Mechanism of Proton Removal from 2-Phenylazoresorcinol Monoanion by Hydroxide Ion in 95% (v/v) Dimethyl Sulphoxide–Water

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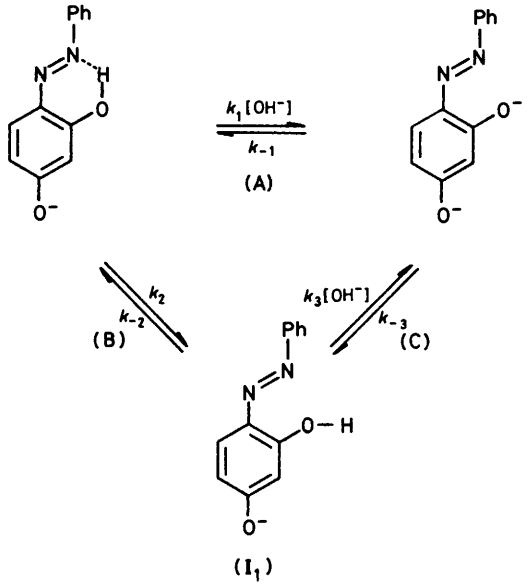
Dissociation of the hydrogen-bonded proton from 2-phenylazoresorcinol monoanion requires high concentrations of sodium hydroxide in aqueous solution but occurs at low hydroxide ion concentrations in 95% (v/v) Me_2SO–H_2O. Kinetic studies in 95% (v/v) Me_2SO–H_2O show that proton removal takes place by single-step attack of hydroxide ion on the hydrogen-bonded proton and by a two-step process through a non-hydrogen-bonded open form, with half-lives for the reaction in the range 8—20 μs.

The mechanism of proton removal from hydrogen-bonded acids is of some interest.[1] For most acids which have been studied in detail, such as salicylate ion,[2] naphthylammonium ions,[3] and phenylazoresorcinol monoanions under certain conditions,[4] the mechanism involves a rapid pre-equilibrium to give an open non-hydrogen-bonded form of the acid from which the proton is removed. A strong indication that single-step removal of a hydrogen-bonded proton may occur is provided by results obtained[5] for substituted 4-phenylazoresorcinol monoanions in aqueous hydroxide ion solutions. The complex dependence of rate on hydroxide ion concentration observed under these conditions is fitted by equation (1) which is deduced for the mechanism in Scheme 1. Step (A) involves direct attack of hydroxide ion on the hydrogen-bonded proton. Steps (B) and (C) are identical with the usual mechanism of proton removal from a hydrogen-bonded acid except that in deriving equation (1) it is necessary to assume that proton removal from the open form (I_1) is fast compared with the rate at which the open form

$$\tau^{-1} = (k_2 + k_1[OH^-])(1 + 1/K_{2b}[OH^-]) \quad (1)$$

reverts to the hydrogen-bonded monoanion ($k_{-2} < k_3[OH^-]$). In equation (1), K_{2b} is the overall equilibrium constant for the reaction, K_{2b} = [dianion]/[monoanion][OH^-]. The mechanism in Scheme 2 also leads to equation (1) and has been put forward[6] as an alternative explanation of the results for 4-phenylazoresorcinol monoanion. In this case step (A) may consist of direct attack on the hydrogen-bonded species or pre-equilibrium formation of the open form (I_1) followed by slow proton removal. Steps (B) and (C) involve formation of an intermediate (I_2) which differs from the open form (I_1) in the location of a proton. It was considered[6] that formation of the intermediate (I_2) occurs by protonation of the hydrogen-bonded monoanion to give the conjugate acid (4-phenylazoresorcinol) which then undergoes deprotonation by hydroxide ion. Scheme 2 shows that it is possible to explain the kinetic behaviour of 4-phenylazoresorcinol monoanion by a mechanism that does not involve direct attack on the hydrogen-bonded proton.

We now report kinetic and equilibrium studies of proton removal from 2-phenylazoresorcinol monoanion in 95% (v/v) Me_2SO–H_2O containing tetramethylammonium hydroxide [equation (2)]. In 2-phenylazoresorcinol, the hydroxy groups

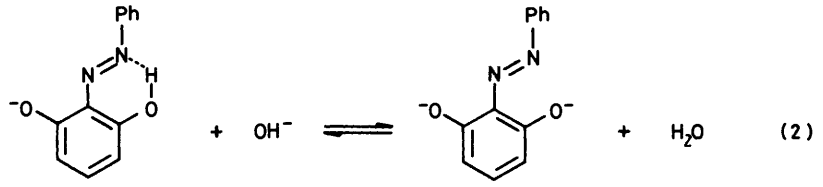


Scheme 1.

are both adjacent to the phenylazo group and the proton in the monoanion cannot be located at a site where it is unable to participate in an intramolecular hydrogen bond. Hence, for the reaction of 2-phenylazoresorcinol monoanion, it is not possible to propose an intermediate like (I_2) which differs from the open form (I_1). This permits conclusions to be reached about proton transfer from 2-phenylazoresorcinol monoanion which were not possible for 4-phenylazoresorcinol.

Experimental and Results

Materials.—The preparation of 2-phenylazoresorcinol was carried out in two stages.[7] The intermediate 7-hydroxy-8-phenylazo-4-methylcoumarin, obtained by reaction of benzenediazonium chloride with 7-hydroxy-4-methylcoumarin under alkaline conditions, was purified by flash chromatography[8] on MN silica gel 60 (Camlab) using 2:5 ethyl acetate–light petroleum as eluant. Reflux with sodium hydroxide

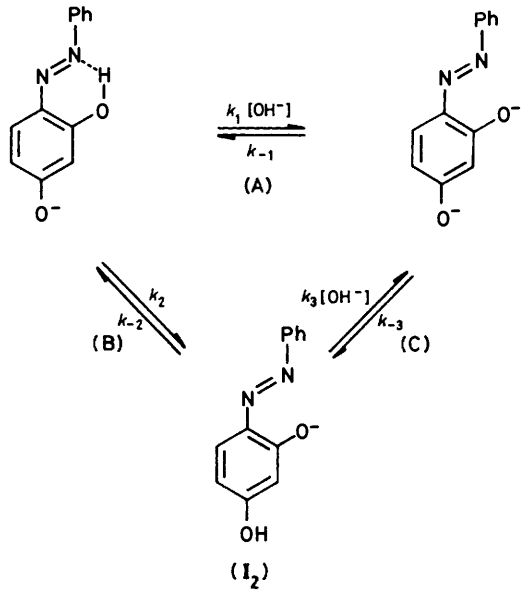


followed by acidification gave 2-phenylazoresorcinol which was obtained pure by recrystallisation from ethanol–water and by flash chromatography with toluene as eluant. The product was an orange solid, m.p. 146 °C, δ ([$^2H_6$]Me_2SO) 11.7 (s, 2 H, OH), 8.2—7.5 (m, 5 H, PhN_2), 7.4—7.1 (t, 1 H), and 6.5—6.4 (d, 2 H). In [$^2H_6$]Me_2SO at ambient temperature a singlet, integrating for two protons, was observed for the hydroxy protons. In CD_2Cl_2 at 213 K, the hydroxy protons gave two singlets at δ 13.03 and 7.85, but at 298 K a very broad singlet (δ *ca.* 10.5) was observed for both protons. Detailed studies of the temperature dependence of the n.m.r. spectrum of 2-phenylazoresorcinol in various solvents have been carried out[9] and will be described elsewhere.

Equilibrium Measurements.—Solutions of 2-phenylazoresorcinol in the presence of base are unstable unless protected from the atmosphere. Thus, before use, solvents and apparatus were flushed with nitrogen gas and reaction solutions were made up by injecting a stock solution of 2-phenylazoresorcinol in Me_2SO through a serum cap into the basic solution.

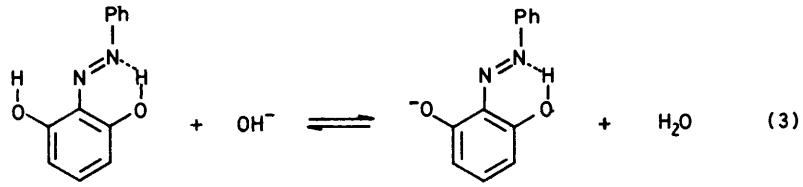
Aqueous solution. Measurements of the first dissociation of 2-phenylazoresorcinol were not possible in aqueous solution because of the low solubility of the undissociated acid. The equilibrium between the monoanion and dianion [equation (2)] was studied spectrophotometrically in aqueous solutions containing 8.3×10^{-5} mol dm^{-3} 2-phenylazoresorcinol and concentrated sodium hydroxide. Half-dissociation of the monoanion to the dianion was observed in the presence of *ca.* 0.8 mol dm^{-3} sodium hydroxide, corresponding to $pK_{2a}^{H_2O}$ *ca.* 14 for 2-phenylazoresorcinol. Because these conditions were found to be unsuitable for kinetic studies, detailed equilibrium measurements were not carried out in aqueous solution.

80% (v/v) Me_2SO–H_2O. The first and second dissociations of 2-phenylazoresorcinol were studied separately in 80% (v/v) Me_2SO–H_2O. Spectrophotometric measurements were made



Scheme 2.

dissociation [equation (2)] measurements of the absorbance (A) at 512 nm, where the monoanion absorbs more strongly than the dianion, were made for solutions containing 8.2×10^{-5} mol dm^{-3} 2-phenylazoresorcinol in the presence of tetramethylammonium hydroxide (0.01—0.5 mol dm^{-3}). Dissociation into the dianion is not complete even in the presence of 0.5 mol dm^{-3} tetramethylammonium hydroxide so that a value for A_d, the absorbance of solutions of the dianion, could not be measured. A value for the equilibrium constant K_{2b} = [dianion]/[monoanion][OH^-] was obtained as the gradient of a plot of $(A_m - A)$/[OH^-] against A as in equation (4) and the



for solutions containing 6.8×10^{-5} mol dm^{-3} 2-phenylazoresorcinol at 20.0 °C and with an ionic strength 0.5 mol dm^{-3} maintained by addition of tetramethylammonium chloride. For the first dissociation [equation (3)] the pH of the solutions was controlled by 2-bromophenol–2-bromophenolate buffers.[10] For solutions containing various buffer ratios, absorbance readings (A) were taken at 512 nm where the monoanion absorbs strongly. The absorbance (A_a) due to undissociated phenylazoresorcinol was obtained from measurements in the absence of buffer and the absorbance for solutions with complete dissociation into the monoanion (A_m) was obtained in the presence of a 1:1 phenol–phenolate buffer. The hydroxide ion concentrations in solutions of 2-bromophenol–2-bromophenolate buffers at various buffer ratios are known[10] and hence values for the equilibrium constant for the first dissociation were calculated from K_{1b} = [monoanion]/[2-phenylazoresorcinol][OH^-] = $(A - A_a)/(A_m - A)$[OH^-]. The average value $K_{1b} = 4.5 \pm 0.6 \times 10^9$ dm^3 mol^{-1} and the value of the ionic product of water in 80% (v/v) Me_2SO–H_2O[10] were used to calculate $pK_{1a} = -\log_{10}$[monoanion][H^+]/[2-phenylazoresorcinol] = 10.24 ± 0.04 for the first acid dissociation of 2-phenylazoresorcinol in 80% (v/v) Me_2SO–H_2O at 20.0 °C and ionic strength 0.5 mol dm^{-3}. For the second result $K_{2b} = 4.0 \pm 0.5$ dm^3 mol^{-1} was calculated. This was converted to $pK_{2a} = -\log_{10}$[dianion][H^+]/[monoanion] = 19.29 ± 0.05 for the second acid dissociation of 2-phenylazoresorcinol in 80% (v/v) Me_2SO–H_2O at 20.0 °C and ionic strength 0.5 mol dm^{-3}.

$$(A_m - A)/[OH^-] = K_{2b}A - K_{2b}A_d \qquad (4)$$

95% (v/v) Me_2SO–H_2O. Equilibrium studies of the second dissociation of 2-phenylazoresorcinol were also made in 95% (v/v) Me_2SO–H_2O at 15.0 °C and ionic strength 0.1 mol dm^{-3}. The procedure was the same as that used in 80% (v/v) Me_2SO–H_2O. Dissociation into the dianion occurred at lower concentrations of tetramethylammonium hydroxide in 95% (v/v) Me_2SO–H_2O and the result $K_{2b} = 58.3 \pm 10$ dm^3 mol^{-1} was obtained.

Kinetic Measurements.—The kinetics of the reaction in equation (2) were studied in 95% (v/v) Me_2SO–H_2O at 15.0 °C and ionic strength 0.1 mol dm^{-3}. Similar precautions to those used in the equilibrium measurements were taken to eliminate decomposition. Solutions of 2-phenylazoresorcinol (1—3 × 10^{-4} mol dm^{-3}) in the presence of tetramethylammonium hydroxide (0.001 75—0.075 mol dm^{-3}), and with tetramethyl-

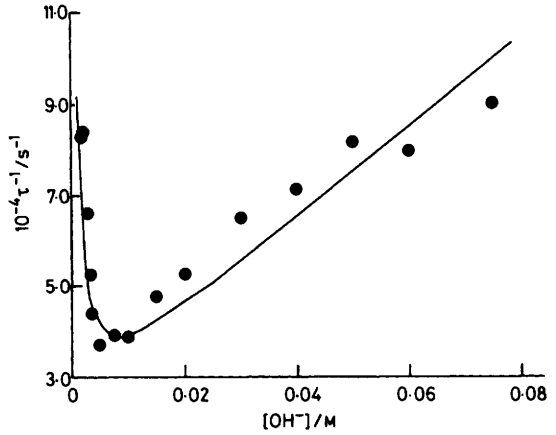
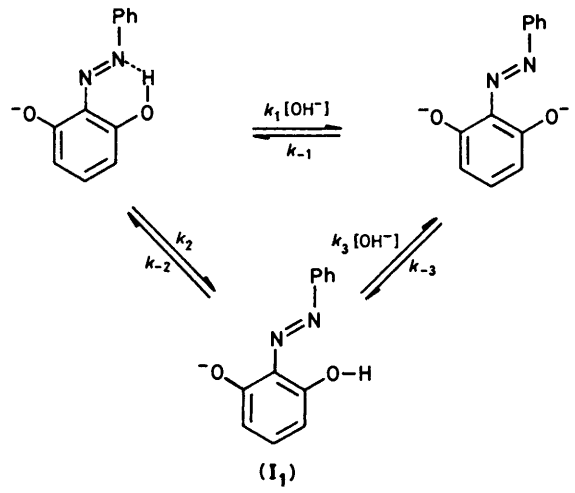


Figure. Variation of reciprocal relaxation time (τ^{-1}) with hydroxide ion concentration for equilibration of the monoanion and dianion of 2-phenylazoresorcinol in 95% (v/v) Me_2SO–H_2O. Points are experimental values and the curve is a plot of equation (1) with k_1 = 1.03 × 10^6 dm^3 mol^{-1} s^{-1}, k_2 = 0.42 × 10^4 s^{-1}, and K_{2b} = 58.3 dm^3 mol^{-1}



Scheme 3.

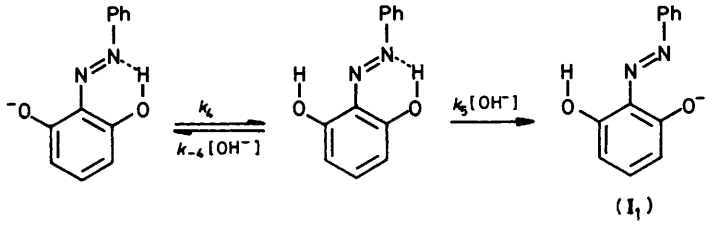
ammonium chloride to maintain an ionic strength of 0.1 mol dm^{-3}, were thermostatted at 13.0 °C. The temperature was raised to 15.0 °C within 5 μs by discharge of 20 kV from a 0.01 μF capacitor and the relaxation of the equilibrium in equation (2) to a new equilibrium position was observed spectrophotometrically at 435 nm where the dianion absorbs strongly. For each solution, the average of five determinations of the reciprocal relaxation time (τ^{-1}) was taken and the results are plotted in the Figure. The standard deviation of the average value of the reciprocal relaxation time at a particular hydroxide ion concentration was typically 15%. This large uncertainty arises because the amplitude of relaxation was low and because the reactions were quite fast. The results were also plotted in the form $\tau^{-1}/(1 + 1/K_{2b}[OH^-])$ against $[OH^-]$ as in equation (5),

$$\tau^{-1}/(1 + 1/K_{2b}[OH^-]) = k_1 + k_2[OH^-] \quad (5)$$

which is a rearranged form of equation (1). The value K_{2b} = 58.3 dm^3 mol^{-1} determined from equilibrium measurements was used in plotting equation (5) and the resulting straight line gave k_1 = 1.03 ± 0.08 × 10^6 dm^3 mol^{-1} s^{-1} and k_2 = 0.42 ± 0.1 × 10^4 s^{-1}. The curve in the Figure was constructed using these values.

intermediate corresponding to (I_2), formed by protonation of the monoanion followed by deprotonation, will either be the original hydrogen-bonded monoanion or the open form of it. If the original monoanion is re-formed, protonation–deprotonation cannot be a productive route to the dianion. If the open form is produced and is an intermediate on the lower pathway, the upper route cannot involve the open form and must occur by direct attack on the hydrogen-bonded proton in order to satisfy the observed kinetics.[11] The mechanism which is then obtained is shown in Scheme 4.

Schemes 3 and 4 differ in the mechanism of formation of the open form (I_1). The kinetic results for 2-phenylazoresorcinol are fitted by equation (1) with k_1 = 1.03 ± 0.08 × 10^6 dm^3 mol^{-1} s^{-1}, k_2 = 0.42 ± 0.1 × 10^4 s^{-1}, and K_{2b} = 58.3 dm^3 mol^{-1}. In Scheme 3 the rate coefficient k_2 refers to unimolecular opening of the intramolecular hydrogen bond in the monoanion. In Scheme 4 it is considered that formation of the open form may occur by a two-step reaction through the conjugate acid (2-phenylazoresorcinol) as in equation (6). On the basis of equilibrium studies of the first and second dissociations of 2-phenylazoresorcinol and by making reasonable assumptions about the rates of the proton transfer steps, a value for the rate coefficient [k_0; equation (7)] can be predicted for reaction by this route. Equation (7) is obtained on the assumption that 2-phenylazoresorcinol is a low concentration intermediate under the conditions of the experiment. The rate coefficients k_{-4}



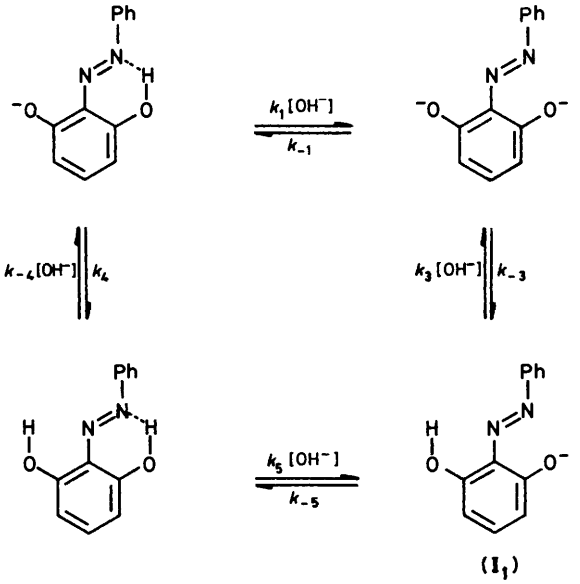
(6)

Discussion

The complex dependence of reciprocal relaxation time on hydroxide ion concentration observed for 2-phenylazoresorcinol (Figure) is explained by the mechanism in Scheme 3. This mechanism has been proposed[5] to explain the very similar behaviour of 4-phenylazoresorcinol (Scheme 1). The mechanism in Scheme 2 has been put forward[6] as an alternative explanation of the results for 4-phenylazoresorcinol. If Scheme 2 is considered for 2-phenylazoresorcinol monoanion, the and k_5 refer to thermodynamically favourable deprotonations of 2-phenylazoresorcinol by hydroxide ion. The hydrogen bond

$$d[(I_1)]/dt = k_o[\text{monoanion}]; \; k_o = k_4k_5/(k_{-4} + k_5) \quad (7)$$

in 2-phenylazoresorcinol is weak so that the value k_5 *ca.* 1.0 × 10^{10} dm^3 mol^{-1} s^{-1} or a slightly lower value can be assumed[1] and k_{-4} will have the value *ca.* 1.0 × 10^{10} dm^3 mol^{-1} s^{-1} expected for a normal proton transfer. The equilibrium



Scheme 4.

constant (k_4/k_{-4}) for the first step in equation (6) is identical to $1/K_{1b}$. The result $K_{1b} = 4.5 \times 10^9$ dm^3 mol^{-1} has been obtained for the first dissociation of 2-phenylazoresorcinol in 80% (v/v) Me_2SO–H_2O but a value in 95% (v/v) Me_2SO–H_2O, the solvent used for kinetic measurements, could not be measured. However, values of $K_{2b} = 4.0$ and 58.3 dm^3 mol^{-1} for the second dissociation of 2-phenylazoresorcinol were obtained in 80 and 95% (v/v) Me_2SO–H_2O respectively and by assuming that the solvent effects on K_{1b} and K_{2b} are similar, the result $K_{1b} = 6.6 \times 10^{10}$ dm^3 mol^{-1} is predicted in 95% (v/v) Me_2SO–H_2O. Combination of this result with $k_{-4} = k_5 = 1.0 \times 10^{10}$ dm^3 mol^{-1} s^{-1} and using equation (7) gives $k_o = 0.076$ s^{-1}. If a lower value for k_5 is chosen, the calculated value of k_0 is lower than 0.076 s^{-1}. Since the value calculated for k_o is well below the value for k_2 obtained by fitting equation (1) to the kinetic results, it follows that equation (6) does not provide a satisfactory route to (I_1). Hence Scheme 3 is preferred over 4 in explaining the results for 2-phenylazoresorcinol.

The complex dependence of reciprocal relaxation time on hydroxide ion concentration that is observed for 2-phenylazoresorcinol depends upon a delicate balance of the rate coefficients in Scheme 3. At low hydroxide ion concentrations, the reverse reaction of the lower pathway makes the largest contribution to the reciprocal relaxation time. This step shows an inverse dependence of rate on hydroxide ion concentration because the reaction proceeds through pre-equilibrium formation of a low concentration intermediate, the concentration of which is inversely proportional to hydroxide ion concentration. At high hydroxide ion concentrations, the reciprocal relaxation time increases linearly because the upper route, which is first-order in hydroxide ion, becomes dominant. The forward direction of the lower pathway is now more important than the reverse direction and hence at high hydroxide ion concentrations the lower pathway makes a small and hydroxide ion-independent contribution to the reciprocal relaxation time.

For 4-phenylazoresorcinol, analysis of the kinetic results by equation (1) and Scheme 1 gave $k_1 = 0.98 \times 10^6$ dm^3 mol^{-1} s^{-1} and $k_2 = 0.77 \times 10^4$ s^{-1} for reaction in aqueous solution at 298 K.[5] These results are close to those obtained for 2-phenylazoresorcinol in 95% (v/v) Me_2SO–H_2O. Based on pK_{2a} *ca.* 14 for 2-phenylazoresorcinol compared with pK_{2a} 12.0 for 4-phenylazoresorcinol[5] it appears that the hydrogen bond in 2-phenylazoresorcinol monoanion may be slightly stronger. However, the similar values of k_1 and k_2 for the two compounds probably indicate that proton removal occurs by the same mechanism.

Acknowledgements

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