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SOLVOLYSIS OF 1,1-DIPHENYLETHYL DERIVATIVES IN HIGHLY AQUEOUS MEDIA. REACTION VIA ION PAIRS*

ALF THIBBLIN
Institute of Chemistry, University of Uppsala, P.O. Box 531, S-751 21 Uppsala, Sweden

Solvolysis of 1,1-diphenyl-1-X-ethane (1-X) [X = 4-nitrobenzoate (PNB), 3,5-dinitrobenzoate (DNB), AcO, $MeOH^+$, $EtOH^+$ or H_2O^+] was studied in 20 vol% dimethyl sulphoxide in water, in which specific salt effects are very small, and in 25 vol% acetonitrile in water. Substrates with negatively charged leaving groups yield more elimination product 1,1-diphenylethene (3) than those with uncharged groups, indicating the intermedicacy of ion pairs. Thus, three times more alkene is formed in the reactions of the substrates 1-OAc and 1-PNB than in the acid-catalysed hydrolysis of 1-OMe and 1-OAc. The substitution products may be formed via the solvent-equilibrated carbocation since the measured nucleophilic selectivities are very similar with different leaving groups.

INTRODUCTION

This work is part of an investigation of the role of ion pairs and ion–molecule pairs as intermediates in heterolysis reactions in water and highly aqueous media. The equilibrium constant ($K_{as} = k_d/k_{-d}$) for formation of ion pairs from singly charged ions in water is generally $< 1\ \mathrm{l\,mol^{-1}}$.[1] Accordingly, it has been pointed out that a substantial fraction of reaction products is not likely to originate from the reaction of the ion pair with a dilute reactant since the lifetime of the intermediate should be too short to allow it to encounter, and react with, reactants other than those which are already close to the ion pair when it is formed.[2] Thus, a substantial k_p/k_{-d} ratio [equation (1)] requires a preassociation mechanism whereby the dilute reactant C assumes a reaction position before the R—X bond is ruptured, or reaction with the solvent.

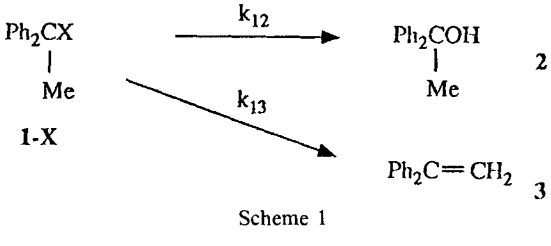
$$\begin{tikzcd} RX \arrow[r, shift left] & \text{ion pairs} \arrow[l, shift left] \arrow[r, shift left, "k_{-d}"] \arrow[d, "k_p", "C"'] & R^+ \arrow[l, shift left, "k_d"] \arrow[r] & \text{products} \\ & \text{products} & & \end{tikzcd} \qquad (1)$$

The stability of the carbocation is one of the factors that is expected to govern what proportion of the products comes from the ion pair. A high carbocation stability is thought to favour reaction via the 'free' solvent-equilibrated carbocation compared with reaction directly from the ion pair.[3]

This paper presents a study of solvolysis reactions of 1,1-diphenylethyl derivatives in highly aqueous media. Despite the relatively high stability of the 1,1-diphenylethyl carbocation, the results show that the ion pair has a significant lifetime. Reaction via the ion pair is the main route to elimination product.

RESULTS

The solvolysis of 1,1-diphenyl-1-X-ethane (**1-X**) in 20 vol% dimethyl sulphoxide (DMSO) in water produces mainly the alcohol **2**, in addition to some 1,1-diphenylethene (**3**) (Scheme 1). The kinetics of the reactions were studied at 25 °C by a sampling high-performance liquid chromatographic procedure. Addition of salt has very little effect on the rate of reaction of **1-OAc**, as shown in Table 1. A small common-ion effect is exhibited, however. The salt



Scheme 1

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Table 1. Rate constants[a] for the reactions of **1-X** in 20 vol% DMSO in water at 25 °C

Substrate	Salt (0·80 M)	10^6 ($k_{12}+k_{13}$) (s^{-1})	10^3 k_{13}/k_{12}
1-OAc	None	127·2	44
	NaOAc	85·2	89
	NaClO$_4$	109	38
	NaCl	129	45
	NaI	140	
	NaN$_3$	126	
		22·2[b]	13
1-OMe		9·5[b]	15

[a] The rate constants (defined in Scheme 1) were obtained by measuring the mol% of the substrate and the products by HPLC as a function of time (see Experimental). The total yield of alcohol **2** and alkene **3** is 100%.

[b] Second-order rate constant (l mol^{-1} s^{-1}) obtained from the slope of plot k_{obs} versus [HClO$_4$] (0·01–0·05 M); ionic strength maintained constant at 0·05 M with NaClO$_4$.

Table 2. Rate constants[a] for the reactions of **1-X** in 25 vol% MeCN in water at 25 °C

Substrate	Salt (0·75 M)	10^6 ($k_{12}+k_{13}$) (s^{-1})	10^3 k_{13}/k_{12}
1-OAc	None	37·4	41
	NaOAc	17·9	162
	NaClO$_4$	40·8	
	NaN$_3$	41·3	
1-PNB[b]	None	498	42
	NaOAc	259	164
	NaClO$_4$	513	37
	NaCl	407	58
	NaI[d]	606	
	NaN$_3$	607	
1-DNB[c]	None	6000	
	None[e]	405	

[a] The rate constants (defined in Scheme 1) were obtained by measuring the mol% of the substrate and the products by HPLC as a function of time (see Experimental). The total yield of alcohol **2** and alkene **3** is 100%.

[b] 4-Nitrobenzoate.

[c] 3,5-Dinitrobenzoate.

[d] 0·375 M.

[e] 50 vol% MeCN.

effects are larger in 25 vol% acetonitrile (MeCN) in water (Table 2). A very low solubility and a high reactivity made it impossible to study accurately the kinetics of **1-PNB** (PNB = 4-nitrobenzoate) in DMSO-water.

Acetate anion catalyses the elimination reaction. A fourfold increase in the amount of alkene product **3** is obtained with 0·75 M NaOAc in acetonitrile–water (Table 2). The yield of alkene from **1-OAc** is doubled by the addition of 0·80 M NaOAc in DMSO–water (Table 1).

The acid-catalysed reaction of **1-OAc** is illustrated in Figure 1. The fraction of elimination is considerably smaller for this reaction than for the uncatalysed route and is similar to that obtained for the acid-catalysed reaction of the methyl ether (Table 1). The fact that similar fractions of alkene from acid-catalysed reaction of **1-OAc** and **1-OMe** are observed indicates that acyl—oxygen fission in the acetate ester is negligible.

Nucleophilic selectivities, i.e. ratios of second-order rate constants with different nucleophiles, have been measured for reactions with many different leaving groups (Table 3). Attempts have been made to measure

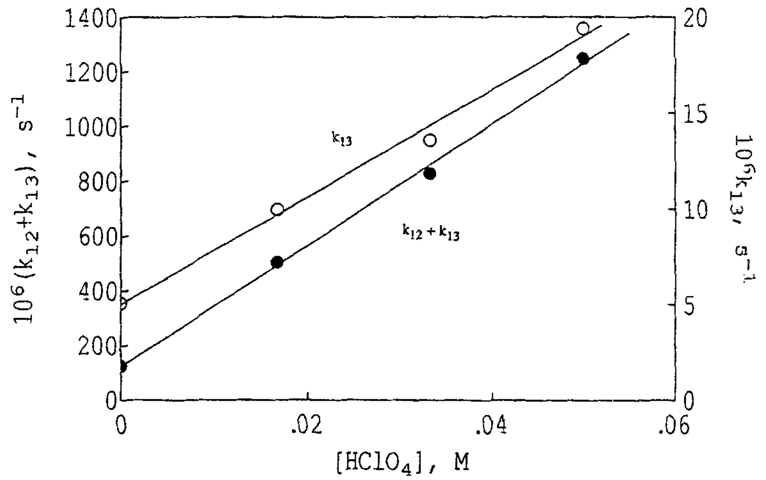

Figure 1. Catalysis by perchloric acide of the reaction of **1-OAc** in 20 vol% DMSO in water at ionic strength 0·05 M maintained with NaClO$_4$

Table 3. Nucleophilic selectivities for the reactions of **1-X** at 25 °C

Substrate	Solvent	Salt, etc.	Ratio of second-order rate constants[a]
1-OAc	25% MeCN	0·75 M NaN_3	$k_{az}/k_w = 1235$
	20% DMSO	0–0·8 M NaN_3	$k_{az}/k_w = 610$
	50% MeOH		$k_{MeOH}/k_w = 6{\cdot}4$
1-PNB[b]	25% MeCN	0–0·15 M NaN_3	$k_{az}/k_w = 1420$
	25% MeCN	0·75 M NaOAc	$k_{OAc}/k_w \approx 11$
	50% MeOH	0·05 M NaN_3	$k_{az}/k_w = 660$
	50% MeOH		$k_{MeOH}/k_w = 6{\cdot}5$
1-DNB[c]	50% MeOH		$k_{MeOH}/k_w = 6{\cdot}4$
1-OMe	20% EtOH	$HClO_4$	$k_{EtOH}/k_w = 3{\cdot}0$
	50% EtOH	$HClO_4$	$k_{EtOH}/k_w = 3{\cdot}0$
1-OEt	50% MeOH	$HClO_4$	$k_{MeOH}/k_w = 7{\cdot}3$
1-OH	25% MeOH 25% EtOH	$HClO_4$	$k_{MeOH}/k_{EtOH} = 2{\cdot}3$

[a] For formation of substitution products; e.g. k_w is the second-order rate constant for formation of alcohol **2** from **1-X**. The rate ratios were obtained by measuring the mol% of the products by HPLC as a function of time (see Experimental) and the concentrations of the nucleophiles. No by-products were found.

[b] 4-Nitrobenzoate.

[c] 3,5-Dinitrobenzoate.

the ratio of azide and alcohol product in the reaction of **1-OMe**. However, the reaction is very slow in HN_3–N_3^- buffers and the azide product **1-N₃** is not stable for such long reaction times. Therefore, no reliable results were obtained.

The alkene **3** is stable in DMSO–water and in MeCN–water at pH 2 for at least several hours.

DISCUSSION

The solvolysis of **1-X** is expected to be of the S_N1 type. Experimental support for this mechanism is the following. Despite the fact that the reactivity of an azide ion is much greater than that of solvent water molecule toward **1-OAc** in 20% DMSO–water, the observed reaction rate is constant (Table 1), within the limits of experimental error, up to an azide concentration of 0·8 M, at which the yield of **1-N₃** is over 90%. Hence azide ion is not involved in the rate-limiting transition state.

Azide concentration has a small effect on the rate of reaction of **1-OAc** and of **1-PNB** in MeCN–water, which may be due to a second-order reaction with azide ion or to a specific salt effect. Specific salt effects have been found to be significant for other solvolysis reactions in MeCN–water mixtures[4,5] and in other mixtures of water and organic solvents.[6,7] The reason for using 20% DMSO in water in this work was that this solvent mixture was expected to minimize specific salt effects. Thus, specific solvation has been shown to be insignificant in DMSO–water mixtures in contrast to MeCN–water mixtures[8] and salt effects on solvolysis of alkyl chlorides in 70% and 80% aqueous DMSO have been found to be small.[9] The data in Table 1 confirm that such effects are very small in 20% DMSO–water. However, sodium perchlorate has a small negative salt effect in DMSO–water on the solvolysis rate of **1-OAc**. The reason for this is not known.

The variation of rate with nature of the salt in MeCN–water (Table 2) is similar to that observed for the solvolysis in the very same solvent of 9-(2-chloro-2-propyl)fluorene, which was concluded to involve rate-limiting ionization.[5] A small common-ion effect is exhibited by AcO^- in DMSO–water. The rate depression by AcO^- is larger in MeCN–water (Table 2). The effect is probably a combination of a common-ion effect and a negative specific salt effect.[5]

The measured ratio of second-order rate constants (Table 3) indicates that the azide anion is about 1200 times as reactive as a water molecule toward the carbocation intermediate in MeCN–water. In DMSO–water and in 50% MeOH–water the selectivity is about half as large. The k_{az}/k_w ratio is roughly 25–50% as large as that of 1-(4-methoxyphenyl)ethyl carbocation in 50% trifluoroethanol–water.[3,10] The rate constant for the reaction of the carbocation intermediate with water in the MeCN–water solvent is estimated to be *ca* $1{\cdot}7 \times 10^8\ s^{-1}$, assuming a diffusion-controlled reaction with azide ion with $k_d = 5 \times 10^9\ l\,mol^{-1}\,s^{-1}$.[11,12] The carbocation intermediate formed in the solvolysis of cumyl chloride, i.e. 2-chloro-2-phenylpropane, exhibits a much smaller nucleophilic selectivity value, $k_{az}/k_w = 42$, and a higher reactivity toward solvent water, rate constant *ca* $5 \times 10^9\ s^{-1}$.[13] Also, the selectivity ratios k_{OAc}/k_w and k_{MeOH}/k_w are smaller for the reactions with the cumyl derivatives.[13]

The very similar selectivities toward nucleophiles exhibited with different leaving groups (Table 3) may suggest that the substitution products are formed by nucleophilic attack on a 'free' solvent-equilibrated carbocation. However, it has been shown that an intramolecular ion pair with sulphonate as leaving group behaves in much the same way as the unpaired cation in reactions with nucleophiles.[14] Accordingly, the nucleophilic selectivity data in Table 3 may be consistent with a significant one-step reaction of the ion pair to substitution product.

The fraction of elimination product is three times larger in the reaction of **1-OAc** and **1-PNB** than in the acid-catalysed reactions of **1-OAc** and **1-OMe**. This indicates that ion pairs are intermediates in the reactions and that the negatively charged leaving groups promote hydron transfer within the ion pair. Apparently, contrary to what has been found with the cumyl system,[13] the pK_a difference of the negatively charged leaving groups, 1·3 pK_a units, does not have a significant effect on the rate of elimination from the ion pair. Other reports on solvolysis catalysed by the leaving group have appeared.[3,5,13,15] However, the 1,1-diphenylethyl derivatives seem to be the most reactive substrates for which indications for ion-pair intermediates have been found for solvolysis in highly aqueous media.

Catalysis by added general bases other than acetate anion has not been investigated for the present system. The less stable cumyl carbocation undergoes general-base catalysed elimination with $\beta = 0{\cdot}13$.[13]

The amount of internal return may be estimated for the reaction of **1-OAc** based on the mechanistic model of equation (2), the kinetic data given in Table 2 and the discrimination rate ratio $k_{OAc}/k_w = 11$ given in Table 3. The carbocation R^+ and the ion pair $R^+\,{}^-OAc$ are expected to be formed in solvolysis of **1-PNB** in the presence of acetate anion. Thus, combination of the data for the reaction of **1-OAc** with the data for **1-PNB** in the presence of acetate ion, corrected for elimination from free carbocation R^+ and ion pair R^+X^-, indicates that about 4% of the ion pairs return to substrate **1-OAc**.

$$\begin{tikzcd}
 & & \mathrm{ROH} & & \\
\mathrm{ROAc} \arrow[r, shift left] & R^+\,{}^-\mathrm{OAc} \arrow[l, shift left] \arrow[r, shift left] \arrow[dr] & R^+ \arrow[u] \arrow[l, shift left, "\mathrm{AcO}^-"] \arrow[d] & R^+X^- \arrow[l] \arrow[r, shift left] \arrow[dl] & \mathrm{RX} \arrow[l, shift left] \\
 & & \mathrm{alkene} & &
\end{tikzcd} \qquad (2)$$

The ion pairs in equation (2) include both contact (intimate) and solvent-separated ion pairs. The experimental results do not enable these two types of species to be distinguished. The model assumes that the ion pair that returns is kinetically indistinguishable from the type that undergoes elimination. It is possible that the geometric requirements are different. It is conceivable that the barrier for interconversion of the different types of ion pairs is very small in this type of solvent.

CONCLUSIONS

The diphenylethyl derivatives **1-X** with negatively charged leaving groups solvolyse via ion pairs that have a significant lifetime. The internal return is rather slow compared with reaction of the ion pair to substitution product. The latter process is presumably a multi-step reaction which involves diffusional separation as the first and rate-limiting step. Most of the alkene is formed directly via the ion pairs.

EXPERIMENTAL

The ^1H NMR analyses were performed with a Varian XL 300 spectrometer equipped with a 5 mm dual probe (^1H, ^{13}C). The high-performance liquid chromatographic (HPLC) analyses were carried out with a Hewlett-Packard 1090M liquid chromatograph equipped with a diode-array detector and a C_8 reversed-phase column (200 × 3·0 mm i.d.). The mobile phase was a solution of acetonitrile in water. The reactions were studied at constant temperature in an HETO 01 PT 623 thermostat or in an aluminium block thermostated with circulated water from the thermostat.

Materials. Acetonitrile, DMSO, methanol and ethanol were of spectroscopic quality and were used as solvents without further purification. All other chemicals were of reagent grade. A stock solution of sodium perchlorate was prepared from perchloric acid and sodium hydroxide solution.

1,1-Diphenyl-1-hydroxyethane (**2**) was purified by recrystallization of commercially available material (Aldrich) from pentane.

1,1-Diphenyl-1-methoxyethane (**1-OMe**)[16] was prepared from 1·225 g of the alcohol **2** dissolved in 4·7 ml of methanol containing two drops of 100% sulphuric acid. After 2 days at room temperature, the reaction mixture was placed in a refrigerator. The crystalline ether was purified by two recrystallizations from methanol.

1,1-Diphenyl-1-ethoxyethane (**1-OEt**) was prepared in a small amount from **2**, ethanol, and 100% sulphuric acid. The product mixture was diluted with pentane and the pentane solution was washed. The residue obtained after evaporation of the solvent was used without further purification.

Diphenylmethylcarbinyl acetate (**1-OAc**) was made from **2** by $ZnCl_2$-catalysed acetylation with acetic anhydride (30 s).[13,17] Semi-preparative HPLC gave pure material.

Diphenylmethylcarbinyl 3,5-dinitrobenzoate (**1-DNB**) and diphenylmethylcarbinyl 4-nitrobenzoate (**1-PNB**) were prepared from **2** and 3,5-dinitrophenylbenzoyl chloride or 4-nitrophenylbenzoyl chloride, respectively, in pyridine.[13,18]

Kinetics and product studies. The reactions were run at constant ionic strength in solutions prepared by mixing a water solution of the salt(s) with the organic solvent(s) at room temperature (*ca* 22 °C). The reaction vessel was a 2 ml HPLC flask, sealed with a tight PTFE septum, which was placed in an aluminium block in the water thermostat or, in the faster reactions, directly in the HPLC apparatus in an aluminium block held at constant temperature with circulating water from the thermostat. The reactions were initiated by addition of a few microlitres of the substrate dissolved in acetonitrile by means of a spring-loaded syringe. The concentration of the substrate was $<0{\cdot}1$ mM. The reaction solution was analysed at appropriate intervals on the HPLC apparatus. The mol% of the starting material and each of the products were measured by means of the relative response factors, which were determined in separate experiments. The rate constants were calculated from plots of ln(area of starting material) or ln(mol%) versus time and product compositions. The response factor of the azide **1-N$_3$** was assumed to be the same as that of **2**. Corrected total peak areas in experiments in which the half-life of the substrate was a few hours or less with and without azide did not differ significantly, indicating similar response factors. In the slow reactions of **1-OMe** with formic acid buffers, fluorene was used as an internal standard; the rate constants were calculated from plots of ln(area of substrate/area of reference) versus time.

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