Kinetic Acidity of Carbon Acids: The Hydroxide Ion-catalysed Ionization of Chloroform and Acetophenone in Aqueous Hexamethylphosphoric Triamide

Markku Lahti,* Alpo Kankaanperä* and Pasi Virtanen
Department of Chemistry, University of Turku, SF-20500 Turku, Finland

The rate coefficients for the detritiation of [^{3}H]chloroform and [^{3}H]acetophenone have been measured in aqueous hexamethylphosphoric triamide (HMPTA). The rate acceleration, caused by the HMPTA in the solvent is higher in the reaction of chloroform than in that of acetophenone. The difference is even greater than that observed earlier in a less basic solvent system, aqueous dimethyl sulfoxide (DMSO). The activation entropy for the detritiation of chloroform decreases sharply from the highly positive value in pure water to negative values at mole fractions of HMPTA higher than 0.1. The observed effects may be explained in terms of changes in solvation on going from the initial to the transition state. The change in the activation entropy in the reaction of chloroform is taken to indicate a decrease in the extent of internal return.

The rate of detritiation of [^{3}H]chloroform is more sensitive to solvent basicity in aqueous dimethyl sulfoxide (DMSO) mixtures than that of other carbon acids *e.g.* acetophenone.[1,2] The activation entropies reported for the reaction of chloroform[2] are much higher than for the other carbon acids[3] and, being highly positive, refer to a different molecularity in the rate-limiting step.[4]

Initial and transition state enthalpies of transfer from water to aqueous dimethyl sulfoxide mixtures in the hydroxide ion-catalysed ionization of chloroform[5] and acetophenone[6] have been determined from the enthalpies of solution and activation. The transition state enthalpies of transfer for the two reactions change quite differently when DMSO content in the solvent is increased. The values for acetophenone are very close to those presented for the hydroxide ion.[7,8] The low sensitivity of the rate of detritiation of [^{3}H]acetophenone to solvent basicity may be regarded as due to the strong desolvation of both the activated complex and the hydroxide ion.

To gain new insights into the factors leading to the differences in both sensitivity and entropies of activation for different carbon acids in highly basic solvents, kinetic measurements were performed in aqueous hexamethylphosphoric triamide (HMPTA), a solvent which has higher ability than DMSO to increase the basicity of the system at a given mole fraction.[9]

Experimental

Materials.—Tritium labelling of chloroform and acetophenone has been described earlier.[10]

Hexamethylphosphoric triamide (Aldrich-Chemie, 99%) was purified, after standing overnight over calcium hydride, by fractional distillation over calcium hydride under a nitrogen atmosphere. The fraction collected had the boiling point 86.5 °C at 3.5 torr.[11] Mixtures of this and water were prepared by weight. Tetramethylammonium hydroxide was used as catalyst with concentration 0.011 mol dm^{-3}.

Kinetics.—Accurate 1 cm^3 aliquots of reaction mixture were withdrawn at suitable time intervals using Macro-Transferpettor (Rudolf Brand GmbH + Co) equipped with a precision plastic tip made of polypropylene and a plunger of polyethylene. These were run into stoppered cylinders containing accurate 10 cm^3 of cyclohexane and 5 cm^3 of 0.1 mol dm^{-3} hydrochloric acid to neutralize the base. The cylinders and their contents were shaken for 1 min, and the layers were allowed to separate. Accurate 5 cm^3 samples of cyclohexane layers were taken and combined with 10 cm^3 of toluene-based scintillation counting solution [5 g of 2,5-diphenyloxazole and 1 g of *p*-bis(*o*-methylstyryl)benzene per 1 dm^3], and subjected to liquid scintillation counting (LKB-Wallac 8100).

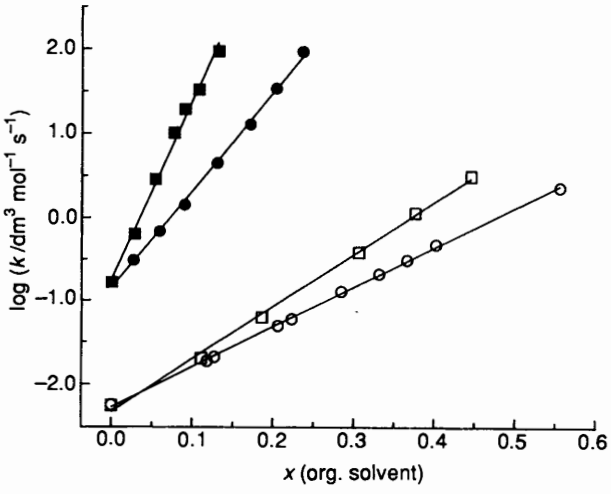

Fig. 1 Sensitivity of the rate of detritiation of [^{3}H]chloroform (filled symbols) and [^{3}H]acetophenone (open symbols) to dipolar aprotic solvent in aqueous HMPTA (■,□) and DMSO (●,○)

First-order rate constants were calculated as slopes of plots of $\ln[(C_0 - C_\infty)/(C_t - C_\infty)]$ as a function of time (C = counts per minute). Second-order rate constants were obtained by dividing by the hydroxide ion concentration (0.011 mol dm^{-3}).

Results and Discussion

The rate coefficients for the detritiation of [^{3}H]chloroform and [^{3}H]acetophenone were measured in aqueous HMPTA at four different temperatures with 10 K intervals. The temperature range used in the measurements varied according to the rate of the reaction from 243 K with chloroform in high HMPTA content to 318 K with acetophenone in low HMPTA content. From these measurements the activation parameters and the second-order rate constant at 298.15 K were calculated. The results are presented in Table 1.

The sensitivity of the rate of detritiation to the solvent composition may be described by the slope of the plot of $\log(k/\text{dm}^3\ \text{mol}^{-1}\ \text{s}^{-1})$ *vs.* mole fraction of the dipolar aprotic solvent (Fig. 1). In the studied system, aqueous HMPTA, these

Table 1 Activation parameters for the detritiation of chloroform and acetophenone in aqueous hexamethylphosphoric triamide mixtures at 298.15 K

Carbon acid	x(HMPTA)	$\Delta S^{\ddagger}$/J K^{-1} mol^{-1}	$\Delta H^{\ddagger}$/kJ mol^{-1}	k(calc)/dm^3 mol^{-1} s^{-1}
Chloroform	0.028 2	61.3(80)	92.4(23)	0.634(5)
	0.053 6	39.4(39)	82.2(11)	2.85(13)
	0.076 9	21.4(43)	73.7(11)	10.1(4)
	0.090 1	19.1(45)	71.4(12)	19.0(9)
	0.107	−8.6(50)	61.8(13)	32.5(17)
	0.131 5	−13.4(56)	57.8(9)	92.4(24)
	0[a]	64.9	97.1	0.165
Acetophenone	0.111	−77.9(8)	59.5(2)	0.020 1(2)
	0.186	−74.8(40)	57.6(12)	0.062 3(23)
	0.306	−71.0(20)	54.3(6)	0.378(7)
	0.376	−62.0(37)	54.3(10)	1.12(4)
	0.445	−71.4(15)	49.0(4)	3.05(5)
	0[b]	−73.9	63.8	0.005 65

[a] Ref. 2. [b] Ref. 3.

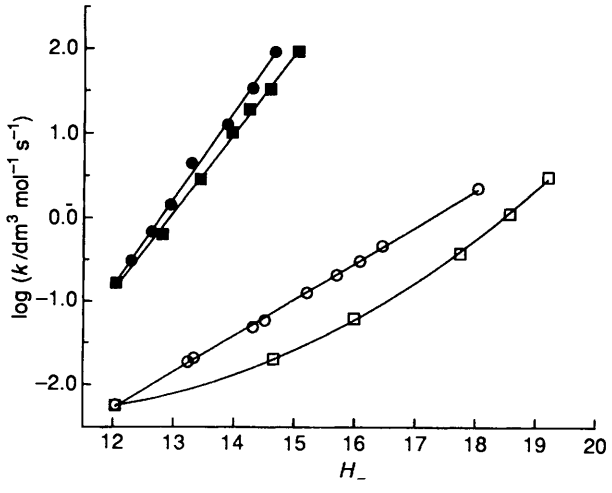

Fig. 2 Rate–acidity function correlations for the detritiation of [^{3}H]chloroform (filled symbols) and [^{3}H]acetophenone (open symbols) in aqueous HMPTA (■,□) and DMSO (●,○)

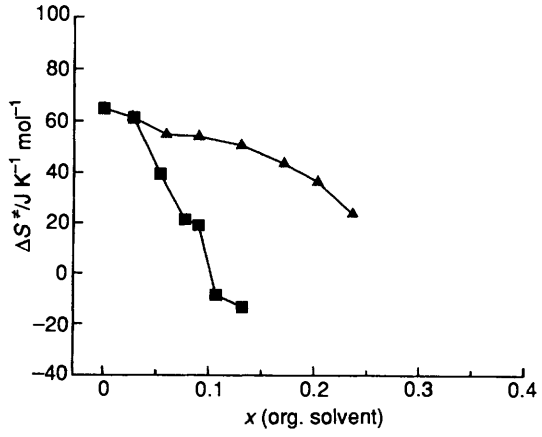

Fig. 3 Activation entropies for the detritiation of [^{3}H]chloroform in aqueous HMPTA (■) and DMSO (▲)

slopes are 21.3 and 6.25 for chloroform and acetophenone, respectively. These are considerably higher than the corresponding slopes in aqueous DMSO, 11.6[2] and 4.76.[1] Firstly, the results confirm that aqueous HMPTA is a more basic solvent system than DMSO. Secondly, the comparison shows that the sensitivity of the rate of detritiation of [^{3}H]chloroform to the content of dipolar aprotic solvent in the studied system is higher than that of [^{3}H]acetophenone, and that the difference is further enhanced in the more basic solvent system.

The acidity function H_- for aqueous HMPTA containing 0.011 mol dm^{-3} TMAH has been constructed for mixtures where mole fraction of dipolar aprotic solvent varied between 0.1339 and 0.5424.[9] Using the fourth degree curve-fit of these values and the H_- value for pure water, 12.04, interpolated values were obtained for the mixtures used in the measurements.

For chloroform (Fig. 2), the rate–acidity function correlation gives a good linear relation with a slope of 0.93 and correlation coefficient 0.998. The slope of the correlation in aqueous DMSO is 1.04 using H_- values available in literature.[12]

When the rate of detritiation of acetophenone is used for comparison of the two solvent systems, different behaviour is observed (Fig. 2). In aqueous DMSO, the correlation gives very good linear relation with a slope of 0.43. For aqueous HMPTA a slightly upward concave plot below the linear plot for DMSO is obtained, indicating that the accelerating effect of HMPTA on the rate of detritiation of acetophenone is less than expected from the value of H_- acidity function.

The thermodynamic parameters for the detritiation of chloroform and acetophenone are presented in Table 1. They show that the increase in the rate with the HMPTA content of the solvent is brought about by the change in activation enthalpy. The change in the activation entropy is rate-retarding for chloroform. For the detritiation of acetophenone, activation entropy remains highly negative up to a mole fraction of HMPTA of 0.445. The behaviour is similar to that observed in aqueous DMSO solvents.[3] For the detritiation of chloroform, the activation entropy has been shown to decrease rapidly with the mole fraction of DMSO.[2] In aqueous HMPTA, the activation entropy decreases even more rapidly, from 65 J K^{-1} mol^{-1} in pure water to slightly negative values at a mole fraction of HMPTA of 0.1 (Fig. 3).

The differences, both in the sensitivity of the rate to added dipolar aprotic solvent and in the change of the activation entropy, when the two dipolar aprotic solvents are compared, may be explained in terms of changes in the solvation of hydroxide ion on going from the initial to the transition state. When changing to more basic solvent systems, the hydroxide ion becomes less solvated. If the corresponding change in solvation of the activated complex is less, as in the detritiation of chloroform,[5] less desolvation takes place in the reaction and the rate of the reaction increases strongly. If the changes in solvation of hydroxide ion and activated complex are comparable, as in the detritiation of acetophenone,[6] less increase in the rate is expected. Strong desolvation decreases the order in the system on going from the initial to the transition state and may be expected to lead to positive activation entropies, as in the detritiation of chloroform in water. When

dipolar aprotic solvent is added, the effect of desolvation on the change in order will become smaller and the activation entropy will decrease. According to this interpretation, when changing the solvent from aqueous DMSO to the more basic aqueous HMPTA, both the rate increase and the decrease in activation entropy with the mole fraction of dipolar aprotic solvent should be more notable in the detritiation of chloroform.

Additional explanation for the observed behaviour of the activation entropy is obtained when the multistep mechanism of the detritiation reaction is considered.[13] The first step, ionization of the C–T bond [eqn. (1)] is bimolecular and it is

$$R\text{–}T + HO^- \longrightarrow R^-\cdot TOH \qquad (1)$$

proposed to be rate determining for carbon acids producing delocalized carbanions. This explains the highly negative activation entropies for the detritiation of [^{3}H]acetophenone.

The conjugate base of chloroform is a carbanion in which the basic electron pair is located on a single carbon atom, and in the detritiation reaction, proton transfer is presented to be rapid and reversible.[14] The system undergoes internal return and the second step, loss of the labelled water molecule from the solvation shell [eqn. (2)], becomes rate-limiting. This step is

$$R^-\cdot TOH \longrightarrow R^- + TOH \qquad (2)$$

unimolecular and the reaction will be characterized by positive activation entropies.

Addition of dipolar aprotic solvent to the aqueous system will have different effects on the rates of the two steps. The transition state of the first step is more hydroxide ion-like than that of the second step. Stabilization of the hydroxide ion by solvation will be decreased when dipolar aprotic solvent is added to the aqueous solution. Similar destabilization will take place to a greater extent in the transition state of the first step than in that of the second step. Internal return will become less favourable and the bimolecular ionization [eqn. (1)] partly rate determining. This change could explain the decrease in the activation entropy in the detritiation of chloroform with the content of dipolar aprotic solvent.

When the ability of the dipolar aprotic solvent to increase the basicity of the system becomes higher, the difference in the sensitivities of the rate to the solvent composition is enhanced between acetophenone and chloroform (Fig. 1). This indicates that destabilization of the former transition state compared to the latter becomes stronger. The rates of the two steps are affected similarly and internal return becomes even less favourable in aqueous HMPTA than in DMSO.

The assumption that internal return becomes less favourable in basic solvent systems, gets some support from the rate–acidity function correlations for the ionization of chloroform in HMPTA and DMSO (Fig. 2). The slightly smaller slope for HMPTA might indicate a decrease in the extent of internal return.

In the detritiation of acetophenone, where ionization is rate determining, the accelerating effect, lower than expected from the values of H_- acidity function, can be explained by a more hydroxide ion-like transition state in the more basic solvent system. This is possible when triton transfer to the hydroxide ion is less advanced in the transition state.

References

1 A. Kankaanperä, M. Lahti and P. Scharlin, *Acta Chem. Scand., Ser. A*, 1986, **40**, 387.
2 Z. Margolin and F. A. Long, *J. Am. Chem. Soc.*, 1973, **95**, 2757.
3 M. Lahti, T. Kallio, M. Luukkonen, P. Scharlin and A. Kankaanperä, *Acta Chem. Scand., Ser. A*, 1987, **41**, 447.
4 L. L. Schaleger and F. A. Long, in *Advances in Physical Organic Chemistry*, ed. V. Gold, Academic Press, London, 1963, p. 1.
5 J. R. Jones and R. Fuchs, *Can. J. Chem.*, 1977, **55**, 99.
6 M. Lahti, A. Kankaanperä and H. Säpyskä, *J. Chem. Soc., Perkin Trans. 2*, 1990, 1081.
7 R. Fuchs and C. P. Hagan, *J. Phys. Chem.*, 1973, **77**, 1797.
8 R. Fuchs, C. P. Hagan and R. F. Rodewald, *J. Phys. Chem.*, 1974, **78**, 1509.
9 K. Bowden and S. Prasannan, *J. Chem. Soc., Perkin Trans. 2*, 1987, 185.
10 A. Kankaanperä, L. Oinonen and P. Salomaa, *Acta Chem. Scand., Ser. A*, 1977, **31**, 551.
11 T. Fujinaga, K. Izutsu and S. Sakura, in *Recommended Methods for Purification of Solvents and Tests for Impurities*, ed. J. F. Coetzee, Pergamon Press, Exeter, 1982, p. 38.
12 R. A. Cox and R. Stewart, *J. Am. Chem. Soc.*, 1976, **98**, 488; D. Dolman and R. Stewart, *Can. J. Chem.*, 1967, **45**, 911.
13 A. J. Kresge and M. F. Powell, *Int. J. Chem. Kinet.*, 1982, **14**, 19.
14 A. C. Lin, Y. Chiang, D. B. Dahlberg and A. J. Kresge, *J. Am. Chem. Soc.*, 1983, **105**, 5380.

Paper 3/01349I
Received 8*th March* 1993
Accepted 2*nd April* 1993