Menschutkin Reactions of Aliphatic Diamines with Methyl Iodide in Acetonitrile–Methanol Mixtures. Evaluation of the Role of the Non-reacting Nitrogen Atom

Yasuhiko Kondo,* Hideyuki Kambe, and Shigekazu Kusabayashi
Department of Applied Chemistry, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan

Kinetic and thermodynamic analyses have been performed for the reactions of aliphatic diamines with methyl iodide in acetonitrile–methanol mixtures. Solvation patterns around non-reacting nitrogen atoms have been evaluated for activated complexes and for product cations. These analyses enable the two transition-state indices due to physical interaction, *i.e.* extended Brønsted coefficients, α_{PHYS} and isokinetic temperatures, β_{PHYS} to be determined. An empirical correlation between β_{PHYS} and α_{PHYS} multiplied by the dipole moment of an initial state, has been found, and the physical significance of the correlation is discussed. Multiple use of transition-state indices and their empirical analyses are indispensable for characterizing the particular roles played by non-reacting nitrogen atoms in these reactions.

Characterization of reactivity patterns for aliphatic compounds has been a long-standing problem in organic chemistry.[1,2] Within the series of the Menschutkin reactions, less tractable characteristics of aliphatic amine reactions have been pointed out in comparison with those of aromatic amine reactions.[3–5] Structural perturbations introduced into aliphatic systems are likely to be accommodated by various other factors rather than such generally invoked effects as variations in electronic population at a reaction centre, *viz.* by geometrical variations at a reaction centre, variations in steric requirement for solvation and so on, partly because of the lower polarizability of the aliphatic carbon skeletons.[4,5]

Thus, analysis of the effects induced by structural variations at remote sites from a reaction centre would be more valuable in characterizing reactivity patterns for aliphatic amine series than for aromatic amine series.

In this work, rate behaviour and solute–solvent interactions are analysed in acetonitrile–methanol mixtures primarily for the *N,N,N′,N′*-tetramethylethylenediamine (TMEDA)–methyl iodide and for the *N,N′*-dimethylpiperazine (DMPIPRA)–methyl iodide, and partly for the 1,4-diazabicyclo[2,2,2]octane (DABCO)–methyl iodide reactions. The roles of the non-reacting nitrogen atom in solute–solvent interaction as well as in reaction behaviour are discussed.

Results

Rate constants and activation parameters for the diamine–methyl iodide reactions, *i.e.* *N,N′*-dimethylpiperazine (DMPIPRA)–methyl iodide and *N,N,N′,N′*-tetramethylethylenediamine (TMEDA)–methyl iodide, in acetonitrile–methanol mixtures are summarized in Table 1. Enthalpies of solution in the same solvent mixtures for relevant amines, reaction products, and quaternary ammonium iodides which will be used as a reference compound in later analysis are summarized in Table 2.

According to equation (1), which has been derived on the basis of a thermodynamic cycle, (AC and Nu in parentheses represent an activated complex and a nucleophile respectively), transfer enthalpies for the activated complexes of these reactions were calculated and are summarized in Table 3. Single ion enthalpies of transfer for quaternary ammonium ions have been calculated for tetrabutylammonium/tetrabutylborate according to equation (2) and are summarized in Table 3. Quantities

$$\Delta H_t^{AN\rightarrow mix}(AC) = \delta\Delta H^{\ddagger} + \Delta H_t^{AN\rightarrow mix}(Nu) + \Delta H_t^{AN\rightarrow mix}(MeI) \quad (1)$$

$$\Delta H_t^{AN\rightarrow mix}(R_3N^+CH_3) = \Delta H_t^{AN\rightarrow mix}(R_3N^+CH_3I^-) - \Delta H_t^{AN\rightarrow mix}(I^-) \quad (2)$$

required for these calculations but not given here, *i.e.* transfer enthalpies of methyl iodide and single ion enthalpies of transfer for iodide ion are taken from our previous works.[6,7] Since most of the measurements have been carried out at fairly low concentration of solute, *ca.* 0.5–5 × 10^{-2} mol dm^{-3}, the transfer quantities were assumed to be the difference between the standard quantities at a hypothetical concentration of 1 mol dm^{-3}.

Discussion

Transfer enthalpy can usually be simulated well by the sum of two terms, equations (3) and (4).[4,5,8]

$$\Delta H_t^{AN\rightarrow mix} = \Delta H_{t.PHYS}^{AN\rightarrow MeOH}\, x_{MeOH} + \Delta H_{t.SI}^{AN\rightarrow MeOH}\, K_{se}\, x_{MeOH}/(x_{AN} + K_{se}\, x_{MeOH}) \quad (3)$$

$$\Delta H_t^{AN\rightarrow MeOH} = \Delta H_{t.PHYS}^{AN\rightarrow MeOH} + \Delta H_{t.SI}^{AN\rightarrow MeOH} \quad (4)$$

The first term which expresses a rather weak response to solvent composition, is likely to contain the various contributions from such interactions as cavity term, protophobic interaction, dipole–dipole interaction, *etc.*, and is referred to as 'more physical' interaction enthalpy. The second term which expresses rather steep changes over the region of low methanol content, contains the contribution from such essentially chemical interactions as hydrogen-bonding, charge-transfer, and dipole–dipole association interactions, and is referred to as specific interaction enthalpy.

In order that the analysis and the subsequent discussion can be made on the same theoretical basis throughout for mono-amine and diamine reactions, transfer enthalpies for diamines have been dissected into constituent terms, $\Delta H_{t.PHYS}^{AN\rightarrow MeOH}$ and

Table 1. Rate constants and activation parameters in acetonitrile–methanol mixtures (30.0 °C).

	N,N'-Dimethylpiperazine + MeI			*N,N,N',N'*-Tetramethylethylenediamine + MeI		
x_{MeOH}	$k/10^{-3}$ dm^3 mol^{-1} s^{-1}	$\Delta H^{\ddagger}$/kJ mol^{-1}	$\Delta S^{\ddagger}$/J K^{-1} mol^{-1}	$k/10^{-3}$ dm^3 mol^{-1} s^{-1}	$\Delta H^{\ddagger}$/kJ mol^{-1}	$\Delta S^{\ddagger}$/J K^{-1} mol^{-1}
0	83.4	40.5	−132.1	445.0	37.1	−129.4
0.1	41.6	48.4	−111.8	188.0	47.0	−103.9
0.25	20.0	54.6	−97.5	85.9	51.9	−94.25
0.50	8.73	57.75	−94.0	35.8	54.5	−92.95
0.75	3.66	60.5	−92.0	15.2	54.9	−98.75
1.0	1.12	65.3	−86.1	4.38	57.2	−101.5

x_{MeOH}: mole fraction of methanol.

Table 2. Enthalpies of solution in acetonitrile–methanol mixtures (kJ mol^{-1}) (25.0 °C).

x_{MeOH}	DMPIPRA	TMEDA	TMPIPRA$^+$I$^-$	PMEDA$^+$I$^-$	DMPIPRI$^+$I$^-$	TMPA$^+$I$^-$
0	1.61	1.95	16.2	19.55	16.15	12.4
0.1	−9.64	−9.68	12.65	15.85	12.8	9.00
0.25	−16.0	−16.2	13.7	16.4	14.0	10.4
0.50	−18.6	−19.2	17.85	20.4	18.2	14.4
0.75	−18.5	−19.3	23.7	24.85	23.7	19.65
1.0	−17.15	−18.2	33.4	33.8	32.6	28.0

DMPIPRA, *N,N'*-dimethylpiperazine: TMEDA, *N,N,N',N'*-tetramethylethylenediamine: TMPIPRA$^+$I$^-$, *N,N,N'*-trimethylpiperazinium iodide: PMEDA$^+$I$^-$, *N,N,N',N',N'*-pentamethylethylenediammonium iodide: DMPIPRI$^+$I$^-$, *N,N*-dimethylpiperidinium iodide: TMPA$^+$I$^-$, trimethylpropylammonium iodide.

Table 3. Transfer enthalpies for diamines, activated complexes, and quaternary ammonium ions, and interaction parameters in acetonitrile–methanol mixtures (enthalpies in kJ mol^{-1}).

x_{MeOH}	DMPIPRA	TMEDA	AC (DMPIPRA)	AC (TMEDA)	AC (TEA)	TMPIPRA$^+$	PMEDA$^+$	DMPIPRA$^+$	TMPA$^+$
0	0	0	0	0	0	0	0	0	0
0.1	−11.2	−11.6	−3.3	−1.7	2.1	−0.95	−1.1	−0.75	−0.8
0.25	−17.6	−18.15	−3.5	−3.35	2.8	−1.5	−2.15	−1.15	−1.0
0.50	−20.2	−21.15	−3.15	−3.95	3.9	−1.15	−1.95	−0.75	−0.8
0.75	−20.1	−21.25	−0.6	−3.95	4.2	0.3	−1.9	0.35	0.05
1.0	−18.75	−20.15	5.05	−1.05	8.9	3.5	0.55	2.75	1.9
$\Delta H^{\mathrm{AN\rightarrow MeOH}}_{\mathrm{t,PHYS}}$	11.25	9.85	8.9^a + 9.15	8.9^a + − 2.95	8.9	2.75^a + 6.75	1.9^a + 1.65	2.75	1.9
$\Delta H^{\mathrm{AN\rightarrow MeOH}}_{\mathrm{t,SI}}$	−30.0	−30.0	−13.0	−7.0	0	−6.0	−3.0	0	0
K_{se}	6.3	6.5	6.5	9.5	1.0	1.6	3.0	1.0	1.0

^{a} The value for a reference compound, see the text.

AC (DMPIPRA), activated complex for the DMPIPRA + MeI reaction: AC (TMEDA), activated complex for the TMEDA + MeI reaction: AC (TEA), activated complex for the triethylamine + MeI reaction.

$\Delta H^{\mathrm{AN\rightarrow MeOH}}_{\mathrm{t,SI}}$, by equations (3) and (4);[4,5,8] the parameters, thus determined, are given in Table 3.

Generally, the physical interaction enthalpy is likely to be a composite quantity from various interactions, and so far its exact interpretation has not been easy.[4,6] The physical interaction enthalpies for diamines are approximately twice as large as those for mono-amines, *i.e.* 9.85, 11.25, and 13.75 for TMEDA, DMPPIPRA, and DABCO[4] respectively, and 2.9 for triethylamine,[8] 4.9 for quinuclidine,[4] and 0.35–7.3 for pyridine[4] and *N*-methylimidazole derivatives[5] (all values are in kJ mol^{-1}). For these various amines, there do not seem to be systematic differences between diamines and mono-amines either in terms of molar volume or in the size of the hydrocarbon moiety. However, the overall dipole moment of *N,N*-dimethylpiperazine is rather small, 0.67, compared with that of *N*-methylpiperidine, 0.91[9] (in debye*), plausibly as a result of intramolecular compensation of partial dipoles. Thus, the partial solute dipole around nitrogen atom–solvent dipole interaction, but not the overall solute dipole–solvent dipole interaction, could be invoked for the discriminative molecular factor between diamine and mono-amine transfers. Alternatively, only dipole–dipole interactions over a relatively short molecular distance effectively contribute to transfer enthalpies.

Hydrogen-bond accepting basicity of amine per nitrogen atom as expressed by the term, $-\Delta H^{\mathrm{AN\rightarrow MeOH}}_{\mathrm{t,SI}}/q$ (which is given in parentheses) decreases along the series, quinuclidine[4] (22.0) > DABCO[4] (17.8) > DMPIPRA (15.0) = TMEDA (15.0). Reactivity of amine per nitrogen atom which is measured as the rate of the Menschutkin reaction with methyl iodide in acetonitrile (at 30.0 °C), $\log(k_{\mathrm{AN}}/q)$ (given in parentheses), although partly coincidentally, follow the same trend as observed above, except for the higher reactivity of TMEDA, *viz.*, quinuclidine[4] (0.52) > DABCO[4] (0.01) > TMEDA (−0.65) > DMPIPRA (−1.36). The electron-withdrawing inductive effect of the nitrogen atom will be transmitted to another nitrogen through the polarization of the intervening C–N and C–C bonds and the polarization of the respective bond will become less with an increasing number of intervening aliphatic chains. The observed trends suggest that the more

---

* 1 D = 3.34×10^{-30} C m.

Table 4. Extended Brønsted coefficients, α_{PHYS}, solvation numbers, Z and isokinetic temperatures, β_{PHYS} in acetonitrile–methanol mixtures.

Reaction	α_{PHYS}	Z (Nu)	Z (AC)	β_{PHYS}/K
DABCO + MeI	0.45[a]	2.7	1.8	560
DMPIPRA + MeI	0.37	2.5	1.0	630
TMEDA + MeI	(−0.35)	—	—	—

[a] Ref. 4.

effectively the inductive effect is transmitted, the more polarized is the intervening respective chain.

In the reactions of diamine with methyl iodide, one of the nitrogen atoms remains unchanged throughout the reaction. Transfer enthalpies either for the activated complexes and for the product cations should contain the contributions ascribable to solvation changes around the non-reacting nitrogen atom. Quantitative evaluation especially of specific interaction enthalpies around non-reacting nitrogen atom could effectively be achieved in two steps. First, the differential quantity could be obtained by subtracting the contributions ascribable to the reacting part of the molecule, which could be estimated by the use of a structurally related reference compound, from observed quantities, equation (5), where R in parentheses represents a

$$\delta_R \Delta H_t^{AN\rightarrow mix} \equiv \Delta H_t^{AN\rightarrow mix} - \Delta H_t^{AN\rightarrow mix}\,(R) \qquad (5)$$

reference compound. Secondly, a quantitative analysis of the differential quantity by use of equations (3) and (4), could be carried out.

The activated complex for the triethylamine–methyl iodide reaction AC(TEA), was selected as a reference compound for the analysis of transfer enthalpies for the activated complex of diamine reactions, *N*,*N*-dimethylpiperidinium ion as that for *N*,*N*,*N*′-trimethylpiperazinium ion, *i.e.* product cation of *N*,*N*′-dimethylpiperazine reaction, and trimethyl propylammonium ion as that for *N*,*N*,*N*′,*N*′,*N*′-pentamethylethylenediammonium ion, *i.e.* product cation of *N*,*N*,*N*′,*N*′-tetramethylethylenediamine reaction. The interaction parameters are given in Table 3.

For cyclic diamine reactions, DABCO + MeI and DMPIPRA + MeI, specific interaction enthalpies for the activated complex are approximately half of those for neutral diamines, *i.e.* −17.8 and −35.5 for the former reaction[4] and, −13.0 and −30.0 for the latter reaction, while for the TMEDA plus methyl iodide reaction both specific and physical interaction enthalpies ascribable to the solvation around the non-reacting nitrogen atom are significantly reduced on going from reactant to transition state, *i.e.* (−30.0/2) to −7.0 for the former interaction and (9.85/2) to −2.95 for the latter (see Table 3). Similar trends, though less marked, are observed on going from reactant to product.

Two parameters which give a quantitative description of the behaviour of the specific interaction enthalpy, have been determined for the initial, transition, and final states. The required quantities for extended Brønsted treatments in terms of physical interaction enthalpy, $\delta\Delta H^{\ddagger}{}_{PHYS}$ and $\delta\Delta H^{0}{}_{PHYS}$ can be calculated through equations (6) and (7),[4.8] where specific

$$\delta\Delta \bar{H}^{\ddagger}{}_{PHYS} = \delta\Delta H^{\ddagger} - [\Delta H_{t.Sl}^{AN\rightarrow mix}\,(AC) - \Delta H_{t,Sl}^{AN\rightarrow mix}\,(Nu)] \qquad (6)$$

$$\delta\Delta H^{0}{}_{PHYS} = \delta\Delta H^{0} - [\Delta H_{t.Sl}^{AN\rightarrow mix}\,(PC) + \Delta H_{t.Sl}^{AN\rightarrow mix}\,(I^{-}) - \Delta H_{t.Sl}^{AN\rightarrow mix}\,(Nu)] \qquad (7)$$

interaction enthalpies for the activated complex (AC), nucleophile (Nu), and product cation (PC) have been calculated from equation (8) with use of the relevant parameters given in Table

$$\Delta H_{t.Sl}^{AN\rightarrow mix} = \Delta H_{t.Sl}^{AN\rightarrow MeOH} \frac{K_{se}\cdot x_{MeOH}}{(x_{AN} + K_{se}\cdot x_{MeOH})} \qquad (8)$$

3,[4.8] and the specific interaction enthalpies for iodide ion which have been given elsewhere.[7]

The coefficients, α_{PHYS}, are summarized in Table 4. The coefficients for cyclic diamine reactions are in a quite reasonable range, *i.e.* between zero and unity,[4.5.8] whereas that for TMEDA reaction is, quite unusually, negative. The close similarity between the extended Brønsted coefficient for DMPIPRA reaction and that for the reaction of triethylamine *i.e.* 0.37 for the former and 0.35 for the latter[4] can be ascribed to the common steric requirement which enables solvent molecules to approach the rear side of the reacting nitrogen.[4] A through-space interaction between lone-pair electrons on the non-reacting nitrogen atom and the developing positive charge has been invoked for rationalizing the larger coefficients for DABCO reaction.[4] The argument is supported by the smaller coefficient for DMPIPRA reaction in which a through-space interaction is less feasible. Thermodynamically, the unreasonable coefficient for TMEDA reaction is a natural consequence of the much reduced sensitivity of transfer enthalpy to solvent variation at the transition state.

In the TMEDA reaction, the partial positive charge developed at transition state on the methyl group of methyl iodide (and the full positive charge on the product) is likely to be internally solvated by the non-reacting nitrogen lone pair. This internal solvation diminishes the solvation area open to external solvation around non-reacting as well as reacting nitrogen atom, resulting in the reduced sensitivity to solvent variation. The higher than expected reactivity of TMEDA, as nucleophile, on the basis of hydrogen-bond accepting basicity (mentioned above) and the abnormal Brønsted coefficient for the TMEDA reaction are two aspects of the same phenomenon, *i.e.* nucleophilic assistance or internal solvation at transition state by non-reacting nitrogen atom.

Variation of activation entropy due to physical interaction can be calculated by use of equation (9), since the transfer entropy due to specific interaction can be evaluated by use of equation (10),[4.8] where X in parentheses represents an activated

$$\delta\Delta S^{\ddagger}{}_{PHYS} = \delta\Delta S^{\ddagger} - [\Delta S_{t.Sl}^{AN\rightarrow mix}\,(AC) - \Delta S_{t.Sl}^{AN\rightarrow mix}\,(Nu)] \qquad (9)$$

$$\Delta S_{t.Sl}^{AN\rightarrow mix}\,(X) = \left(\frac{Z\Delta H_{se}}{T}\right)\left(\frac{K_{se}x_{MeOH}}{x_{AN} + K_{se}x_{MeOH}}\right) + R\ln\,(x_{AN} + K_{se}x_{MeOH})^{Z} \qquad (10)$$

complex or nucleophile. The solvation number, Z, either for nucleophile or for activated complex, can be evaluated separately, *viz.* from the separation of specific interaction enthalpy, $\Delta H_{t.Sl}^{AN\rightarrow MeOH}$ into constituent terms, Z and ΔH_{se} [*cf.* equation (11)].[4.6]

$$\Delta H_{t.Sl}^{AN\rightarrow MeOH} = Z\Delta H_{se} \qquad (11)$$

Throughout the Menschutkin reactions in acetonitrile–methanol mixtures, isokinetic relationships given in terms of physical interaction quantities conform to known empirical rules governing activation parameters.[4.5.8]

The assumption that the isokinetic relationship between physical interaction quantities holds in acetonitrile–methanol mixtures has been used as a criterion for the separation of the term $\Delta H_{t.Sl}^{AN\rightarrow MeOH}$ into its constituents. Calculations were repeated by adjusting alternately two solvation numbers, *i.e.*

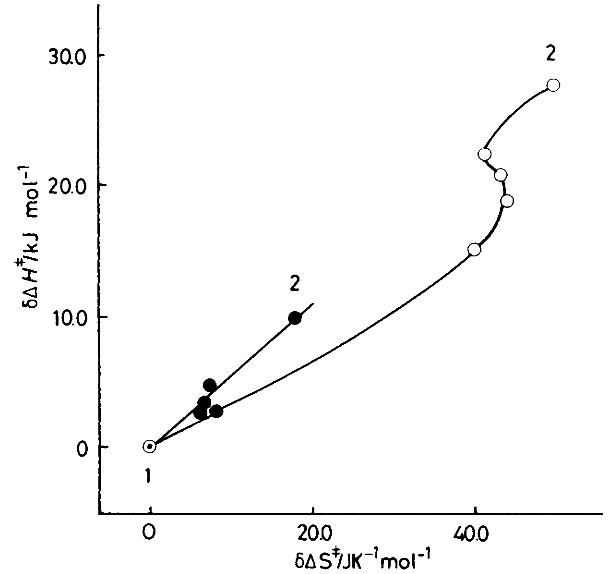

Figure 1. Activation enthalpy *versus* activation entropy correlations for DABCO plus MeI reaction in acetonitrile–methanol mixtures. Experimental results were taken from ref. 4. ○, overall quantities; ●, physical interaction quantities. 1, AN; 2, MeOH.

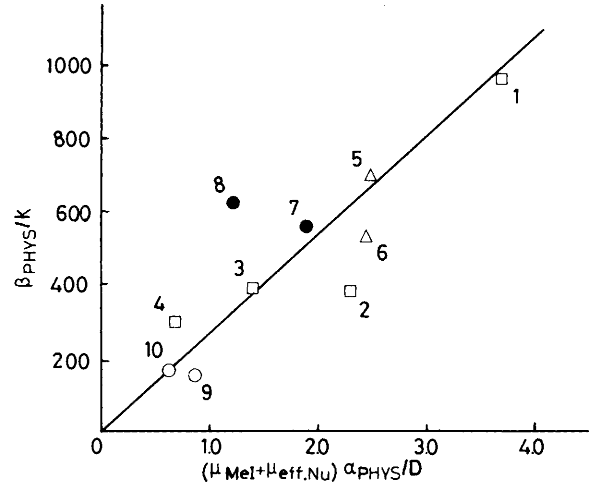

Figure 2. Empirical correlation between isokinetic temperatures, β_{PHYS} and extended Brønsted coefficients, α_{PHYS}, both derived through the analysis on physical interaction quantities.

Symbols are: □, pyridines; △, imidazoles; ○, aliphatic amines; ●, aliphatic diamines. 1, 4-(dimethylamino)pyridine; 2, 4-t-butylpyridine; 3, pyridine; 4, 4-cyanopyridine; 5, *N*-methylimidazole; 6, *N*-methylbenzimidazole; 7, DABCO; 8, *N*,*N'*-dimethylpiperazine; 9, triethylamine; 10, quinuclidine.

Most of the dipole moments are taken from ref. 9. The dipole moment of quinuclidine, 1.36 D was estimated from the value of *N*-methylpiperidine multiplied by the factor ascribable to cyclization (μ_{THF}/μ_{Et_2O} = 1.5). Other quantities which are not given in this paper were taken from refs. 4, 5, and 8.

Z(Nu) and Z(AC), until the relationship was realized. One of the plausible sets of parameters is summarized in Table 4 and one of the results derived through these procedures is shown in Figure 1.

The solvation numbers determined above might possibly be mutually dependent and thus be an artifact of the treatment, since they have been derived through multiple curve-fitting procedures. That the numbers are reasonable is suggested by an independent treatment, as follows. In previous work, after being averaged over various nucleophiles, a reasonable value of ΔH_{se} has been evaluated[10] to be *ca.* −11.0 kJ mol^{-1}. Present results for the value, $\Delta H^{AN\rightarrow MeOH}_{t,SI}/Z$, are −35.5/2.7, −17.8/1.8, −30.0/2.5, and −13.0/1.0 for DABCO, the activated complex for DABCO plus MeI reaction, DMPIPRA, and the activated complex for DMPIPRA plus methyl iodide reaction, respectively, and the present estimate for ΔH_{se} is − 12.0 kJ mol^{-1}, after being averaged over nucleophiles and activated complexes.

The relationships between activation parameters at various levels, ranging from the credibility of the relationship itself to its predictive power on chemical events have been much disputed.[11–14] The isokinetic temperature, β_{PHYS} determines the relative contribution of enthalpy term to entropy term as a constituent of free-energy changes perturbed through solvent variation. Thus, β_{PHYS} is a specific characteristic of the reacting system. However, extended Brønsted coefficient, α_{PHYS} is usually taken as the index giving the transition-state position on a reaction co-ordinate for a relevant system. Characterization of activated complex solvation deduced from the quantitative dissection of the transfer enthalpies into constituents is one of the key steps commonly involved in determining two transition-state indices. From the operational point of view as well as on empirical grounds, inter-relationships between the two transition-state indices is thus conceivable. Searches were made to discover the inter-relations and one of the primary results is shown in Figure 2, where $\mu_{eff.Nu}$ stands for the effective dipole moment of nucleophile.

On the basis of the above discussion, observed physical interaction enthalpies for diamines have been ascribed to the sum of contributions from the partial solute dipole–solvent dipole interaction around respective nitrogen atom. This view can be accommodated into our treatment through the definition of effective dipole moment for nucleophile, $\mu_{eff.Nu}$ as follows: for mono-amines it is equal to an experimental dipole moment, and for diamines it is twice the dipole moment for structurally related mono-amine, *viz.* for DMPIPRA it is twice the dipole moment of *N*-methylpiperidine and for DABCO it is twice that of quinuclidine. Experimental results for diamines (7 and 8 in Figure 2) together with those for mono-amines provide only one correlation after this treatment, and this suggests that solvation around the remote site from the reaction centre affects, significantly the transition-state indices.

Solvation of a dipolar molecule induces a polarization in the surrounding solvents and the polarization will cause back-induction to the polarization of the dipolar solute. Thus, the polarization of a solute and of solvents will be taken as co-operative phenomena.

For Menschutkin reactions, the polarity of a reacting system increases along a reaction co-ordinate and the polarization of surrounding solvents, together with various solute properties back-induced from the polarization of solvents simulated by a function, which responds to a reaction co-ordinate variable, x, and gives a non-zero finite value over the region of an initial state ($x = 0$) to a final state ($x = 1$). One of the simplest forms of such a function which satisfies the above constraints, will be the term, $\mu_I e^{(Ax)}$, in which μ_I stands for a dipole moment of an initial state, and A is a proportionality constant which plausibly allows for the subtleties of a relevant system. The total amount of polarization of solvents induced by a reacting system accompanying activation (and, therefore, a number of the transition-state indices determined through probing the polarization) will be proportional to the integral, PI.

$$\mathrm{PI} = \int_0^{\alpha_{PHYS}} \mu_I e^{(Ax)}\,\mathrm{d}x \qquad (12)$$

To a first approximation the leading term of the integral is always, $\mu_I\alpha_{PHYS}$, irrespective of the constant, A. This

Table 5. Solvents for recrystallization and elementary analysis.

Salts	Solvents	Formula	Calculated (%)				Observed (%)			
			C	H	N	I	C	H	N	I
N,*N*,*N*′-Trimethylpiperazinium iodide	ethanol	$C_7H_{17}N_2I$	32.83	6.69	10.94	49.55	32.86	6.62	10.73	49.47
N,*N*,*N*,*N*,′,*N*′-Pentamethylethylene-diammonium iodide	butan-2-one	$C_7H_{19}N_2I$	32.57	7.42	10.85	49.16	32.81	7.21	10.74	49.35
N,*N*-Dimethylpiperidinium iodide	ethanol	$C_7H_{16}NI$	34.87	6.69	5.81	52.63	34.76	6.67	5.81	52.50
Trimethyl-n-propylammonium iodide	propan-2-ol	$C_6H_{16}NI$	31.46	7.04	6.11	55.39	31.39	6.95	5.99	55.52

constitutes a plausible explanation for the correlation shown in Figure 2.

Stated more qualitatively, a generalized concept obtained from the correlation is that solvent effects on reaction rates become more enthalpy controlled with increase in the polarity integral of reaction, PI.

The particular roles played by a non-reacting nitrogen atom in diamine reactions are clearly shown in the extended Brønsted coefficient, ranging from internal solvation for the TMEDA reaction to a through-space interaction for the DABCO reaction. While a close similarity in the coefficient for the DMPIPRA reaction to that for triethylamine reaction suggests a minor role played by a non-reacting nitrogen atom in the former reaction, the higher isokinetic temperature, β_{PHYS} for the former reaction than that for the latter, *i.e.* 630 K for the former and 150 K for the latter,[8] definitely characterizes a major role of the non-reacting nitrogen atom. Multiple use of transition-state indices and their empirical analysis are indispensable for empirical characterization of reactions in solution. An empirical correlation as shown in Figure 2 is useful as a check on the credibility of the indices as well as for extracting physical features of reactions from these indices.

Experimental

Materials.—*N*,*N*′-Dimethylpiperazine and *N*,*N*,*N*′,*N*′-tetramethylethylenediamine were stored first over potassium hydroxide, then over calcium hydride and were then distilled. Quaternary ammonium iodides were prepared in acetonitrile from the corresponding amine and methyl iodide, and recrystallized three times from the solvents summarized in Table 5. Other materials were treated as described in the literature.[6,10]

Kinetic Measurements.—Reactions were followed by determination of iodide ion by potentiometric titration with silver nitrate solution. Rate constants were determined at four of the following temperatures, 0.0, 10.0, 20.0, 30.0, 40.0, and 50.0 °C. Experimental errors were estimated to be $\pm 2\%$. Standard errors of activation enthalpy and of activation entropy are *ca.* ± 0.7 kJ mol^{-1} and ± 2.0 J K^{-1} mol^{-1}, respectively.

Heat of Solution Measurements.—Heats of solution were measured with a Tokyo Riko twin isoperibol calorimeter (TIC – 2D) at 25.0 ± 0.05 °C. Experimental error was estimated to within $\pm 2\%$. Final ranges of concentration were $(2.6–8.0) \times 10^{-2}$ mol dm^{-3} for diamines and $0.65–1.2 \times 10^{-2}$ mol dm^{-3} for quaternary ammonium iodides.

Acknowledgements

We thank Dr. M. H. Abraham, University College London, for his critical reading of the original version of this manuscript, and Professor J. Hayami, Kyoto University, for his helpful comments.

References

1 R. W. Taft, in 'Steric Effects in Organic Chemistry,' ed. M. S. Newman, Wiley, New York, 1956, ch. 13.
2 J. Shorter, 'Correlation Analysis of Organic Reactivity,' Research Studies Press, Chichester, 1982.
3 Y. Kondo, A. Zanka, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, 1985, 827.
4 Y. Kondo, R. Uematsu, Y. Nakamura, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, 1988, 1219.
5 Y. Kondo, S. Izawa, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, 1988, 1925.
6 Y. Kondo, M. Ittoh, and S. Kusabayashi, *J. Chem. Soc., Faraday Trans. 1*, 1982, **78**, 2793.
7 Y. Kondo, M. Inoue, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, 1983, 1217.
8 Y. Kondo, M. Ogasa, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, 1984, 2093.
9 A. L. McClellan, 'Tables of Experimental Dipole Moments,' W. H. Freeman and Company, San Francisco and London, 1963.
10 Y. Kondo, T. Fujiwara, A. Hayashi, and S. Kusabayashi, *J. Chem. Soc., Perkin Trans. 2*, in the press.
11 J. E. Leffler and E. Grunwald, 'Rates and Equilibria of Organic Reactions,' Wiley, New York, 1963.
12 O. Exner, *Prog. Phys. Org. Chem.*, 1973, **10**, 41.
13 L. G. Hepler, *Thermochim. Acta*, 1986, **100**, 171.
14 J. Halpern, *Bull. Chem. Soc. Jpn.*, 1988, **61**, 13.

Paper 9/05258E
Received 11*th December* 1989
Accepted 2*nd February* 1990