Temperature Dependence of Enthalpy, Entropy, and Heat Capacity of Activation in the Neutral Ester Hydrolysis in 2-Butoxyethanol–Water Solutions

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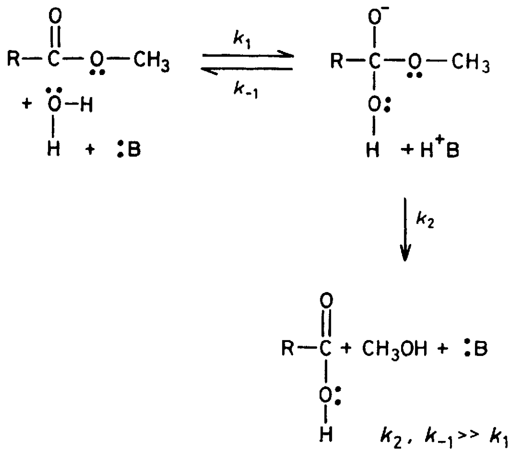
The kinetic behaviour of the neutral hydrolysis of methyl trifluoroacetate in 2-butoxyethanol–water solutions when x_w is close to 0.98 was studied and the calculated activation parameters have been compared with the kinetic data of the hydrolysis of chloromethyl dichloroacetate in the same conditions. In these hydrolyses not only $\Delta H^\ddagger$ and $\Delta S^\ddagger$ but also $\Delta C_p^\ddagger$ are highly temperature dependent, $d\Delta C_p^\ddagger/dT$ for $x_w = 0.980$ being $+38 \pm 2$ and $+67 \pm 5$ J mol^{-1} K^{-2} in the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate, respectively. Thus the temperature dependence of $\Delta C_p^\ddagger$ is less pronounced in the hydrolysis of methyl trifluoroacetate than in that of chloromethyl dichloroacetate. The temperature dependence of $\Delta C_p^\ddagger$ and the S-shaped Arrhenius plots in the hydrolyses studied in butoxyethanol–water mixtures can be explained on the basis of the formation of 'moving units' of clathrate hydrate-like structures when the temperature is raised. Thus with increasing temperature the solvent effects on $\Delta C_p^\ddagger$, generally found in typically aqueous solutions, are surpassed by the effects of the transition to a microphase structure.

It is well known that many solvolytic reactions in water or water–organic co-solvent mixtures do not follow the Arrhenius equation exactly but usually have a negative heat capacity of activation, $\Delta C_p^\ddagger = d\Delta H^\ddagger/dT$.[1-3] For instance, in the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in water the values of $\Delta C_p^\ddagger$ have been found to be -245 ± 5 and -182 ± 8 J mol^{-1} K^{-1}, respectively.[3] Various explanations have been given for this observation. It is usually assumed that the curvature in the Arrhenius plots can be attributed to the dependence of the related enthalpy of activation on temperature.[1-3] Recently, it was suggested by Blandamer *et al.*[4-8] that the two stage reaction scheme, proposed by Albery and Robinson,[9] would explain the temperature dependence of rate constants in various solvolyses better than the old treatment of Robertson.[1]

Recent results obtained in this laboratory for the neutral hydrolysis of chloromethyl dichloroacetate in 2-butoxyethanol-water (2-BE–water) mixtures, at the mole fraction of water (x_w) close to 0.98, have shown that the Arrhenius plots are S-shaped.[10] This seems to be the first case when such behaviour cannot be explained by the change in mechanism with increasing temperature. In that case $\Delta C_p^\ddagger$ is highly temperature dependent, $d\Delta C_p^\ddagger/dT$ being $+78 \pm 4$ and $+67 \pm 5$ J mol^{-1} K^{-2} for x_w 0.981 and 0.980, respectively. The positive values of $\Delta C_p^\ddagger$ found at higher temperatures are in agreement with the results of the neutral hydrolysis of *p*-methoxyphenyl dichloroacetate ($\Delta C_p^\ddagger$ + 937 J mol^{-1} K^{-1}) and 2,2-dichloropropionate ($\Delta C_p^\ddagger$ +1 431 J mol^{-1} K^{-1}) in a 2-BE–water system at temperatures from 293 to 321 K when x_w 0.98.[11]

According to the thermodynamic excess functions the binary system 2-BE–water belongs to a class of typically aqueous (TA) solutions.[12,13] The phase diagram for 2-BE–water mixtures is closed and the lower critical solution temperatures vary from 341.55 to 322.98 K when x_w goes from 0.983 37 to 0.967 08.[14] Beyond the transition region 2-BE exists as microphases or aggregates.[15] Further, it has been found by Ito *et al.*[16] that at the 'magic' mole fraction (x_w 0.98) of 2-BE–water solutions the formation of aggregates, which they call 'moving units', is beginning. The formation of these aggregates depends considerably on temperature [15] and they have clathrate hydrate-like structures, $3[(H_2O)_{50}2\text{-BE}]^{16}$.

The aim of this work was to study the behaviour of the neutral hydrolysis of methyl trifluoroacetate in 2-BE–water mixtures when x_w varies from 0.994 to 0.967 and to compare the calculated activation parameters with the data from the neutral hydrolysis of chloromethyl dichloroacetate in the different 2-BE–water mixtures studied earlier.[10] The reaction is assumed to take place as a general base catalysed ester hydrolysis, $B_{AC}3$, with a second water molecule acting as a general base :B.[17] In the case of methyl esters of halogenoacetic acids equation (1) represents the reaction mechanism.



(1)

Experimental

Methyl trifluoroacetate, a commercial product (E. Merck AG, zur Synthese), was redistilled before use. The solvent mixtures were prepared by diluting a known weight of distilled water with 2-BE (Fluka AG, purum), purified by ion exchange and redistillation, to a known volume in a volumetric flask. The initial ester concentrations were *ca.* 10^{-4}M. The temperature was stable to *ca.* 0.01 K.

The reaction was followed conductometrically as described earlier.[18] Actually the concentrations of trifluoroacetic acid were measured. It has been previously shown that, at high dilutions ($\leqslant 10^{-4}$M) a linear relationship between the conductance and the concentration of an acid can be expected.[18,19]

Table 1. Temperature range (T/K), number of data points (N), first-order rate constants (k/s^{-1}), activation enthalpies ($\Delta H^\ddagger$/J mol^{-1}), activation entropies ($\Delta S^\ddagger$/J mol^{-1} K^{-1}), and the heat capacities of activation ($\Delta C_p^\ddagger$/J mol^{-1} K^{-1}), calculated from equation (2) in its five parametric form, for the neutral hydrolysis of methyl trifluoroacetate in 2-BE–water solutions with the mole fraction x_w of water at 298.15 K

x_w	T	N	$10^3\,k$	$\Delta H^\ddagger$	$-\Delta S^\ddagger$	$\Delta C_p^\ddagger$
0.994	273—313	11	7.759	38 900 ± 200	154.9 ± 0.7	−229 ± 29
0.984	278—318	10	6.302	33 870 ± 120	173.4 ± 0.4	−623 ± 34
0.982	278—321	12	5.512	29 490 ± 180	189.3 ± 0.6	−504 ± 43
0.980	278—321	13	5.106	27 940 ± 140	195.1 ± 0.5	−309 ± 33
0.973	278—321	11	3.195	26 390 ± 120	204.2 ± 0.4	+33 ± 29
0.967	277—318	11	2.324	28 240 ± 70	200.6 ± 0.2	−47 ± 17

Table 2. Temperature range (T/K), number of data points (N), first-order rate constants (k/s^{-1}), activation enthalpies ($\Delta H^\ddagger$/J mol^{-1}), activation entropies ($\Delta S^\ddagger$/J mol^{-1} K^{-1}), and the heat capacities of activation ($\Delta C_p^\ddagger$/J mol^{-1} K^{-1}), calculated from equation (2) in its five parametric form, for the neutral hydrolysis of chloromethyl dichloroacetate in 2-BE–water solutions with the mole fraction x_w of water at 298.15 K

x_w	T	N	$10^3\,k$	$\Delta H^\ddagger$	$-\Delta S^\ddagger$	$\Delta C_p^\ddagger$
0.988	273—311	16	10.659	35 080 ± 160	165.0 ± 0.5	−365 ± 19
0.984	276—318	21	8.698	28 470 ± 250	188.9 ± 0.8	−640 ± 54
0.981	276—318	20	5.804	20 650 ± 160	218.5 ± 0.5	+181 ± 35
0.980	276—318	21	5.089	20 670 ± 190	219.5 ± 0.6	+373 ± 44
0.975	276—318	18	3.255	25 240 ± 180	207.9 ± 0.6	+614 ± 40

The rate constants were calculated by Guggenheim's method.[20] The standard deviations of the rate constants were in general <0.05% but were sometimes *ca.* 0.1%. The thermodynamic activation parameters were calculated by an extended Arrhenius equation (2), after orthogonalization, by the method

$$\ln k = A + B/T + C\ln T + DT + ET^2 + \ldots \quad (2)$$

of Clarke and Glew.[21] Calculations up to seven parameters show that the five-parametic equation (2) is flexible enough to represent the data correctly.

Results and Discussion

Kinetic data for the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in the 2-BE-water solutions studied at 298.15 K are given in Tables 1 and 2, respectively. As seen from the Tables, 2-BE lowers the rates of the hydrolyses considerably in a quite narrow concentration range. Further, at 298.15 K $\Delta H^\ddagger$ and $\Delta S^\ddagger$ are of the magnitude typical for $B_{Ac}3$ hydrolysis reactions,[2,17] and their values decrease with decreasing water content to a minimum when the mole fraction of water is *ca.* 0.973 and 0.980 for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate, respectively. In accord with other solvolytic reactions in aqueous organic co-solvent mixtures the changes in $\Delta H^\ddagger$ and $\Delta S^\ddagger$ counteract each other.[2,3,11,12]

The logarithms of the experimental first-order rate constants for the neutral hydrolysis of methyl trifluoroacetate in 2-BE–water mixtures are plotted *versus* $1/T$ in Figure 1. The Arrhenius plots are S-shaped when x_w is 0.984, 0.982, 0.980, and 0.973. Further, in the above mole fractions, the lower the water content of the solution the wider is the temperature range that gives a positive value for $\Delta C_p^\ddagger$; at lower temperatures $\Delta C_p^\ddagger$ is negative. These results are in agreement with the results of the neutral hydrolysis of chloromethyl dichloroacetate in 2-BE–water solutions when x_w is from 0.984 to 0.975.[10] Nevertheless, the S-shaped character and so the temperature dependence of $\Delta C_p^\ddagger$ (Figure 2) in the solvent systems studied are less pronounced in the hydrolysis of methyl trifluoroacetate than chloromethyl dichloroacetate, $\mathrm{d}\Delta C_p^\ddagger/\mathrm{d}T$ for the former ester being +35 ± 4 and +38 ± 2 J mol^{-1} K^{-2} for x_w 0.982 and 0.980, respectively, and for the latter ester +78 ± 4 and +67 ± 5 J mol^{-1} K^{-2} for x_w 0.981

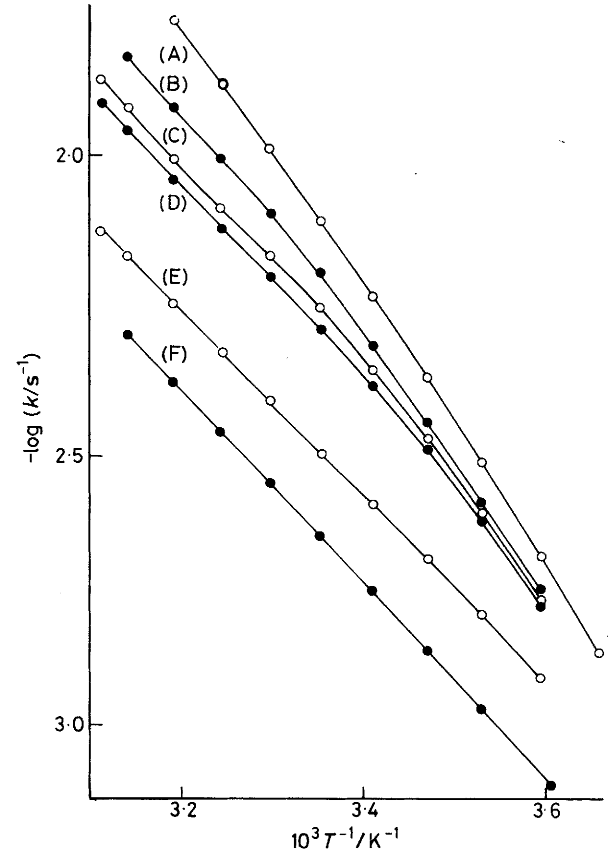


Figure 1. The Arrhenius plots of $-\log k$ *versus* $(1/T)$ for the neutral hydrolysis of methyl trifluoroacetate in 2-butoxyethanol-water. x_w = 0.994 (A); 0.984 (B); 0.982 (C); 0.980 (D); 0.973 (E); 0.967 (F)

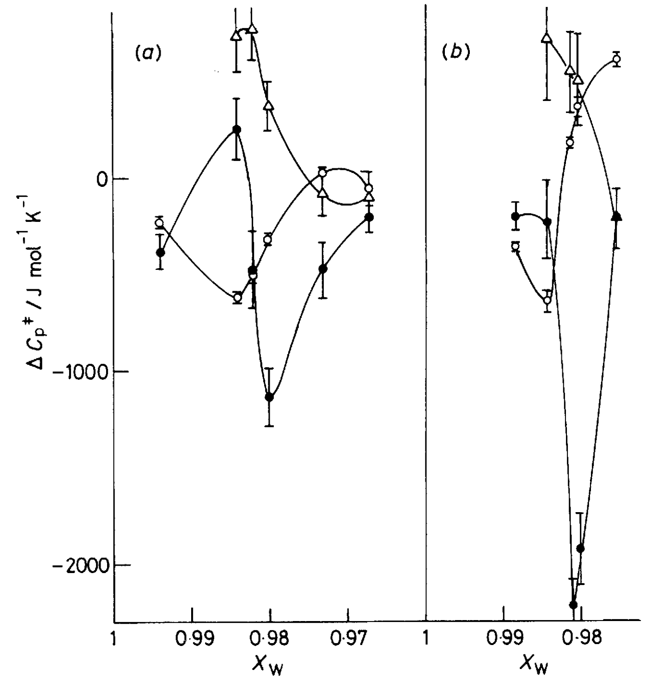


Figure 2. Plots of $\Delta C_p{}^{\ddagger}$ *versus* x_w for the neutral hydrolyses of methyl trifluoroacetate (*a*) and chloromethyl dichloroacetate (*b*) in 2-butoxyethanol–water mixtures. T = 278 K ●; 298 K ○; 318 K △

and 0.980, respectively. The temperature dependence of $\Delta C_p{}^{\ddagger}$ found in these hydrolyses have their origin in the fact that at the mole fractions of water close to 0.98, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ go through a minimum when the temperature is raised (Figures 3 and 4).

Positive values of $\Delta C_p{}^{\ddagger}$ have usually been caused by the change in mechanism when the temperature is raised as in the neutral hydrolysis of bromomethyl chloroacetate,[22] the change being from $B_{AC}3$ to an S_N displacement of bromine. In the neutral hydrolysis of chloromethyl dichloroacetate the same change in mechanism could be possible but is very improbable under the reaction conditions used.[10] When the alkyl component is a methyl group, as in the case of methyl trifluoroacetate, the change in mechanism from $B_{AC}3$ to an S_N solvolysis is impossible.

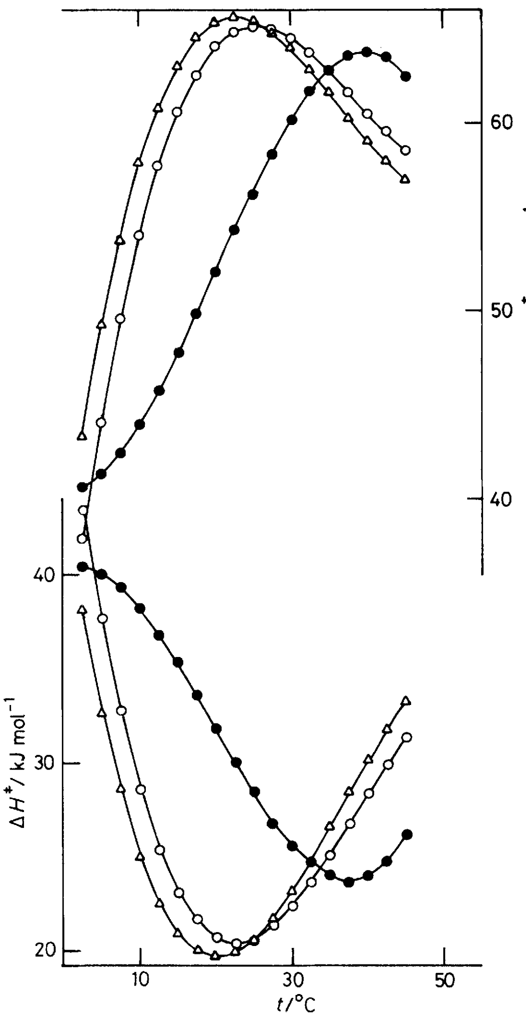


Figure 3. Plots of $\Delta H^{\ddagger}$ and $T\Delta S^{\ddagger}$ *versus* T for the neutral hydrolysis of methyl trifluoroacetate in 2-butoxyethanol–water mixtures. x_w = 0.984 ●; 0.982 ○; 0.980 △

Blandamer *et al.*[4-8] have recently applied a hypothetical two-stage ion-pair mechanism of Albery and Robinson[9] to explain the temperature dependence of rate constants in both S_N1 and S_N2 solvolyses. However, Bentley and Carter[23] have seriously criticized this interpretation of $\Delta C_p{}^{\ddagger}$ because, *e.g.*, for the hydrolysis of ethyl bromide an ion-pair intermediate is firmly excluded. It is well known that a two-stage reaction scheme is evident in the neutral ester hydrolysis, but in the place of an ion-pair intermediate there is a tetrahedral intermediate [equation (1)]. In the neutral hydrolysis of ethyl trichloroacetate in water, however, Kurz and Ehrhardt[24] have shown that the partition of the intermediate explains only a minor part (-13 J mol^{-1} K^{-1}) of the observed $\Delta C_p{}^{\ddagger}$ (-230 ± 4 J mol^{-1} K^{-1}). Further, the two-stage mechanism cannot explain the positive values of $\Delta C_p{}^{\ddagger}$ found at higher temperatures in the hydrolyses studied because it always gives a negative $\Delta C_p{}^{\ddagger}$. The S-shaped Arrhenius plots in the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in 2-BE–water mixtures can be explained on the basis of interactions between ' moving units ' and both the hydrophobic character and the size of the reactant. In general, the more hydrophobic an organic molecule is the greater is its attraction in a hydrophobic micelle. It can be expected that this is also true in respect to microphases or aggregates. Further, it seems that when the size of an apolar ester increases the Arrhenius plots become more S-shaped and so $\Delta C_p{}^{\ddagger}$ more dependent on temperature when x_w is close to 0.98. This can be seen from the hydrolyses of the present work (Figures 1 and 2; ref. 10) and from that of *p*-methoxyphenyl dichloroacetate and 2,2-dichloropropionate[11] in 2-BE–water mixtures rich in water. Consequently, in the circumstances when the formation of these aggregates has not yet begun, the values of $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ decrease when temperature is raised (Figures 3 and 4) because the solvation shell around the reactant in the initial state becomes looser at higher temperatures. When x_w is close to 0.98 the formation of aggregates is beginning. Because the transition concentration for the formation of these units decreases with increasing temperature[15] it can be expected that for the initial state the reacting ester at higher temperatures, accommodated in ' moving units ', is in a more ordered environment than at lower temperatures. Thus $\Delta S^{\ddagger}$ of the hydrolyses studied first decreases and then increases when the temperature is raised. Owing to this entropy effect the rate constants at higher temperatures increase more than can be expected on the basis of the

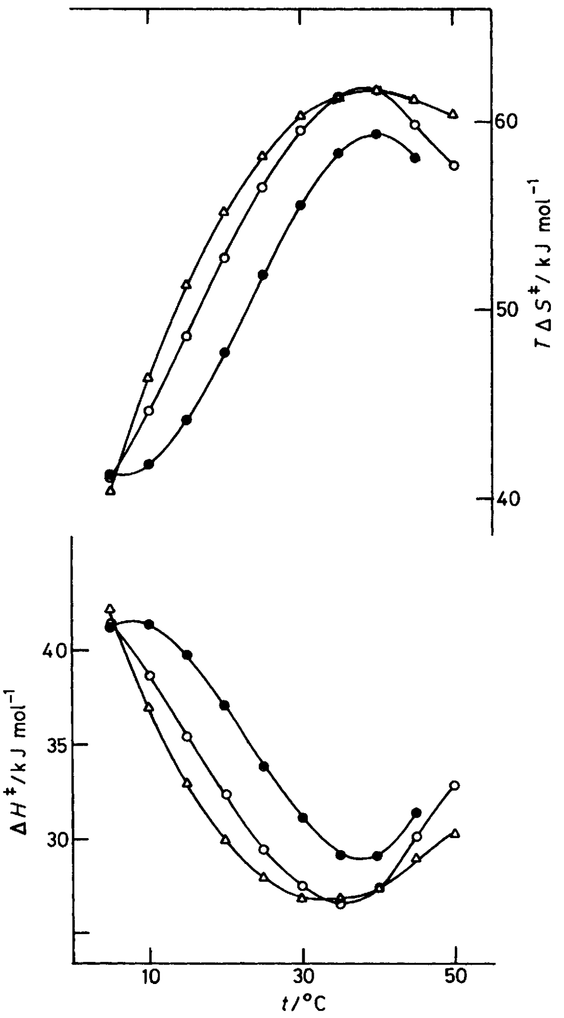


Figure 4. Plots of $\Delta H^‡$ and $T\Delta S^‡$ *versus* T for the neutral hydrolysis of chloromethyl dichloroacetate in 2-butoxyethanol–water mixtures. x_w = 0.984 ●; 0.981 ○; 0.980 △

Arrhenius equation. Also $\Delta H^‡$ increases with increasing temperature.

The heat capacity of activation is by far the most sensitive indicator of solvent effects. It is usually assumed that, for solvolyses in TA mixtures, $\Delta C_p^‡$ has a minimum at the concentration of water when the collapse of the solvent structure occurs.[3,12,13] The position of the extrema depends on the co-solvent used and the structure of the reactant. At lower temperatures this seems to be true also in the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in the 2-BE–water solutions studied (Figure 2). When the temperature is raised the minimum vanishes and at the same time moves to more water-rich regions until at higher temperatures there is a maximum in $\Delta C_p^‡$. This is in agreement with the formation of aggregates: with increasing temperature the normal solvent effects on $\Delta C_p^‡$, generally found in TA solutions, are surpassed by the solvent effects of the transition to a microphase structure.

The present results demonstrate an extraordinary solvent effect on $\Delta C_p^‡$ for the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in 2-BE–water mixtures. However, more work is needed to better understand the solvent effects on $\Delta C_p^‡$ caused by the formation of microphases or aggregates in solvolytic reactions. This is important because, in general, conclusions based on $\Delta C_p^‡$ values calculated from results obtained when studying a limited temperature range or using different temperature intervals have been made without taking into account the possible temperature dependence of $\Delta C_p^‡$. Unfortunately, the existence of the lower critical solution temperatures in 2-BE–water solutions makes it impossible to extend kinetic runs to higher temperatures than those in this experiment.

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