Solvent Effects on ^{13}C Nuclear Magnetic Resonance Shifts of Polar Aliphatic Compounds. A Charge Separation Model

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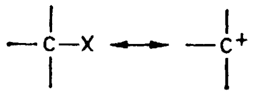
A model is proposed which explains the large solvent effects on the shielding of carbon atoms bearing polar bonds (ΔC_α) with an increased charge separation in solvents of a higher dielectric constant. Using *cis*-1-iodo-1-methyl-4-t-butylcyclohexane and t-butyl chloride as conformationally homogeneous solutes, one obtains for a series of solvents a linear correlation ($r > 0.95$) for ΔC_α in the expected range of 415 p.p.m./electron charge unit and 320 p.p.m./e, respectively. In a second set of experiments, the sensitivity of ΔC_α against solvent changes for differing C_α–X bonds is obtained, again yielding a linear correlation ($r > 0.99$) with 380 p.p.m./e. In addition, a ΔC_α enhancement with increasing carbon substitution at C_α is found for several alkyl iodides and rationalized in terms of an increasing contribution of the charged form to the resonance hydride.

MEDIUM effects on the shielding of carbon atoms are expected to be of relatively smaller magnitude than for protons, which, due to their situation on the periphery of organic molecules, are more exposed to intermolecular interactions. Nevertheless, solvent effects on ^{13}C shifts have been found to be sizeable even with the older instrumentation and are at present of considerable theoretical and practical interest. Besides providing information on shielding mechanisms and intermolecular interactions, the variation of ^{13}C shielding with solvent properties bears on many applications of ^{13}C n.m.r. spectroscopy such as spectral comparison, interpretation of smaller long range substituent effects, and, particularly, on the use of time averaged signals for equilibrium measurements at different temperatures.[1] In this report we concentrate on solvent effects on alkanes containing one C–X bond of pronounced polarity and/or polarizability. The systems are so chosen that conformational changes due to intermolecular interactions are excluded, that medium effects on several carbon atoms in different positions are measureable, and that the dependence of solvent effects on properties of different C–X bonds can be studied.

The older literature on ^{13}C solvent interactions, which contains many large and specific effects, *e.g.* by hydrogen bonds, has been already reviewed.[2] Several more recent studies have shown that medium effects for non-polar or slightly polar compounds even in polar solvents are largely determined by weak van der Waals interactions.[3-6] Reaction field theory has been applied to solutes of higher polarity, such as acrylonitrile[7] and acetone,[8] where specific interactions as hydrogen bonding or self-association could also be demonstrated. Solvation effects on acetonitrile and acetone have been evaluated quantum chemically;[9] carbonyl shifts were related to corresponding changes in i.r. frequencies.[10] Some of the large solvent effects reported previously for alkyl iodides[11] could be obscured by conformational changes, such as those found with n-pentane.[12]

A major problem in solvent studies on n.m.r. shifts is the choice of a proper reference signal. Detailed investigations have shown that the ^{13}C absorbance of tetramethylsilane (TMS) undergoes substantial solvent effects;[13,14] in some preliminary measurements similar medium shifts are found even for the quaternary carbon signal of the less polar neopentane (see Experimental section). For the study of larger solvent effects, however, TMS can be used as internal reference, as evident from the shifts observed in this work for all carbon atoms not bearing a polar bond; these atoms show variations, relative to TMS, which are smaller by an order of magnitude in comparison to functional carbon atoms.

In the description of a polar bond as a resonance hybrid, a higher contribution of the ionized form is expected in solutions of higher polarity. Onsager's formula (1) for the increase of a molecular dipole moment from the gas state (g) to the solution (s) as a function of the dielectric constant ε[15,16] can be applied to an



$$\text{—C—X} \longleftrightarrow \text{—C}^+\ \text{X}^-$$

$$\frac{\mu_g}{\mu_s} = 1 - \frac{4\pi N_A}{3V} \cdot \alpha \cdot \frac{2\varepsilon - 2}{2\varepsilon + 1} \qquad (1)$$

isolated C–X bond instead of a whole molecule, if the polarizability α is replaced by that of a C–X bond (P_{C-X}). This approximation seems to be justified because for the observed compounds the C–X bond is much more polar than all other bonds in the molecule, and these moreover remain constant while only the C–X bond is varied for the observation of relative solvent effects. For V in equation (1) the molar volume of the whole molecule is used, since V refers to the cavity diameter.[6,16] With $\mu = q \cdot l_{CX}$ and the approximation that in going from the gas state to solution the dipole length l will change to a much lesser degree than the charge distribution represented by q, equation (1) can be written as (2). Simplifying (2) by putting $1/(1 - x) \approx 1 + x$ one obtains (3). As far as the paramagnetic

$$\frac{q_s}{q_g} = \left(1 - \frac{4\pi N_A}{3V} \cdot P_{CX} \cdot \frac{2\varepsilon - 2}{2\varepsilon + 1}\right)^{-1} \qquad (2)$$

$$q_s = q_g \cdot \left(1 + \frac{4\pi N_A}{3V} \cdot P_{CX} \cdot \frac{2\varepsilon - 2}{2\varepsilon + 1}\right) \qquad (3)$$

TABLE 1

The effects of various solvents on ^{13}C n.m.r. shifts [a]

Solvent	t-Butyl chloride C-1	t-Butyl chloride C-2	1(a)-Iodo-1(e)-methyl-4(e)-t-butylcyclohexane C-1	C-2	C-3	C-4	eq-CH_3	Bu^t-CH_3	Bu^t-quat.C
TMS	64.67	34.65	55.60	46.76	26.40	48.13	39.70	32.65	27.78
C_6H_{12}	64.49	34.47							
CCl_4	64.88	34.13	57.05	45.95	25.72	47.23	39.16	32.30	27.52
CS_2	64.94	34.10	57.29	46.07	26.06	47.36	39.13	31.79	27.47
$CHCl_3$	67.27	34.51	60.34	46.15	26.03	47.26	39.35	32.36	27.55
C_6H_5Br	66.45	33.95	59.49	45.77	25.83	46.84	39.12	31.99	27.39
CH_2Cl_2	67.81	34.48	61.29	46.55	26.46	47.60	39.56	32.61	27.67
Me_2CO	67.70	34.24	61.70	46.65	26.76	47.78	39.64	32.87	27.78
HMPA [b]	68.07	34.45							

[a] In p.p.m. relative to internal TMS, extrapolated to zero solute concentration. [b] Hexamethylphosphoramide.

carbon shielding constant can be related to gross atomic charges, equation (3) could be useful to describe ^{13}C shifts as a function of both solution dielectric constant ε and C–X bond polarity. Square electric fields also can contribute to deshielding by solvent-enhanced C–X polarizability, as quantified by equation (4).[1]

$$\Sigma \langle E^2 \rangle \cong 1 - \text{const}\,.\,(0.333 - k_i)\,.\,(\varepsilon - 1)\,.\,(\varepsilon + 2)^{-1} \qquad (4)$$

Temperature-dependence measurements with spherically symmetrical molecules had already suggested that changes in $\langle E^2 \rangle$ by the solvent must be of minor importance.[1] Indeed, measurements with carbon tetrahalides, which, since $k_i = 0.333$, should give negligible effects by equation (4), do show substantial changes from $\delta_{TMS} = 95.92$ to 96.50 (CCl_4) and −30.41 to −28.83 p.p.m. (CBr_4) between carbon tetrachloride as solvent (ε 2.22) and dichloromethane (ε 8.72).

The influence of solution polarity as predicted by equation (3) was investigated for nine solvents using t-butyl chloride and *cis*-1-iodo-1-methyl-4-t-butylcyclohexane as substrate. The first compound, although present in only one conformation, can still assume different torsional angles in different solutions, but the second one is rather rigid. The expected deshielding with increased charge separation in the more polar solvents is observed for the functional C_α atoms, the other carbon atoms showing small irregular effects (Table 1), which might in fact be partially due to variations of the internal reference TMS.

For both substrates linear correlations with coefficients $r > 0.95$ according to equation (3) are found (Figure 1). From the observed slopes of 6.25 p.p.m. per $[(2\varepsilon - 2)/(2\varepsilon + 1)]$ unit (≡ εu) for t-butyl chloride and 10.6 p.p.m./εu for the iodide, and from the independent values for q_g, P_{CX}, and V (Table 2), sensitivities of 320 and 415 p.p.m./electron charge unit, respectively, can be calculated. That both these values are in the generally accepted range of 300 p.p.m./e [17] is considered to be more significant than the observed linearity, which can be obscured by certain specific solvent effects such as anisotropy (with bromobenzene) or hydrogen bonds (with chloroform).

Another test for equation (3) is provided by observing the magnitude of a solvent effect as a function of C–X bond polarizability. For this purpose (3) is written in the form (5) for two different solvents with ε_1 and ε_2. As a suitable solvent pair for the observation of Δq, or the

$$\Delta q = q_g \cdot \frac{4\pi N a}{3V} \cdot \left(\frac{2\varepsilon_1 - 2}{2\varepsilon_1 + 1} - \frac{2\varepsilon_2 - 2}{2\varepsilon_2 + 1} \right) \cdot P_{CX} \qquad (5)$$

corresponding shielding difference, we have chosen carbon tetrachloride and dichloromethane because of their relatively large difference in εu units and the absence of specific effects; t-butyl compounds provided the necessary P_{CX} variations. As expected, the largest shift differences are observed for the more polarizable bonds (Table 3). The linear function (Figure 2) of P_{CX} and particularly the sensitivity of 380 ± 20 p.p.m./e again supports the underlying concept of a charge separation mechanism as described by equation (3). The correlation coefficient r is 0.995, if one omits X = F, which is susceptible to specific interaction with dichloromethane.[18]

TABLE 2

Molecular constants used for Δq calculations with t-butyl compounds Bu^tX

X	V [a]/cm^3	$10^{24}P_{C-X}$ [b]/ cm^{-3}	q_{gas} [c]/e units	Δq/e units
H	118	0.79	−0.058	−0.0004
CH_3	118	1.12	0	0
F	100.9	0.96	0.285	0.0027
Cl	110	3.67	0.23	0.0075
Br	112	5.04	0.205	0.0090
I	119	8.09	0.162	0.0108
OCH_3	119	0.84	0.258	0.0018
NH_2	105	0.86	0.206	0.0016

[a] From molecular weights and densities, R. C. Weast, ' Handbook of Chemistry and Physics,' Chemical Rubber Co., Cleveland, 1972, 53rd edn. [b] V. I. Minkin and Y. A. Zhdanov, ' Dipole Moments in Organic Chemistry,' Plenum Press, New York–London, 1970, p. 1966. [c] From INDO-calculated Mulliken populations and bond dipole moments, see text and H.-J. Schneider and W. Freitag, *J. Amer. Chem. Soc.*, 1977, **99**, 8363.

TABLE 3

Solvent effects on ^{13}C n.m.r. shifts with various t-butyl compounds [a] Bu^tX

X	$\delta_{^{13}C}$ (p.p.m.) In CCl_4 C-1	In CCl_4 C-2	In CH_2Cl_2 C-1	In CH_2Cl_2 C-2	$\delta_{CH_2Cl_2} - \delta_{CCl_4}$
CH_3	27.92	31.52	28.14	31.62	0.22
F	91.86	28.41	94.28	28.61	2.42
Cl	64.88	34.13	67.81	34.48	2.93
Br	59.96	36.26	63.55	36.62	3.59
I	40.42	20.27	44.72	40.68	4.30
OCH_3	71.80	26.93	72.86	27.17	1.06

[a] See footnote to Table 1.

Finally, differences in solvent effects for primary, secondary, tertiary, and quaternary carbon atoms were investigated with four alkyl iodides (Table 4). The regular increase of C_α shift differences between dichloromethane and carbon tetrachloride as solvent is expected on the basis of an increasing contribution of the (C^+X^-) resonance structure with more alkyl substituents on C_α, leading to higher values of q_g in equation (3) and thus to a larger sensitivity. Moreover, longitudinal bond polarizabilities increase in the same direction, as *e.g.* from 6.70×10^{24} cm^3 (MeI) to 9.19×10^{24} cm^3 (Me_3CI),[19] but this contribution will be partially mitigated by the accompanying increase in molar volume (62.3 cm^3 for MeI; 119 cm^3 for Me_3CI).

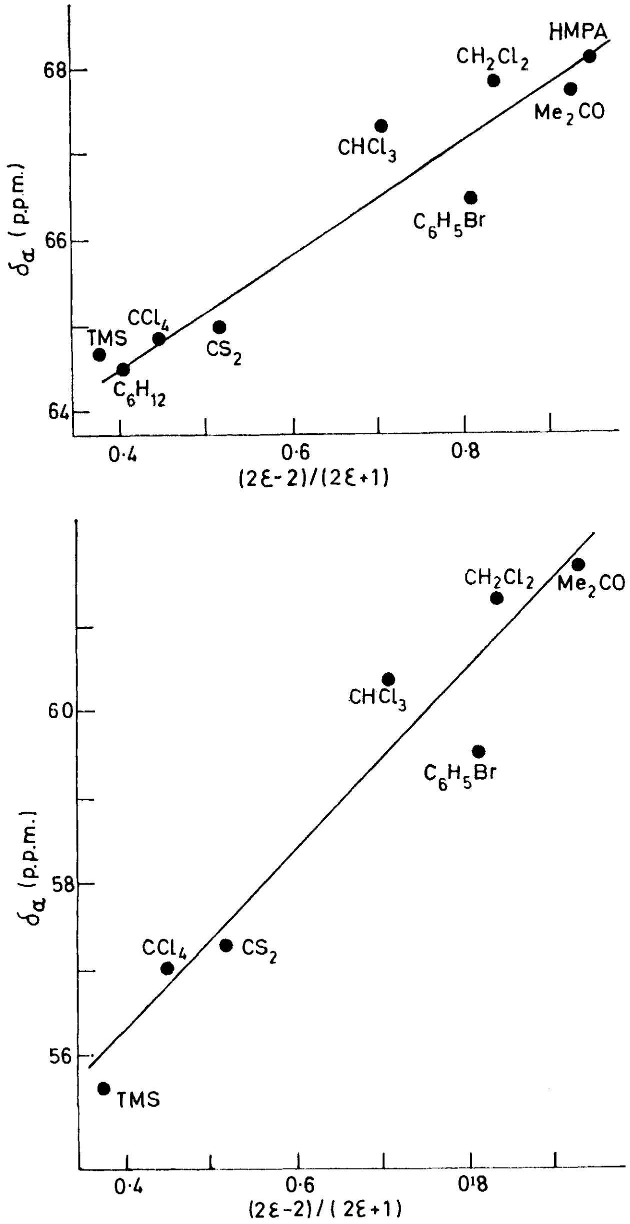


FIGURE 1 ^{13}C N.m.r. shifts of the functional carbon atom of (a) t-butyl chloride and (b) 1(a)-iodo-1(e)-methyl-4(e)-t-butylcyclohexane, plotted as a function of solvent dielectric constant ε as in equation (3)

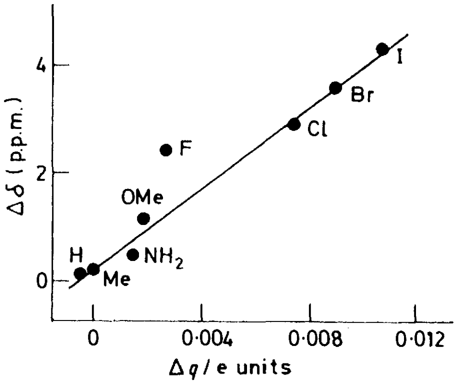


FIGURE 2 ^{13}C Solvent sensitivity ($\Delta\delta = \delta_{CH_2Cl_2} - \delta_{CCl_4}$) of the $C\alpha$ shifts of various t-butyl compounds, plotted against calculated charge variations Δq of equation (5)

TABLE 4

Solvent effects on ^{13}C n.m.r. shifts as a function of substitution at C_α[a]

	δ_{CCl_4}		$\delta_{CH_2Cl_2}$		$\delta_{CH_2Cl_2} - \delta_{CCl_4}$
Solute	C-1	C-2	C-1	C-2	C-1
MeI	−25.21		−23.28		1.93
EtI	−3.13	20.35	−0.26	20.88	2.87
Pr^{i}I	18.82	30.94	22.51	31.42	3.69
Bu^{t}I	40.42	40.27	44.72	40.68	4.30

[a] See footnote to Table 1.

EXPERIMENTAL

^{13}C N.m.r. spectra were recorded in the pulsed Fourier transform mode on a Bruker HX 90 spectrometer at 22.63 MHz with a digitally limited resolution of 0.015 p.p.m. Hexafluorobenzene in an external capillary served as ^{19}F lock reference. Usually shifts with 15, 10, and 5% solute concentration were taken and then extrapolated to zero concentration. All compounds and solvents were either analytical grade or purified prior to use. As internal reference TMS was used at concentrations which were a third of those of the observed solute. Measurements with neopentane in CCl_4 and CH_2Cl_2, in which solvents TMS shows an extreme difference of Δδ 0.72 p.p.m.,[14] gave for the quarternary carbon Δδ 0.50 p.p.m. and for the methyl signal Δδ 0.62 p.p.m. [calculated from their shifts relative to TMS in a mixture of 4% (2%) TMS, 4% (2%) cyclohexane, and 8% (8%) neopentane in CCl_4 (CH_2Cl_2)].

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