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The Relationship between Acid–Base Level and the Rate of Alkaline Hydrolysis of Halohydrins in Methanol–Water and Dioxane–Water Systems[1]

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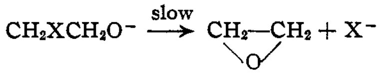
Apparent p_aH values of sodium hydroxide solutions in methanol–water and in dioxane–water are correlated with available kinetic data for the alkaline hydrolysis of ethylene halohydrins. Calculations show that if the halohydrin dissociates as a weak monobasic acid, then the ratio $[CH_2XCH_2O^-]/[CH_2XCH_2OH]$ should decrease sharply as the amount of non-aqueous solvent is increased in methanol–water solutions containing fixed alkali concentrations, but it should remain relatively constant in dioxane–water solutions. The change in this ratio accounts semi-quantitatively for the decrease in reaction rate with increasing methanol content in methanol–water systems; on the other hand, the comparative constancy of the ratio in dioxane–water systems suggests that the observed rate increase with increasing dioxane content must be attributed to the effect of decreasing dielectric constant on the rate constant for the second step of the postulated reaction sequence. The calculated change in ratio of dissociated to undissociated halohydrin which occurs on passing from dioxane–water solutions to isodielectric methanol–water solutions of the same ionic strength is shown to agree substantially with the experimentally observed change in rate of alkaline hydrolysis under similar conditions. These agreements constitute further evidence in support of the postulated reaction sequence.

Kinetic studies have shown[2,3] that the rate of hydrolysis of ethylene halohydrins in solutions containing a fixed amount of sodium hydroxide in aqueous methanol decreases as the methanol concentration increases; in similar solutions in aqueous dioxane the rate increases with increasing dioxane concentration. The rate increase with decreasing solvent dielectric constant observed in aqueous dioxane solutions was shown to be consistent with the view that the reaction proceeds in accordance with the general mechanism first suggested by Winstein and Lucas[4] for transformations of this type. The rate decrease with decreasing dielectric constant observed in aqueous methanol solutions was subject to qualitative explanation if methanol is assumed to "level" the base strength of sodium hydroxide solutions in aqueous methanol. Very recently, such a base leveling effect of methanol was demonstrated experimentally, and in the course of the same study an increase was observed in the apparent p_aH values of dioxane–water solutions containing constant sodium hydroxide concentrations as the dielectric constant decreased.[5] The purpose of this paper is to show that the observed acid–base behavior of dioxane–water and methanol–water solutions of sodium hydroxide affords a satisfactory semi-quantitative explanation for the kinetics of the alkaline hydrolysis of halohydrins in these solvent mixtures, assuming the hydrolysis reaction sequence previously proposed[2,3]

$$CH_2XCH_2OH + B^- \overset{\text{fast}}{\rightleftharpoons} BH + CH_2XCH_2O^- \quad (A)$$



$$CH_2XCH_2O^- \xrightarrow{\text{slow}} \underset{\diagdown O \diagup}{CH_2—CH_2} + X^- \quad (B)$$

If this reaction sequence is correct, then in general any change in reaction conditions, such as solvent change, which has the effect of increasing the equilibrium concentration of halohydrin anion should produce an increase in the over-all reaction rate. One method of arriving at an approximate evaluation of the effect on the rate of a change from the solvent water to another solvent has as its starting point the relationship 1, derived from the expression defining the thermodynamic dissociation constant for the halohydrin.

$$p_aH = pK_{CH_2XCH_2OH} + \log \frac{[CH_2XCH_2O^-]}{[CH_2XCH_2OH]} + \log (\gamma^-/\gamma) \quad (1)$$

where γ^- and γ are the activity coefficients for halohydrin anion and undissociated halohydrin, respectively. Because $pK_{CH_2XCH_2OH}$ values have not been determined, the ratio $[CH_2XCH_2O^-]/[CH_2XCH_2OH]$ cannot be computed or estimated by means of equation 1; however, the change in this ratio which is brought about by a change from the reference solution (infinite dilution in water) to a solution in another solvent is subject to an approximate solution If the reasonable assumption is made that γ changes but little with a change in solvent, then 1 may be transformed into

$$\log \frac{[CH_2XCH_2O^-]}{[CH_2XCH_2OH]} = \log \frac{[CH_2XCH_2O^-]}{[CH_2XCH_2OH]} - \left(\log \frac{[CH_2XCH_2O^-]}{[CH_2XCH_2OH]}\right)_0 = p_aH - (p_aH)_0 - \log \gamma^- \quad (2)$$

where the subscript zero indicates the reference solution. Inasmuch as values for p_aH and $(p_aH)_0$ are now available,[5] an estimation of $\Delta \log [CH_2XCH_2O^-]/[CH_2XCH_2OH]$ values for solvent mixtures is possible if $\log \gamma^-$ can be evaluated. Although an exact evaluation of this term cannot be made at present, it may be approximated by employing the relationship[5] 3. In calculating $\log \gamma^-$ values for

$$\log \gamma^- = \frac{\epsilon^2}{4.606rkT}\left[\frac{1}{D_X} - \frac{1}{D_{H_2O}}\right] \quad (3)$$

the chlorohydrin anion from 3, r, the ionic radius, has been arbitrarily assigned the magnitude 3 Å. The $\log \gamma^-$ values thus estimated were substituted into 2, along with p_aH data taken from the 3 Å. plots for aqueous methanol and for aqueous dioxane solutions shown in Fig. 5 of the preceding paper,[5] and the results are summarized in Table I.

The data in columns 5 and 6 of Table I permit an explanation to be given of solvent effects in the

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(1) Abstracted from a dissertation by W. C. Woodland to the Committee on Graduate Degrees, Carnegie Institute of Technology, in partial fulfillment of the requirements for the degree of Doctor of Science.

(2) J. E. Stevens, C. L. McCabe and J. C. Warner, THIS JOURNAL, **70**, 2449 (1948).

(3) C. L. McCabe and J. C. Warner, *ibid.*, **70**, 4031 (1948).

(4) S. Winstein and H. J. Lucas, *ibid.*, **61**, 1576 (1939).

(5) W. C. Woodland, R. B. Carlin and J. C. Warner, *ibid.*, **75**, 5835 (1953).

TABLE I

	p_aH			$\Delta \log CH_2XCH_2O^-/CH_2XCH_2OH$		$\Delta_{II,I} \log$	
D	Dioxane-water	Methanol-water	$\log \gamma^-$	Dioxane-water	Methanol-water	$\frac{[CH_2XCH_2O^-]}{[CH_2XCH_2OH]}$	$\log \frac{k_{II}}{k_I}$
40	11.98	...	0.497	−0.014	....		
45	11.78	...	.385	− .10	....		
50	11.64	10.57	.294	− .15	−1.22	1.06	1.11
55	11.55	10.67	.221	− .17	−1.04	0.87	0.87
60	11.50	10.80	.159	− .15	−0.85	.69	.66
65	11.47	10.97	.107	− .13	− .64	.50	.45
70	11.47	11.15	.063	− .09	− .41	.31	.27
75	11.48	11.34	.024	− .04	− .18	.13	.11
78.8 $(p_aH)_0$	11.49						

kinetics of the alkaline hydrolysis of ethylene halohydrins in terms of acid–base levels of the solutions. Figures in column 6 show that the ratio of concentration of halohydrin anion to that of undissociated halohydrin decreases continuously in aqueous methanol having constant stoichiometric concentrations of base as the methanol content of the solvent increases; and a comparison of the column 6 data with those of columns 3 and 4 reveals that p_aH changes are principally responsible for the ratio changes shown in column 6. Thus, the decrease in degree of conversion of undissociated halohydrin to its anion with increasing methanol content of the solvent may be attributed largely to the base leveling effect of the methanol. Since, according to the postulated reaction sequence, the reaction rate should decrease with decreasing equilibrium concentration of halohydrin anion, it follows from the data in column 6 that the rate should be reduced as the methanol concentration in the solution increases. This behavior has been observed experimentally.[2,3] The data of column 5, Table I, suggest that the ratio $[CH_2XCH_2O^-]/[CH_2XCH_2OH]$ changes very little in aqueous dioxane solutions over a considerable dielectric constant range. If this is true, then the observed[2,3] rate increase with increasing dioxane content of the solvent cannot be the result of an increasing equilibrium concentration of halohydrin anion but must be attributed mainly to the effect of a decreasing dielectric constant on the rate of step b of the reaction sequence. To be sure, the top and bottom values of column 5 differ comparatively markedly from adjacent ones, but owing to the several approximations and assumptions required to arrive at values for $\log \gamma^-$, such deviations probably have little significance. The qualitative conclusions should not be affected.

A relationship may be derived between the ratios $[CH_2XCH_2O^-]/[CH_2XCH_2OH]$ and the experimental rate constants, k, for the alkaline hydrolysis of a halohydrin in isodielectric aqueous methanol and aqueous dioxane solutions of identical ionic strengths and at the same temperature; this relationship is free of the limitations imposed by the necessity of approximating values of $\log \gamma^-$. The derivation begins with the expression 7, as it was employed by McCabe and Warner[4] to represent

$$k_{expt} = \frac{k_3 K_{CH_2XCH_2OH}\, f_{CH_2XCH_2OH}\, f_{OH^-}}{[a_{SH}K_2 + a_{H_2O}K_3]\, f_{CH_2XCH_2O^-}} \qquad (7)$$

the experimental rate constant for the alkaline hydrolysis of halohydrins in mixed aqueous solvents. For isodielectric solutions of identical ionic strengths, the activity coefficients and values of k_3 of equation 7 should be identical. Therefore, inasmuch as K_2 is negligible compared to K_3 when dioxane is the organic liquid in the solvent mixture, it follows from 7 that

$$\frac{k_{II}}{k_I} = \frac{[a_{SH}K_2 + a_{H_2O}K_3]_I}{[a_{H_2O}K_3]_{II}} \qquad (8)$$

where the subscripts I and II designate aqueous methanol and aqueous dioxane solutions, respectively. By making use of definitions and notation employed by McCabe and Warner, one can deduce

$$[a_{SH}K_2 + a_{H_2O}K_3]_I = \left[\frac{K_{CH_2XCH_2OH}\; a_{CH_2XCH_2OH}}{a_{CH_2XCH_2O^-}}\right]_I y \qquad (9)$$

and

$$[a_{H_2O}K_3]_{II} = \left[\frac{K_{CH_2XCH_2OH}\; a_{CH_2XCH_2OH}}{a_{CH_2XCH_2O^-}}\right]_{II} a_{OH^-} \qquad (10)$$

When 9 and 10 are substituted appropriately into 8, and when account is again taken of the fact that activity coefficients should be identical for like species in the two solutions, then

$$\frac{k_{II}}{k_I} = \frac{([CH_2XCH_2O^-]/[CH_2XCH_2OH])_{II}}{([CH_2XCH_2O^-]/[CH_2XCH_2OH])_I}$$

and

$$\begin{aligned}\log k_{II}/k_I = {} & \log([CH_2XCH_2O^-]/[CH_2XCH_2OH])_{II} - \\ & \log([CH_2XCH_2O^-]/[CH_2XCH_2OH]_I = \\ & \Delta_{II,I} \log([CH_2XCH_2O^-]/[CH_2XCH_2OH]) \qquad (11)\end{aligned}$$

The theoretical considerations which lead to the derivation of 11 receive experimental support when the figures in columns 7 and 8 of Table I are compared. The rate constant values in column 8 were computed from the data of Stevens, McCabe and Warner[2] on the rates of alkaline hydrolysis of ethylene chlorohydrin in methanol–water and in dioxane–water at 30, 15 and 0°. Graphical interpolation was employed to obtain values for rate constants at 25° and for solutions whose solvent dielectric constants were intermediate among those in which measurements were actually made. The values of $\Delta_{II,I} \log([CH_2XCH_2O^-]/[CH_2XCH_2OH])$ (column 7) were simply the differences between the corresponding figures in columns 5 and 6.

The substantial agreement between the data in columns 7 and 8, Table I, is therefore considered to constitute a powerful argument in support of the hypothesis that differences between rates of alkaline hydrolysis of halohydrins in isodielectric mixed aqueous solvents are functions mainly of differences in acid–base levels of the solutions. All of the evidence is subject to satisfactory interpretation in terms of the two-step reaction sequence A and B.

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