Temperature Dependence of Activation Parameters in the Neutral Ester Hydrolysis in t-Butyl Alcohol–Water Solutions

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The kinetic behaviour of the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in t-butyl alcohol–water solutions, rich in water, has been studied. In these hydrolyses at x_w close to 0.95, $\Delta C_p^\ddagger$ depends on temperature, $d\Delta C_p^\ddagger/dT$ being +23 ± 1 (x_w 0.951) and +21 ± 2 (x_w 0.957) J mol^{-1} K^{-2} for the hydrolysis of methyl trifluoroacetate and chloromethyl dichloroacetate, respectively. The temperature dependence of $\Delta C_p^\ddagger$ found has been explained by the formation of ' moving units ' so that at x_w *ca.* 0.95 there are two pseudo-phases representing the transition from the aggregates of the form $(H_2O)_{20}(Bu^tOH)$ into the aggregates of the form $4[(H_2O)_{20}(Bu^tOH)]$.

The heat capacity of activation, $\Delta C_p^\ddagger = d\Delta H^\ddagger/dT$, as a genuine rate parameter of most ionogenic solvolytic reactions, is mainly determined by the solvation differences between the initial and transition states.[1-3] Its value may include a ' spurious ' contribution from the partitioning of a possible intermediate as has been elegantly shown by Kurz *et al.*[4] for the neutral hydrolysis of ethyl trichloroacetate in water. In this instance the partitioning of the tetrahedral intermediate explains -13 J mol^{-1} K^{-1} of the observed value, -230 ± 4 J mol^{-1} K^{-1}, for $\Delta C_p^\ddagger$. Usually the value of $\Delta C_p^\ddagger$ has been found to be negative and, within the limits of the experimental accuracy, independent of temperature. Thus for 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.[5] However, Holterman and Engberts have found positive $\Delta C_p^\ddagger$ values for the hydrolyses of *p*-methoxyphenyl dichloroacetate and 2,2-dichloropropionate in 2-butoxyethanol (2-BE)–water mixture at the ' magic ' mole fraction 0.98 of 2-BE–water solutions.[6,7] By assuming a constant heat capacity of activation for the above-mentioned reactions, the calculated values of $\Delta C_p^\ddagger$ were found by them to be $+937 \pm 213$ and $+1\,431 \pm 213$ J mol^{-1} K^{-1}, respectively. Recently, the results from the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in 2-BE–water mixtures at the mole fractions of water (x_w) close to 0.98 have revealed that in this aqueous binary the Arrhenius plots are S-shaped and $\Delta C_p^\ddagger$ highly temperature dependent so that $d\Delta C_p^\ddagger/dT$ at x_w 0.980 is $+38 \pm 2$ and $+67 \pm 5$ J mol^{-1} K^{-2} for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate, respectively.[8,9]

The aim of the present work was to study the behaviour of the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in different t-butyl alcohol (Bu^tOH)–water mixtures and to compare the results with the kinetic data of the same esters in methanol (MeOH)- and 2-BE–water solutions.[5,8,9] In accord with the hydrolyses of these esters in other aqueous binaries, the reactions are assumed to take place by a general base-catalysed ester hydrolysis, $B_{AC}3$.[2,5,8-10]

The structural properties of alcohol–water solutions have been reviewed by Franks and Ives [11] and more recent work confirms the earlier findings.[12-22] According to their thermodynamic properties, monohydric alcohol–water mixtures belong to a class of typically aqueous (TA) solutions. The important feature of TA solutions is the dominant role of the excess of entropy of mixing together with the positive excess of Gibbs free energy of mixing that are encountered in systems that separate into two liquid phases at a lower critical solution temperature (LCST). Simple alcohol–water systems do not show an LCST. Also Bu^tOH is known to dissolve in all proportions in water, but it seems that the phase separation into Bu^tOH-rich and water-rich phases may occur at higher temperatures so that a pseudo-LCST exists above the boiling temperature.[20] In 2-BE–water solutions the LCST varies from 341.55 to 322.98 K, when x_w moves from 0.983 37 to 0.967 08.[23]

Experimental

Methyl trifluoroacetate, a commercial product (E. Merck AG, zur Synthese), was redistilled before use. Chloromethyl dichloroacetate was prepared as described previously.[24] The solvent mixtures were prepared by diluting a known mass of distilled water with Bu^tOH (E. Merck AG, zur Analyse) 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 conductimetrically as described previously.[25] The concentrations of trifluoroacetic acid in the hydrolysis of methyl trifluoroacetate and that of hydrochloric and dichloroacetic acids in the hydrolysis of chloromethyl dichloroacetate were actually measured.[25] Using initial ester concentrations of 10^{-2}M in a gas-chromatographic product analysis, the possible alcoholysis products, t-butyl trifluoroacetate and dichloroacetate, could not be detected, although less than 1% concentration levels were detectable.

The rate constants were calculated by Guggenheim's method.[26] The standard deviations of the rate constants were, in general, <0.05% but were sometimes *ca.* 0.1%. The thermodynamic activation parameters were calculated from an extended Arrhenius equation (1) by the method of Clarke and

$$\ln k = A + B/T + C \ln T + DT + ET^2 + \ldots + \varepsilon \quad (1)$$

Glew [27] in its four-parameter form, although for the hydrolysis of methyl trifluoroacetate at x_w 0.963 and 0.938 even the fifth parameter was significant at least at a 95% level, $d^2\Delta C_p^\ddagger/dT^2$ being $+1.9 \pm 0.4$ and -2.2 ± 0.5 J mol^{-1} K^{-3} for the two mole fractions of water, respectively. However, taking into account the limited temperature range and available accuracy of the kinetic results it seems unjustifiable to use equation (1) in its five-parameter form in the two exceptional cases (Table 1).

Results and Discussion

Kinetic data for the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in Bu^tOH–water solutions at 298.15 K are given in Tables 1 and 2, respectively. As can be seen from the Tables, Bu^tOH lowers the rates of the hydrolyses considerably in the narrow concentration range

Table 1. Temperature range (T/K), number of data points (N), first-order rate constants (k/s^{-1}), activation enthalpies ($\Delta H^‡$/J mol^{-1}), activation entropies ($\Delta S^‡$/J mol^{-1} K^{-1}), and the heat capacities of activation ($\Delta C_p^‡$/J mol^{-1} K^{-1}) and their derivatives [(d$\Delta C_p^‡$/dT)/J mol^{-1} K^{-2}], calculated from equation (1) in its four-parameter form, for the neutral hydrolysis of methyl trifluoroacetate in Bu^{t}OH–water solutions with the mole fraction x_w of water at 298.15 K

x_w	T	N	10^3k	$\Delta H^‡$	$-\Delta S^‡$	$-\Delta C_p^‡$	d$\Delta C_p^‡$/dT
0.978	273—318	27	6.595	37 630 ± 130	160.5 ± 0.4	317 ± 10	+1 ± 2
0.963	273—321	23	5.292	33 890 ± 130	174.8 ± 0.4	414 ± 8	+5 ± 2
0.951	273—321	24	3.846	27 940 ± 110	197.4 ± 0.4	378 ± 6	+23 ± 1
0.938	273—321	27	2.477	26 210 ± 130	206.9 ± 0.4	127 ± 9	+20 ± 2
0.924	273—321	24	1.478	29 840 ± 180	199.0 ± 0.6	50 ± 12	+0 ± 3
0.872	273—316	17	0.476	38 410 ± 150	179.7 ± 0.5	274 ± 15	+9 ± 3

Table 2. Temperature range (T/K), number of data points (N), first-order rate constants (k/s^{-1}), activation enthalpies ($\Delta H^‡$/J mol^{-1}), activation entropies ($\Delta S^‡$/J mol^{-1} K^{-1}), and the heat capacities of activation ($\Delta C_p^‡$/J mol^{-1} K^{-1}) and their derivatives [(d$\Delta C_p^‡$/dT)/J mol^{-1} K^{-2}], calculated from equation (1) in its four-parameter form, for the neutral hydrolysis of chloromethyl dichloroacetate in Bu^{t}OH–water solutions with the mole fraction x_w of water at 298.15 K

x_w	T	N	10^3k	$\Delta H^‡$	$-\Delta S^‡$	$-\Delta C_p^‡$	d$\Delta C_p^‡$/dT
0.989	273—305	17	12.238	37 370 ± 140	156.2 ± 0.5	195 ± 40	+6 ± 4
0.973	273—313	18	9.118	34 590 ± 80	168.0 ± 0.3	235 ± 12	+4 ± 2
0.967	273—318	22	8.121	33 200 ± 120	173.6 ± 0.4	252 ± 9	+8 ± 2
0.962	273—320	21	7.176	32 050 ± 100	178.5 ± 0.3	213 ± 6	+11 ± 1
0.957	273—323	23	6.105	29 930 ± 140	186.9 ± 0.5	222 ± 8	+21 ± 2
0.949	273—323	21	4.588	28 790 ± 80	193.1 ± 0.3	53 ± 5	+20 ± 1

studied. The retarding effect is smaller than that found in 2-BE–water mixtures but much greater than in MeOH–water solutions for the same esters.[5,8,9] Further, at 298.15 K the activation enthalpy ($\Delta H^‡$) and activation entropy ($\Delta S^‡$) show almost compensatory changes and pass through extrema located at x_w *ca.* 0.938 for the hydrolysis of methyl trifluoroacetate, but in the case of chloromethyl dichloroacetate $\Delta H^‡$ and $\Delta S^‡$ decrease continuously under the reaction conditions used. In accord with the earlier results for the neutral ester hydrolyses in water-rich aqueous binaries the entropy of activation controls the kinetics.

The heat capacity of activation is the most sensitive indicator of solvent effects. Its values have been found to exhibit minima around the solvent composition of maximum hydrophobic hydration when an ionogenic reaction takes place in a TA solution.[2,12,13,28-30] These ' magic ' mole fractions of water have been found to be *ca.* 0.85, 0.96, and 0.98 for MeOH–, Bu^{t}OH–, and 2-BE–water solutions, respectively.[12,14,18] Thus, by assuming that the heat capacity of activation is independent of temperature, Robertson and Sugamori [31] have found a steep minimum of $\Delta C_p^‡$ for the solvolysis of t-butyl chloride in the Bu^{t}OH–water solution at x_w 0.95. The minima of $\Delta C_p^‡$ for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in Bu^{t}OH–water mixtures at 298 K occur at x_w 0.963 and 0.967, respectively (Tables 1 and 2). However, as can be seen from the Tables, not only $\Delta H^‡$ and $\Delta S^‡$ but also $\Delta C_p^‡$ depends considerably on temperature.

In Figures 1 and 2 the values of $\Delta C_p^‡$ are plotted *versus* x_w at three different temperatures for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in Bu^{t}OH–water solutions, respectively. As can be seen from the Figures, the minima of $\Delta C_p^‡$ at x_w *ca.* 0.95 at 278 K vanish with increasing temperature and at the same time the places of the minima move to more water-rich regions. At higher temperatures there are maxima in $\Delta C_p^‡$ in agreement with the results for the hydrolyses of the same esters in water-rich 2-BE solutions.[9] However, in Bu^{t}OH–water solutions the temperature dependence of $\Delta C_p^‡$ seems to be almost the same for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate. Thus the effect of the substrate on d$\Delta C_p^‡$/dT in Bu^{t}OH–water mixtures differs from that observed in 2-BE–water solutions, the highest values found for d$\Delta C_p^‡$/dT in Bu^{t}OH–water mixtures being +23 ± 1 (x_w 0.951) and +21 ± 2 (x_w 0.957) J mol^{-1} K^{-2} for the hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate, respect-

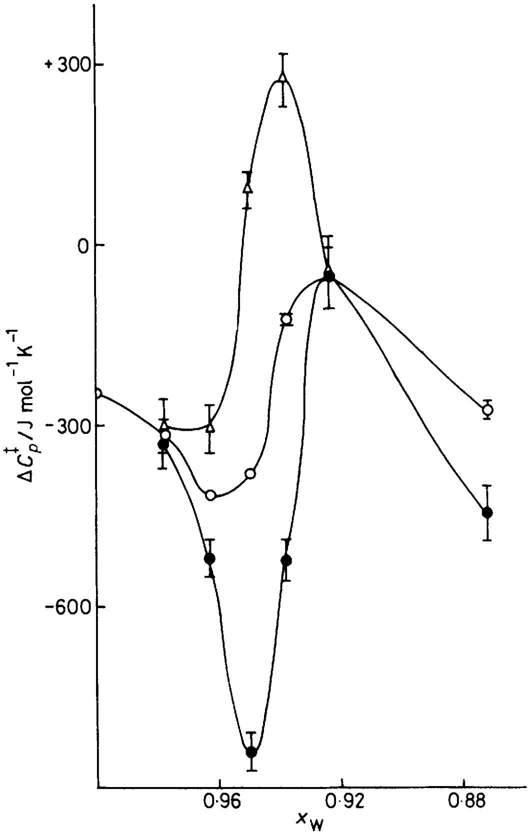

Figure 1. Plots of $\Delta C_p^‡$ *versus* x_w for the neutral hydrolysis of methyl trifluoroacetate in Bu^{t}OH–water solutions. T = 278 K, ●; 298 K, ○; 318 K, △

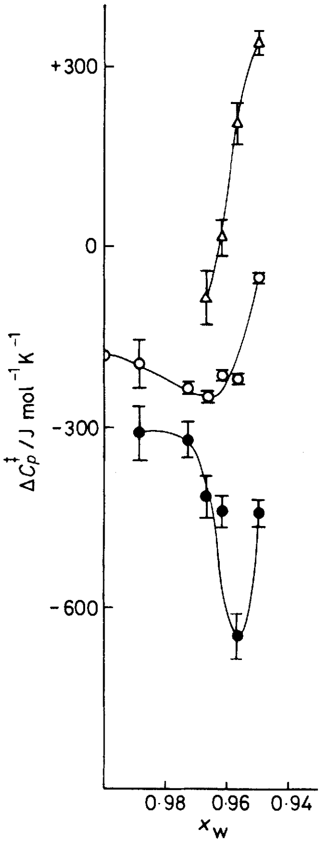

Figure 2. Plots of $\Delta C_p^{\ddagger}$ *versus* x_w for the neutral hydrolysis of chloromethyl dichloroacetate in Bu^tOH–water solutions. T = 278 K, ●; 298 K, ○; 318 K, △

ively, and in 2-BE–water mixtures +38 ± 2 (x_w 0.980) and +78 ± 4 (x_w 0.981) J mol^{-1} K^{-2} for methyl trifluoroacetate and chloromethyl dichloroacetate, respectively (*cf.* Tables 1 and 2; refs. 8 and 9). On the other hand, the solvent effects on $\Delta C_p^{\ddagger}$ and $d\Delta C_p^{\ddagger}/dT$ caused by Bu^tOH are much smaller than those caused by 2-BE for the hydrolyses studied. This is in agreement with the larger structural changes that take place in 2-BE–water solutions at x_w *ca.* 0.98 compared with those in Bu^tOH–water mixtures at x_w *ca* 0.95. For the same reactions in MeOH–water solutions the solvent effects on $\Delta C_p^{\ddagger}$ seem to be small and the values of $\Delta C_p^{\ddagger}$ independent of temperature, at least over the temperature range studied.[5]

In the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in Bu^tOH–water solutions studied, the temperature dependence of $\Delta C_p^{\ddagger}$ cannot be explained by the change in mechanism from $B_{AC}3$ to an S_N solvolysis with increasing temperature because this change in mechanism is impossible for the hydrolysis of methyl trifluoroacetate, but rather by the formation of ' moving units ' in the aqueous binary in question.[9,19–21] By Rayleigh light-scattering spectra it has been shown that for the very first increments of Bu^tOH in water, ' moving units ' of the form $(H_2O)_{20}(Bu^tOH)$, dispersed in water, are formed, which at x_w *ca.* 0.95 change into aggregates of the form $4[(H_2O)_{20}(Bu^tOH)]$, now dispersed in alcohol.[19–21] The above observations are in agreement with the results for the neutral hydrolyses of the same esters in 2-BE–water solutions explained by the ' moving units ' $(H_2O)_{50}$(2-BE), which change into the form $3[(H_2O)_{50}$(2-BE)] at x_w *ca.* 0.98.[9,21] Thus when the solvent system includes only units $(H_2O)_{20}(Bu^tOH)$ or $(H_2O)_{50}$(2-Be) in water, $\Delta C_p^{\ddagger}$ is negative and independent of temperature (Tables 1 and 2; ref. 9) in agreement with the general observations for most ionogenic solvolytic reactions in water and aqueous binaries.[1–5,12,13,28–31] However, when the transition into larger aggregates takes place the temperature dependence of $\Delta C_p^{\ddagger}$ can be observed.

For the hydrolyses of the present esters in 2-BE–water solutions at x_w *ca.* 0.98 it has been found that the Arrhenius plots are S-shaped and thus $\Delta C_p^{\ddagger}$ is negative at lower but positive at higher temperatures. In this case it has been assumed that the S-shaped Arrhenius plots and the positive values for $d\Delta C_p^{\ddagger}/dT$ can be explained by assuming that the substrate, incorporated into aggregates $3[(H_2O)_{50}$(2-BE)], is in a more ordered environment than outside the units.[9] Holterman[7] suggested that the positive values found for the neutral hydrolyses of *p*-methoxyphenyl dichloroacetate and 2,2-dichloropropionate in 2-BE–water solution at x_w 0.980 can be explained assuming that the substrate is preferentially dissolved in the co-solvent-rich microphase and thus the reaction rate is reduced when compared with that in the water-rich microphase. If the reaction rate follows first-order kinetics in both pseudo-phases, the rate constants being k_1 and k_2 in the water-rich and co-solvent-rich pseudo-phases, respectively, and if the partition coefficient (K) of the substrate S between the two pseudo-phases is $[S]_1/[S]_2$, equation (2) gives the rate constant observed.

$$k_{obs} = \frac{K k_1 + k_2}{K + 1} \qquad (2)$$

It can be shown, using Holterman's data, that the positive $\Delta C_p^{\ddagger}$ found in these reactions is mainly caused by the temperature dependence of K rather than some ' spurious ' terms. Thus in the case of the pseudo-phase separation model the values of $\Delta C_p^{\ddagger}$ and their derivatives are also genuine rate parameters of an ionogenic solvolytic reaction. It seems possible that the temperature dependence of $\Delta C_p^{\ddagger}$ found in the present hydrolyses in Bu^tOH- and 2-BE–water solutions can be explained by a pseudo-phase separation model, the two pseudo-phases representing the transition into aggregates of the form $4[(H_2O)_{20}(Bu^tOH)]$ and $3[(H_2O)_{50}$(2-BE)], respectively. However, it should be borne in mind that under the reaction conditions the solvent systems Bu^tOH- and 2-BE–water are homogeneous and all efforts to interpret the temperature dependence of $\Delta C_p^{\ddagger}$ by the aid of the temperature dependences of the individual rate constants and partition coefficients are very approximate, even at best.

It is clear that the present results for the neutral hydrolyses of methyl trifluoroacetate and chloromethyl dichloroacetate in Bu^tOH–water solutions demonstrate an extraordinary solvent effect on $\Delta C_p^{\ddagger}$. Further, the present results support the expectations of Visser *et al.*[16] that in Bu^tOH–water solutions at x_w *ca.* 0.95 there are structural changes that resemble a microphase separation. On the other hand, the solvent effects on $\Delta C_p^{\ddagger}$ and its temperature dependence in Bu^tOH–water solutions have been found to be smaller than in 2-BE–water mixtures, owing to the smaller hydrophobic interactions found in the former solvent system. In the case of MeOH–water mixtures the solvent effects on $\Delta C_p^{\ddagger}$ for the hydrolyses of the present esters are small, the values of $\Delta C_p^{\ddagger}$ being negative and independent of temperature.[5]

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