

# Kinetic Acidity of Carbon Acids in Water/Dimethyl Sulfoxide Mixtures. Part II. Activation Entropies of Proton Exchange Reactions for Different Carbon Acids

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The temperature dependence of the rate of detritiation for various carbon acids was measured in water/dimethyl sulfoxide mixtures. The activation entropies obtained show variation from highly negative to highly positive values. Differences in the dependence of activation entropy on the solvent composition were observed. The observations could be explained, in most cases, in terms of differences in solvation within a bimolecular rate-determining ionization. For haloforms, the observed values are consistent with a rate-limiting loss of labelled water from the solvation shell in a system undergoing internal return.

The sensitivity of the rate of proton transfer to solvent basicity of water/dimethyl sulfoxide mixtures has been shown to be very different for different carbon acids.<sup>1</sup> In our former study,<sup>2</sup> we suggested that the localization or delocalization of the negative charge in the intermediate carbanion was not necessarily the only factor responsible for the observed differences. They were explained in terms of differences in the ability of the activated complex to structure the solvent. For hydrocarbon acids producing either localized or delocalized anions, this ability is smaller than for the hydroxide ion, leading to a considerable rate acceleration by dimethyl sulfoxide in the solvent. When the negative charge in the carbanion is distributed between oxygen and carbon atoms, solvation of the activated complex, or the structuring effect of the latter on the solvent, can be expected to be comparable to that of the hydroxide ion. They cancel each other almost entirely, and consequently the accelerating effect of dimethyl sulfoxide remains negligible compared with that of hydrocarbon acids.

The factors leading to the sensitivity differences discussed above can also be expected to

lead to differences in the entropies of activation. Values for the activation entropy for proton transfer from carbon acids in water/dimethyl sulfoxide mixtures, required to make an extensive comparison, are not available in the literature. Margolin and Long<sup>3</sup> presented data for the detritiation of chloroform in solutions with  $x(\text{DMSO})$  between 0 and 0.236. The highly positive activation entropies showed a marked tendency to decrease with the mole fraction of dimethyl sulfoxide in the solvent. This is certainly not to be expected for the normal bimolecular abstraction of the proton from the carbon acid by a base.

Other structurally related solvent systems, viz. alcohol/dimethyl sulfoxide mixtures, have been used to determine the temperature dependence of proton transfer from carbon acids.<sup>4–8</sup> The activation entropies show great variation, changing from positive values for 9-phenylxanthene, triphenylmethane and diphenylmethane<sup>7,8</sup> to highly negative values for fluorenes,<sup>5,7,8</sup> indenenes,<sup>5,6</sup> and cyclopentadiene.<sup>6</sup> A change in the reaction mechanism with the acidity of the carbon acids has been suggested to be the reason for this variance.<sup>7</sup>

To obtain more information on the magnitude of activation entropies for proton transfer from carbon acids and their dependence on the solvent composition, measurements of the rate of detritiation of acetophenone-*t*, fluorene-*t*, triphenylmethane-*t*, bromoform-*t* and diphenylmethane-*t* in water/dimethyl sulfoxide mixtures were made at different temperatures.

### Experimental

The labelling of acetophenone and triphenylmethane had been performed previously,<sup>9</sup> and bromoform had been labelled in another context.<sup>10</sup> Fluorene and diphenylmethane were la-

belled in this work using the following procedure: The substrate (7 g) was dissolved in water/dimethyl sulfoxide mixture with  $x(\text{DMSO})$  of about 0.7 for fluorene and about 0.9 for diphenylmethane. Tetramethylammonium hydroxide ( $c = 0.01\text{--}0.05 \text{ mol dm}^{-3}$ ) was used as catalyst. The volume of the tritiated water added (The Radiochemical Centre, 1 Ci ml<sup>-1</sup>) was 20  $\mu\text{l}$ . The reaction mixture was stirred for about 20 h and the substrate was precipitated by addition of water. After filtration, the product was crystallized from ethanol. The liquid substrate, diphenylmethane, was purified by first washing with water, drying over calcium chloride and then distilling under reduced pressure. The activity of the

Table 1. Activation parameters for the detritiation of carbon acids in water/dimethyl sulfoxide mixtures at 298.15 K.

Substrate	$x(\text{DMSO})$	$H_{-}^a$	$\Delta S^{\ddagger}/\text{J K}^{-1} \text{ mol}^{-1}$	$\Delta H^{\ddagger}/\text{kJ mol}^{-1}$
Acetophenone	0.000	12.04	-73.9±5.4	63.8±1.7
	0.103	13.07	-71.2±7.0	62.1±2.1
	0.203	14.28	-75.0±0.6	58.2±0.2
	0.310	15.48	-73.3±4.7	55.6±1.4
	0.402	16.45	-75.0±2.9	52.5±0.8
	0.509	17.54	-67.8±1.3	51.8±0.4
Fluorene	0.205	14.30	-29.5±3.1	83.8±1.0
	0.308	15.45	-45.9±1.8	73.8±0.6
	0.400	16.43	-58.8±4.8	65.6±1.5
	0.504	17.48	-56.7±3.9	61.9±1.2
	0.602	18.51	-58.5±1.4	57.4±0.4
Triphenylmethane	0.701	19.52	-24.3±0.2	88.3±0.1
	0.750	20.03	-31.2±3.6	83.7±1.2
	0.794	20.51	-22.3±4.1	84.3±1.3
	0.848	21.19	-25.4±0.6	80.3±0.2
	0.900	21.97	-29.8±3.7	75.6±1.2
	0.928	22.53	-33.7±5.7	72.0±1.7
Diphenylmethane	0.899	21.95	-33.2±5.7	81.9±1.8
Bromoform	0.000	11.00	62.4±3.2	85.9±0.9
	0.079	11.68	51.5±4.6	78.2±1.3
Chloroform <sup>b</sup>	0.000	12.04	64.9	97.1
	0.027	12.29	61.5	94.2
	0.059	12.63	54.8	90.4
	0.090	12.94	54.0	88.2
	0.130	13.28	50.6	84.6
	0.171	13.87	43.5	79.5
	0.203	14.28	36.4	75.3
	0.236	14.66	23.8	69.1

<sup>a</sup>Ref. 14. <sup>b</sup>Calculated from the kinetic values of Ref. 3.

crystalline products varied from  $2 \cdot 10^5$  to  $7 \cdot 10^5$  cpm  $\text{mg}^{-1}$ , while that of diphenylmethane-*t* was 250 cpm  $\mu\text{l}^{-1}$ .

Dimethyl sulfoxide was purified by distillation over calcium hydride.<sup>11</sup>

The kinetic measurements were performed in water with  $0.1 \text{ mol dm}^{-3}$  NaOH and in water/dimethyl sulfoxide mixtures with  $0.011 \text{ mol dm}^{-3}$  tetramethylammonium hydroxide as catalyst. When the detritiation of bromoform was studied, the hydroxide ion concentration in the solvent was  $0.001 \text{ mol dm}^{-3}$ .

Kinetic measurements with acetophenone and fluorene were performed at three temperatures between 278 K and 318 K. The mole fraction of dimethyl sulfoxide was between 0 and 0.65. The detritiation of triphenylmethane and diphenylmethane was too slow to be easily studied under these conditions. The measurements were performed in solutions with  $x(\text{DMSO})$  higher than 0.7 and at temperatures between 298 K and 338 K for triphenylmethane, and in one solvent mixture only [ $x(\text{DMSO}) = 0.9$ ] at three temperatures between 308 K and 328 K for diphenylmethane. The detritiation of bromoform was too fast to be followed in solutions more basic than water and

water/dimethyl sulfoxide mixture with  $x(\text{DMSO}) = 0.08$  at temperatures between 278 K and 298 K.

The methods employed for kinetic measurements have been described earlier.<sup>12</sup> The rate coefficients for detritiation reactions were calculated from the measured activity of the organic layer by plotting  $\ln[(A_0 - A_\infty)/(A_t - A_\infty)]$  vs.  $t$  and using the method of least squares. The standard error of the slope of this plot was generally less than 1%.

## Results and discussion

The logarithms of the measured second-order rate coefficients exhibit linear correlation with the reciprocal temperature within the limits of experimental error. The activation parameters given in Table 1 were calculated from these relationships.

The activation entropies for the detritiation of acetophenone are highly negative ( $-60$  to  $-70 \text{ J K}^{-1} \text{ mol}^{-1}$ ) and almost independent of the solvent composition (Fig. 1). These values provide evidence of an increase in order on going from the initial state to the transition state of the

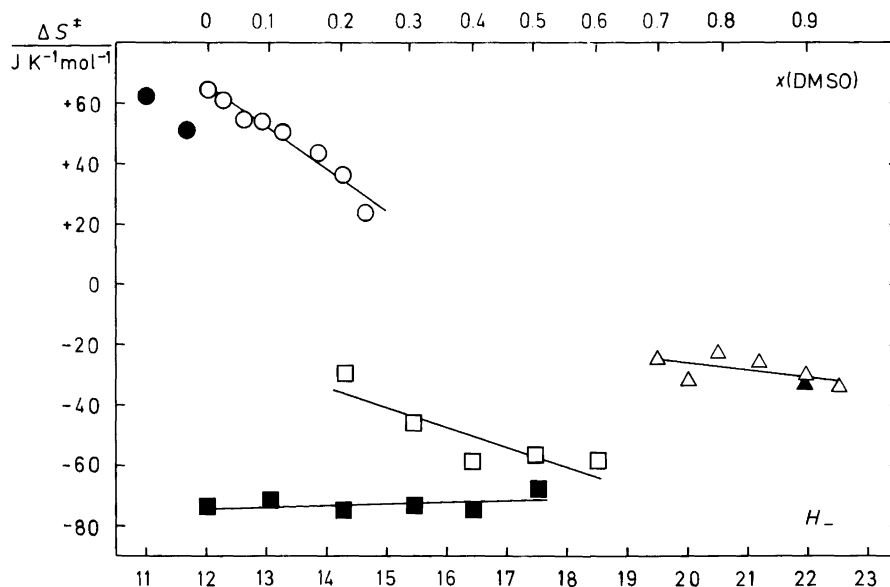
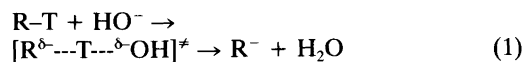


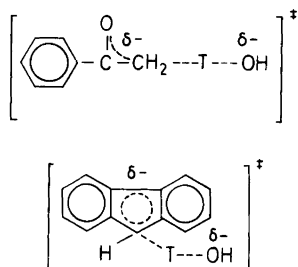
Fig. 1. Activation entropies at 298.15 K for the detritiation of different carbon acids in water/dimethyl sulfoxide mixtures. Notations: chloroform (○), bromoform (●), fluorene (□), acetophenone (■), triphenylmethane (△) and diphenylmethane (▲). The data points for bromoform refer to the  $H$ -scale only. Corresponding mole fractions of DMSO are 0.000 and 0.079.

reaction. This is in accordance with a bimolecular mechanism<sup>13</sup> in which the proton is transferred from the carbon acid to the hydroxide ion in the rate-determining step of reaction (1).



The activation entropies for the detritiation of fluorene, diphenylmethane and triphenylmethane are somewhat less negative than for acetophenone, and they show a slight tendency to decrease with increasing DMSO content of the solvent (Fig. 1).

In our previous paper,<sup>2</sup> we suggested that differences in the type of charge delocalization in the carbanion are reflected in the sensitivity of the rate of proton transfer to solvent basicity. The kinetic data obtained in this work give additional evidence for this assumption. The plots of  $\log(k/s^{-1})$  vs.  $H_-$  give slopes of 0.74 and 0.69 for fluorene and diphenylmethane, respectively. These are of the same magnitude as that for triphenylmethane. All these carbon acids produce carbanions with negative charge delocalized in the hydrocarbon system only. They exhibit similarities both in their activation entropies and in their sensitivity to solvent basicity. The same factors, i.e. differences in the solvation of the activated complex, may be assumed to be operative in both cases.



Scheme 1.

The structures of the transition states for the detritiation by hydroxide ion of acetophenone and fluorene corresponding to rate-determining ionization are presented in Scheme 1. Comparison of the two structures shows that when tritium is abstracted from acetophenone, the negative charge transferred from the hydroxide ion becomes distributed partly to the carbonyl oxygen

atom, whereas in the reaction of fluorene, the negative charge of the developing anion resides wholly in the aromatic hydrocarbon system. On going from the initial state to the transition state of the former reaction, only small changes in solvation are expected, since most of the negative charge stays on an oxygen atom, either hydroxy or carbonyl oxygen. In the latter reaction, the change in the nature of negative charge distribution brings about a change in solvation. The ability of the transition state to structure the solvent is lower than that of the initial state. The increase in order associated with the bimolecularity of the reaction will be reduced by the lower order in the solvation of the activated complex. Consequently, less negative entropies for the detritiation of fluorene than for that of acetophenone may be explained in terms of solvation effects within the same bimolecular reaction mechanism.

For the detritiation of triphenylmethane and diphenylmethane, activation entropies are slightly higher than those of fluorene. This may be a consequence of the differences in the  $pK_a$ -values of these carbon acids: fluorene 22.1, triphenylmethane 31.5 and diphenylmethane 33.0.<sup>15</sup> According to the Hammond principle,<sup>16</sup> the lower acidity of triphenylmethane and diphenylmethane leads to a more carbanion-like transition state for rate-determining ionization. Therefore, even less negative charge is left on the oxygen atom of the hydroxide ion moiety and there is less order in solvation of the activated complex compared to that of fluorene. Less negative activation entropies are to be expected.

Changes in solvation may be used to explain the slight decrease in activation entropies observed for the detritiation of carbon acids producing carbanions with negative charge delocalized to the hydrocarbon system, when the DMSO content in the solvent is increased. In the initial state, the hydroxide ion becomes less solvated when water in the solvent is replaced by DMSO. The difference in the structuring effect on the solvent between initial and transition states becomes smaller with increases in the DMSO content. The effect leading to higher activation entropies for the reaction of these acids than of acetophenone gradually diminishes.

The activation entropies for the detritiation of chloroform and bromoform (Table 1) deviate drastically from those of other carbon acids. They are highly positive and show a marked tendency

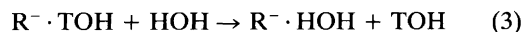
to decrease with increasing DMSO content of the solvent, although a rather narrow range of solvent basicity has been used in the measurements.

The acidic behaviour of chloroform, different from that of other carbon acids, has been discussed earlier.<sup>3,17</sup> In the isotope exchange reaction, the proton from chloroform is fully transferred to hydroxide ion in the transition state. The transition state for the reaction of haloforms is less solvated than transition states for the other reactions discussed here. The decrease in order attending the desolvation of the hydroxide ion will be greater, and the activation entropy higher than for other acids. When DMSO is added to the solvent the solvation of the hydroxide ion decreases, and the effect of desolvation on the change in order will become smaller and the activation entropy will decrease. This is not necessarily a fully satisfactory explanation for the observed behaviour of the activation entropy.

Another interpretation of the observed behaviour arises when the three-step mechanism for the detritiation reaction is considered.<sup>18</sup> The first step, ionization of the C-T bond (2), is proposed to be rate-determining for carbon acids producing delocalized carbanions. The reactions are bi-



molecular and are characterized by highly negative activation entropies. For carbon acids which produce localized carbanions, the system may be proposed to undergo internal return. The second step, solvent replacement (3), where the labelled solvating water molecule is replaced with ordinary water, becomes rate-limiting. The thus formed intermediate collapses in the third step (4).



Haloforms produce carbanions in which the basic electron pairs presumably are localized on single carbon atoms. In their detritiation reactions, proton transfer is rapid and reversible.<sup>17</sup> The solvent replacement step in the proposed form would be bimolecular in nature, and association of this step with highly positive activation entropies is unexpected.

The solvent replacement stage may be repre-



sented by two separate steps, (5) and (6). The first of these is loss of the labelled water molecule from the solvation shell, producing the carbanion intermediate more or less solvated by ordinary water molecules. This step is unimolecular. The positive activation entropies obtained for the detritiation of chloroform and bromoform refer to this kind of unimolecular rate-limiting step.

The decrease in the activation entropies for the detritiation of haloforms on increasing the DMSO content of the solvent may be explained by decrease of the extent of internal return. The Gibbs energy profile for a system undergoing internal return is presented in Fig. 2. The Gibbs energy of activation for reversal of the proton transfer-step,  $\Delta G_{-1}^\ddagger$ , is lower than that for the solvent reorganization step,  $\Delta G_2^\ddagger$ . The transition state (TS)<sub>1</sub> is more hydroxide ion-like than (TS)<sub>2</sub>. Increase in the DMSO content of the solvent will lower the Gibbs energy of activation corresponding to the former,  $\Delta G_1^\ddagger$ , less than that of the latter,  $\Delta G_{\text{obs}}^\ddagger$ . This assumption is based on the observed sensitivity of the rate of proton transfer to solvent basicity.<sup>2</sup> Thus internal return becomes less favourable the greater the DMSO content of the solvent. The decrease in the activation entropies is to be expected.

Although the differences in the entropies of activation can be explained in terms of these factors which lead to differences in the sensitivity of the rate of proton exchange to solvent basicity,

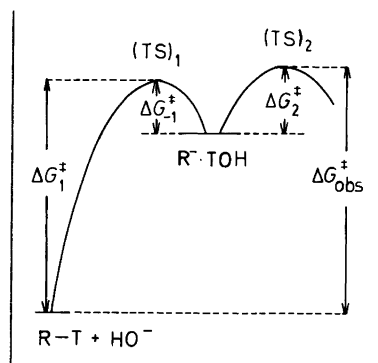


Fig. 2. Free energy profile for a system undergoing internal return.

the accelerating effect itself is not due to a favourable change in the activation entropy. The  $\Delta S^\ddagger$ -values are either independent of  $x(\text{DMSO})$  or decrease when the DMSO content of the solvent is increased. This, however, increases the Gibbs energy of activation, i.e. the effect is rate-retarding. The change in the activation enthalpy term brings about the increase in the rate of detritiation with  $x(\text{DMSO})$ . These changes vary for different carbon acids (Table 1) and can be explained by differing changes in solvation on going from initial to transition state.

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