

Looking for a contribution of the non-equilibrium solvent polarization to the activation barrier of the S_N2 reaction

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Received 5 August 2001; revised 6 January 2002; accepted 6 February 2002

ABSTRACT: The solvent effect on the activation free energy of the Finkelstein reaction between methyl iodide and Cl^- ions was analysed in terms of the recent Marcus theory unifying the S_N2 and the electron transfer reactions. The homolytic bond dissociation energy and the related resonance energy of interaction of the states seem to be almost solvent independent. The sum of the work term w_r and the solvent reorganization energy $\lambda_0/4$ depends strongly on the solvent acidity parameter, *e.g.* E_T^N , describing the solvation/desolvation of anions. However, after removing the contribution of the specific solvation the linear increase of the remaining part of $\lambda_0/4$ with the Pekar factor, describing the non-equilibrium solvent polarization, was observed for six aprotic solvents. Copyright © 2002 John Wiley & Sons, Ltd.

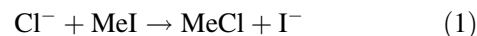
KEYWORDS: Finkelstein reaction; solvent effects; electron transfer; Marcus theory

INTRODUCTION

A detailed mechanism of S_N2 reactions and their relations to single electron transfer (ET) have been explored for more than 20 years, since the pioneering work of Alberty and Kreevoy,^{1,2} who described methyl transfer kinetics in terms of the Marcus equation, relating the rate constants of cross and identity reactions as was originally proposed for the outer-sphere ET processes.³ Two problems were addressed repeatedly in the literature: (i) possible competition between S_N2 and ET reactions (papers on this aspect were reviewed recently by Savéant⁴) and (ii) the description of the S_N2 mechanism as a single electron shift in a one-step reaction, as originally proposed by Pross and Shaik.^{5–7} A unified model based on two interacting states for the rates of S_N2 and ET reactions was proposed by Marcus.⁸ In that model, the S_N2 activation barrier includes the thermodynamic driving force component, the resonance energy and the reorganization energy, which takes into account solvent and bond breaking/making contributions. A successful comparison of the model with experimental results obtained in the gas phase and aqueous solutions was presented.⁸

The Marcus model predicts⁸ an important contribution to the activation free energies originated from the non-equilibrium solvent polarization in a transition state (TS). Such contributions, described by the solvent reorganization energy λ_0 , were experimentally shown in the case of outer-sphere ET processes and recently also in the

kinetics of bond cleavage of radical anions;^{9,10} the last process can be described¹¹ as a concerted bond breaking and an intramolecular electron shift. On the other hand, the large solvent effect on S_N2 rate constants, in particular observed on going from water to dipolar aprotic solvents, was explained^{12–14} in terms of the equilibrium solvation of reactants and a TS. Marcus, in the comparison of his model with experiments, obtained⁸ the solvent reorganization energy for identity Finkelstein reactions in aqueous solutions as the difference between the solution and gas-phase activation barriers and showed that they are comparable with values estimated using the single-ion vertical reorganization energy obtained from threshold energies of photoelectron emission by ions in aqueous solutions. Then, the effect of the non-equilibrium solvent polarization in TS for S_N2 reactions in different solvents was not directly demonstrated. It can be added that the non-equilibrium polarization effect was also incorporated to the state correlation diagram model of Shaik for S_N2 reactions;¹⁵ however, calculated and experimental activation barriers were compared only for water and DMF. The purpose of this paper is to analyse the kinetic data in various solvents according to the Marcus model⁸ in order to show a contribution from the non-equilibrium solvent polarization to the activation free energy of the reaction between MeI and Cl^- ions:

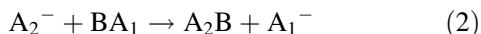


That reaction was chosen because its rate constant was measured in the largest number of solvents of all the S_N2 reactions discussed by Parker.¹²

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The Marcus model of S_N2 reactions

The Marcus theory of S_N2 kinetics predicts⁸ for the reaction



with the tight TS the rate constant expression

$$k = Z(q_{\text{vib}}/q_{\text{rot}})^3 \exp(-\Delta G^*/RT) \quad (3)$$

where Z is a collision frequency, q_{vib} and q_{rot} are individual reactant's vibrational and rotational partition functions, respectively, and the activation free energy can be approximated by

$$\Delta G^* = w_r + (\lambda_0 + D_1 + D_2)/4 - \beta_{ij} + \Delta G^{\circ'}/2 + (\Delta G^{\circ'})^2/\lambda \quad (4)$$

with $\lambda = \lambda_0 + D_1 + D_2$, where w_r is the work term for the formation of the encounter complex, D_1 and D_2 are homolytic bond dissociation energies in BA_1 and BA_2 (including the effect of the change of bond angles from tetrahedral in BA , e.g. when B is a methyl group, to trigonal planar in B^-) and β_{ij} is the resonance energy of interaction of the states, depending on D_1 and D_2 (for a symmetric reaction $\beta_{ii} = \gamma_i D_i'$). The thermodynamic driving force in Eqn. (4) is given by

$$\Delta G^{\circ'} = E^\circ(A_2^\bullet/A_2^-) - E^\circ(A_1^\bullet/A_1^-) + D_1 - D_2 + w_p - w_r + RT \ln Q(1)/Q(0) \quad (5)$$

where w_p is the work term for the product complex, E° the standard potentials for the redox couples given in parentheses and $Q(1)$ and $Q(0)$ the partition functions for products and reactants, respectively. The last term in Eqn. (5) can be cancelled with a minor approximation⁸ because both the reactants and the products include neutrals.

Thus, the strong equilibrium effect of the solvent on the rate constants can be expected from the thermodynamic contribution $\Delta G^{\circ'}$.

RESULTS

The values of the activation barrier ΔG^*_{exp} for reaction (1) were calculated from the experimental rate constants extracted from the Parker compilation,¹² assuming the pre-exponential term to be equal to $10^{12} \text{ M}^{-1} \text{ s}^{-1}$ in accordance with the Marcus suggestion⁸ that a somewhat larger value than a classical collision frequency is expected taking into account a higher pair-distribution function for the pair of reactants in the solution, similarly as for the ET process.¹⁶ The values obtained for ΔG^*_{exp} are collected in Table 1. For reaction (1) in aqueous and DMF solutions, the values of ΔG^* are close to those originally obtained by Albery and Kreevoy^{1,2} and used more recently.^{8,15}

Considering first the solvent effects on the energies of homolytic bond cleavage D_{MeI} and D_{MeCl} , the solvation of the neutral methyl radical and the halogen atom can be neglected but the solvation of dipole molecules of MeI and MeCl should be taken into account. Fortunately, the solvent activity coefficient for MeI and MeCl has been determined in a few solvents^{12,17} and it is possible to estimate the solvent change of D_{MeX} as follows.

The solvation free energy change of methyl halide in water, $\Delta G_{\text{solv}} = 4.3$ and 5.9 kJ mol^{-1} for MeI and MeCl, respectively, was calculated from the formation free energy of MeX in aqueous solution¹⁸ (20 and -57 kJ mol^{-1} for MeI and MeCl, respectively) and in the gas phase¹⁹ (15.7 and 62.9 kJ mol^{-1} for MeI and MeCl, respectively). ΔG_{solv} of MeI in methanol (MeOH), formamide (FA), *N,N*-dimethylformamide (DMF), *N,N*-dimethylacetamide (DMA), acetonitrile (ACN), acetone (AC), nitromethane (MeNO_2) and *N*-methylpyrrolidinone (NMP) were calculated using the experimental activity coefficients γ_{MeI} in water and the above solvents

Table 1. Activation free energy and its components (all in kJ mol^{-1}) according to Eqn. (11) for the reaction of MeI with Cl^- in different solvents

Solvent	ΔG^*_{exp}	$F\Delta E^\circ$	D_{MeI}	D_{MeCl}	$-0.5\Delta G^\circ$	$w_r + \lambda_0/4$	$\lambda_0/4$
MeOH	99.9	110	238	351	1.4	66.0	34.1
H ₂ O	99.6	116	230	346	-0.1	65.0	23.0
FA ^a	93.0	109	234	350	3.6	61.6	28.0
MeNO ₂	75.9	96	240	353	8.5	48.8	28.6
ACN ^b	73.6	91	241	352	11.2	49.2	29.5
DMF	66.2	88	241	353	12.4	43.0	25.8
AC ^c	64.5	84	243	352	14.2	43.0	28.3
DMA	63.4	82	242	353	15.2	42.9	26.1
NMP ^d	60.5	84	243	354	14.2	38.9	24.2

^a Formamide.

^b Acetonitrile.

^c Acetone.

^d *N*-Methylpyrrolidinone.

against MeOH taken as the reference solvent.^{12,17} The coefficients γ_{MeCl} were measured only for water, FA, MeOH and DMF; for other solvents they were estimated from the linear correlation with the free energy of transfer of BPh_4^- ion from water to a given solvent:

$$RT \ln \gamma_{\text{MeCl}} = 0.20(\pm 0.04) \Delta G^\circ_{\text{tr}}(\text{BPh}_4^-) + 5(\pm 1) \\ n = 4, r = 0.9977, F = 429.2, \delta = 0.19 \quad (6)$$

where n is the number of solvents, r the correlation coefficient, F the value of the Snedecor test, δ the mean quadratic deviation from the correlation line, 95% errors of regression coefficients are given in parentheses and the values $\Delta G^\circ_{\text{tr}}(\text{BPh}_4^-)$ were taken from Ref. 20. Homolytic dissociation energies in different solvents were estimated assuming $D_{\text{MeX}} = D_{\text{MeX}}^{\text{gas}} - \Delta G_{\text{solv}}$. The resulting values (calculated for $D_{\text{MeI}}^{\text{gas}} = 234$ and $D_{\text{MeCl}}^{\text{gas}} = 351.5 \text{ kJ mol}^{-1}$)²¹ are collected in Table 1. From the inspection of that data it is evident that the solvent effect on D_{MeX} is very small.

Neglecting the last term in Eqn. (5) and assuming to a first approximation that $w_p = w_r$, one can express $\Delta G^{\circ'}$ as the sum of differences between formal potentials, $E^\circ(\text{I/I}^-) - E^\circ(\text{Cl/Cl}^-)$, and between bond energies, $D_{\text{MeI}} - D_{\text{MeCl}}$. Formal potentials in aqueous solutions ($E^\circ = 1.4$ and 2.6 V for I^- and Cl^- , respectively) were taken from Ref. 22 and those for other solvents were calculated using the free energy of transfer²⁰ of each halogen ion from water to a given solvent. The differences obtained, $F\Delta E^\circ = FE^\circ(\text{I/I}^-) - FE^\circ(\text{Cl/Cl}^-)$ are collected in Table 1. The thermodynamic driving force was finally calculated as

$$\Delta G^{\circ'} = FE^\circ(\text{I/I}^-) - FE^\circ(\text{Cl/Cl}^-) + D_{\text{MeI}} - D_{\text{MeCl}} \quad (7)$$

and the values of $0.5\Delta G^{\circ'}$ obtained are also collected in Table 1.

The activation free energy of the S_N2 reaction depends linearly on the reaction free energy as expressed by the following equation:

$$\Delta G^*_{\text{exp}} = 1.3(\pm 0.2) \Delta G^{\circ'} + 101(\pm 4), \\ n = 9, r = 0.9891, F = 316.6, \delta = 2.2 \quad (8)$$

The addition of the quadratic term, as predicted by Eqn. (4), is statistically insignificant. However, the slope of the line obtained is about twice the theoretical value of 0.5, predicted by Eqn. (4). This high value indicates that some other contribution to the activation barrier depends linearly on the same solvent properties as the values of $\Delta G^{\circ'}$. The solvent change of the last parameter describes mainly the solvation of an anionic reactant and product and thus $\Delta G^{\circ'}$ should be dependent on the solvent acidity in the Lewis sense. Indeed, there is the acceptable correlation with the Dimroth and Reichardt E_T^N par-

ameter:²³

$$\Delta G^{\circ'} = 48(\pm 13) E_T^N - 45(\pm 8) \\ n = 9, r = 0.9606, F = 83.7, \delta = 3.1 \quad (9)$$

On the other hand, the resonance energy can be described approximately by

$$\beta_{ij} = 0.5(\gamma_i D_i + \gamma_j D_j) \quad (10)$$

[neglecting in the original Marcus Eqn. (13d) in Ref. 8 the last term $1 - (\Delta G^{\circ'}/\lambda)^2$ because $\Delta G^{\circ'}/\lambda$ is very small, as is indicated by the negligibly small quadratic term in Eqn. (4) and neglecting the term $(\gamma_i D_i)^{0.5} - (\gamma_j D_j)^{0.5}$ as discussed by Marcus⁸]. Assuming additionally that $\gamma_i = \gamma_j = 0.38$ in each solvent, as for the symmetric identity Finkelstein reactions considered by Marcus,⁸ one can obtain $\beta_{ij} = 0.19 (D_i + D_j)$ and finally

$$\Delta G^* = w_r + \lambda_0/4 + 0.06(D_i + D_j) + \Delta G^{\circ'}/2 \quad (11)$$

The solvent effect on $0.06(D_{\text{MeI}} + D_{\text{MeCl}})$ is negligibly small; $0.06(D_{\text{MeI}} + D_{\text{MeCl}})$ is equal to 36 and 35 kJ mol^{-1} in aprotic and protic solvents, respectively. The calculated solvent-dependent contributions to ΔG^*_{exp} ($0.5\Delta G^{\circ'}$ and the sum $w_r + \lambda_0/4$) are given in Table 1. It is evident that the increase in the activation free energy on going from aprotic to protic solvents is caused by a very strong increase in the $w_r + \lambda_0/4$ contribution and a 1.8 times weaker increase in the thermodynamic driving force $0.5\Delta G^{\circ'}$ (the last contribution is negative).

DISCUSSION

Albery and Kreevoy, in their classical papers^{1,2} on the methyl transfer reactions, assumed that work terms are negligibly small ($w_r \approx 10 \text{ kJ mol}^{-1}$ in aqueous solution) and omitted them. However, the above assumption is not acceptable if one looks for solvent effects on the activation barrier. The formation of the encounter pair of reactants includes at least a partial desolvation of the halide ion and therefore w_r should be dependent on the solvent acidity described, e.g., by the E_T^N parameter. In general, there is also a contribution to the static component of the solvent reorganization energy due to the specific solvation, i.e. the non-continuum solvent effect. Hupp and Weaver showed²⁴ that the non-continuum effect can be taken into account for the homogeneous outer-sphere ET process for cationic redox couples by the addition to $\lambda_0/4$ [described in terms of the Born model of solvation, cf. Eqn. (13) below] the correction term $\Delta G^{\circ}_{\text{nc}}/(4n + 2)$, where n is the charge number of a reduced form of a reactant and $\Delta G^{\circ}_{\text{nc}}$ the free energy change of the equilibrium specific solvation of a redox couple of interest. The values of $\Delta G^{\circ}_{\text{nc}}$ were

determined²⁴ from the plot of the formal potential against the solvent parameter donor number, DN , assuming that for $DN = 0$ the specific solvation is completely cancelled. Unfortunately, that procedure gives only relative values of the correction term, because different solvent scales include different contributions from non-specific and specific solvent effects.²³ Nevertheless, applying a similar procedure to the S_N2 reaction of interest with the charge number change $0/-1$ results in an increase of the reorganization energy by $\Delta G^\circ/2$, which can reasonably explain the higher coefficient in Eqn. (8). However, the above procedure is not certain for the S_N2 reaction and a different approach is therefore proposed below.

Both effects indicated above predict an additional dependence on the solvent Lewis acidity. A correlation of $w_r + \lambda_0/4$ with the E_T^N parameter was indeed found:

$$w_r + \lambda_0/4 = 42(\pm 12)E_T^N + 27(\pm 8)$$

$$n = 9, r = 0.9504, F = 65.3, \delta = 3.1 \quad (12)$$

Similar correlations were found using other parameters describing the solvation of anions: the acceptor number¹⁴ or the free energy of transfer of the halide ion from water to a given solvent. The correlation (12) explains the high slope in Eqn. (8) irrespective of its origin and supports the view on the domination of specific solvation effects described by the solvent acidity over the effect of the non-equilibrium solvent polarization.

On the other hand, the solvent reorganization energy λ_0 is the barrier resulting from a slow reorientation of solvent molecules which cannot follow the instantaneous position of the electronic charge in the TS and they therefore adjust to some averaged charge distribution.⁸ According to Marcus,⁸ such non-equilibrium solvent polarization can be described using a linear response approximation by a difference between equilibrium solvation free energies which takes into account the total (electronic and nuclear) and only electronic polarizability, respectively; in terms of a dielectric continuum model, the oversimplified two-sphere expression⁸ (well known from the previous ET theory) is

$$\lambda_0/4 = (e^2/4)(1/2a_1 + 1/2a_2 - 1/R)(1/\epsilon_{op} - 1/\epsilon_s) \quad (13)$$

where a_1 and a_2 represent the radii of spheres of an electron localization and R is the distance between them in TS and the term in the last parentheses, called the Pekar factor γ_{solv} , depends on ϵ_s and ϵ_{op} , the static and optical permittivity of a solvent, respectively. The dependence of $w_r + \lambda_0/4$ on the Pekar factor is shown in Fig. 1. Two separate correlation lines for protic and aprotic solvents are observed. The above result can suggest the expected contribution from the non-equilibrium solvation to the reorganization energy; however, at the same time, it indicates a dominant role of the

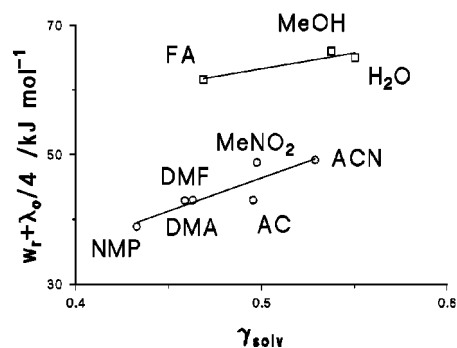


Figure 1. Dependence of the sum of the work term and the solvent reorganization energy for the reaction of MeI with Cl^- on the solvent Pekar factor. Solvent abbreviations as in Table 1

specific solvent effect described by the E_T^N parameter, which is much higher for protic solvents. However, the addition of γ_{solv} as the second explanatory parameter to Eqn. (12) is statistically unjustified.

Thus, the contribution to the reorganization energy described by the Pekar factor could be shown only after extraction of specific solvation effects from the term $w_r + \lambda_0/4$. This can be done calculating

$$\lambda_0/4 + C = w_r + \lambda_0/4 - bE_T^N \quad (14)$$

where C is a solvent-independent constant and the coefficient $b = 42$ is the slope in Eqn. (12). The relationship obtained between $\lambda_0/4 + C$ and the Pekar factor is shown in Fig. 2. For six aprotic solvents there is the acceptable correlation with the intercept equal to zero:

$$\lambda_0/4 + C = 56.5(\pm 0.8)\gamma_{solv}$$

$$n = 6, r = 0.9825, F = 139.3, \delta = 0.34 \quad (15)$$

However, points for protic solvents, in particular water, deviate from the line. The null intercept in Eqn. (15) indicates most probably that the specific solvation of negative charge in TS and the work term w_r were completely removed, the constant $C = 0$ and the values obtained are equal to $\lambda_0/4$ described by Eqn. (13); they are collected in Table 1. The values of $\lambda_0/4$ can be compared with the total activation barrier and with the intrinsic activation barrier after removing the thermodynamic driving force from ΔG_{exp}^* . It is evident that the solvent reorganization energy $\lambda_0/4$ describing the effect of the non-equilibrium solvent polarization represents 42% (in MeNO₂) to 56% (in AC) of the intrinsic activation barrier for aprotic solvents but are lower for protic solvents (23% in water and 35% in methanol).

Considering the slope of the correlation (15) in terms of Eqn. (13), it is evident that reasonable agreement can be obtained if spheres of a negative charge localization include solvent molecules around the ions. Assuming

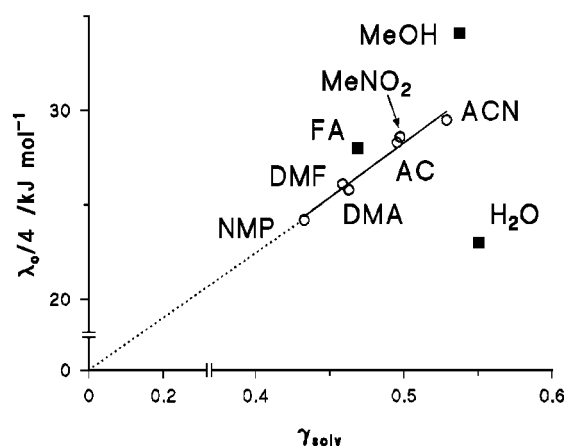


Figure 2. Relationship between the solvent reorganization energy (without the contribution from the specific solvation) and the solvent Pekar factor for the reaction of MeI with Cl^- ions. The correlation line for aprotic solvents (open points) is shown

$a_1 = a_2 = 350$ pm (the radii of hydrated I^- and Cl^- ions²⁵ are 346 and 347 pm, respectively) and $R = a_1 + a_2 + 2r = 854$ pm ($r = 77$ pm corresponds to the covalent radius of the carbon atom), a slope equal to 58 can be calculated from Eqn. (13), whereas for $r = 200$ pm (i.e. the van der Waals radius of the methyl group²⁶) the slope is 67.

The reason for the deviations of points for protic solvents is not clear. However, it should be mentioned that the analysis presented does not take into account the possibility of a change in the structure of the TS with the solvent change (first, a change in the distance between the two halogen atoms, R). The solvent effect on the frequency of barrier crossing, discussed for S_N2 reactions by Gertner *et al.*,²⁷ was not considered either. The above effects can additionally make difficult the observation of any dependence on the solvent Pekar factor.

Unfortunately, for the very simple self-exchange reaction of MeI with I^- ions, no rate constants in aprotic solvents are available (with the exception of acetone¹²) for a similar analysis. In conclusion, although the

equilibrium solvation plays a dominant role in the kinetics of the S_N2 reaction of interest, the prediction of the Marcus model⁸ on the contribution from the non-equilibrium solvent polarization of TS to the intrinsic activation barrier is evident, at least for the aprotic solvents under consideration.

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