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THE ACID-CATALYZED AND NEUTRAL SOLVOLYSIS OF BENZOYLPHENYLDIAZOMETHANE IN WATER, AQUEOUS T-BUTANOL, AND AQUEOUS SALT SOLUTIONS

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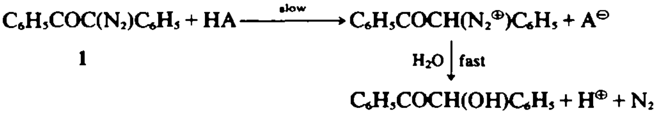
Abstract—The acid-catalyzed and water-catalyzed solvolysis of benzoylphenyldiazomethane (1) have been studied in water and in t-butanol–water mixtures, the mole fraction of water (n_{H_2O}) being varied from 0·75–1·00. Increasing t-butanol concentrations produce a pronounced decrease in both $k_{H^\oplus}$ and k_{H_2O}. In the "water reaction" mutually compensatory changes of ΔH^{+} and ΔS^{+} are associated with the rate variations, with minima in ΔH^{+} and ΔS^{+} at about $n_{H_2O} = 0·95$. In addition it was found that the magnitude of the salt effect of $(n\text{-}Bu)_4NCl$ on the rate of hydrolysis of 1 in water at 25° is much larger than that of LiCl, NaCl and NaBr. Assuming that the rate of the "water reaction" is largely determined by water acidity, the data are suggestive for the existence of a relation between water acidity and solvent structural integrity in highly aqueous t-butanol–water solutions.

The acid-catalyzed hydrolysis of α-diazoketones of the type $RCOCHN_2$ exhibits specific acid catalysis and proceeds according to the A-2 mechanism.[1] If the diazo methine proton is replaced by a phenyl ring, as in benzoylphenyldiazomethane (azibenzil, 1), the mechanism is changed to A-S_E2 involving rate determining protonation at the diazo C atom.[2,3]



$$C_6H_5COC(N_2)C_6H_5 + HA \xrightarrow{slow} C_6H_5COCH(N_2^{\oplus})C_6H_5 + A^{\ominus}$$

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$$\xrightarrow{H_2O,\ fast} C_6H_5COCH(OH)C_6H_5 + H^{\oplus} + N_2$$

Evidence for the latter mechanism is provided by the contribution of undissociated acids to the overall rate in buffer solutions of constant pH and by the solvent deuterium isotope effect, $k_H/k_D = 2·6$ (0·4 N aqueous $HClO_4$, 25°). In aqueous solutions containing less than about 10^{-1} N HCl a considerable contribution of a water induced reaction has been detected.[2] The precise mechanism of this "water reaction" has not been delineated.

In continuation of our studies of solvent effects on hydrogen bonding processes and proton transfer reactions in aqueous media,[4,5] we have investigated the acid-catalyzed and especially the water-catalyzed reaction of 1 in water and in water perturbed by the presence of t-butanol or some neutral salts.

RESULTS AND DISCUSSION

The acid-catalyzed solvolysis of 1. Plots of the pseudo first order rate constants $k_{\psi}^{H^\oplus}$ *vs* c_{HCl} give straight lines at acid concentrations above about 10^{-2} N in water and in highly aqueous t-butanol–water mixtures.† The second order rate constants, $k_{H^\oplus}$, obtained from the slopes of these plots are listed in Table 1. The first additions of t-butanol to water cause a sharp decrease in $k_{H^\oplus}$ while below mole fractions of water (n_{H_2O}) of 0·90 further increments of t-butanol slowly decrease the rate. The decrease in acidity upon addition of alcohols to aqueous hydrogen chloride is well-known and its interpretation has been subject to extensive discussion and speculation.[6] The difficulties encountered in defining useful acidity scales for these media[7] seem to indicate the operation of rather specific solvation effects.

The water-catalyzed reaction of 1. Pseudo first order rate constants ($k\psi$) for the decomposition of 1 in some protic and aprotic solvents are given in Table 2. No simple correlation of $k\psi$ with dielectric constant (ϵ), $(\epsilon - 1)/(2\epsilon + 1)$, or parameters[8] like the Z- or E_T-values is apparent. Low rates are observed in the aprotic media while in protic solvents $k\psi$ seems to correlate with the acidity of the solvent (e.g., $H_2O > CH_3OH > C_2H_5OH > t\text{-}BuOH$). The

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†The non-linearity at low acid concentrations is probably indicative for a salt effect on the "water reaction" (*vide infra*).

Table 1. Rate constants for the acid- and water-catalyzed solvolysis of **1** in t-BuOH–H_2O mixtures at various mole fractions of water (n_{H_2O}) at 25°

n_{H_2O}	ϵ	$k_{H^\oplus}.10^5$ l.mole^{-1}.sec^{-1}	$k\psi^{H_2O}.10^5$ (sec^{-1})	$k_{H_2O}.10^5$ l.mole^{-1}.sec^{-1}
1·00	78	5300	104	1·87
0·95	66	1270	50	1·10
0·89	50	300	15·5	0·42
0·81	36	215	8·5	0·30
0·75	29	182	8·2	0·35

Table 2. Pseudo first order rate constants ($k\psi$) for the breakdown of **1** in various solvents at 25°

Solvent	ϵ	$k\psi.10^5$ (sec^{-1})
H_2O	79	104
H_2O (10^{-3} N NaOH)		102
t-BuOH–H_2O ($n^a_{H_2O}$ = 0·89)	49	15·5
Dioxan–H_2O ($n^a_{H_2O}$ = 0·88)	43	16·0
CH_3OH	32·6	5·8
C_2H_5OH	24·3	2·5
t-BuOH	12·5	2·2
$(CH_3)_2NCHO$	36·7	0·8
CH_2Cl_2	8·9	1·0
CCl_4	2·23	0·3

[a] Mole fraction of water.

solvolysis of **1** in protic solvents differs considerably from the hydronium ion catalyzed-hydrolysis as illustrated by (i) the very small solvent deuterium isotope effect k_H/k_D = 1·06)[2] and (ii) the formation of rearrangement products **3** and **5** besides the "normal" products of solvolysis [e.g., benzoin (**2**) in water or benzoin O-methyl ether (**4**) in methanol].

$$\mathbf{1} \xrightarrow[(n_{H_2O}=0.76)]{\text{dioxane–}H_2O} \underset{\mathbf{2}\,(24\%)}{C_6H_5COCH(OH)C_6H_5} + \underset{\mathbf{3}\,(76\%)}{(C_6H_5)_2CHCOOH}$$

$$\mathbf{1} \xrightarrow{CH_3OH} \underset{\mathbf{4}\,(60\%)}{C_6H_5COCH(OCH_3)C_6H_5} + \underset{\mathbf{5}\,(25\%)}{(C_6H_5)_2CHCO_2CH_3}$$

No straightforward distinction between several possible pathways for the "water reaction" can be made at the moment. Nucleophilic displacement and/or base-catalysis can be excluded because the rates of solvolysis in water and in 10^{-3} N aqueous sodium hydroxide are the same within experimental error (Table 2). The formation of **3** and **5** offers no proof for a carbenoid process (Wolff rearrangement) since there is often a close analogy between carbene rearrangements and carbonium ion rearrangements.[9] The magnitude of k_H/k_D is unexpected for an A-S_E2 mechanism involving water as the Brønsted acid. However, it provides no conclusive evidence for the absence of proton transfer before or in the rate determining step.[10] Previously, large variations in the solvent deuterium isotope effect were found for several types of diazo compounds (including **1**) when the acidity of the medium was varied.[11-13] Solvolysis *via* (i) concurrent A-S_E2 and A-1 or A-2 routes,[11,13] (ii) diazonium ion–hydroxide ion ion-pairs[14] and (iii) complexes in which the protic solvent is hydrogen bonded to the diazo methine carbon atom[15] have all been invoked to explain the "water reaction" of either **1** or of related diazo alkanes. Jugelt and Schmidt[16] have suggested a ketocarbene–ketene mechanism for the breakdown of **1** in 50% dioxane–water at 70°. These authors attributed the rate accelerations observed in protic solvents to H-bonding interaction with the carbonyl moiety of **1**. We feel, however, that this type of ground state interaction is difficult to reconcile with an enhanced propensity for the loss of nitrogen.[17]

Despite the uncertainty regarding the constitution of the reactive intermediate, it does seem reasonable to conclude that the rates of solvolysis of **1** in protic solvents are largely controlled by the hydrogen-bonding capability or dynamic acidity of the medium (in the following discussion we will lump both properties together[18] under the name "solvent acidity").*

In an attempt to investigate how the water acidity, as measured by the rates of hydrolysis of **1**, responds to the addition of additives which are known to influence order-disorder processes in aqueous solvents, we have determined reaction rates in water–t-butanol mixtures and in water containing neutral salts. There is reliable evidence that small additions of t-butanol promote the degree of long-range order in water significantly, leaving open the question whether or not this order is that which is characteristic of pure water.[19] Pseudo first-order

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*Alternatively, this property of the bulk solvent may be referred to as "proton potential".[6]

rate constants ($k\psi^{H_2O}$) and second-order rate constants ($k_{H_2O} = k\psi^{H_2O}.c_{H_2O}^{-1}$) for the solvolysis of 1 in water–t-butanol ($n_{H_2O} = 0{\cdot}75$–$1{\cdot}00$) are given in Table 1. At $n_{H_2O} \geqslant 0{\cdot}85$ the solvolysis will be largely a water induced reaction as indicated by the low rate of solvolysis in pure t-butanol (Table 2). Just as for $k_{H^\oplus}$, there is a pronounced decrease in k_{H_2O} with increasing concentration of t-butanol at $n_{H_2O} \geqslant 0{\cdot}85$. The data indicate that in these media the dielectric constant (ϵ) is not the fundamental parameter determining k_{H_2O}. Activation parameters for the solvolysis of 1 at various mole fractions of water are given in Table 3 and plotted in Fig 1. In the area between n_{H_2O} 0·90 and 1·00, where structure-making effects due to the presence of t-butanol are most significant,[19] we find typical, mutually compensatory changes in ΔH^{+} and ΔS^{+}. Enthalpy–entropy compensation phenomena have been encountered frequently in a number of organic and biochemical processes in (mixed) aqueous solutions.[20] This response of ΔH^{+} and ΔS^{+} to variation in solvent composition may well be a consequence of the unique properties of liquid water regardless of the precise nature of the reactions studied. Interestingly, we observe minima in ΔH^{+} and ΔS^{+} at about $n_{H_2O} = 0{\cdot}95$, the solvent composition for which a maximum in the diffusionally-averaged water structure has been claimed.[19] We are therefore led to suspect that above $n_{H_2O} = 0{\cdot}85$ changes in the structural order of the medium are reflected in the rates of the "water reaction" of 1. It should be noted that we have previously found that a maximum in the water *basicity* (as measured by the rates of base-catalyzed solvolysis of sulfonylmethylperchlorates) occurs at about the same n_{H_2O} in aqueous t-butanol solvents.[5]

The salt effects of LiCl, NaCl, NaBr, and (n-Bu)$_4$NCl on the rate of the "water reaction" of 1 are plotted in Fig 2. These salts all reduce the $k\psi^{H_2O}$ values, the effect of the first three salts being small (at $c_{NaCl} = 3$ M, $k\psi^{H_2O} = 86 \cdot 10^{-5}$ sec^{-1}; $k_H/k_D = 1{\cdot}03$).

Table 3. Activation parameters for the solvolysis of 1 in t-BuOH–H$_2$O mixtures at various mole fractions of water (n_{H_2O})

n_{H_2O}	ΔH^{+} (kcal mole^{-1})	ΔS^{+} (e.u.)
1·00	19·4 ± 0·5	−7 ± 1
0·95	18·7 ± 0·3	−11 ± 1
0·89	21·4 ± 0·3	−4 ± 1
0·81	22·4 ± 0·5	−2 ± 1
0·75	22·2 ± 0·4	−2 ± 1

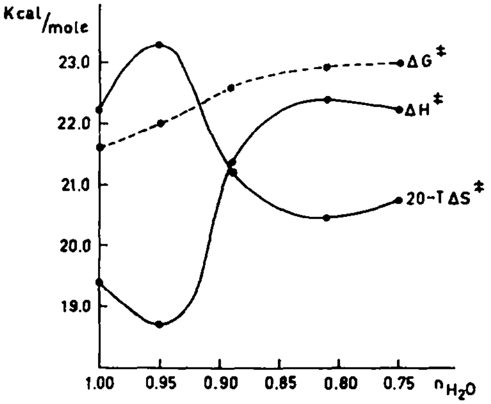

Fig 1. Activation parameters for the "water reaction" of 1 in t-butanol–water mixtures (at 40°).

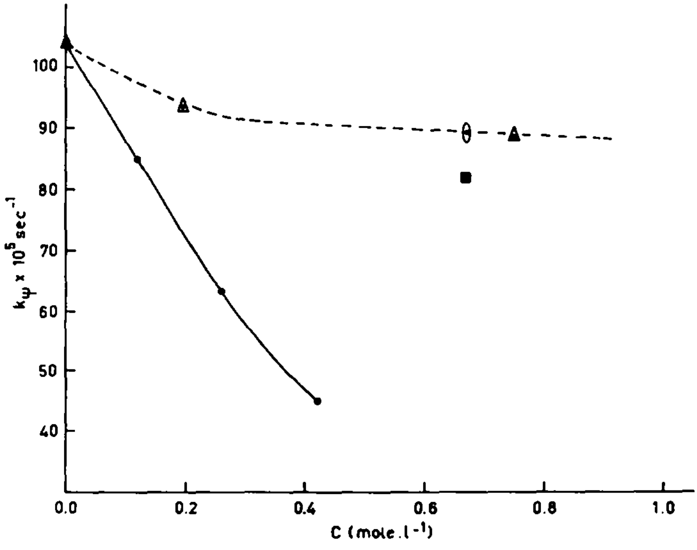

Fig 2. Plot of kψ *vs* salt concentration for the "water reaction" of 1 at 25°: ●, (n-Bu)$_4$NCl; △, NaCl; ⊙, LiCl; ■, NaBr.

In contrast, $k\psi^{H_2O}$ is considerably decreased with increasing concentration of $(n\text{-}Bu)_4NCl$. This is surprising and noteworthy since this difference in salt effect is too large to be ascribed to effects due to changes in dielectric constant. It is tempting to ascribe the origin of the salt effect of $(n\text{-}Bu)_4NCl$ largely to the known[21,22] strong structure making in aqueous solutions of this ammonium salt.* This harmonizes with earlier findings that tetraalkylammonium chlorides increase the dynamic *basicity* of water.[4,5]

In view of the absence of mechanistic details for the "water reaction" of **1**, further interpretation of the above kinetic results would be premature. Although we are aware that the rate variations reported in this paper represent a complex and at the moment inaccessible combination of influences due to solvent perturbations, we like to suggest that the kinetic behaviour of **1** in highly aqueous media is, at least partly, associated with the solvent structural integrity of these solutions.

EXPERIMENTAL

Compound **1** was prepared according to the lit.[23] The water used in the kinetic measurements was demineralized and distilled twice in an all-quartz distillation unit. D_2O was obtained from Reactor Centrum Nederland (99·94% D_2O) and was used as such. t-BuOH and the salts were obtained from Merck A. G. $(n\text{-}Bu)_4NCl$ was crystallized twice from an ether–EtOAc–EtOH (40:40:20) mixture and was dried over P_2O_5 *in vacuo* for 3 days. The solvent mixtures were all made up by weight.

The decay of **1** was followed at 320 nm on a Zeiss PMQ II UV spectrophotometer using 20 mm quartz cells, thermostated at 25·00 ± 0·02°. Pseudo first-order kinetics were observed for at least two half-lives. Rate constants were reproducible to within 3%. The formation of **3** had no effect on the reaction rate. Activation parameters were calculated from rate constants obtained at three temperatures in the range 25–60°.

Solvolysis in dioxan–water ($n_{H_2O} = 0{\cdot}76$). Compound **1** (0·5 g, 2·25 mmole) was dissolved in 400 ml of 60% (v/v) dioxane–water ($n_{H_2O} = 0{\cdot}76$) and the soln was kept in the dark for 7 days at 20°. The yellow oil, obtained after evaporation of the solvent *in vacuo* was dissolved in dichloromethane and the soln was dried over $MgSO_4$. After filtration and removal of the solvent *in vacuo*, GLC analysis indicated the presence of 24% of **2** and 76% of **3**.

Solvolysis in methanol. A soln of **1** (1·5 g; 6·75 mmol) in 50 ml of MeOH was kept at 20° for 4 days. Evaporation of the solvent *in vacuo* gave a light-yellow oil. The NMR spectrum of this product (in $CDCl_3$) indicated the presence of **4** (60%) and **5** (25%) besides some unidentified material(s).

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*Recently, NMR studies have been carried out in the hope to substantiate a structural effect on water acidity, but no definitive conclusion could be reached.[18]

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