

Kinetic Solvent Isotope Effect in the Hydrolysis of Sulphonic Anhydrides

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The hydrolysis of *m*-nitro-, *p*-bromo- and *p*-methyl benzene sulphonic anhydride was studied kinetically in aqueous dioxan and aqueous acetone at room temperature. Rate constants in mixtures containing light water or heavy water were determined in the solvent composition range from 6 to 76 vol. % water. The variation of hydrolysis rate with solvent composition suggests that the hydrolysis follows an S_N2 mechanism, except for toluene sulphonic anhydride at higher water contents, where the hydrolysis appears to follow an S_N1-like mechanism. There is no significant change in the kinetic solvent isotope effect with substrate, solvent and solvent composition. These findings are compared with data from the literature.

In a previous paper studies on the hydrolysis of various sulphonic anhydrides in mixed dioxan-water and acetone-water solvents were reported.¹ On the evidence of substituent effects and salt effects it was concluded that the hydrolysis followed an S_N2-mechanism in 30 vol. % water in acetone. With other solvent compositions the measurements were less accurate due to heat of mixing, but the results indicated that the same mechanism operated in mixtures ranging from 10 vol. % water to 50 vol. % water in acetone.

The work reported in the present paper was undertaken to obtain more data for varying solvent composition. Furthermore, it was found of interest to investigate the hydrolysis in solvents containing heavy water.

EXPERIMENTAL

Materials. Acetone was fractionated over KMnO₄, dried over Drierite and distilled. Dioxan, *p*-toluenesulphonic anhydride, *p*-bromobenzenesulphonic anhydride, and *m*-nitrobenzene sulphonic anhydride were prepared as previously described.¹ Water was distilled twice, having a specific conductance of $\leq 1 \mu\text{mho}\cdot\text{cm}^{-1}$. Deuterium oxide was distilled until the specific conductance was less than $2 \mu\text{mho}\cdot\text{cm}^{-1}$. It was obtained

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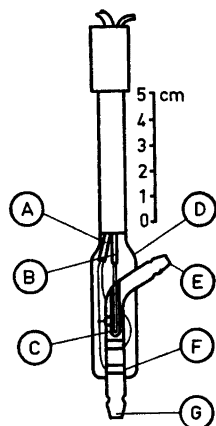


Fig. 1. Flow conductivity cell. A: cable to conductivity meter. B: cable to Wheatstone bridge for temperature recording. C: 100 kohm thermistor. D: protective glass-cap. E: outlet of flow. F: platinum ring. G: inlet of flow.

commercially from Stuart Oxygen Co. or from steel-drums, not previously opened, from reactor DR3. Its isotopic purity by measurements of density was found to be $> 99.5\%$.

Apparatus and measurements. The stopped-flow apparatus described previously¹ was used with slight modifications. In order to avoid heat of mixing, most runs in the previous investigations were restricted to 30.6 vol.% water in acetone and 35.3 vol.% water in dioxan. In the present investigation hydrolysis at other compositions was studied and heat effects could not be avoided. The conductivity cell used in these experiments was a flow cell (Radiometer, Copenhagen, type CDC 114/sp, cell constant 0.62 cm), in which a 100 kohm thermistor cell had been mounted, *cf.* Fig. 1, so that the temperature of the interior of the conductivity cell could be recorded. During rate-measurements only the reservoirs were immersed in the thermostat, the temperature of which was regulated so that the temperature of the reaction mixture was close to room temperature. By this procedure variations in temperature during the kinetic runs were reduced to $\pm 0.06^\circ$, for rate constants $> 0.03 \text{ sec}^{-1}$, and $\pm 0.12^\circ$ for rate constants $0.01 - 0.03 \text{ sec}^{-1}$. In addition to the twin syringe consisting of two coupled 5 ml syringes, a double syringe consisting of a 25 ml syringe coupled to a 5 ml syringe was used in these experiments. In this way the percentage of water in the reaction mixture could be increased to 75.8 vol.%.

Due to the relatively slow response of the recorder, hydrolysis rates larger than 1.5 sec^{-1} cannot be accurately measured.¹ With rates slower than 0.01 sec^{-1} diffusion from the mixing chamber and the poor temperature control will complicate the measurements. With higher water contents the very low solubility of the sulphonic anhydrides in water is another complication. In water-dioxan mixtures with a water content less than 10 vol.% the conductivity is seriously reduced. It has not been possible to perform satisfactory measurements with *m*-nitrobenzenesulphonic anhydride in acetone, because the solution of this anhydride in acetone decomposes within 5–15 min. Solutions of this substrate in dioxan are more stable. Solutions of bromobenzene sulphonic anhydride in acetone are unstable when stored for more than 1 h. Extra drying of the acetone has not improved the stability of the solution. It is possible that an impurity in the acetone or the acetone itself reacts with these reactive compounds. In spite of these restrictions it was possible to cover a broad range of solvent composition.

Analysis of recorded curves. The methods of reading the recorded curves and of calculating of the first-order rate-constant have been given previously.¹ In the present investigation it was necessary to make a calibration plot for each particular solvent mixture, relating recorder reading to acid concentration. Within experimental accuracy these plots could be represented by quadratic expressions. It was assumed that a calibration plot for a mixture of light water and dioxan (or acetone) would be applicable to rate data for dioxan (or acetone) containing the same volume percentage of heavy water. This assumption is partly justified by the fact that specific conductivities of salts follow

parallel trends in the two waters (Swain and Evans²). The assumption was confirmed experimentally for 20 vol.% H₂O in dioxan and 20 vol.% D₂O in dioxan. Calibration plots relating recorder reading to acid concentration in these two solvents showed an isotope effect on the equivalent conductance, $\Delta_{\text{H}_2\text{O}}/\Delta_{\text{D}_2\text{O}}$, of 1.20. However, the curvatures of the two plots were identical, and the rate constants found by applying the two calibration plots to one and the same run (in 20 vol.% H₂O in dioxan) were identical within experimental accuracy.

The rate constants were calculated on a GIER-computer by the method of least squares. Rate constants of repeated runs were reproducible within an accuracy of $\pm 3\%$ relative. The average values of rate constants for replicate runs related to different temperatures between 21°C and 25°C; they were therefore reduced to a common temperature applying the Arrhenius energy found in the previous investigation.¹

RESULTS

Reaction-rates in H₂O-mixtures. The rate data for 22.5°C are presented in Fig. 2, where the logarithm of the rate constant is plotted against the ionising power of the medium, Y , as defined by Grunwald and Winstein.³

The slopes of the plots give some information on the hydrolytic mechanism. The ionising power of the medium is defined so that the slope, $m = \Delta \log k / \Delta Y$, becomes equal to unity, when the substrate is *t*-butyl chloride, which is hydrolysed by an S_N1-reaction in aqueous acetone and dioxan. m -Values in the vicinity of one are therefore generally considered to signify an S_N1-reaction, while lower m -values signify increasing S_N2 character; cf. Wiberg.⁴

In the previous investigation¹ it was found that *p*-bromobenzene sulphonic anhydride is hydrolysed by an S_N2 mechanism in 30 vol.% water in acetone (corresponding to $Y = 0.13$). From the slopes of the plots in Fig. 2 it follows that *m*-nitrobenzene sulphonic anhydride and *p*-bromobenzene sulphonic anhydride are hydrolysed by the S_N2 mechanism throughout the composition range in which they have been investigated. There is evidence, however, that *p*-toluene sulphonic anhydride is hydrolysed by a more S_N1-like mecha-

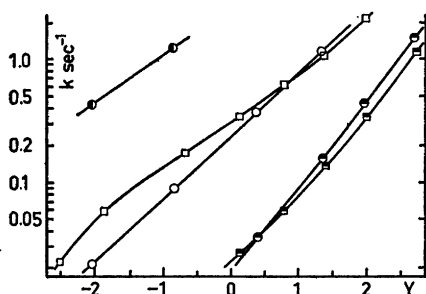


Fig. 2. Rate data for the hydrolysis of *m*-nitro-, *p*-bromo-, and *p*-methyl-benzene sulphonic anhydride at 22.5° in dependence of the Grunwald-Winstein parameter³ for aqueous dioxan and acetone. ●, ○, and ◐: *m*-nitro-, *p*-bromo-, and *p*-methyl b.s.a. in aqueous dioxan; □ and ■ *p*-bromo- and *p*-methyl b.s.a. in aqueous acetone.

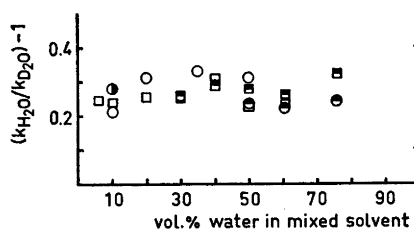


Fig. 3. Kinetic solvent isotope effect in the hydrolysis of sulphonic anhydrides at 22.5°C. For explanation of symbols cf. Fig. 2.

nism at higher water content, the m -value increasing to 0.72 at 60–76 vol. % water (corresponding to Y 1.95–2.7).

Kinetic isotope effects. The rate ratios, k_{H_2O}/k_{D_2O} , have been presented in a diagram, Fig. 3. It will be seen that in spite of a hundredfold variation in the rate constants, the kinetic solvent isotope effect has remained constant. This finding would suggest that the reaction mechanism is fairly unchanged throughout the composition range studied.

DISCUSSION

The hydrolysis of sulphonylchlorides, RSO_2Cl , in aqueous dioxan has previously been investigated by Vizgert.⁵ The Grunwald-Winstein plots of these data (Ref. 5, Fig. 5) show the same features as observed in the present investigation, *viz.* fairly linear plots with low m -values for solvents with less than 50 vol. % water, and increasing m -value for the *p*-toluenesulphonyl chloride for solvents with more than 50 vol. % water.

The low, but significant value of k_{H_2O}/k_{D_2O} found in the present work is in accordance with the results obtained in other investigations of uncatalysed hydrolytic reactions, thus for the hydrolysis of alkyl halides and alkyl sulphonates in water, Robertson and Laughton⁶ have observed rate ratios 1.07–1.35. Literature data for the hydrolysis of sulphonyl chlorides in pure water solvent and in mixed solvents have been compiled in Table 1. The values are slightly higher than those obtained for the hydrolysis of sulphonic anhydrides, but they resemble those of the present investigation in being fairly constant, independent of solvent composition.

While primary and secondary kinetic isotope effects are regarded as useful tools in mechanistic considerations,⁸ this does not apply to kinetic solvent isotope effects of uncatalysed hydrolytic reactions.^{9–12} The possibility of distinguishing S_N1 and S_N2 hydrolyses in pure water solvent by means of kinetic solvent isotope effects is excluded, k_{H_2O}/k_{D_2O} being close to 1.3 for the S_N1 hydrolysis of *t*-butyl chloride as well as for the S_N2 hydrolyses of methyl halides.⁶

Table 1. Kinetic solvent isotope effect for the hydrolysis of sulphonyl chloride.

Substrate	Solvent mixture	Temp. °C	k_{H_2O}/k_{D_2O}
$C_2H_5SO_2Cl$	20 vol. % water in acetone	25	1.49 ^a
»	40 vol. % » »	25	1.49 ^a
»	20 vol. % water in tetrahydrofuran	25	1.75 ^a
$n-C_3H_7SO_2Cl$	20 vol. % water in acetone	25	1.56 ^a
»	40 vol. % » »	25	1.61 ^a
CH_3SO_2Cl	100 % water	20	1.58 ^b
$C_6H_5SO_2Cl$	100 % water	10	1.58 ^b

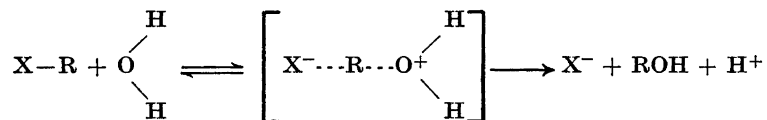
^a Ref. 7. ^b Ref. 6.

Apart from the results of the present investigation and those quoted in Table 1, there are very few reports on kinetic solvent isotope effects in mixed solvents. Considerable attention has been paid, however, to the observation that $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$ is 1.05 for the hydrolysis of *t*-butyl chloride in a mixture of 40 vol. % water in dioxan, but 1.35 for the same hydrolysis in pure water.¹¹⁻¹³ This observation is not consistent with the results of the present investigation and with the data in Table 1. The fact that the solvent-sensitive effect relates to an $\text{S}_{\text{N}}1$ hydrolysis, while the constant rate ratios apply to alleged $\text{S}_{\text{N}}2$ hydrolyses, suggests that the discrepancy may be explicable in terms of different mechanisms.

In spite of the different, and sometimes controversial, explanations given to the origin of kinetic solvent isotope effects, it appears to be common ground to attribute these effects to changes in the zero-point energy associated with the vibrations and librations of the water molecules during the activation process. In the $\text{S}_{\text{N}}1$ hydrolysis in pure water solvent the effect must be attributed to changes in the librational frequencies of those water molecules, which are reorganised during the activation, from a state corresponding to bulk water, to a state corresponding to water molecules solvating charged groups.

The fact that this isotope effect almost vanishes in a mixed solvent indicates that the libration frequencies of the water molecules in the mixed solvent are very close to the libration frequencies of the water molecules solvating the polar transition state. While it is difficult to give other quantitative evidence to support this hypothesis, it is hardly surprising that the presence of an organic solvent component breaks down the structure of the liquid water and thereby changes the sensitivity of the librational frequencies of the water molecules to the presence of charged groups.

The origin of the solvent isotope effect may be different, however, in the $\text{S}_{\text{N}}2$ hydrolysis. According to the reaction scheme the attacking water molecule



is transformed from a neutral molecule to a hydronium-like group in the transition state, and this implies a change in zero-point stretching frequencies of the O—H bonds. An estimate based on a simple model predicts $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}} = 1.5$ for this contribution (*cf.* Ref. 9, p. 3214). This type of effect would be expected to be less sensitive to changes in solvent composition than the solvent isotope effect attributed to solvating molecules, and this may explain the fairly constant isotope effects observed for the hydrolysis of sulphonyl chlorides and sulphonic anhydrides.

If these considerations are correct it is conceivable that the kinetic solvent isotope effect in mixed solvent, contrary to that in pure water solvent, may find some use as a mechanistic tool in the study of $\text{S}_{\text{N}}1$ and $\text{S}_{\text{N}}2$ reactions.

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