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AROMATIC SOLVENT INDUCED SHIFTS (ASIS) IN ^{1}H N.M.R. SPECTRA; A GRAPHICAL ANALYSIS

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Abstract - By plotting ASIS values determined in the conventional way against ASIS values for a polyprotic solute in C_6D_6, approximately straight lines are obtained the slopes of which represent ASIS effects for solvents in comparison with that of benzene. These values are independent of effects introduced by choice of reference solvent and standard, whether internal or external.

Any modification of benzene that introduces an electronegative atom or group reduces the positive ASIS slope of benzene. The effect of several modifications is incremental and eventually produces a marked negative slope. By themselves, ASIS values are not a measure of ring current or of aromaticity.

It is only the presence of electronegative atoms of groups that affects ASIS slopes; orientation is immaterial showing that dipoles in aromatic solvents are not concerned in the ASIS phenomenon.

Mixtures (1:1) of benzene and hexafluorobenzene shield every proton in a solute; the resulting ASIS slopes are nearly zero as expected, but this is not a consequence of competition between the solvents but of a roughly additive property in shieldings. No evidence was obtained in support of the view that ASIS deshielding exists, or that there is any strong tendency of solvent molecules to cluster about a dipolar solute.

The following solvents were studied: benzene, eleven fluorobenzenes, nitrobenzene, 1,2-fluoronitrobenzene, 1,2,4-fluorodinitrobenzene, pyridine, pyrimidine, pyridazine, 3-methylpyridine oxide, pyrrole, thiophene, furan, 3,5-dimethylisoxazole, 1,2-dimethylimidazole, methoxybenzene, 1,3-dimethoxybenzene, methylenedioxybenzene. The chief solute was ethyl 4-dimethylaminobenzoate.

INTRODUCTION

Aromatic solvent-induced shifts (ASIS) in p.m.r. spectra are commonly believed to result from the shielding/deshielding influences of the aromatic ring current[1] although other causes have been suggested, including the electric field effect of bond dipoles[2] and the influence of non-local atomic anisotropies.[3] The usual view is that benzene molecules, for instance, will tend to face protons in a positive region of a solute and shield them by means of its ring current, while in a negative region they will take up an edgeways stance so that protons will experience deshielding instead. In support of the idea that the benzene molecules are orientated by the solute dipole several workers have obtained correlations between solute dipoles and ASIS effects,[4,5] and Williams and his colleagues[6] have used the idea to postulate a very simple model in which only one benzene molecule is aligned with a carbonyl group by means of its dipole. The resulting 'carbonyl plane rule' rationalised ASIS in various protons in the vicinity of the carbonyl group, and notwithstanding some anomalies[7] could be used to solve structural and conformational problems. Other workers have correlated ASIS effects not with μ, the dipole moment of the solute, but with μ^2 on the grounds that orientation is achieved through dipoles in the solute interacting with induced dipoles in the solvent.[8] In the carborane series ASIS effects could be correlated rather well with MO-derived charges on hydrogen, provided that nearest-neighbour effects were taken into consideration.[9]

The discovery[10] that hexafluorobenzene exhibits ASIS effects very like those of benzene but of opposite sign has suggested that the strong C-F dipoles would cause the halogenated solvent to present its (negative) fluorine atoms to the positive end of a dipole i.e. hexafluorobenzene would take up the edgeways stance where benzene would be face on and vice versa.[8,9,10] More recent studies return to a correlation of ASIS with the solute dipole moment μ , but show that dipole-induced dipole interactions are relatively unimportant compared with dipole-permanent quadrupole interactions.[5] The behaviour of hexafluorobenzene could readily be understood on this basis, because the principal values of the moments on the quadrupolar six-fold axes are opposite in sign to those of benzene; moreover, quadrupolar interactions could account for the carbonyl plane rule of Williams and in general for the angular dependence of ASIS effects. Of course, such calculations depend closely upon the assumption made about the solvation shell.

A few studies of other aromatic solvents have been made,[6,11-15] and Barton, Roth and Verkade[16] have suggested a way of using the ASIS phenomenon to assess aromaticity (i.e. ring currents) in various heterocycles. Whatever approach has been used, there have remained anomalies for which special explanations have been advanced in terms of local dipoles, steric crowding, hydrogen bonding etc. One general observation is that other aromatic solvents are less effective than benzene in producing shifts.

A basic criticism of much of this work has been made by Jutila,[17] who points out that ASIS measurements to an internal standard such as tetramethylsilane are not valid because the internal standard is itself subject to the ASIS phenomenon and so does not provide a fixed zero. The problem is occasionally mentioned by other authors[18,19] but is usually ignored. Following Rummens and Krystynek[20], Jutila shows that the chemical shift of tetramethylsilane is altered by -0.41 p.p.m. in tetrachloromethane, 0.21 in benzene, and 0.36 in benzaldehyde, with respect to external tetramethylsilane. These shifts are so large that, when allowance is made for them, almost no examples of ASIS deshielding remain, with major consequences for interpretation and particularly for solvation shell hypotheses.

In our own work we have sought a method of assessing ASIS effects that is free from distortion by the use of internal standards and of other, lesser sources of error, particularly the use of observations on single protons that may be subject to some unrecognised special effect. We have noted that Onak and his colleagues[9] report for members of the carborane series that ASIS for benzene ($\Delta\tau_B$) and ASIS for hexafluorobenzene ($\Delta\tau_H$) exhibit an inverse linear relationship expressed by Eq. 1:

$$\text{Eq. 1} \quad \Delta\tau_B = -1.12\,(\Delta\tau_H) + 18.5$$

We find that this type of correlation is general and have developed it into a graphical method for comparing the ASIS effects of various solvents with those exerted by benzene. The method makes it possible to separate some of the diverse contributory factors and to remove or minimise distortions arising from bulk solvent effects, choice of reference solvents, use of internal standards etc. It also assists us to discern which effects are truly anomalous and require special explanation. The method can be used to study either the solvent or the solute; this paper concentrates attention upon the solvent and solutes are discussed only so far as is required for that.

Chemical shift values obtained in the course of this work are listed in Table 1-6. Slopes obtained from graphical analysis are listed in Table 7. This Table also gives slopes derived by the application of the graphical method to certain chemical shifts reported by earlier workers.

METHOD

The usual method for determining ASIS has been adopted. The apparent chemical shift values obtainned in the reference solvent ($CDCl_3$) are compared with those obtained in the comparison solvent (C_6D_6), the difference being expressed as $\Delta\delta_{C_6D_6} = \delta_{CDCl_3} - \delta_{C_6D_6}$ (tetramethylsilane as internal standard). Cyclohexane is regarded as a superior reference solvent but its solubility characteristics were unsuitable for some of the solutes of interest to us. A similar shift difference was obtained for the aromatic or other solvent (ArS) under scrutiny and expressed as

$$\Delta\delta_{ArS} = \delta_{CDCl_3} - \delta_{ArS}$$

A polyprotic solute, often ethyl 4-dimethylaminobenzoate (1), was examined in benzene and in the other solvent(s). Since it is aromatic itself it could distort the measurements but we found this effect to exceed about 0.02 p.p.m. only at molar concentrations above 0.6 so we kept concentrations of this ester below 0.2 and made no correction.

Most of the determinations were made using a Varian A60 spectrometer with a field of 60 MHz and a probe temperature of 32.5 °C. For work with the series of fluorobenzenes other than hexafluorobenzene (cf. Figure 4) we used a Perkin-Elmer R32 spectrometer with a field of 220 MHz and a probe temperature of ca. 20 °C.

To compare an aromatic solvent (ArS) with benzene (i.e. C_6D_6) ASIS values for a solute such as (1) were obtained for both solvents and values of $\Delta\delta_{C_6D_6}$ were plotted along an abcissa and of $\Delta\delta_{ArS}$ along the coordinate axis as in Figure 1. In this diagram plot A is a hypothetical result for a solute with five different protons while plot B was obtained by comparing benzene results with themselves. Of necessity plot B is strictly linear, passes through the point (0,0), and has slope 1.00. In general the slope of plot A will not be unity and will depend upon the ability of the solvent under study to exert shielding/deshielding effects; the slope is therefore a measure of the ASIS effect of that solvent. In general plot A will not be perfectly straight; a point will fall off the line if the proton concerned interacts with one solvent in a way for which there is no parallel with the other. For example, a steric factor could hinder access by one solvent but not by the other at some particular point.

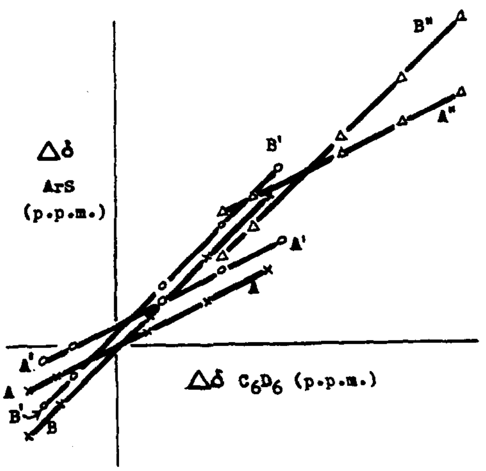


Fig. 1. Hypothetical plots for a solute containing 5 spectroscopically different protons

A. Plot of $\Delta\delta$ for an aromatic solvent ArS against $\Delta\delta$ for C_6D_6 using a reference solvent p and TMS as internal standard.
B. As A, but with ArS = C_6D_6.
A'. As A, but with a different reference solvent q.
B'. As A', but with ArS = C_6D_6.
A''. As A, but with TMS as external standard.
B''. As A'', but with ArS = C_6D_6.

Effects introduced by choice of reference solvents are seen as displacements of the whole plot without change of slope. In general, therefore, plots will not pass through the origin but will be displaced (hypothetical plots A' and B' in Fig. 1). When an external standard was needed we used a 3% solution of tetramethylsilane in $CDCl_3$ contained in a sealed capillary held concentric within the sample tube. Plots obtained with such a standard showed a much larger displacement placing them wholly within the (+,+) quadrant but without change of slope (plots A" and B" in Fig. 1).

Criteria governing the choice of solutes for ASIS studies have been discussed by earlier workers,[10] but for our purposes we add the proviso that there must be enough protons to yield points sufficient to define the slope of the plot with enough clarity. Figure 2 compares by means of ester (1) the solvents d_6-benzene and hexafluorobenzene. The extreme points (for NMe and 2-H) are particularly important since they do most to define the straight line and its slope, -0.65. In this example they are separated by about 1.0 p.p.m. which we would regard as the minimum satisfactory separation; without them the three central points would not necessarily suggest any relation to any straight line. Fig. 2 includes a plot for 1,3-cyclohexadiene showing that it gives a slope close to zero. For all the solutes discussed here and for many (though not all) others the slope determined by using only the extreme points is close to that obtained by using all the points to determine the best straight line, the two often differing by as little as 0.02 or less. A large discrepancy is taken to mean that the protons giving the extreme points are themselves subject to some special influence and such a solute would not be used for a study of the present kind.

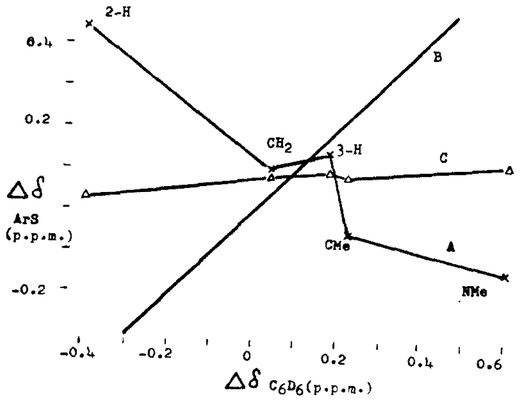
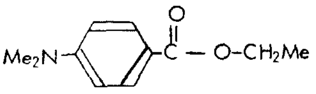


Fig. 2. Plot for ethyl 4-dimethylaminobenzoate, with C_6D_6 as comparison solvent, $CDCl_3$ as reference solvent, and TMS as internal standard.

A. With ArS = C_6F_6.

B. With ArS = C_6D_6.

C. With ArS = 1,3-cyclohexadiene.



(1)

The plots in Figures 1 and 2 are not concerned with the chemical shifts themselves, only with shifts differences, and the order in which protons appear along such lines is therefore not necessarily that in which they would be ranged in a conventional p.m.r. spectrum. The order may vary from one solute to another, including one isomer to another, without any other major change, and so it may itself provide information. The matter is not discussed further in this paper because the main topic is the aromatic solvent rather than the solute.

RESULTS AND DISCUSSION

As noted already, the plot for ester (1) in the benzene-hexafluorobenzene system is -0.65. Plots made from results reported by Bertrand et al.[10] for the trioxabicyclooctane derivative (2) have a slope -0.67 and for the trioxaadamantane derivative (3) -0.70 and, as shown by Fig. 3, they are roughly linear. Results for boranes and carboranes[9] tend to yield more negative slopes when plotted; 2,4-dicarborane (4) is included in Fig. 3 and has slope -0.78. Table 7 gives all the slopes determined as part of the present survey, and Table 1-6 provide the chemical shift data from which the plots were derived.

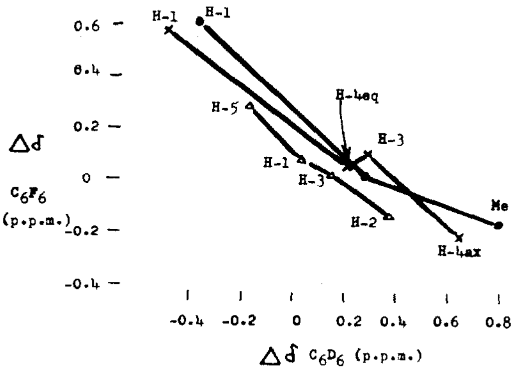


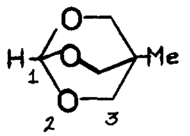
Fig. 3.

● Plot for bicyclooctane derivative (2); CCl_4 as reference solvent and TMS as internal standard.[10]

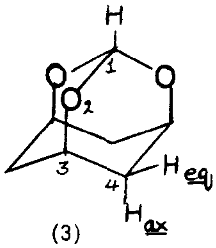
x Plot for adamantane derivative (3); CCl_4 as reference solvent and TMS as internal standard.[10]

△ Plot for carborane (4); cyclohexane as reference solvent and TMS as internal standard.[9]

The fluorobenzenes offer a unique set of solvents for testing ASIS phenomena. Mosbo and Verkade[12] have used some of them (fluorobenzene, 1,4-difluorobenzene, 1,2,4,5-tetrafluorobenzene,



(2)



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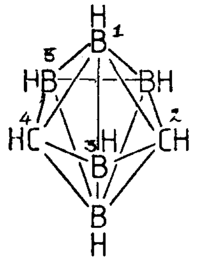
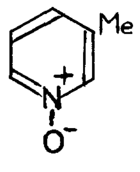


(4)



(5)

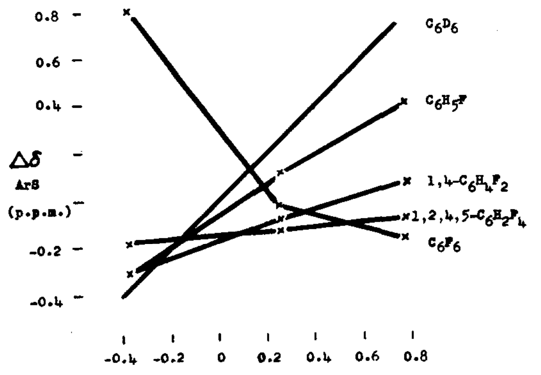


Fig. 4.

Plots for bicyclooctane derivative (2) in variously fluorinated benzenes, with CCl_4 as reference solvent and TMS as internal reference.[12]

and hexafluorobenzene) in a study of bicyclooctane such as (2) which they regarded as having a molecular dipole lying along the axis of symmetry with the methyl group as the negative end. They noted that benzene caused an upfield shift in the methine proton and a downfield shift in the methyl group. Increasing the degree of fluorination altered these effects somewhat but in passing from the tetrafluorobenzene to hexafluorobenzene a dramatic change seemed to occur in which the methine proton became deshielded and the methyl group shielded i.e. the effect of benzene was reversed. The explanation offered depended upon a degree of hydrogen bonding of solvent protons to solute oxygen atoms that prevented reorientation of the solvent. Special effects were noted at the 'waist' methylene protons.

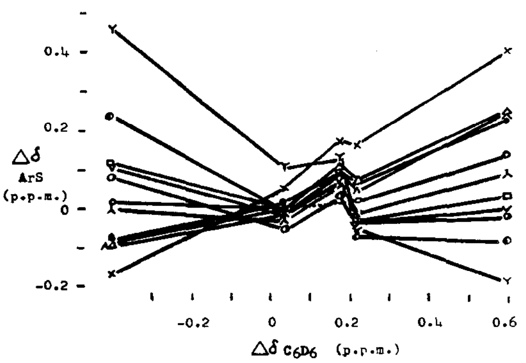


Fig. 5A.

Plots for ethyl 4-dimethylaminobenzoate (1) in variously fluorinated benzenes measured at 220 MHz with $CDCl_3$ as reference solvent and TMS as internal standard. Not all individual points in the central region are shown by symbols. The solvents ArS are shown thus: × C_6H_5F,

● 1,2-$C_6H_4F_2$, △ 1,3-$C_6H_4F_2$, ⋀ 1,4-$C_6H_4F_2$,

○ 1,3,5-$C_6H_3F_3$, ⅄ 1,2,4-$C_6H_3F_3$, □ 1,2,3,5-$C_6H_2F_4$,

∨ 1,2,3,4-$C_6H_2F_4$, ◑ 1,2,4,5-$C_6H_2F_4$, ◐ C_6HF_5,

Y C_6F_6. The dotted line bridges a gap left by a resonance overlaid by others.

When these results are plotted a series of lines (Figure 4) appear which suggest that there need be no very sudden change at any point. Since the solute has only three kinds of proton it is not ideal for our purposes so we have re-investigated the question using the ester (1) and a fuller range of fluorinated benzenes, giving the plots presented in Figure 5A which makes it clear that there is a steady change of slope dependent upon the number of fluorine atoms but not upon their distribution. It is particularly interesting that the three difluorobenzenes yield almost identical plots even though they range from 1,4-difluorobenzene with no net molecular dipole moment to 1,2-difluorobenzene with a high resultant dipole moment. There are small discrepancies of slope amongst the various trifluoro- and tetrafluoro-benzene isomers. However, when the slopes themselves are plotted against the numbers of fluorine atoms per solvent molecule (Fig. 5B) the points are found to lie upon a closely defined straight line and indeed hexafluorobenzene is somewhat anomalous with a slope greater (more negative) than expected. But the striking anomaly is provided by benzene which shows a much larger (positive) slope than expected, Benzene may therefore not provide an ideal basis for comparing solvent ASIS effects, but for the present we continue to use it.

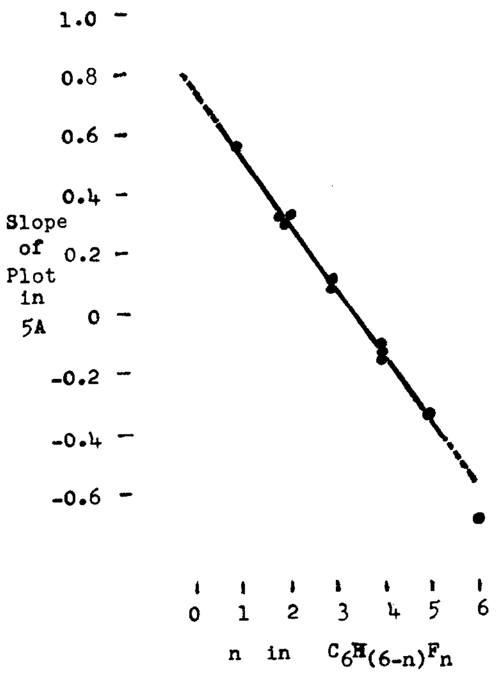


Fig. 5B
ASIS slopes from Fig. 5A plotted against the number of fluorine atoms per molecule of solvent.

It is now evident that the slope is proportional to the number of fluorine atoms and that their orientation is of little consequence, and it seems clear that resultant (molecular) dipoles in the solvent play no part. Steric (bulk) effects also seem to be ruled out since fluorine is hardly 'larger' than hydrogen,[21] and in any case no pattern emerges, but they may contribute to the small deviations between isomers. The change of slope might therefore be a result of individual C-F dipoles acting statistically or of an increase in electron withdrawal from the aromatic nucleus as the number of fluorine atoms increases. It might also result from some specific interaction between individual fluorine atoms and solute hydrogen atoms, although this is unlikely because similar changes of slope occur in the absence of fluorine atoms but in the presence of electron-withdrawing groups or atoms of any kind.

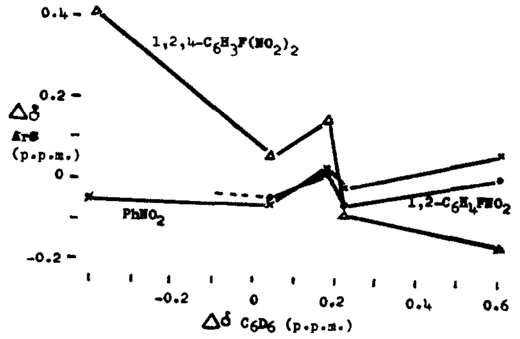


Fig. 6
Plots for nitrobenzene derivatives.

Figure 6 presents plots demonstrating the way in which nitro groups affect the slope. One nitro group has about the same effect as three fluorine atoms (that nitrobenzene hardly shields or de-shields solvate protons has been noted occasionally before[16, 19, 22]). Although the dinitrobenzenes are all too high-melting to be examined, 2-nitrofluorobenzene and 2,4-dinitrofluorobenzene (containing a little $CDCl_3$) proved to be suitable solvents, the latter simulating hexafluorobenzene as regards the slope it produces. Solutions of ester (1) in these solvents were deep yellow or orange, indicating some charge transfer complexation, but no corresponding effect in the p.m.r. spectrum could be discerned.

Figure 7 displays the plots obtained when the methine groups of benzene are replaced by nitrogen atoms. The slope becomes more negative with each new nitrogen atom, there being little difference between the isomers pyridazine and pyrimidine. The presence of a formal positive charge on a nitrogen atom could be expected to have a very large effect and probably it does; however, the only such only such compound available as a liquid (in the presence of a little $CDCl_3$) is the N-oxide (5) in which electron release from the oxygen atom would act in opposition. In the event, this oxide produces a small slope like that of the azines or of nitrobenzene.

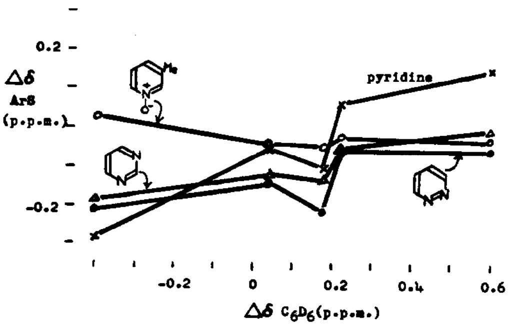


Fig. 7
Plots for pyridine and related compounds.

Five-membered heterocyclic solvents exhibit similar properties. As might be expected, thiophene closely resembles benzene (Figure 8) while furan, with a more electronegative heteroatom, shows a greater change in slope and also a more marked central aberration. 3,5-Dimethylisoxazole produces a slope near zero with surprisingly little aberration, and 1,2-dimethylimidazole behaves likewise.

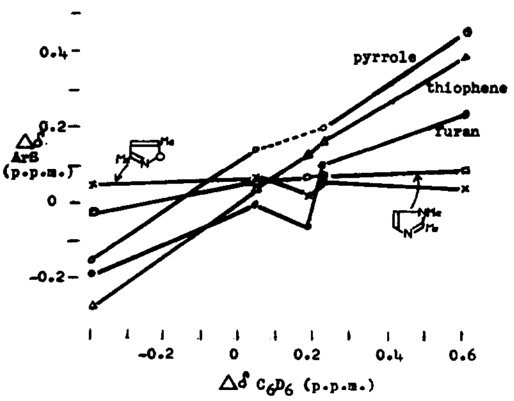


Fig. 8
Plots for five-membered heterocycles

Anisole was also examined, because its heteroatom, though electronegative, is also strongly electron releasing when circumstances require it. Figure 9 shows that the net effect is a reduction in slope, with a further decrease in passing to 1,3-benzodioxole or to 1,3-dimethoxybenzene; these two solvents are once more very similar notwithstanding the different orientations of the oxygen atoms.

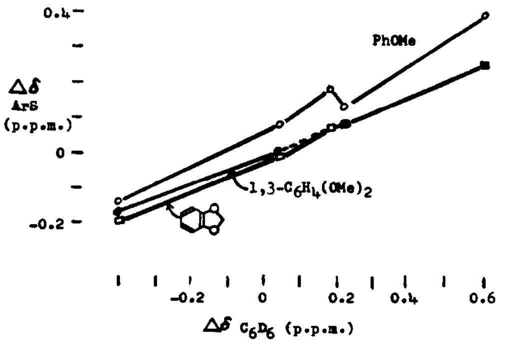


Fig. 9
Plots for compounds related to anisole

Barton, Roth and Verkade[16] have examined solutes similar to (2) and (3) in various solvents. We have confirmed a selection of their results for (2) itself, and plotted them as in Figure 10. Though only three points are possible for each line it is obvious that the slopes are affected in just the same way as for the aromatic solute (1). Hence the phenomenon does not depend upon aromaticity in the solute, only upon aromaticity in the solvent. Nevertheless, ASIS effects do not measure aromaticity or ring current in the way suggested.[16] It is true that non-aromatic solvents afford slopes that are seldom far from zero (as in examples included in Figs. 2 and 10), but solvents of accepted aromaticity may do likewise if they contain the appropriate electronegative atoms or groups; in any case, it is not acceptable that aromaticity varies through the fluorobenzene series in the manner shown by the slopes (Figs. 5A and 5B). Furthermore, ASIS effects cannot yield information about ring currents unless the degree of association between solute and solvent molecules and particularly their relative orientations are also known or can be controlled. In studies where a high degree of control is implicit, the furan ring induces shifts at least 60% of those induced by benzene rings.[23,24] From the ASIS slopes in Table 1 furan appears to have a ring current of only about 44% of that in benzene and the difference is presumed to be due to one or both of the other factors.

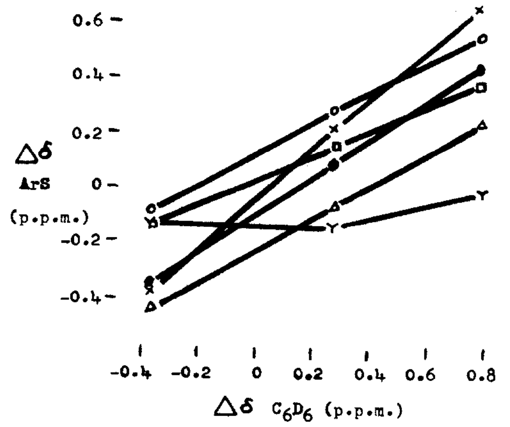


Fig. 10

Plots for the bicyclooctane derivative (2) in various solvents, with CCl_4 as reference solvent and an internal TMS standard presumed.[16]

× thiophene, ○ N-methylpyrrole, ● furan, □ cyclopentadiene, △ pyridine, Y $PhNO_2$.

Anet and Schenck introduced S values as a measure of aromaticity.[25] These values depend upon a single proton resonance (acetonitrile) measured with respect to cyclohexane in the same conditions. Several of them seemed to be anomalous and to require special explanation: pyrrole was unexpectedly strongly shielding, furan too weakly; cyclo-octatetraene gave a negative value tentatively attributed to residual anti-aromaticity in the puckered ring system. A comparison of ASIS slopes with relevant S values (Table 3) shows that the slopes remove these anomalies except for that of cyclopentadiene, which continues to simulate the behaviour of furan. This hydrocarbon is anomalous in other respects also.[26] Norbornadiene shows a similar but less pronounced effect. Evidently strong ASIS effects are possible in the absence of a conventional aromatic ring current.

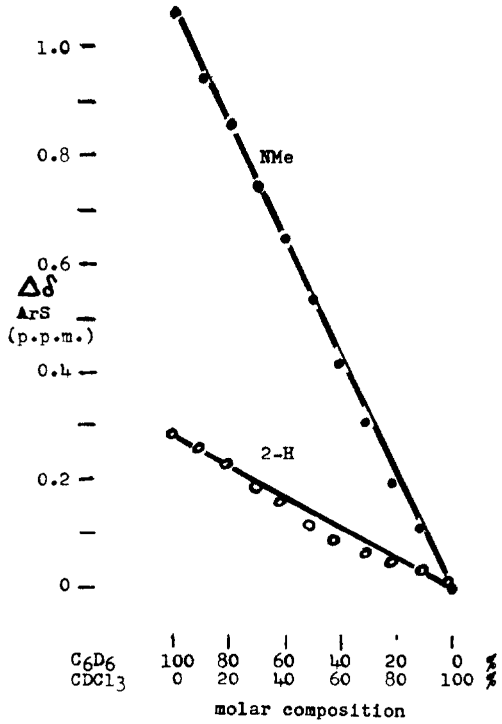


Fig. 11

Effect upon shift differences for NMe and 2-H in ester (1) of diluting C_6D_6 with $CDCl_3$; with TMS as external standard.

If ASIS effects require a clustering of solvent molecules around a pole or some kind of complex formation, plots of ASIS slopes against molar concentrations of the aromatic solvent would be expected to deviate from a straight line. Plots for C_6D_6 and C_6F_6 (Figs. 11 and 12) show that there are small deviations but that, if anything, they are in the wrong direction suggesting that such clustering or complex formation is not important. The method is not sensitive, however, so we sought other evidence.

If it is true that the positive end of a solute dipole attracts benzene in the face-on stance and hexafluorobenzene in the edge-on stance, then in a mixture of these solvents they will have to compete with each other (as also at the negative end). For an equimolecular mixture the resulting ASIS slope should be nearly zero, and the plot should lie roughly half way between plots for the

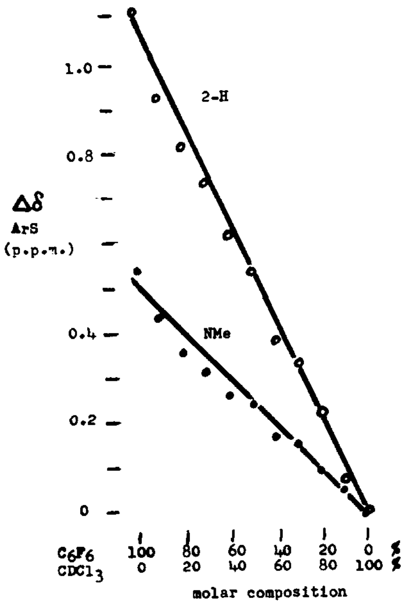


Fig. 12.

Effect upon shift differences for NMe and 2-H in ester (1) of diluting C_6F_6 with $CDCl_3$, with TMS as external standard.

neat solvents. But when ASIS effects are corrected for the use of an internal solvent as recommended by Jutila[17] the plots cease to enter a negative region (hypothetical plots A" and B" in Fig. 1) leaving no direct evidence for deshielding, only for net shielding. If there is no deshielding, then there can be no competition between solvents and the mixed solvent should shield the positive end by means of benzene and, at the same time, the negative end by means of hexafluorobenzene. Whereas the ASIS plot would again have a slope near zero, this would be achieved not by averaging the separate plots but by summing them. That this is the observed result is shown by Figs. 13 and 14. (In addition, the systems were diluted with $CDCl_3$ to reduce the tendency of the mixed solvent to form a weak 1:1 complex[27].) We have not yet tested the point extensively, but it seems likely that mixtures of solvents of opposite slope will always be relatively strongly shielding

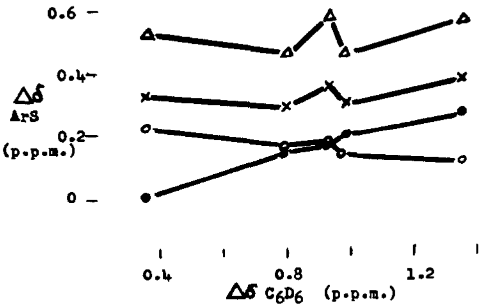


Figure 13

Effect of mixed solvents on plots for ethyl 4-dimethylaminobenzoate (1). Reference solvent $CDCl_3$ with TMS as external standard. Ratios are molar.

△ $CDCl_3$: C_6D_6 : C_6F_6 (1:1:1)
× $CDCl_3$: C_6D_6 : C_6F_6 (3:1:1)
● $CDCl_3$: C_6D_6 (4:1)
○ $CDCl_3$: C_6F_6 (4:1)

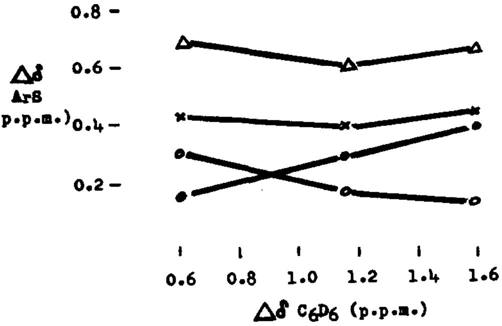


Fig. 14

Effect of mixed solvents on plots for the bicyclooctane derivative (2). Reference solvent $CDCl_3$ with TMS as external standard. Ratios are molar.

△ $CDCl_3$: C_6D_6 : C_6F_6 (1:1:1)
× $CDCl_3$: C_6D_6 : C_6F_6 (3:1:1)
● $CDCl_3$: C_6D_6 (4:1)
○ $CDCl_3$: C_6F_6 (4:1)

for every proton in any solute.

The mixture of benzene and hexafluorobenzene was also compared with neat 1,3,5-trifluorobenzene, which might be regarded as a molecular average between the other two solvents. Fig. 15 shows that both plots have slopes near zero, but that the mixed solvent is again shielding.

We consider that our results support the following conclusions.

(i) ASIS slopes offer a more reliable measure of ASIS effects than others currently used; they are also independent of choice of reference compounds and reference solvents, (ii) ASIS effects do not measure aromaticity, and may be zero in solvents that would normally be regarded as fully aromatic (benzenoid), (iii) ASIS effects are not dependent upon the molecular dipole moment of the solvent, (iv) ASIS effects are exerted by cyclopentadiene and are therefore unlikely to be dependent upon aromatic ring currents, (v) ASIS effects are shielding only, appropriate mixtures of solvents shielding every proton in any solute, and (vi) ASIS effects do not depend upon a highly organised solvent shell or upon complexes of much stability.

We have also examined the relationships between ASIS slopes and some other molecular parameters and hope to describe the results separately.

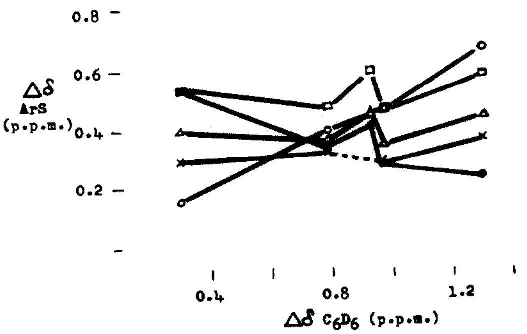


Fig. 15

Comparison of mixed solvents with 'average' solvent by means of ester (1). Reference solvent $CDCl_3$ with TMS as internal standard.

○ C_6D_6 : $CDCl_3$ 1:1
● C_6F_6 : $CDCl_3$ 1:1
× 1,3,5 - $C_6H_3F_3$
□ C_6D_6 : C_6F_6 1:1
△ C_6D_6 : C_6F_6 : $CDCl_3$ 1:1:1

Table 1. Chemical Shifts (δ) for ester (1) in various solvents[a]

	C-Me	CH_2	N-Me	2-H	3-H
$CDCl_3$	1.35	4.33	2.98	7.90	6.63
C_6D_6	1.13	4.29	2.38	8.30	6.45
C_6F_6	1.41	4.23	3.13	7.47	6.49
Nitrobenzene-$\underline{d}_5$	1.37	4.39	2.91	7.95	6.60
1-Fluoro-2-nitrobenzene	1.41	4.37	2.97	8.01[b]	6.60
2,4-Dinitrofluorobenzene	1.43	4.27	3.14	7.49	6.48
Pyridine-$\underline{d}_5$	1.28	4.38	2.82	8.19	6.73
Pyrimidine	1.37	4.45	2.98	8.09	6.76
Pyridazine	1.41	4.47	3.03	8.12	6.84
3-Methylpyridine-N-oxide[c]	1.36	4.36	3.00	7.88	6.67
1,2-Dimethylimidazole	1.27	4.27	2.88	7.92	6.64
3,5-Dimethylisoxazole	1.28	4.25	2.93	7.84	6.60
Thiophene	1.16	4.28	2.56	8.16	6.48
Furan	1.23	4.23	2.72	8.08	6.68
Pyrrole	1.13	4.17	2.53	8.05	
Anisole	1.22	4.25	2.59	8.04	6.45
1,3-Benzodioxole	1.27	4.34	2.73	8.09	6.56
1,3-Dimethoxybenzene	1.27	4.33	2.73	8.07	
1,3-Cyclohexadiene	1.26	4.24	2.86	7.86	6.53
Cyclopentadiene	1.24	4.25	2.79[b]	8.03	

[a] At 60 MHz, with TMS as internal standard

[b] ± 0.03 [c] Containing 5% $CDCl_3$.

Table 2 Chemical shifts (δ) for ester (1) in fluorinated benzenes[a]

	CMe	CH_2	NMe	2-H	3-H
C_6D_6	1.10	4.24	2.32	8.25	6.37
C_6H_5F	1.19	4.26	2.61	8.07	6.46
1,2-$C_6H_4F_2$	1.30	4.30	2.78	7.89	6.53
1,3-$C_6H_4F_2$	1.29	4.31	2.77	7.99	6.52
1,4-$C_6H_4F_2$	1.30	4.32	2.77	7.99	6.53
1,2,4-$C_6H_3F_3$	1.36	4.34	2.92	7.90	6.57
1,3,5-$C_6H_3F_3$	1.33	4.32	2.87	7.88	
1,2,3,4-$C_6H_2F_4$	1.39	4.34	3.02	7.79	6.56
1,2,3,5-$C_6H_2F_4$	1.38	4.33	2.98	7.78	6.53
1,2,4,5-$C_6H_2F_4$	1.39	4.36	2.99	7.82	6.57

Table 2 contd.

	CMe	CH_2	NMe	2-H	3-H
C_6HF_5	1.43	4.32	3.10	7.66	6.54
C_6F_6	1.42	4.20	3.20	7.44	6.50

[a] At 220 MHz with TMS as internal standard.

Table 3. Chemical shifts^a (δ) for ester (1) in C_6D_6 - $CDCl_3$ *mixtures*

Mol. % C_6D_6	CMe	CH_2	NMe	2-H	3-H
10	1.26	4.25	2.865	7.86	6.53
20	1.17	4.18	2.74	7.84	6.45
30	1.09	4.12	2.60	7.83	6.39
40	1.00	4.04	2.46	7.80	6.30
50	0.89	3.94	2.31	7.75	6.19
60	0.78	3.86	2.16	7.71	6.09
70	0.68	3.78	2.04	7.66	5.99
80	0.58	3.69	1.89	7.62	5.89
90	0.49	3.62	1.78	7.58	5.80

[a] With external TMS in $CDCl_3$ as standard

Table 4. Chemical shifts^a (δ) for ester (1) in C_6F_6 - $CDCl_3$ mixtures

Mol. % C_6F_6	CMe	CH_2	NMe	2-H	3-H
10	1.28	4.26	2.98	7.83	6.56
20	1.23	4.19	2.89	7.68	6.46
30	1.17	4.11	2.83	7.57	6.37
40	1.14	4.08	2.815	7.52	6.36
50	1.07	3.99	2.74	7.37	6.22
60	1.03	3.94	2.725	7.29	6.19
70	0.97	3.845	2.67	7.17	6.10
80	0.91	3.78	2.63	7.09	6.04
90	0.83	3.68	2.55	6.98	5.96

[a] With external TMS in $CDCl_3$ as standard

Table 5. Chemical shifts^a (δ) for ester (1) in C_6D_6-C_6F_6 mixtures

Molar ratios $CDCl_3$:C_6D_6:C_6F_6	CMe	CH_2	NMe	2-H	3-H
4 : 1 : 0	1.14	4.17	2.70	7.86	6.45
4 : 0 : 1	1.20	4.16	2.85	7.67	6.45
3 : 1 : 1	1.04	4.03	2.59	7.57	6.26
2 : 1 : 1	1.01	3.97	2.545	7.51	6.185
1 : 1 : 1	0.89	3.86	2.40	7.37	6.04
b	1.01	4.01	2.615	7.61	c

[a] With external TMS in $CDCl_3$ as standard

[b] $CDCl_3$: 1,3,5-$C_6H_3F_3$ in 1:1 ratio. [c] Obscured

Table 6. Chemical shifts (δ) for bicyclooctane (2) in various solvents.

A. In neat solvents^a.

	C_6D_6	C_6F_6	Cyclopentadiene	$CDCl_3$
CH	5.755	4.64	5.485	5.60
CH_2	3.54	3.78	3.65	3.935
CH_3	0.00	0.95	0.45	0.83

B. *In mixed solvents (molar ratios* $CDCl_3$:C_6D_6:C_6F_6)^b

	1:4:0	1:0:4	1:1:1	3:1:1
CH	5.445	5.295	4.915	5.17
CH_2	3.645	3.76	3.315	3.535
CH_3	0.425	0.68	0.155	0.37

[a] With internal TMS as standard

[b] With external TMS in $CDCl_3$ as standard.

Table 7. ASIS slopes for solvents.^{a}

	Slopes		$\underline{S}$ values^b
Solvent	ester(1)	bicyclo-octane(2)	MeCN
C_6D_6	1.00	1.00^c	1.00
C_6H_5F	0.57	0.62^d	
1,2-$C_6H_4F_2$	0.31		
1,3-$C_6H_4F_2$	0.33		
1,4-$C_6H_4F_2$	0.33	0.41^d	

Table 7 Contd.

Solvent	Slopes		S values[b]
	ester(1)	bicyclo-octane(2)	MeCN
1,3,5-$C_6H_3F_3$	0.12		
1,2,4-$C_6H_3F_3$	0.09		
C_6D_6-C_6F_6(1:1)	0.08		
1,2,4,5-$C_6H_2F_4$	-0.10	0.09[d]	
1,2,3,4-$C_6H_2F_4$	-0.12		
1,2,3,5-$C_6H_2F_4$	-0.11		
C_6HF_5	-0.31		
C_6F_6	-0.66	-0.84[c]	
$PhNO_2$-d_5	0.12	0.10[d]	
1,2-$C_6H_4FNO_2$	0.07		
1,2,4-$C_6H_3F(NO)_2$	-0.57		
d_5-pyridine	0.45	0.58[d]	
pyridazine	0.17		
pyrimidine	0.19		
3-methyl-pyridine N-oxide	-0.04[e]		
furan	0.44	0.66[d]	0.42
thiophene	0.68	0.87[d]	
pyrrole	0.55		0.82
N-methylpyrrole		0.54[d]	
3,5-dimethyl-isoxazole	- 0.01		
1,5-dimethyl-imidazole	0.12		
1,3-cyclohexadiene	0.08		
cyclooctatetraene	0.04	0.10[d]	- 0.16
norbornadiene	0.19		0.16
cyclopentadiene	0.41	0.44[c]	0.31

[a] At ambient temperatures

[b] Taken from ref. 25.

[c] This work

[d] Calculated from data in ref. 16.

[e] In the presence of 5% $CDCl_3$

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