The Association of Dimethylformamide Molecules in Carbon Tetrachloride Solution

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Quantitative evidence from n.m.r. spectroscopy is presented which strengthens the assumption that dimethylformamide molecules associate as dimers at low concentrations in carbon tetrachloride solution. Values for $\Delta H°$ and $\Delta S°$ for the dimerization are estimated as well as for δ_m and δ_d, the limiting *N*-methyl-hydrogen chemical shift for monomer and dimer.

RECENTLY, n.m.r. studies on the hindered internal rotation of amides have revealed unusual proton chemical shift behaviour at low temperatures.[1-5] This temperature-dependence of non-exchanging chemical shifts (by which we mean chemical shifts at temperatures at which the rate of internal rotation is negligible) has been attributed mainly to the influence of solute and solvent interactions. The concentration-dependence of proton shifts of some amides in a series of solvents was studied by Hatton and Richards and their results were interpreted in terms of the formation of solute–solute and solute–solvent complexes.[6,7] Further, the effects of dipolar interactions were put forward as a probable reason for the concentration- and solvent-dependence of activation parameters calculated for internal rotation in some amide solutions.[2,8,9]

An understanding of the nature of these effects is essential for a complete dynamic study of such compounds by n.m.r., and when their influence on the chemical shifts is taken into account, even approximately,[1,2] improvements in activation parameter calculations ensue.[1-4]

We have noticed effects similar to those described above in a series of compounds which we are studying [10] and this has led us to reconsider in detail the behaviour of dimethylformamide and other amides.

To begin with, we have examined the n.m.r. spectra of dimethylformamide in a series of CCl_4 solutions at several temperatures (at which the rate of internal rotation in dimethylformamide is considered negligible [1]) in order to estimate the extent of dipolar interaction in this system.

Table 1 shows the results for the dependence of the internal *N*-methyl doublet chemical shift on the concentration of dimethylformamide in CCl_4 at three temperatures. Assuming a dimerization of the dimethylformamide molecules and taking solvent concentration into account, we obtain equation (1),[11,12] where X

$$\delta_{obs} = \delta_m + (\delta_d - \delta_m)\frac{2X}{m} \qquad (1)$$

is the mole fraction of dimer, m the mole fraction of total dimethylformamide, δ_m the internal chemical shift of the *N*-methyl doublet in the monomer, δ_d in the dimer, and δ_{obs} the observed chemical shift. In terms of mole fractions the dimerization equilibrium constant is (2).

TABLE 1

Dependence on temperature and concentration of the doublet chemical shift of the *N*-methyl group in dimethylformamide in carbon tetrachloride

		Chemical shift *		
No.	Concn.†	$T = 36° \pm 1°$	$T = 53° \pm 1°$	$T = 63° \pm 1°$
1	0·019	7·30	6·90	6·60
2	0·039	7·75	7·42	7·00
3	0·051	8·03	7·59	7·31
4	0·068	8·32	7·88	7·66
5	0·080	8·47	8·00	7·73
6	0·082	8·52	8·06	7·81
7	0·094	8·62	8·16	7·92
8	0·119	8·85	8·42	8·12
9	0·132	8·95	8·55	8·23
10	0·135	8·97	8·57	8·29
11	0·149	9·08	8·59	8·38
12	0·236	9·50	9·13	8·83
13	0·286	9·69	9·28	9·00
14	0·328	9·75	9·39	9·14
15	0·591	9·99	9·68	9·50

* Between the two *N*-methyl signals in c./sec. on a Varian A 56/60 spectrometer. Reproducibility error range ±0·03 c./sec. from at least six determinations. † Mole fraction of dimethylformamide.

$$K_d = X(1 - X)/(m - 2X)^2 \qquad (2)$$

With the aid of an IBM digital computer and a FORTRAN IV program 'REEP'[13] for non-linear estimation problems, values of K_d, δ_m, and δ_d leading to a best fit of the experimental data for the dependence of δ_{obs} on X, and a theoretical curve derived from (1) were

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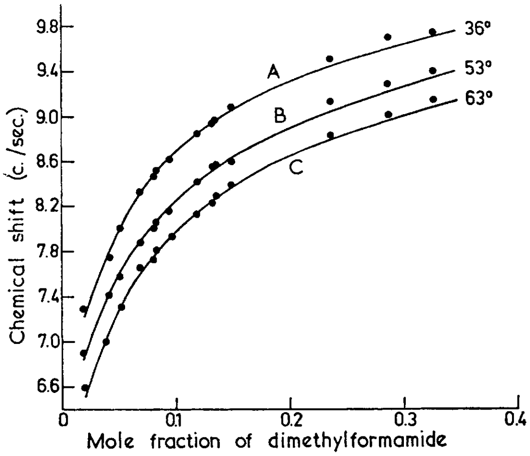
[13] From Share Programme Library, SDA Number 3492 (this was slightly modified for our purposes).

computed at each temperature. The resulting theoretical lines are depicted in the Figure together with the data from Table 1. The values of the parameters appear in Table 2. The root-mean-square-deviation is 0·05 ± 0·01 c./sec. which is roughly the range of our experimental reproducibility accuracy. A consistent deviation towards higher chemical shifts occurs at high concentrations; this can be rationalized by assuming that aggregations of order greater than 2 are involved in this region, with larger chemical shifts, as hypothesized previously.[3] However, even in this region the dimerization approximation is very good. Eliminating the high concentration points, excellent fits with r.m.s. deviations of 0·01—0·03 are obtained, and these lend strength to the adequacy of the dimerization model at low concentrations.



Chemical shift-dependence of *N*-methyl doublet on concentration of dimethylformamide in carbon tetrachloride,* (A) 36°, (B) 53°, (C) 63°; ● experimental points, —— best fit theoretical curves

* The data for solution 15 has not been included, but its chemical shifts also deviate to higher values

TABLE 2

Dependence of limiting chemical shift and equilibrium constant on temperature*

Temp.	δ_m	δ_d	K_d
36°	6·0	11·3	10·2
53	5·9	11·2	7·4
63	5·5	11·0	7·1

* For estimated errors see text.

It can be seen that the calculations and resulting fits are relatively insensitive to K_d; thus small changes in the values of data points induced large fluctuations (up to 40%) in the computed values of this parameter. Graphical methods[14] were also of no avail as we had no reliable value for the high and low edges of the concentration scale. At high concentrations, deviations occur as mentioned previously and the concentration region below our lowest concentration is limited by lack of experimental accuracy.

Therefore the following approach was used to obtain values of $\Delta H°$ and $\Delta S°$ for the dimerization. It was assumed that δ_m and δ_d are constant over the temperature range studied [the temperature range is narrow and the changes in δ_m and δ_d are within the range of their estimated error (±0·5 c./sec.)] and values of these parameters as well as $\Delta H°$ and $\Delta S°$ were computed for a best fit with the experimental data at all three temperatures by use of equations (1), (2), and (3). The resulting values

$$K_d = \exp\frac{(\Delta S°)}{R}\exp\frac{(-\Delta H°)}{RT} \qquad (3)$$

of δ_m, δ_d, $\Delta H°$, and $\Delta S°$ are shown in Table 3.

TABLE 3

Limiting chemical shifts and thermodynamic functions for dimerization of dimethylformamide in carbon tetrachloride

Data points used * at all temperatures	δ_m	δ_d	$\Delta H°$ † (kcal./mole)	$\Delta S°$ † (e.u.)
1—15	5·7	11·2	−6·1	−14·7
1—14	5·9	11·5	−5·9	−14·5
1—13	5·9	11·5	−5·9	−14·5
1—12	5·9	11·5	−5·9	−14·4
1—11	5·8	11·3	−5·9	−14·3

* See Table 1. † For estimated errors see text.

Systematic elimination of the high concentration points gave values of $\Delta H°$ and $\Delta S°$ which were relatively unaffected and also appear in Table 3. The values of the r.m.s. deviation were again 0·05 ± 0·01 showing that our assumption of constant δ_m and δ_d is reasonable for this calculation. From the effect of changes in $\Delta H°$ and $\Delta S°$ on the 'experimental–theoretical' fits at each temperature we concluded that the reliability range of $\Delta H°$ and $\Delta S°$ calculated in this way is ±10% and ±30% respectively.

It has been shown[2,8] that the formyl hydrogen in dimethylformamide does not participate in any hydrogen bonding in this system because its resonance frequency is temperature- and concentration-invariant as is the centre of the *N*-methyl doublet. Thus, the bonding presumably arises through the nitrogen and oxygen moieties in the dimethylformamide molecule which is substantially dipolar.

[8/577 *Received, April 22nd*, 1968]

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