Kinetics and Mechanism of the Acid-Catalysed Hydrolysis of Benzaldehyde Diaryl Thioacetals and of Benzaldehyde *S*-Aryl, *S*-Ethyl Acetals in Aqueous Perchloric Acid

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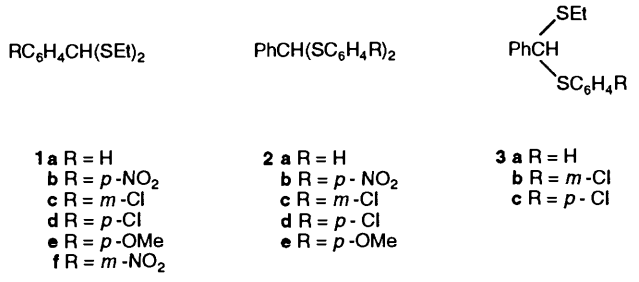
The effects on the rate of hydrolysis of changes in aryl substituents, acid concentration, temperature, and solvent isotope, show that the acid-catalysed hydrolyses of five benzaldehyde diaryl thioacetals and three benzaldehyde *S*-aryl, *S*-ethyl acetals in 2–7 mol dm^{-3} aqueous perchloric acid proceed *via* essentially A1 mechanisms. The pattern of the substituent effects found for the leaving, and remaining, *S*-aryl groups is similar to that found previously for leaving and remaining groups in *O,O*- and *O,S*-acetals.

Little previous work concerns the kinetics of the Brönsted acid-catalysed hydrolysis of open-chain *S,S*-acetals,[1] but we reported recently[2] on the hydrolyses in aqueous perchloric acid of a series of substituted benzaldehyde diethyl thioacetals, (**1**). We describe now, for similar conditions, the hydrolytic behaviour of



benzaldehyde diaryl thioacetals, (**2**), and of benzaldehyde *S*-aryl, *S*-ethyl acetals, (**3**). Eqns. (1) and (2) show the overall reactions. Dithioacetals hydrolyse very slowly compared with

$$(2) + H_2O \xrightarrow{H_3O^+} PhCHO + 2RC_6H_4SH \quad (1)$$

$$(3) + H_2O \xrightarrow{H_3O^+} PhCHO + RC_6H_4SH + EtSH \quad (2)$$

the corresponding *O,O*-acetals, and relatively concentrated solutions of Brönsted acids are required to provide convenient rates of hydrolysis. For all the thioacetals studied here, the rates of the spontaneous hydrolyses are negligibly slow compared with the acid-catalysed rates now reported.

Experimental

Materials.—Thioacetals **2** were prepared from benzaldehyde and the appropriate benzene thiol (Aldrich) by the general method[2] used previously for compounds **1**. These symmetrical diaryl thioacetals are solids, or high-boiling liquids. All had appropriate NMR spectra, and their m.p. or b.p. (Torr) were **2a**, 83; **2b**, 138; **2c**, 45; **2d**, 122 (1 Torr); **2e**, 77 °C. Hydrolysis led to excellent yields of the expected products. Thioacetals **3** containing most of the above R groups, were prepared in two steps. First, the corresponding benzaldehyde *S*-aryl, *O*-methyl acetal was prepared using Jensen's method.[3] The crude *O,S*-acetals were purified by vacuum distillation, and all had appropriate NMR spectra. In the second step, equimolar amounts of the *S*-aryl, *O*-methyl acetal and of ethane thiol were dissolved in methylene chloride–diethyl ether containing boron trifluoride. After standing for 2 h at 25 °C the product was worked up as in our other *S*-acetal preparations.[2,4] The NMR spectra showed that in most cases the (liquid) product contained 60–65% of the desired mixed *S,S*-acetal **3**, with the remainder being approximately equal (17–20%) amounts to the diethyl **1a** and diaryl **2** thioacetals. Various attempts to obtain samples containing a higher percentage of **3** failed. For some of the aryl substituents used, the mixture of **1a**, **2** and **3** proved satisfactory for kinetic studies of the hydrolysis of **3** – see below. All the other materials employed are described in our previous work with thioacetals.[2,5]

Kinetics.—As for the diethyl derivatives **1**, the hydrolyses of **2** and **3** were monitored by UV spectroscopy, and the same general procedure was adopted.[2,5] Thioacetals **1**, and the ethane thiol product, absorb only weakly in the region 230–300 nm, and the spectral change observed in the hydrolysis of **1** is essentially the appearance of the aldehyde absorption (centred at *ca.* 250 nm for **1a**). Thioacetals **2** and **3** absorb moderately in the region 230–300 nm, their absorbance increasing steadily from long to short wavelengths. On hydrolysis this absorption falls in the long and short wavelength regions, and the spectrum characteristic of benzaldehyde and the appropriate benzene thiol increases in the centre of the region (at *ca.* 250 nm). Good isobestic points were observed for all the systems studied. *S,S*-Acetals **2** and **3** are less soluble than **1**, so our initial concentrations were normally *ca.* 1×10^{-5} mol dm^{-3}; reaction mixtures contained 1–2% dioxane, and remained homogeneous throughout a run. The pure thioacetals **2** lead to benzaldehyde and two moles of the benzene thiol [eqn. (1)]; artificial product mixtures had spectra in excellent agreement with those obtained at the end of kinetic runs. At a given acid concentration the thioacetals **2** were found to hydrolyse more slowly than **1a**, and the thioacetals **3** also hydrolyse more slowly than **1a** if the substituent R in **3** is either H or electron-withdrawing. These latter thioacetals can also hydrolyse much more rapidly than their diaryl analogue **2**. The detailed acid dependencies of the observed first-order rate constants, k_{obs}, for **1a**, **2** and **3** are also slightly different, and by working in appropriate acidity ranges it was sometimes possible to study the hydrolysis of mixtures of **1a**, **2** and **3** under circumstances where the desired hydrolysis of **3** was monitored after that of the contaminant **1a** was largely complete, and that of **2** had scarcely begun. In these experiments it was occasionally necessary to allow about one half-life of the hydrolysis of **3** to occur before taking measurements, to measure the absorbance changes during the second and third half-lives, and to use a computer programme to establish the appropriate infinity value. In this way distortions of the

Table 1 Catalytic rate constants and $m^{\ddagger}$ values at 25 °C

	1[a]		2		3	
R[b]	$10^6 k_{H^+}$/dm^3 mol^{-1} s^{-1}	$m^{\ddagger}$	$10^6 k_{H^+}$/dm^3 mol^{-1} s^{-1}	$m^{\ddagger}$	$10^6 k_{H^+}$/dm^3 mol^{-1} s^{-1}	$m^{\ddagger}$
p-NO_2	2.5	1.2	0.21	1.1		
m-Cl	12	1.7	0.50	1.0(4)	53	1.2
p-Cl	52	1.7	4.6	1.2	95	1.2
H	191	1.5	28	1.2	150	1.3
p-OMe	1950	2.6	134	0.95		

[a] From ref. 2. [b] In **1**, **2** or **3**.

Table 2 Effects of temperature on k_{obs}

Acetal	$[H_3O^+]$/mol dm^{-3}	*T*/°C	$10^4 k_{obs}$/s^{-1}	$\Delta H^{\ddagger}$/kJ mol^{-1}	$\Delta S^{\ddagger}$/J K^{-1} mol^{-1}
2a	2.40	24.0	4.4		
		31.0	10		
		36.2	20		
		42.6	48	100 ± 12	3 ± 0.5
2d	4.40	19.7	6.4		
		24.8	14		
		31.7	41		
		38.2	140	123 ± 15	66 ± 10
2c	5.00	25.4	5.5		
		33.3	15		
		38.0	30		
		45.1	78	104 ± 12	−20 ± 4
3a	2.60	19.1	24		
		24.7	53		
		30.8	130		
		37.0	240	95 ± 11	−2 ± 0.3
1a[a]				90 ± 3	−13 ± 0.5

[a] From ref. 2.

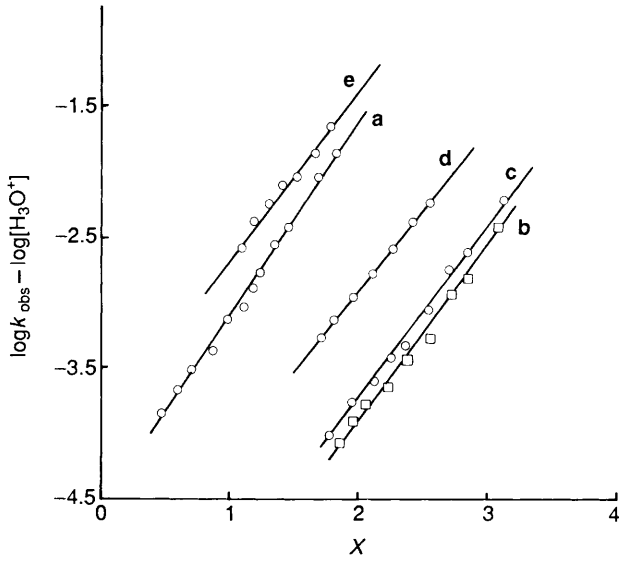


Fig. 1 Plots against the excess of acidity for the acetals **2a–e** at 25 °C

observed hydrolysis of the major component of these acetal mixtures by the minor components was largely avoided. In most cases the hydrolysis of **3** was complete before any significant hydrolysis of **2** had occurred; infinity spectra were then in satisfactory agreement with those of artificial product mixtures based on the (approximate) content of the sample being hydrolysed. For both thioacetals **2** and **3**, k_{obs} was normally reproducible to within ± 12%. Besides the effect of acid concentration on k_{obs}, we studied the effects of temperature, and of a deuteriated solvent. Our results are in Tables 1 and 2 and Figs. 1 and 2.

Results and Discussion

Hydrolysis of S,S-*Acetals* **2**.—We studied five thioacetals, **2**. Convenient rates of hydrolysis were obtained in the range 2–7 mol dm^{-3} perchloric acid. For each thioacetal k_{obs} increases more rapidly than does $[H_3O^+]$, and plots of log k_{obs} − log $[H_3O^+]$ against *X* (the excess acidity[6]) are rectilinear (Fig. 1). The slopes[7] of these plots ($m^*m^{\ddagger}$) are all > 1, and assuming[6] that $m^* \sim 1.3$ for these *S*-bases, give values of $m^{\ddagger}$ close to, but normally > 1 (Table 1). The second-order (catalytic) rate constants k_{H^+}, can be obtained[7] from the intercepts of the plots in Fig. 1, and are given in Table 1. A Hammett plot against σ gives $\rho \sim -2.7$, with the point for the *m*-Cl derivative below the line. The effects of temperature on k_{obs} for three of the thioacetals are illustrated in Table 2. $\Delta S^{\ddagger}$ is positive or slightly negative. Finally, the solvent deuterium isotope effect for **2a** measured at $[L_3O^+] = 1.90$ mol dm^{-3} and at %D = 90.6 is $k_{obs}^{D}/k_{obs}^{H} \sim 1.5$ (Table 3).

Several thioacetals **1** have been shown to hydrolyse in perchloric acid *via* the A1 mechanism, with perhaps some shift towards the AS_E2 mechanism for the least reactive **1b** or **f** compounds.[2] The A1 scheme for **1** is given in eqn. (3)–(6). In the AS_E2 mechanism[1] steps (3) and (4) are amalgamated into a single slow step. Different degrees of concertedness and proton transfer are conceivable.[1] With **1** no evidence for the accumulation of the hemithioacetal **5** is found, and such accumulation would not be expected in hydrolyses of open-chain *S*,*S*-acetals.[2] We have also identified clear-cut AS_E2 mechanisms for certain cyclic *S*,*S*-acetals,[5] and the A2 mechanism for particularly unreactive *S*,*S*-acetals.[5,8] On the basis of the patterns of behaviour found in these previous studies, the various results for the thioacetals **2** outlined above point to an essentially A1 mechanism of hydrolysis, with possibly some AS_E2 character. All the pieces of evidence are compatible with an A1 scheme, although the $m^{\ddagger}$ values are

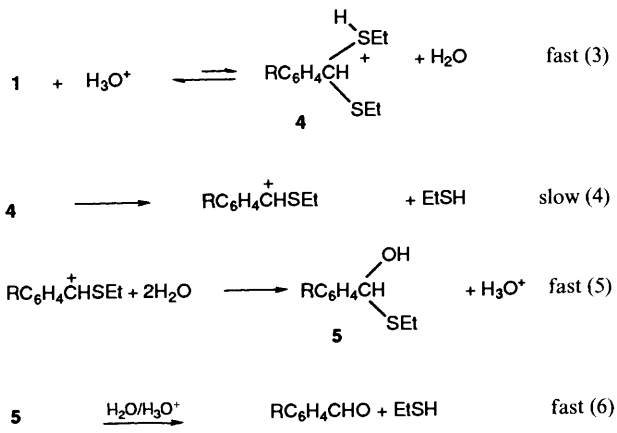


Table 3 Effect of isotopic solvent on hydrolysis of **2a** at 25 °C

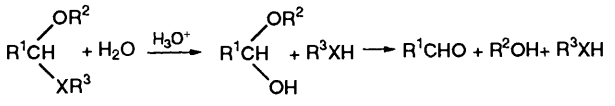
$[L_3O^+]$	$k^H_{obs}/10^{-4}$ s^{-1}	$k^D_{obs}/10^{-4}$ s^{-1}	k^D/k^H
1.90	2.52[a]	3.67[a]	1.46(±0.10)[b]

[a] Average values. [b] Deuterio-solvent contained 90.6% D.

rather small.[2,7] However, these values are significantly larger than would be expected[5,7] for a clear AS_E2 sheme, and the large (for *S*-protonation)[4,5] solvent isotope effect, and mainly positive values of $\Delta S^‡$, argue rather strongly against such a scheme,[9] whilst the acidity dependencies, the substantial deceleration produced by electron-withdrawing substituents, and (especially) the positive or slightly negative $\Delta S^‡$ values all argue against an A2 mechanism.[8,10]

No exact *O,O*- or *O,S*-analogues of **2** appear to have been studied mechanistically, so that comparisons of that sort are not yet possible. Acetals **6** can[11] have AS_E2 mechanisms, but the *O,S*-species **7** are believed[12] to hydrolyse *via* A1 mechanisms

with C–S cleavage. If we assume that essentially A1 schemes indeed apply to the thioacetals **2** (as seems likely) then the magnitude and direction of the observed substituent effects can be compared with existing collected findings[1,10] for open-chain *O,O*- and *O,S*-compounds. For such acetals **8** (X = O or S) it is found that, for the A1 mechanism, if any of the groups R^1, R^2 or R^3 (where R = alkyl or aryl) is made more electron-releasing, then the hydrolysis is accelerated (ρ is negative). The effect of a given change in the carbonyl moiety (R^1) is often rather



(7)

greater than the effect of a similar change in the remaining group (rg, R^2), while the latter is greater than the effect of a change in the leaving group (lg, R^3). A comparison of our present results with our previous findings[2] for the thioacetals **1** shows that for these *S,S*-acetals the sensitivity to substituent effects in the carbonyl moiety (for **1** $\rho \sim -2.9$) is approximately equal to the sensitivity to the combined effects of substituent changes in the leaving and remaining groups (for **2**

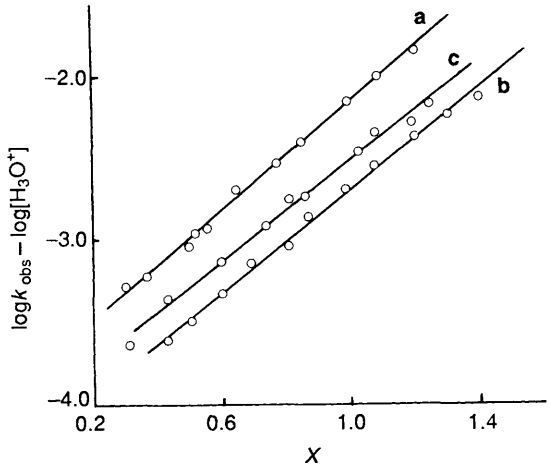


Fig. 2 Plots against the excess of acidity for the acetals **3a–c** at 25 °C

$\rho \sim -2.7$). That result is compatible with previous findings for *O,O*- and *O,S*-compounds, as outlined above. In a comparison of the absolute reactivities of **1**, (R = R) with **2** (R = R) we find (Table 1) that k_{H^+} for **1** is *ca.* 7–20-fold larger than k_{H^+} for **2**. Although simple comparisons of the effect of changing -SEt to -SPh for either the remaining or the leaving group to not appear to be available from earlier work,[1,10,13] results for *O,O*-acetals suggest a combined factor of this magnitude is reasonable. The results for the thioacetals **3** discussed below, throw more light on this point.

Hydrolysis of S,S-*acetals* **3**.—We studied three of these acetals under satisfactory kinetic conditions (see Experimental). As for most other *S,S*-acetals studied[2,5,8] in aqueous acid, k_{obs} increases faster than $[H_3O^+]$ and *X*-plots (Fig. 2) are rectilinear. For **3** the slopes of the *X*-plots are intermediate between those for the corresponding thioacetals **1** and **2**, and therefore lead to intermediate $m^‡$ values (Table 1). The k_{H^+} values, obtained from extrapolation of the *X*-plots, show that the substituents R have a notably smaller effect on the reactivity of **3** ($\rho \sim -1.2$) than on that of **1** or **2**. Work with acetals **6** and **7** indicates[11,12] that the -OAr (or -SAr) group is the (initial) leaving group in their hydrolyses. If it is assumed that this is also true for the *S,S*-acetals **3**, then the observed relatively small acceleration on increasing the electron-release of R is in line with expectations: a similar value[12] of ρ_{lg} (= −1.0) was found with **7**. For **2** $\rho \sim -2.7$. If we assume this value is approximately equivalent to $(\rho_{lg} + \rho_{rg})$ we find that $\rho_{rg} \simeq -1.5$ for **2**. This value is in line with results for *O,O*-acetals following an A1 mechanism.[3,10] Thus all the substituent effects are compatible with essentially A1 mechanisms of hydrolysis for both **2** and **3**. The value of $\Delta S^‡$ for **3a** is also supportive of an A1 scheme (Table 2). The activation parameters for **1a**, **3a** and **2a** show a systematic trend.

Comparisons of k_{H^+} values show that **3a** is *ca.* 1.3-fold less reactive than **1a** and *ca.* 5.5-fold more reactive than **2a**. Therefore changing the leaving group from -SEt to -SPh in **1a** has a rather small effect, and a significantly smaller effect than making the same change in the remaining group. This type of result is expected from existing work with *O,O*-acetals.[1,10] In all, our work with various open-chain *S,S*-acetals derived from benzaldehyde suggests that (i) their mechanism of hydrolysis in aqueous perchloric acid is predominantly A1 in type, and (ii) the general pattern of substituent effects conforms closely to that found for *O,O*-acetals believed to follow essentially A1 mechanisms (*i.e.* with proton transfer substantially more advanced than leaving group departure).

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