 ± 0.1	$\pm 2.5 \pm 0.5$	$\pm 2.5 \pm 0.5$	
i,j	7,8						
J_{ij}	16.5 ± 0.1						
		^{13}C chemical shifts relative to C3/ppm					
i	1	2	3	4			
δ_i	7.787 ± 0.001	44.096 ± 0.001	00.000 ± 0.001	14.000 ± 0.001			
i	5	6					
δ_i	8.299 ± 0.001	15.850 ± 0.001					
		^{19}F isotope shifts/ppm					
i	1	2	3	4			
δ_i^{FF}	0.0162 ± 0.0003	0.0735 ± 0.0003	0.0210 ± 0.0003	0.0044 ± 0.0003			

the signs of all the C–F couplings were assumed to be positive, except for $^1J_{\text{CF}}$ for which there is good evidence for a negative sign (8). The separation of the center pair of lines, 3 and 4, then fixes δ_{AB} to be about 4 Hz, a positive sign meaning that F_{A} resonates at higher field than F_{B} . This set of parameters gave a good reproduction of the observed spectrum, and so can be used to assign calculated to observed transitions. The shifts δ_{AB} and δ_{X} were fixed and J_{AB} , J_{AX} , and J_{BX} varied to fit the line positions, with the result shown in Fig. 2b. This process was repeated with δ_{AB} fixed successively at 5, 6, 7, and 8 Hz to produce the results shown in Figs. 2c–2f. Inspection of the relative intensities then allowed a value for $\delta_{\text{AB}} = 5.5$ Hz to be chosen which then led to the best match with experimental line positions and intensities, as shown in Fig. 2g, and gave the parameters in Table 2. Carbons 3 and 4 have similar spectra and were analyzed in the same way, and yielded the shifts and couplings in Table 2.

The spectrum given by C2 is shown in Fig. 3a, and at first sight seems to have just four lines. However, this carbon is expected to produce the largest isotope shift on the fluo-

rines, and to have very different magnitudes of J_{AX} and J_{BX} , and so there should be six observable transitions. The missing pair of lines is of very weak intensity near the center of the multiplet, as shown on an expanded vertical scale in Fig. 3b. Location of all six lines now allowed all the spectral parameters to be obtained.

Figure 4a shows the experimental spectrum from C5, and now the center of the multiplet is a single line, so that either δ_{AB} or $J_{\text{AX}} - J_{\text{BX}}$ is zero. If $J_{\text{AX}} \neq J_{\text{BX}}$ there should be a pair of lines (3 and 4 in Table 1) with a separation of $2(C_+ + C_-)$. Expanding the vertical scale (Fig. 4b) shows that there is an outer pair of lines of very low intensity. Having located these lines the spectrum can be analyzed by setting $\delta_{\text{AB}} = 0$. The relative intensities of the outer pair (lines 1 and 6 in Fig. 4b) to the pair 2 and 5 (Fig. 4a) had to be used, together with the line positions to give the parameters in Table 2. The intensity of the outer doublet depends on the ratio of $|J_{\text{AX}} - J_{\text{BX}}|$ to $|J_{\text{AB}}|$, and even when this ratio is as large as 0.3, as is the case for C5, the lines are easily overlooked. When $J_{\text{AX}} - J_{\text{BX}}$ and δ_{AB} both approach zero, the two outer lines become too small to detect, and the

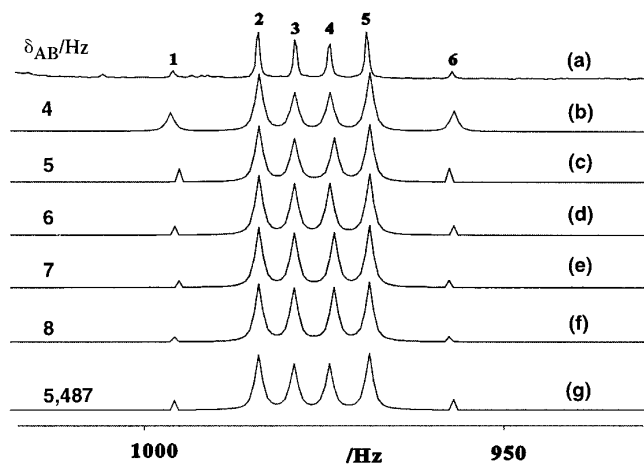


FIG. 2. Expansion of the resonances in Fig. 1 given by C1. (a) Experiment and (b)–(g) the results from fits to the line positions with δ_{AB} fixed at the values marked against each spectrum.

spectrum becomes a 1:2:1 triplet. In the case of the spectrum from C6 (Fig. 5) the outer lines were not detected, and simulations suggest that with the signal-to-noise achieved the two couplings are equal to a precision of ± 0.5 Hz.

$^{13}\text{C}-\{^1\text{H}\}$ Spectra of the Liquid Crystalline Solution

The theoretical expressions for the frequencies and intensities of the X nucleus in an oriented ABX spin system are given in Table 1. There is a maximum of six lines, as in the isotropic case, and the center doublet also collapses to a single line if $\delta_{AB} = 0$. However, there are important differences with the isotropic case, the most obvious being that

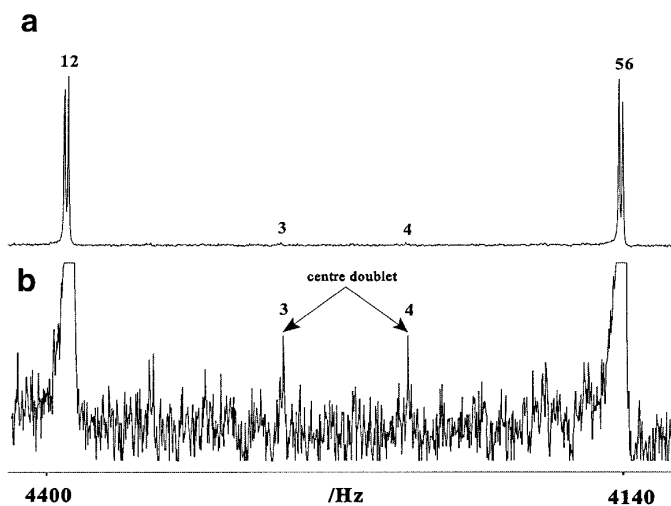


FIG. 3. (a) Horizontal expansion of the resonances in Fig. 1 given by C2 and (b) an additional vertical expansion ($\times 32$) to show the weak pair of lines near the center.

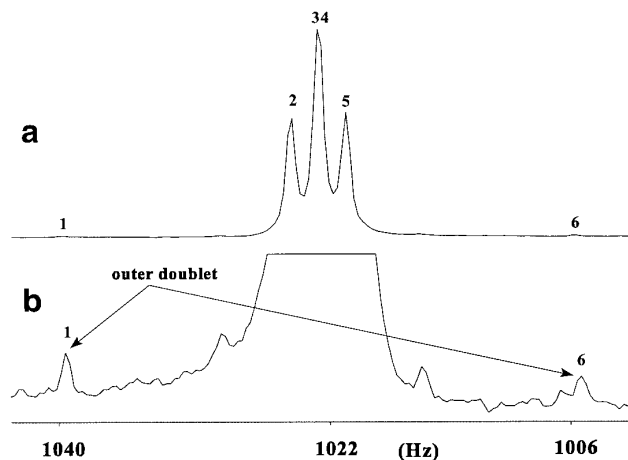


FIG. 4. (a) Horizontal expansion of the resonances in Fig. 1 given by C5 and (b) an additional vertical expansion ($\times 32$) to show the weak outer doublet.

even if all six lines can be detected there is insufficient information to fix all eight parameters (three scalar and three anisotropic couplings, plus δ_{AB} and δ_X); the carbon shift, δ_X , is, however, still obtained as the center of the symmetrical multiplets, and so seven parameters remain to be obtained from the spectrum. The scalar couplings may have a dependence on the solvent, but this is expected to be small, and it is neglected. There will also be a contribution to the total spin–spin coupling in the isotropic sample from a field-induced dipolar coupling, but at 8.4 T this will be < 0.1 Hz and can be neglected (9, 10). With these assumptions it is possible that the remaining four parameters can all be extracted in principle, from the positions and relative intensities of the lines, provided that all six transitions are resolved and detectable. In practice, the relative values of the parameters

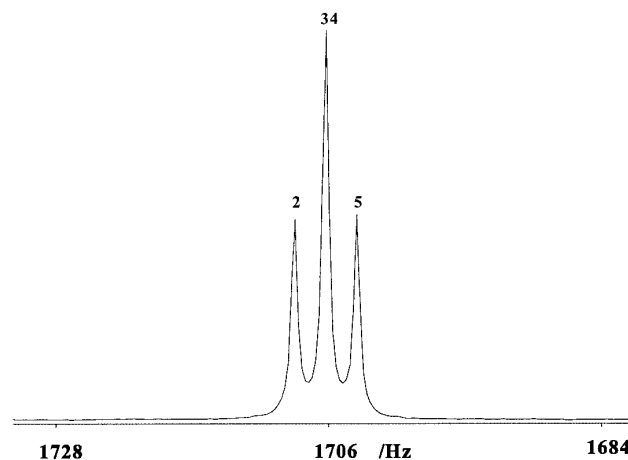


FIG. 5. Horizontal expansion of the resonances in Fig. 1 given by C6.

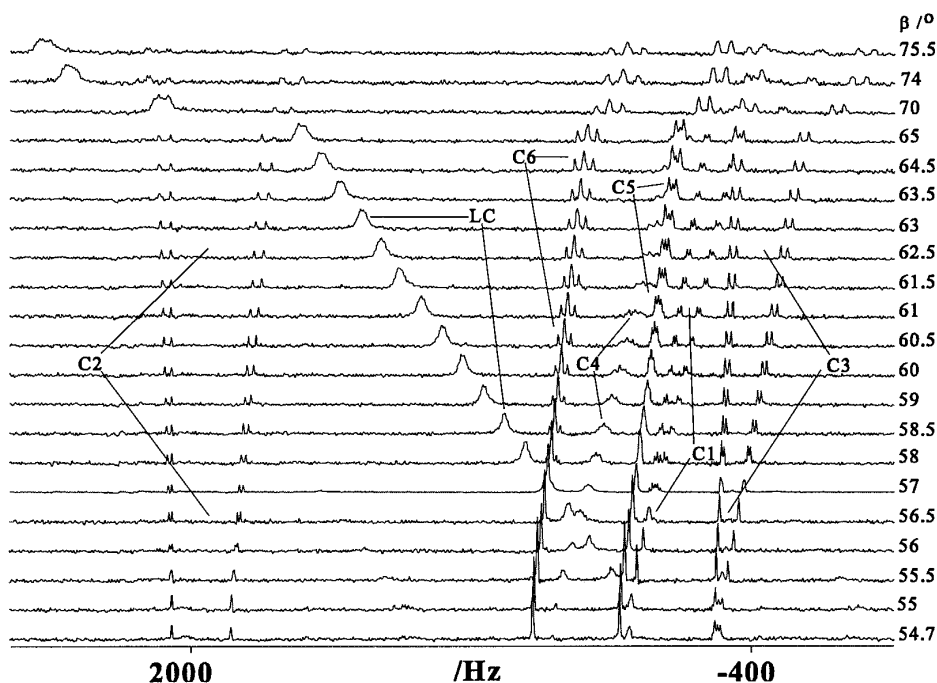


FIG. 6. VASS 50.3-MHz $^{13}\text{C}-\{^1\text{H}\}$ spectra of a sample of 2,2'-difluorobiphenyl dissolved in the nematic solvent ZLI 1167. Most of the peaks from the solvent are at high field and are not shown. The angle, β , between the spinning axis and B_0 is shown against each spectrum.

are such that usually only four of the lines are observed, and in this case it is necessary to assume values for δ_{AB} and D_{AB} , in addition to the three scalar couplings in order to obtain D_{AX} and D_{BX} from the spectrum. However, there are combinations of the parameters, which is denoted as the *sensitive region*, when more of the parameters can be obtained. The dipolar couplings have magnitudes determined by the structure, the internal motion (in the case of 2,2'-difluorobiphenyl, this is rotation about the interring bond through an angle ϕ), and the orientational order parameters, $S_{\alpha\beta}(\phi)$, of the molecules in the liquid crystalline phase. The order parameters can vary within the range $-\frac{1}{2} \leq 1$, and so the dipolar couplings can also vary widely in magnitude and sign. For any particular molecule in a liquid crystalline phase it is improbable that the parameters for all the carbons in the molecule will lie in the sensitive region, but it is shown here that they can be brought into this region by using the technique of variable angle sample spinning (2, 3).

Rotation of a liquid crystalline sample about an axis making an angle β to the magnetic field B_0 leads to alignment of the liquid crystalline directors along the spinning axis provided that a threshold spinning rate is exceeded, and that β is between 0° and 54.7° for a material with a positive anisotropy, $\Delta\chi$, in the magnetic susceptibility, and in the range $54.7^\circ < \beta \leq 90^\circ$ when $\Delta\chi$ is negative. The solvent used for 2,2'-difluorobiphenyl has a negative $\Delta\chi$. The effect of aligning the directors uniformly along the spinning axis is to change the chemical shifts to

$$\delta_i(\beta) = \delta_i^0 + \delta_i^{\text{aniso}}(3 \cos^2\beta - 1)/2, \quad [1]$$

where

$$\delta_i^{\text{aniso}} = (2/3) \sum_{\alpha\beta} S_{\alpha\beta} \sigma_{\alpha\beta}. \quad [2]$$

$\sigma_{\alpha\beta}$ are elements of the shielding tensor in the same molecular frame used to define the order parameters $S_{\alpha\beta}$. Note that in the case of a molecule undergoing intramolecular motion on a time scale sufficiently fast to average the NMR parameters, the shielding tensor and the order parameters are averages over the motion. The shift δ_i^0 is that observed for no orientational order, and apart from a solvent shift is expected to equal that in the isotropic phase.

The dipolar couplings for the spinning sample change to

$$D_{ij}(\beta) = D_{ij}(3 \cos^2\beta - 1)/2, \quad [3]$$

where D_{ij} is the value when the director is along B_0 .

Figure 6 shows the $^{13}\text{C}-\{^1\text{H}\}$ VASS spectra for the solution of 2,2'-difluorobiphenyl in the nematic solvent as β is changed from 54.7° to 75.5° ; for this particular sample it was not possible to spin when β was greater than 75.5° . The first use of these spectra is to follow the position of each ^{13}C multiplet so as to assign the peaks in the spectrum for $\beta = 75.5^\circ$, which is similar to that for a static sample, shown

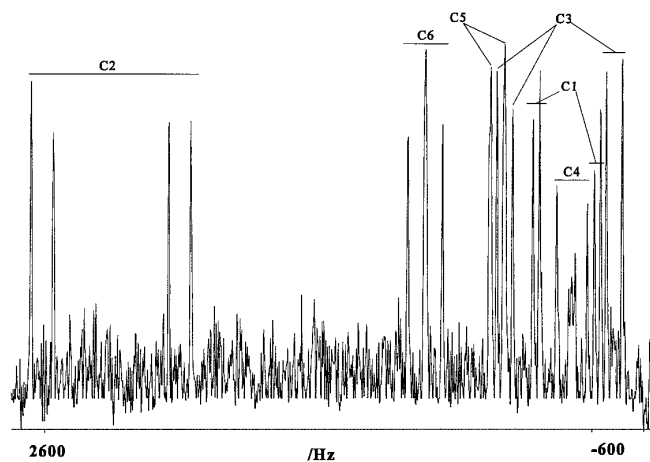


FIG. 7. The 50.3-MHz $^{13}\text{C}-\{^1\text{H}\}$ spectrum from a static sample of 2,2'-difluorobiphenyl dissolved in the nematic solvent ZLI 1167.

in Fig. 7. The spectrum for $\beta = 54.7^\circ$ is very similar to that of the sample dissolved in CDCl_3 , shown in Fig. 1, and so the multiplets are easily assigned to their respective carbons. The carbon shifts, $\delta_i(\beta)$ are plotted in Fig. 8 against $(3 \cos^2\beta - 1)/2$, and the slopes give the values of δ_i^{aniso} which are shown in Table 3.

Having assigned the spectrum of the static sample, it can be seen that all the carbons have four-line spectra, except carbon 4 which gives a five-line spectrum, as shown on an expanded scale in Fig. 9. A maximum of five lines for this carbon is expected since the isotope shift is much smaller than the width of the lines (>10 Hz) in the anisotropic spectra. Simulations of the spectra, as shown in Fig. 9, reveal that the intensity of the center line is very sensitive to the relative magnitudes of J_{AB} and D_{AB} when they are close in

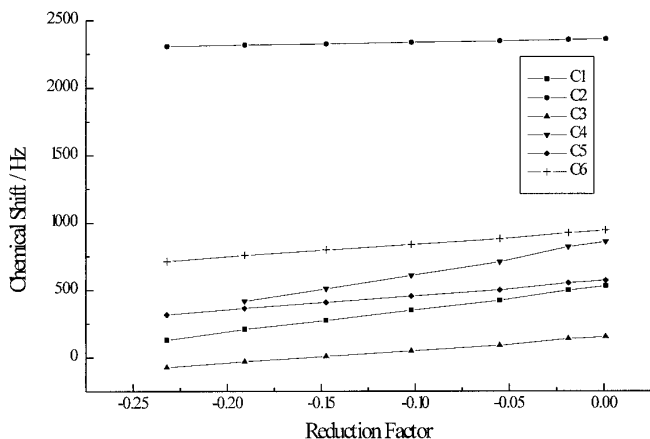


FIG. 8. Variation with $R = (3 \cos^2\beta - 1)/2$ of the center of the resonances from the individual carbons in a sample of 2,2'-difluorobiphenyl dissolved in the nematic solvent ZLI 1167.

TABLE 3
The Chemical Shift Anisotropies, δ_i^{aniso} , for the ^{13}C Nuclei in 2,2'-Difluorobiphenyl Dissolved in the Nematic Solvent ZLI 1167

i	1	2	3
$\delta_i^{\text{aniso}}/\text{ppm}$	33.9 ± 0.6	5.0 ± 0.1	19.4 ± 0.5
i	4	5	6
$\delta_i^{\text{aniso}}/\text{ppm}$	46.4 ± 1.4	21.6 ± 0.4	19.6 ± 0.4

value and is zero when they are identical. Using both the positions and the relative intensities of the five lines for carbon 4 enabled values of D_{AB} , D_{AX} , and D_{BX} to be obtained for the static spectrum, and these are given in Table 4. This value of D_{AB} will be identical for each of the ABX spin systems, and so was used in subsequent analyses of the four-line spectra from each of the other carbons in Fig. 7.

The Absolute Signs of the J_{ij}^{CF}

In order to obtain the D_{ij} it is necessary to know the magnitude and *sign* of the J_{ij} . As noted earlier, the magni-

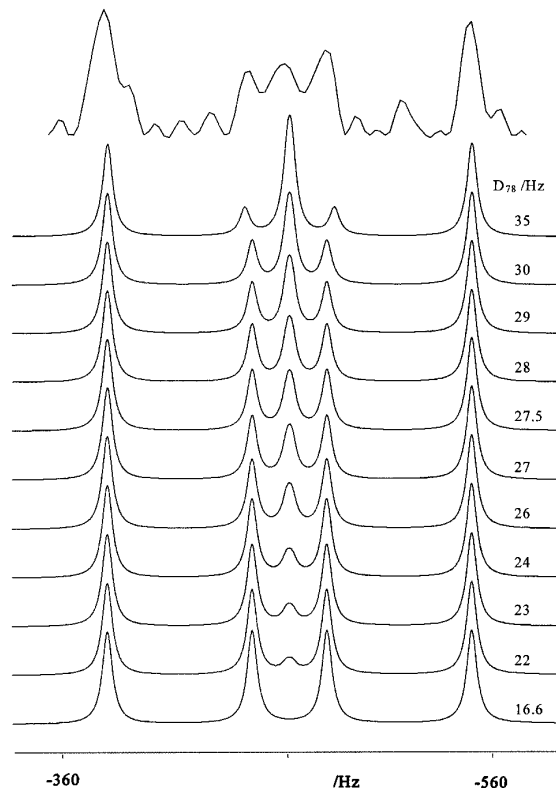
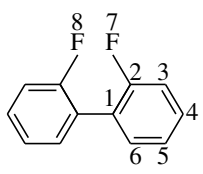


FIG. 9. Experimental (top) and simulated $^{13}\text{C}-\{^1\text{H}\}$ spectra from C4 in a static sample of 2,2'-difluorobiphenyl dissolved in the nematic solvent ZLI 1167. The simulated spectra differ only in the value of D_{78} whose value is given alongside each spectrum.

TABLE 4
Chemical Shifts, δ_p , and Dipolar Couplings, D_{ij} , Obtained from the Analysis of the ^{13}C - $\{^1\text{H}\}$ Spectrum of a Static Sample of 2,2'-Difluorobiphenyl Dissolved in the Nematic Solvent ZLI 1167

						
Dipolar couplings/Hz						
i,j	1,7	1,8	2,7	2,8	3,7	3,8
D_{ij}	-186.2 ± 0.1	18.8 ± 0.1	-275.7 ± 0.1	63.7 ± 0.1	306.9 ± 0.1	46.9 ± 0.1
i,j	4,7	4,8	5,7	5,8	6,7	6,8
D_{ij}	47.5 ± 0.1	37.6 ± 0.1	-7.5 ± 0.1	41.1 ± 0.1	-48.6 ± 2.5	52.2 ± 2.5
i,j	7,8					
D_{ij}	27.5 ± 0.5					
^{13}C chemical shifts relative to C3/ppm						
i	1		2		3	
δ_i	0.781 ± 0.001		50.365 ± 0.001		0.00 ± 0.001	
i	4		5		6	
δ_i	1.146 ± 0.001		7.955 ± 0.001		16.242 ± 0.001	
^{19}F isotope shift/ppm						
i	1	2	3	4	5	6
δ_i^{FF}	0.04 ± 0.02	0.40 ± 0.02	0.06 ± 0.02	0.0 ± 0.02	0.0 ± 0.02	0.0 ± 0.02

tudes are taken to be those obtained from analysis of the isotropic solutions, and the absolute signs of the couplings J_{CF} were assumed to be positive except for $^1J_{27}$. Courtieu *et al.* (3) have shown how VASS spectra may be used to obtain the relative signs of the J_{FF} and D_{FF} couplings in an AMX spin system, and the same method has been used for the ^{13}C - ^{19}F couplings. This is done by observing how the multiplets evolve as β is changed in small steps from the magic angle (54.7°). The absolute signs of the D_{ij} are known for this solution of 2,2'-difluorobiphenyl in ZLI 1167 because the $S_{\alpha\beta}(\beta)$ have been obtained from an analysis of proton-proton and proton-fluorine dipolar couplings of a partially deuterated sample dissolved in the same solvent at a similar concentration and temperature (11). Thus, for this molecule it is possible to obtain absolute rather than relative signs of the scalar couplings, and the same is true in principle for other molecules.

Consider first the evolution of the spectrum of C2, which is shown in Fig. 10. The spectrum at the magic angle is dominated by $^1J_{27}$, the much smaller $^4J_{28}$ being unresolved in the liquid crystalline solution, and so the spectrum is a

doublet. As β is increased the splitting becomes $^1J_{27} + 2^1D_{27}$, and is observed to increase. Since $^1D_{27}$ is negative the observed increase shows that $^1J_{27}$ is also negative, and this agrees with theoretical predictions, and the measured relative sign of $^1J_{\text{CF}}$ and $^1J_{\text{CH}}$ in dichlorofluoromethane (8).

The evolution with β of the spectrum of C1 is shown on an expanded scale in Fig. 11. The spectra near $\beta = 54.7^\circ$ are determined by the relative values of $^2J_{17}$ and $^2D_{17}$, the couplings between C1 and F8 being much smaller in magnitude. At the magic angle the multiplet is broad but unresolved. As $^2D_{17}$, which is negative, is added the multiplet narrows, and then broadens again, and eventually begins to show resolvable structure. This shows that $^2J_{17}$ is of opposite sign to $^2D_{17}$, and is positive. Between $\beta = 57^\circ$ and 58° the multiplet has five resolved lines and is in the sensitive region where all the dipolar couplings can be obtained. At larger values of β the spectra revert to being four lines. The center line in the spectrum at $\beta = 58^\circ$ should in fact be resolved into a doublet if the isotope shift, δ_1^{FF} , has the same value as in the isotropic, CDCl_3 solution. The width of the central peak places an upper limit on δ_1^{FF} in the liquid crystalline

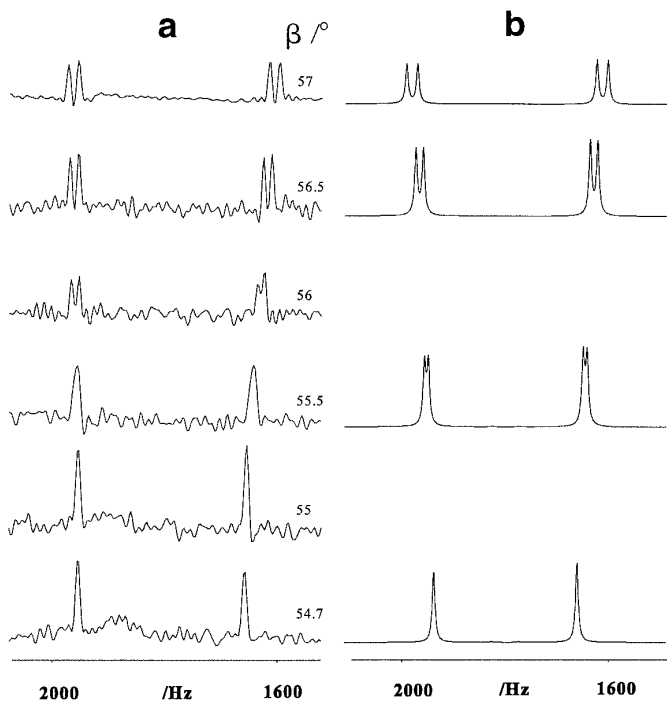


FIG. 10. Experimental (a) and simulated (b) VASS $^{13}\text{C}-\{^1\text{H}\}$ spectra from C2 near the magic angle. The angle of the spinning axis with the field is given alongside each spectrum.

phase of 2 Hz. This reduction in the value of δ_1^{FF} could be because there is an appreciable contribution of an anisotropic component of the isotope shift, which is of opposite sign to the isotropic component, or it could be an effect on δ_1^{FF} , the isotropic contribution to the isotope shift, of changing the solvent.

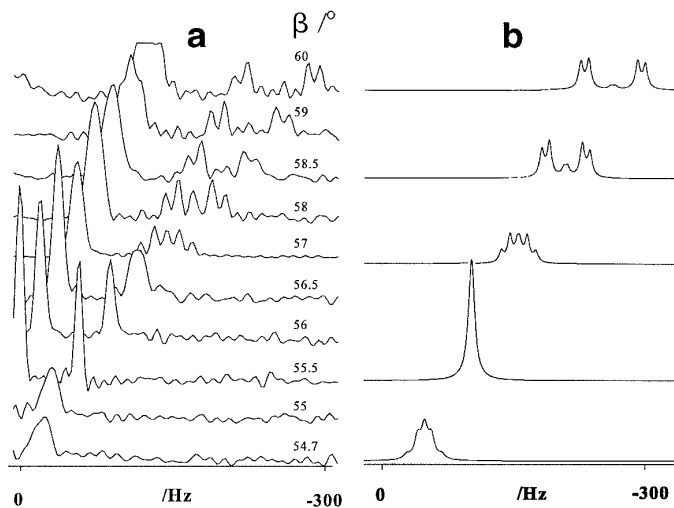


FIG. 11. Experimental (a) and simulated (b) VASS $^{13}\text{C}-\{^1\text{H}\}$ spectra from C1 near the magic angle. The angle of the spinning axis with the field is given alongside each spectrum.

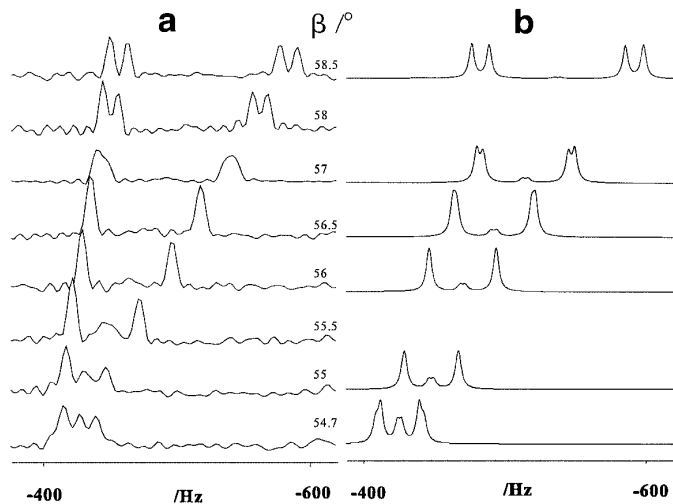


FIG. 12. Experimental (a) and simulated (b) VASS $^{13}\text{C}-\{^1\text{H}\}$ spectra from C3 near the magic angle. The angle of the spinning axis with the field is given alongside each spectrum.

A similar reduction in the magnitude of the isotope shift δ_3^{FF} is apparent in the spectra of C3 close to the magic angle, where the spectra also show a broadened but unresolved central peak, as shown in Fig. 12. The width of the central peak gives an upper limit to δ_3^{FF} of 3 Hz. The evolution of the multiplet given by C3 close to the magic angle is dominated by the relative values of $^2J_{37}$ and $^2D_{37}$, and the spectra show that these couplings have the same sign and so are both positive.

The spectrum from C4 close to the magic angle is poorly resolved, and has a low signal-to-noise, but even so the development of the peak structure as β increases is consistent only with the signs of the couplings in Table 2.

The spectrum from C5 is not resolved at the magic angle. Peak structure begins to evolve from $\beta = 59^\circ$, as shown on an expanded scale in Fig. 13. The largest scalar coupling to C5 is J_{57} , which has a magnitude of 4.0 Hz, while $|J_{58}|$ is only 0.4 Hz. The dipolar couplings are in a reverse order of magnitude; thus D_{27} is -7.5 Hz, and D_{28} is 41.1 Hz. This means that the evolution of structure in the VASS spectra of this peak is dominated by the relative signs of J_{27} compared with D_{28} . However, since the relative signs of J_{27} and J_{28} are known, as are the relative signs of D_{27} and D_{28} , then there are only two possible relative sign combinations of the scalar and dipolar couplings which need be considered. This is done in Fig. 13, which shows spectra calculated for the two sign combinations of the couplings, and quite clearly the relative signs of the scalar and dipolar couplings can be established.

The scalar couplings involving C6 are both equal at 2.5 ± 0.5 Hz, and changing their signs relative to the dipolar couplings does not lead to a sufficiently large effect on the

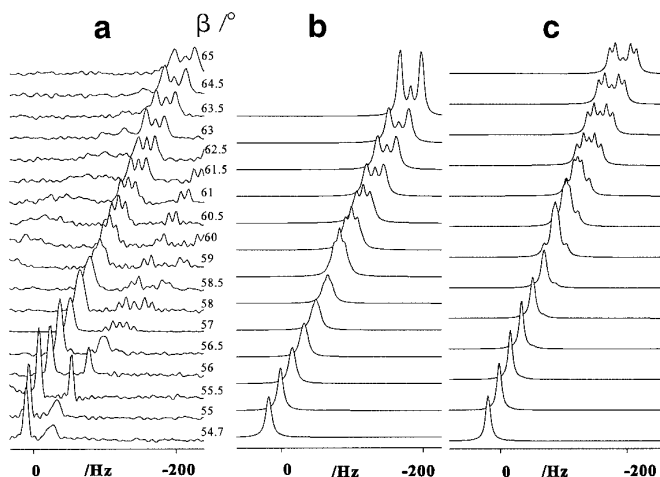


FIG. 13. Experimental (a) and simulated (b) and (c) VASS $^{13}\text{C}-\{^1\text{H}\}$ spectra from C5 near the magic angle. The simulations have (b) $J_{57} = 4.0$ and $J_{58} = -0.4$ Hz, while in (c) $J_{57} = -4.0$ and $J_{58} = 0.4$ Hz. In both cases the dipolar couplings are appropriate reductions of the static dipolar couplings $D_{57} = -7.5$ Hz and $D_{58} = 41.1$ Hz. The angle of the spinning axis with the field is given alongside each spectrum.

lineshape near the magic angle for a decision to be reached on their signs. In this case, therefore, the limit of sensitivity of the method has been reached, and absolute signs of the couplings must be assumed. They have been assumed to be positive. Changing both their signs to be negative changes the dipolar couplings measured from the splittings in the spectrum of the static spectrum by 2.5 Hz, and so this can be taken as the error in D_{67} and D_{68} .

CONCLUSION

The $^{13}\text{C}-\{^1\text{H}\}$ spectra of 2,2'-difluorobiphenyl dissolved in an isotropic solvent demonstrate that their analysis by numerical iterative processes can give an incorrect result unless some of the smallest of the peaks in the ^{13}C spectrum are detected. The spectrum from C5 is a good example, in

that the strong peaks suggest that the two couplings should be equal at 2.0 Hz, whereas detection of the weak outer peaks shows that in fact J_{AX} and J_{BX} are very different (4.0 and -0.4 Hz respectively). The experiments on the sample dissolved in a liquid crystalline solvent demonstrate how the absolute signs of the couplings J_{AB} , J_{AX} , and J_{BX} can be obtained by using the technique of variable angle sample spinning. The use of the VASS technique on liquid crystalline samples is limited by the ability to obtain a resolved $^{13}\text{C}-\{^1\text{H}\}$ spectrum, and the smallest coupling whose sign can be established depends on the width of the lines near the magic angle. In the present case the limit was close to 2.5 Hz.

ACKNOWLEDGMENT

This work was supported by the award of a research grant from the Engineering and Physical Sciences Research Council.

REFERENCES

1. F. J. Weigert and J. D. Roberts, *J. Am. Chem. Soc.* **93**, 2361 (1971).
2. J. Courtieu, J. P. Bayle, and B. M. Fung, *Prog. NMR Spectrosc.* **26**, 141 (1994).
3. J. Courtieu, D. W. Alderman, D. M. Grant, and J. P. Bayle, *J. Chem. Phys.* **77**, 723 (1982).
4. G. Celebre, G. De Luca, M. Longeri, and E. Sicilia, *J. Chem. Inf. Comp. Sci.* **34**, 539 (1994).
5. S. Castellano and A. A. Bothner-By, *J. Chem. Phys.* **41**, 3863 (1964).
6. M. A. Cooper, H. E. Weber, and S. L. Manatt, *J. Am. Chem. Soc.* **93**, 2369 (1971).
7. V. Wray, L. Ernst, and E. Lustig, *J. Magn. Reson.* **27**, 1 (1977).
8. G. V. D. Tiers, *J. Am. Chem. Soc.* **84**, 3972 (1962).
9. A. A. Bothner-By, P. J. Domaille, and C. Gayathri, *J. Am. Chem. Soc.* **103**, 5602 (1981).
10. A. A. Bothner-By, in "Encyclopedia of NMR" (D. M. Grant and R. K. Harris, Eds.), p. 2932, Wiley, Chichester (1996).
11. G. De Luca, M. Edgar, S. Edgar, J. W. Emsley, M. I. C. Furby, and M. Webster, submitted for publication.