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# Association between Polar Molecules. III. $^1H$ and $^{13}C$ NMR Studies on the Dipole Association of Acetonitrile Derivatives with Tetramethylurea and Dibutyl Sulfoxide in Nonpolar Solvents

Tatsuya Takagi,* Hideaki Fujiwara, and Yoshio Sasaki
*Faculty of Pharmaceutical Sciences, Osaka University, 1-6 Yamadaoka, Suita, Osaka 565*

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Dipole association between acetonitrile derivatives and polar substances such as tetramethylurea and dibutyl sulfoxide is investigated in nonpolar solvents. Association parameters and thermodynamic parameters are derived and discussed in relation to the substituent constants. $^1H$ and $^{13}C$ NMR chemical shifts show that the major structures of the associate are antiparallel. Association energies are also determined using semiempirical MNDO MO method, which supports the experimental results for energies as well as structures.

It is important to study the association between polar molecules in order to elucidate the structure of polar liquids, various solvent effects, *etc.* Hitherto, few studies have been reported[1-3] about major structures of super systems for dipolar association; Saito *et al.*[1] and Frurip *et al.*[2] indicated that a partial dipole was more important than a classical one for dipolar association, using $^{13}C$ NMR and *ab initio* SCF MO method respectively. However, more exhaustive studies are surely necessary to understand the factors governing the strength of association and the structre of the associate.

In previous reports,[4] we have investigated the intermolecular interactions between *p*-substituted benzonitriles or *p*-substituted nitrobenzenes and hexamethylphosphoric triamide (HMPA), dibutyl sulfone (DBSN), dibutyl sulfoxide (DBSX), and tetramethylurea (TMU) by analyzing the NMR concentration dependence. One conclusion of the study is that the association is governed mainly by electrostatic interactions. It also indicated that the association takes place around the CN group in the case of the association of *p*-substituted benzonitriles with HMPA, as evidenced by the correlation between the association parameters and the substituent constants ($\sigma_I$, $\sigma_\pi$)[5] or dipole moments, and by the $^{32}P$ chemical shift in HMPA.

In the present study, we have investigated the association of aliphatic nitriles, in which the electric charges are less delocalized than in aromatic ones and the local dipole moments are expected to play an important role in the association. $^1H$ and $^{13}C$ NMR measurements and MO calculations are utilized to obtain more detailed information about the association, especialy the equilibrium structure of such super systems.

## Experimental

(Dimethylamino)acetonitrile was synthesized from dimethylamine and formaldehyde according to the literature.[6] Other nitriles were of commercial grade; they were distilled under reduced pressure and stored over Molecular Sieve 4A. Cyclohexane for solvent was washed with mixed acid, alkaline solution and water succesively; and dried over calcium chloride. It was stored over Molecular Sieve 4A after distilling three times over calcium hydride. Carbon tetrachloride was similarly washed with alkaline solution and water, distilled over calcium hydride, and finally stored over Molecular Sieve 4A. TMU and DBSX were prepared in the same way as in the previous report.[4b]

$^{13}C$ NMR spectra were observed with a HITACHI R-900M FT NMR spectrometer operating at 22.36 MHz and at 35 °C with 16k data points, using the peak of $CCl_4$ as internal references. Errors in the shift measurements were less than ±0.05 ppm. $^1H$ NMR measurements were made as in the previous report[4b] using cyclohexane as solvent.

The sample solution for $T_1$ measurements was sealed under nitrogen atmosphere and the height of the solution was adjusted to 20 mm. The spin-lattice relaxation times were measured by the fast inversion-recovery method[7] which uses the (180°-$\tau$-90°-5″-HS) pulse sequence. $T_1$ values were obtained from the regression coefficients for 17 data points of $\tau$ and such measurements were repeated more than twice to test the reproducibility of the experiment. Errors in the measurements of $T_1$ were estimated to be ±10%.

The association parameters were determined in the same way as in the previous report.[4b] Molecular orbital calculations using semiempirical CNDO/2,[8a] INDO,[8b] and MNDO[8c] MO methods were performed by the programs[8d,e] after slight modifications by the authors. The molecular geometries used for the MO calculations were experimental ones from microwave spectra and calculated ones from MNDO MO method *i.e.*, TMU.

All numerical calculations were performed on an NEAC S-900 model II computer at the Computer Center, Osaka University and HITAC M-200H computer at the Computer Center, Institute of Molecular Sciences.

## Results and Discussion

*Changes in $^1H$ and $^{13}C$ NMR Shift. Estimated Structure of the Associate*: Variations of $^1H$ NMR Shifts in $CH_3OCH_2CN$ and $(CH_3)_2NCH_2CN$ on addition of TMU or DBSX are shown in Fig. 1. In contrast to the shifts of the methylene group, those of the methyl group show only small concentration dependences. Also the change was very small for the $^1H$ shift of TMU when these nitriles were added to the solution. These facts suggest that the association takes place near the CN and C=O groups.

$^{13}C$ NMR shift also changes on addition of the partner molecule (Tables 1 and 2). The changes of shifts are evident at 1-C of each nitrile (Table 1) and at the carbonyl carbon (Table 2). These facts are also consistent with the above results for the $^1H$ shift.[9]

*$^{13}C$ Spin-Lattice Relaxation Times*: It is well known that in monosubstituted benzenes $^{13}C$ spin-lattice relaxation times at the ortho or the meta positions are smaller than those at the para position. Levy *et al.*[10]

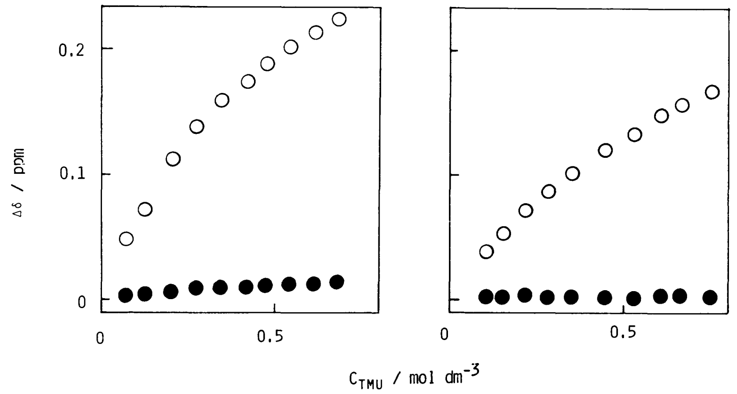

Fig. 1. Concentration dependence of $^1H$ NMR shifts for the $CH_3OCH_2CN$ (left) or $(CH_3)_2NCH_2CN$ (right) plus TMU systems.
○: methylene proton, ●: methyl proton.

Table 1. Variations of $^{13}C$ chemical shifts of $R-CH_2CN$ on addition of TMU(upper) or DBSX(lower) in $CCl_4$[a)]

| | Δδ/ppm | | | | | | |
|---|---|---|---|---|---|---|---|
| | H | $(CH_3)_2N$ | $CH_3$ | $C_6H_5$ | $CH_3O$ | Cl | $CH_3S$ |
| 1-C | 0.48 | 0.39 | 0.42 | 0.50 | 0.42 | 0.69 | 0.51 |
| 2-C | 0.24 | −0.09 | 0.06 | −0.14 | 0.07 | 0.36 | −0.18 |
| 3-C | | | −0.09 | 0.45[b)] | | | |
| 4-C | | 0.00 | | | −0.03 | | −0.09 |
| 1-C | 0.70 | 0.53 | 0.54 | 0.62 | 0.50 | 0.85 | 0.63 |
| 2-C | 0.29 | 0.10 | 0.10 | −0.08 | 0.13 | 0.48 | −0.12 |
| 3-C | | | −0.05 | 0.53[b)] | | | |
| 4-C | | 0.07 | | | 0.01 | | −0.06 |

a) Equimolar (0.7 mol dm$^{-3}$) solutes is added. b) Ipso carbon of $C_6H_5$.

Table 2. Variations of the $^{13}C$ chemical shifts of TMU on addition of $R-CH_2CN$ in $CCl_4$[a)]

| | H | $(CH_3)_2N$ | $CH_3$ | $C_6H_5$ | $CH_3O$ | Cl | $CH_3S$ |
|---|---|---|---|---|---|---|---|
| C*-O | 0.14 | 0.18 | 0.15 | 0.18 | 0.27 | 0.48 | 0.20 |
| $-C^*H_3$ | −0.02 | 0.00 | 0.00 | 0.03 | 0.00 | 0.06 | 0.01 |

a) Equimolar (0.7 mol dm$^{-3}$) solutes is added.

interpreted this is due to anisotropic tumbling, *i.e.*, superior rotation around the symmetry axis. This superiority in rotation is expected to be reduced on addition of another polar molecule if they associate side by side. In the present case, the effect of the association on the relaxation time is investigated with nitrobenzene and TMU, adding 0—2.8 mol dm$^{-3}$ of TMU to the 0.7 mol dm$^{-3}$ solution of nitrobenzene in $CCl_4$. Nitrobenzene is chosen for the reason of higher solubility here. The results are given in Table 3. The higher the concentration of TMU, the more the $r$-value (Eq. 1)

$$r = \frac{T_1(\text{ortho}) + T_1(\text{meta})}{2T_1(\text{para})}, \qquad (1)$$

approaches to 1. This is consistent with the loss of superiority in molecular rotation around the symmetry axis on addition of polar molecules indicating the increased moment of inertia around the axis.

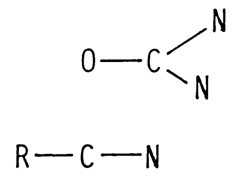

Fig. 2. Association models for the acetonitrile derivatives plus TMU systems.

All above experimental results support the idea that the polar molecules associate in the way shown in Fig. 2. For the compound treated here, electric charges are mainly distributed near the CN, C=O, and S=O groups, as calculated by CNDO/2 MO method or as reported by others.[11)]

*Determination of Association Parameters.* The concentration dependence of the shifts at 2-C of the nitriles were measured and analyzed by nonlinear regression analsis and the equilibrium constant $K$ and the association shift $\Delta_{\mathrm{AB}}$ were obtained (Table 4). 1 : 1 associates were assumed, similarly to the previous reports,[4] considering the results of Job plots. Plots of the association constants for the two systems containing TMU and DBSX show a linear relationship (Fig. 3), indicating similarity in the governing factor and the mode of the association in both systems. Regression analyses of the data according to the relation $y=ax$ result in

$$\ln K(\mathrm{DBSX}) = 1.39 \ln K(\mathrm{TMU}) \qquad (2)$$
$$(n=6,\ R=0.987),^{12)}$$
$$\Delta_{\mathrm{AB}}(\mathrm{DBSX}) = 0.92\Delta_{\mathrm{AB}}(\mathrm{TMU}) \qquad (3)$$
$$(n=6,\ R=0.996).$$

In *p*-substituted benzonitriles plus DBSX or TMU system, similar regression analyses result in

$$\ln K(\mathrm{DBSX}) = 1.56 \ln K(\mathrm{TMU}) \qquad (4)$$
$$(n=6,\ R=0.943),$$
$$\Delta_{\mathrm{AB}}(\mathrm{DBSX}) = 0.87\Delta_{\mathrm{AB}}(\mathrm{TMU}) \qquad (5)$$
$$(n=12,\ R=0.939).$$

As the coefficients are almost the same in both systems, the factor of association in the system containing aliphatic nitriles is similar to the one containing aromatic nitriles. Plots of ln $K$ or $\Delta_{\mathrm{AB}}$ against $\sigma_i$[5] show a significant correlation and the regression analyses in the system with TMU result in

$$\ln K = 4.11\sigma_i + 0.10 \qquad (6)$$
$$(n=6,\ R=0.921,\ t=4.71),^{13)}$$
$$\Delta_{\mathrm{AB}} = 11.08\sigma_i + 0.34 \qquad (7)$$
$$(n=6,\ R=0.895,\ t=4.01),$$

and those in the system with DBSX result in

$$\ln K = 3.43\sigma_i + 0.72 \qquad (8)$$
$$(n=6,\ R=0.958,\ t=6.68),$$
$$\Delta_{\mathrm{AB}} = 11.11\sigma_i + 0.29 \qquad (9)$$
$$(n=6,\ R=0.880,\ t=3.70).$$

Polar substituent effect for aliphatic compounds could be divided into two parts, *i.e.*, field effect and $\sigma$-inductive effect.[14] Tsuno[15] claimed that $\sigma_i$ represent the former mainly. If this is also the case here, the association of the nitriles with TMU or DBSX is seen to be induced by the electric field effect.

Enthalpies ($\Delta H°$), entropies ($\Delta S°$), and Gibbs' free energies ($\Delta G°$) can be determined from van't Hoff plots after measuring the temperature dependence of the association constants (Fig. 4). These plots are obtained from the dependence of the shift on concentration as well as on temperature (Fig. 5). The results are given in Table 5. The $\Delta H°$ values derived amount to −8—−13 kJ mol$^{-1}$, which are about the same as those for the association of aromatic nitro or cyano compounds with HMPA and for weak hydrogen bonding. For this system, an enthalpy-entropy compensation relation, which held approximately for the aromatic nitro or cyano compounds plus HMPA systems, is not appropriate here ($R$=0.621). This may he due to larger steric effects for the aliphatic systems than that for the aromatic ones.

The orders of $\Delta G°$ or $\Delta H°$ are not the same as those of the dipole moments of nitriles, or more correctly, they gave a negative correlation, as was pointed out in the previous reports[4b] with aromatic systems. These facts indicate that multipole-multipole interaction, therefore, partial dipole is more important for the association of the nitriles with other polar molecules.

*Calculation of Association Energy.* In order to

Table 3. $^{13}$C $T_1$ values in $C_6H_5NO_2$

| TMU added | $T_1$/s | | | $r$ |
|---|---|---|---|---|
| mol dm$^{-3}$ | ortho | meta | para | |
| 0 | 11.0 | 12.5 | 5.3 | 2.2 |
| 0.7 | 11.0 | 11.0 | 6.2 | 1.8 |
| 1.4 | 10.5 | 10.1 | 6.9 | 1.5 |
| 2.1 | 9.7 | 8.8 | 6.0 | 1.5 |
| 2.8 | 9.7 | 8.0 | 6.3 | 1.4 |

Table 4. Association constants and association shifts for the R-$CH_2CN$ plus TMU(upper) or DBSX(lower) systems

| | $(CH_3)_2N$ | $CH_3$ | $C_6H_5$ | $CH_3O$ | Cl | $CH_3S$ |
|---|---|---|---|---|---|---|
| $K$/mol$^{-1}$ dm$^3$ | 1.06 | 1.22 | 1.70 | 1.86 | 5.55 | 2.43 |
| $\Delta_{\mathrm{AB}}$/ppm | 0.39 | 0.34 | 0.47 | 0.41 | 0.78 | 0.59 |
| $K$/mol$^{-1}$ dm$^3$ | 2.26 | 1.99 | 3.05 | 3.12 | 7.51 | 3.97 |
| $\Delta_{\mathrm{AB}}$/ppm | 0.31 | 0.30 | 0.43 | 0.36 | 0.76 | 0.54 |

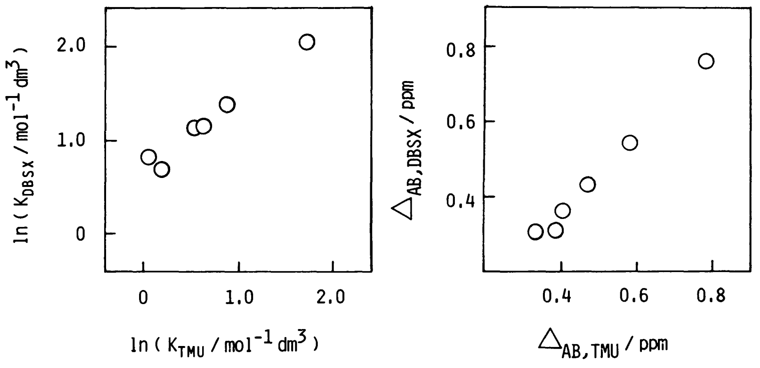

Fig. 3. Correlation of association parameters between the two systems of acetonitriles plus TMU and acetonitriles plus DBSX.

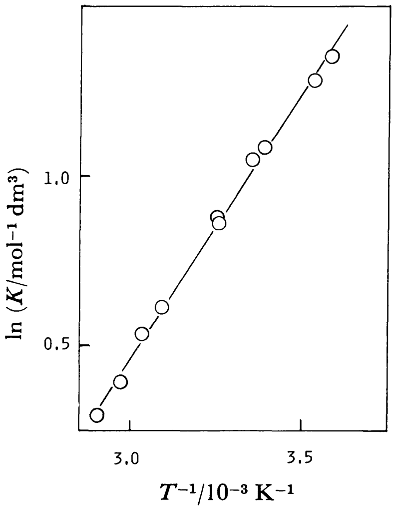

Fig. 4. van't Hoff plots for the dipole association between $CH_3SCH_2CN$ and TMU. Similar results are reached for other systems.

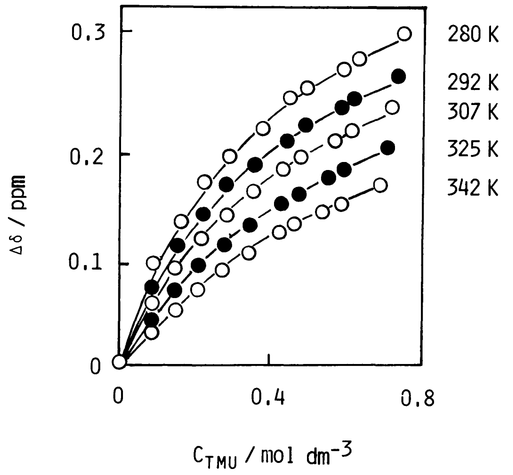

Fig. 5. Concentration and temperature dependence of the $^1H$ chemical shift of methylene protons in the $CH_3OCH_2CN$ for the $CH_3OCH_2CN$ plus TMU system in cyclohexane.

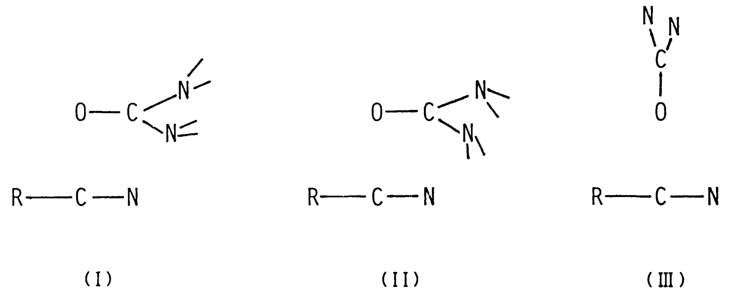

Fig. 6. Association models for the acetonitrile plus TMU systems.

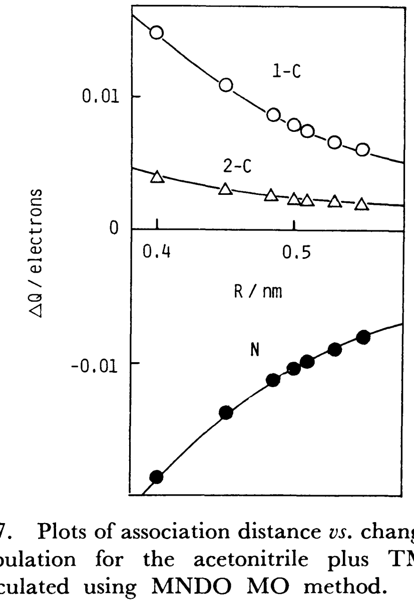

Fig. 7. Plots of association distance *vs.* change of atomic population for the acetonitrile plus TMU system calculated using MNDO MO method.

TABLE 5. THERMODYNAMIC PARAMETERS FOR THE R-$CH_2CN$ PLUS TMU SYSTEMS

| | $\Delta H^\circ$ | $\Delta S^\circ$ | $\Delta G^\circ$ |
|---|---|---|---|
| | kJ mol⁻¹ | J mol⁻¹ K⁻¹ | kJ mol⁻¹ |
| $(CH_3)_2N$ | −9.84 | −31.0 | −0.32 |
| $CH_3$ | −8.17 | −24.8 | −0.54 |
| $C_6H_5$ | −9.76 | −25.5 | −1.33 |
| $CH_3O$ | −10.45 | −29.4 | −1.42 |
| Cl | −11.52 | −22.9 | −4.48 |
| $CH_3S$ | −13.25 | −36.0 | −2.19 |

TABLE 6. ASSOCIATION PARAMETERS FOR THE $CH_3CN$ PLUS TMU SYSTEM CALCULATED BY MNDO MO METHOD

| | $\Delta E$ | $R$ |
|---|---|---|
| | kJ mol⁻¹ | nm |
| I | −2.12 | 0.458 |
| II | −3.40 | 0.471 |
| III | −1.43 | 0.433 |

confirm the predicted structure of the associate, as mentioned before, we calculated the association energy using the super-molecule method under some molecular disposition. Three dispositions are shown in Fig. 6. Calculations by the CNDO/2 MO method gave an association distance $R$=0.147 nm and an association energy $\Delta E$=−241 kJ mol⁻¹ on the model II. Apparently, the energy is overestimated and the distance is underestimated. Similar results are reached by the INDO MO method. This tendency is well known as typical of the

CNDO/2 or INDO MO method. On the other hand, the MNDO MO calculation gives more practical results (Table 6), which accord well with the order of the experimental values. This method also supports model II as the most stable disposition, where the changes in formal charges induced at atoms when association occurs can be calculated against the association distance under model II (Fig. 7). The changes in $^{13}$C chemical shifts are in the same order with the experimental ones, when they are estimated from the changes in formal charges on the basis of ≃200 ppm/electron.

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12) $R$: Multiple correlation coefficient.

13) $t=r\{(n-2)/(1-r^2)\}^{1/2}$, $n$: number of data, $r$: correlation coefficient.

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