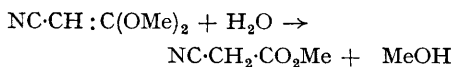


Kinetic Hydrogen Isotope Effects in a Proton-transfer Reaction: the General Acid-catalyzed Hydrolysis of Cyanoketen Dimethylacetal

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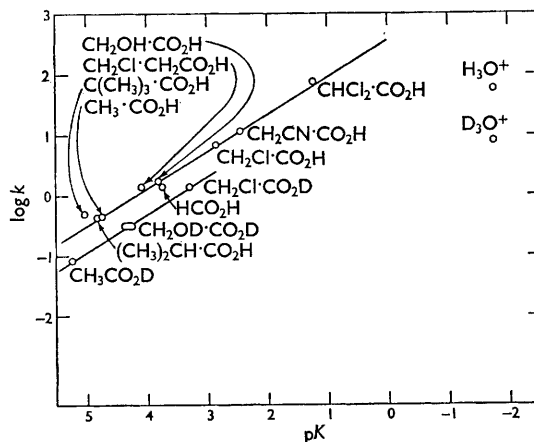
THE current theory of the deuterium solvent isotope effect for slow proton-transfer states that the reaction velocity should depend on the deuterium content of the medium in a predictable manner, partly determined by the value of the Brønsted exponent α .¹ However, several implications of the theory have never been probed because suitable systems for kinetic studies of the requisite precision were not known. We have found a suitable reaction in the hydrolysis of cyanoketen dimethylacetal,² the study of which now allows us to fill in some of these gaps. The reaction is general acid-catalyzed (see Figure) and its rate-limiting step, as in the hydration of isobutene³ and styrenes⁴ or in the hydrolysis of vinyl ethers⁵ is the addition of a proton to the double bond, the final product—



formed quantitatively under all conditions used by us—being methyl cyanoacetate. Since the high value of α in the case of isobutene³ implies a product-like (*i.e.*, carbonium ion-like) transition state, the choice of a system in which a more stable carbonium ion is thought to be formed was expected to lead to a lower value of α and hence to detectable general acid-catalysis.

The main conclusions reached from this study so far are:

(1) The solvent isotope effects on the reaction for catalysis by hydrogen ion and acetic acid are $(k_{\text{H}}/k_{\text{D}})_{\text{H}^+} = 3.0$; $(k_{\text{H}}/k_{\text{D}})_{\text{AcOH}} = 5.4$. The values are similar to the isotope effects for proton (deuteron) transfer from these acids to 1,3,5-



FIGURE

trimethoxybenzene⁶ (3.0 and 5.5) and support the inference that the initial, rate-limiting step of the hydrolysis reaction is likewise protonation (deuteronation) of the substrate. For the hydrogen ion-catalysed hydrolysis of vinyl ethers in mixed

aqueous-organic solvents⁵ the isotope effect is similar to the present result for the hydrogen ion.

(2) The value of α for catalysis by proton carboxylic acids in H₂O as solvent ($\alpha_{\text{H}^+} = 0.63$) is, within the limits of experimental error, the same as α for the corresponding deuterion acids in D₂O ($\alpha_{\text{D}^+} = 0.64$). It is suggested that this agreement represents a new experimental criterion regarding the role of proton tunnelling, the result obtained confirming the absence of such an effect for this reaction.

(3) It is possible to calculate a value of α solely from experiments with a strong mineral acid by fitting the experimental rates in H₂O-D₂O mixtures to the equation for the rate of proton (and deuterion) transfer in such media.^{1,3} Using experimental values obtained with perchloric acid and a value of 0.70 for the fractionation parameter l for the hydronium ion,⁷ a least-squares calculation yielded a value of 0.62 for α , in fortuitously good agreement with the values obtained from the experiments with carboxylic acid buffers and generally confirming the model used. Nevertheless, this procedure for obtaining α is not, in the present refinement of the theory, entirely satisfactory. The calculated value of α is sensitively dependent on the value of l chosen. A satisfactory calculation of α would require l to be known more precisely, and involve a better understanding of minor medium effects which may be comparable in size to the differences between calculated curves using the basic equation with slightly different values of α .

(4) The catalytic coefficient of acetic acid depends linearly on the deuterium atom fraction of the medium. It has been shown that the variation of catalytic coefficient, k_n , with atom fraction, n , of deuterium is given by:⁸

$$\frac{k_n}{k_{\text{H}}} = \frac{\prod(1-n+n\phi_{\text{T.S.}})}{\prod(1-n+n\phi_{\text{R}})}$$

where T.S. and R represent transition state and reactants respectively, and a term $(1-n+n\phi)$ appears for each exchangeable hydrogen atom in the transition state or reactants.

Because there is no significant fractionation of deuterium between acetic acid and water,⁹ this result implies that a single hydrogen atom changes its environment (and hence fractionation factor) during the formation of the transition state from the keten acetal and acetic acid. It therefore appears that in this case it is not necessary to invoke multimolecular models for proton transfer from aqueous acid to carbon, such as that involving the interposition of a water molecule between proton donor and acceptor.¹⁰

(5) The hydrogen atom has an anomalously low catalytic coefficient in this reaction, if it is included in the Brønsted plot (Figure) on the conventional assumption that its acid dissociation constant can be set equal to the molarity of water.

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