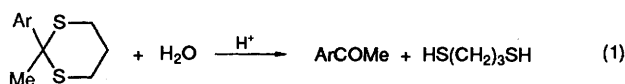


Mechanism of the Brønsted Acid Catalysed Hydrolysis of 2-Aryl-2-methyl-1,3-dithianes in Aqueous Perchloric Acid

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The acid catalysed hydrolysis of five *para*-substituted 2-aryl-2-methyl-1,3-dithianes in aqueous perchloric acid (3–9 mol dm⁻³) has been studied kinetically. The effect of changes in substituents ($\rho = -3.1$), temperature ($\Delta S^\ddagger = -38$ – 60 J K⁻¹ mol⁻¹) and acidity ($m^\ddagger = 0.54$ – 0.74), and the solvent isotope effects ($k_{\text{obs}}^{\text{D}_2\text{O}}/k_{\text{obs}}^{\text{H}_2\text{O}} < 1$), are all compatible with an essentially A_SE₂ mechanism for the MeO, Me, H and Cl derivatives. For the *p*-NO₂ compound the acidity dependence, and the values of ΔH^\ddagger and ΔS^\ddagger (ca. -200 J K⁻¹ mol⁻¹) suggest a change to an A₂-like mechanism. Our results are discussed in the light of previous work on acetal hydrolysis.

There exists little kinetic work concerning the Brønsted acid catalysed hydrolysis of *S,S*-acetals, although it is known that these compounds hydrolyse very slowly by comparison with their *O,O*-analogues.¹ Cyclic *S,S*-acetals are especially unreactive. We report now on the hydrolysis of some 2-aryl-2-methyl-1,3-dithianes in (concentrated) aqueous perchloric acid [eqn. (1)].



Experimental

Materials.—Five 2-aryl-2-methyl-1,3-dithianes were prepared from the corresponding acetophenones and propane-1,3-dithiol, with BF₃–Et₂O as catalyst, using the procedure previously described for other *S,S*-acetals.² The purified products had appropriate NMR spectra, and hydrolysed to give >97% yields of the acetophenone. Perchloric acid was of AnalaR grade, dioxane of spectrophotometric grade, and deuterium oxide (99.9 at. %) was the Aldrich product.

Kinetics.—Reactions were followed by observing the appearance of the acetophenone spectroscopically in the region 220–300 nm. The dithianes absorb rather weakly in this region, except for the *para*-nitro derivative which has a band centred at 276 nm. Good isosbestic points were obtained, and final absorbancies corresponded to effectively quantitative yields of the products [eqn. (1)]. Reactions were studied under pseudo-first-order conditions, and initiated by adding a small volume of a solution of the dithiane in dioxane to the acid solution. Reaction mixtures contained ca. 1% dioxane by volume. Reaction mixtures containing deuterium oxide were prepared by diluting perchloric acid (12.0 mol dm⁻³) in H₂O with D₂O. Accurately first-order behaviour was observed for over three half-lives, and the observed first-order rate constants, k_{obs} , were reproducible to within $\pm 10\%$. There was no evidence for the significant build-up of hemiacetal intermediate sometimes found in acetal hydrolysis. Most experiments were at 25 °C, but the effect of the temperature on k_{obs} was studied for three of the dithianes. Our values of k_{obs} , and the concentration and other conditions, are in the Tables and Fig. 1.

Results and Discussion

The hydrolyses were found to have convenient rates in the concentration range [HClO₄] = 3.0–9.0 mol dm⁻³. Fig. 1

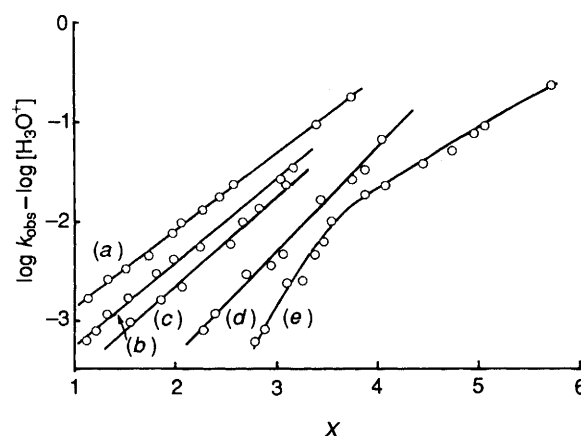
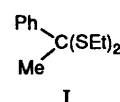


Fig. 1 Plots of $\log k_{\text{obs}} - \log [\text{H}_3\text{O}^+]$ vs. excess acidity [$\text{Dithiane}]_{\text{initial}} \approx 5 \times 10^{-5}$ mol dm⁻³; $T = 25.0 \pm 0.5$ °C; (a) *p*-MeO, (b) *p*-Me, (c) *p*-H, (d) *p*-Cl, (e) *p*-NO₂

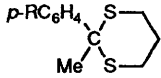
contains plots of $\log k_{\text{obs}} - \log [\text{H}_3\text{O}^+]$ vs. X , where X is the excess acidity.³ The data in Fig. 1 refer to 25 °C and the perchloric acid is assumed to be fully dissociated. Solvent isotope effects and some effects of temperature on k_{obs} are in Table 1. Cox and Yates have shown⁴ that plots such as those in Fig. 1 can be helpful in attempts to identify the mechanisms of Brønsted acid catalysis in strongly acidic media. In their treatment the slope of such plots equals the product of parameters m^*m^\ddagger , where m^\ddagger is related to transition-state structure. For *S*-substrates⁴ $m^* = 1.3$ – 1.6 . Using a value of 1.4 we find the values of m^\ddagger given in Table 2, which also contains data⁵ for the open-chain compound (I) for comparison. Values



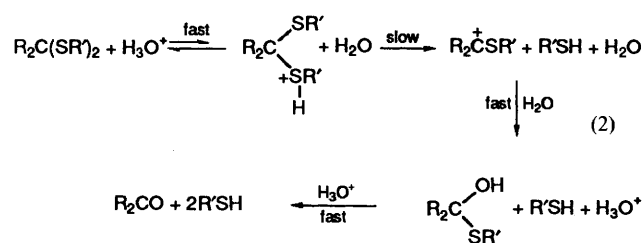
of m^\ddagger significantly greater than 1 are found for reactions with an A₁ mechanism,⁴ and there seems little doubt⁵ that compound I hydrolyses by such a mechanism [eqn. (2)] as do very many open-chain *O,O*-acetals.¹

Our present values of m^\ddagger lie in the range 0.54–0.74 for the four most reactive dithianes; these values are in the range considered⁴ normally to indicate an A_SE₂ mechanism. For acetal hydrolysis this corresponds¹ to eqn. (3). The X -plot for the *para*-nitro derivative has a shape we have not encountered

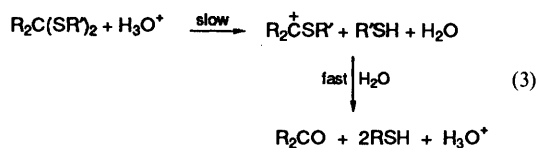
Table 1 Effects of temperature and isotopic solvent on k_{obs} ^a

R in		[H ₃ O ⁺]/mol dm ⁻³	T/K	$k_{\text{obs}}/10^{-4}$ s ⁻¹	$\Delta H^\ddagger/\text{kJ mol}^{-1}$	$\Delta S^\ddagger/\text{J K}^{-1}$ mol ⁻¹
(i) Effects of temperature						
MeO		3.80	299.0	1.25	} 93 ± 4	-38 ± 4
			309.0	4.27		
			312.8	6.72		
			317.8	11.8		
H		5.15	298.5	1.35	} 99 ± 6	-37 ± 4
			305.0	3.15		
			311.7	7.18		
			317.8	15.7		
Cl		6.71	297.8	3.10	} 96 ± 4	-59 ± 5
			305.6	9.58		
			313.0	19.52		
			317.3	40.0		
NO ₂		7.32	298.2	2.78	} 65 ± 5	-195 ± 10 (-160 ± 10)
			304.9	5.10		
			314.6	11.3		
(ii) Solvent isotope effect						
		$k_{\text{obs}}^{\text{D}_2\text{O}}/k_{\text{obs}}^{\text{H}_2\text{O}}$				
MeO		0.90 ± 0.04 ^b				
H		0.96 ± 0.04 ^c				

^a [Dithiane]_{initial} ~ 5 × 10⁻⁵ mol dm⁻³; for k_{obs} see text. ^b 84 at. % D, [L₃O⁺] = 3.70 mol dm⁻³. ^c 75 at. % D, [L₃O⁺] = 4.9 mol dm⁻³.



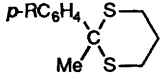
before. Non-rectilinear X -plots bending towards the X axis are often found⁴ to characterise A2 mechanisms of hydrolysis, but



to date the examples refer to aqueous sulphuric acid as the medium. Perhaps curve (e) in Fig. 1 is of this type. The slope m^*m^\ddagger of the steepest part is *ca.* 1.4, so that $m^\ddagger \approx 1.0$, a value considered characteristic of some A2 reactions.⁴ We shall argue further below for the correctness of these assignments of mechanism, but whatever the true interpretation, it seems clear from the X -plots that: (i) these cyclic *S,S*-acetals derived from acetophenone have a different mechanism of hydrolysis from that (A1) enjoyed by the open-chain diethyl derivative; and (ii) there occurs some change in the mechanism on moving from the *p*-MeO to the *p*-NO₂ derivative.

AS_E2 mechanisms⁶ are normally characterised by ΔS^\ddagger values that are more negative than those for A1 mechanisms but less negative than those for A2 mechanisms. Our activation parameters are in Table 1 (and Table 2 for acetal I). The calculation of ΔS^\ddagger requires the second-order catalytic rate

Table 2 Values of k_{H^+} and m^*m^\ddagger

Compound	$k_{\text{H}^+}/10^{-7}$ dm ³ mol ⁻¹ s ⁻¹	m^*m^\ddagger	m^\ddagger
R in 			
MeO	39	0.76	0.54
Me	15	0.82	0.59
H	5.0	0.92	0.66
Cl	0.67	1.03	0.74
NO ₂	0.017	1.44	1.03
I ^a	2.60 × 10 ⁴	3.96	—

^a $k_{\text{obs}}^{\text{D}_2\text{O}}/k_{\text{obs}}^{\text{H}_2\text{O}} = 1.33 \pm 0.10$; 99 at. % D, [L₃O⁺] = 0.05 mol dm⁻³; $\Delta H^\ddagger = 98 \pm 5$ kJ mol⁻¹, $\Delta S^\ddagger = 42$ J K⁻¹ mol⁻¹.

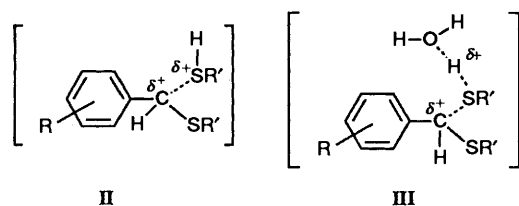
constant, k_{H^+} . This can be obtained from our results in two (approximate) ways: either⁴ the (mostly rectilinear) plots in Fig. 1 can be extrapolated to $X = 0$, or it can be assumed that the stoichiometric acid molarity can be used to obtain k_{H^+} from k_{obs} . We used the second method in our preliminary publication,⁷ but now consider the extrapolation a more valid and accurate method of calculating k_{H^+} ; it was also the method used⁵ for the open-chain acetal I. Our values of k_{H^+} are in Table 2, and lead to the ΔS^\ddagger values in Table 1. For the *p*-NO₂ derivative we extrapolated the rectilinear part of the plot at the lowest X values (extrapolation of the region of the plot at the highest X values leads to the ΔS^\ddagger value given in parentheses in Table 1). It can be seen that all the ΔS^\ddagger values are < 0, and tend to become increasingly negative as the electron-withdrawing power of the *para*-substituent is increased. The values for the *p*-MeO, *p*-H, and *p*-Cl derivatives are typical of AS_E2 reactions. The value for the *p*-NO₂ compound is substantially more negative; it seems unlikely to arise from a normal A1 or AS_E2 mechanism, but is compatible with an A2 scheme. ΔH^\ddagger is also

notably smaller for the *p*-NO₂ derivative, a fact also suggestive of change in mechanism.

The effects on k_{obs} of changing the substituents in remaining groups in reactions following A1 and AS_E2 mechanisms are generally found to be rather similar, whereas A2 mechanisms show a less strong dependence on such changes, since opposed substituent effects are involved in an A2 mechanism. A Hammett plot for the A1 hydrolyses of a series of open-chain *S,S*-acetals⁵ ArCH(SET)₂ gives $\rho \approx -2.9$. The present dithianes give $\rho \approx -3.1$. The point for the *p*-NO₂ compound falls above the best line using k_{H^+} (Table 2) obtained from extrapolation of the steepest slope in Fig. 1(e), and considerably above it using any appreciably lower slope for the extrapolation. These results also seem compatible with essentially AS_E2 mechanisms for the most reactive dithianes, but with a change to a more A2-like scheme for the *p*-NO₂ derivative.

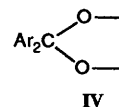
The deuterium solvent isotope effects on the reactions of the *p*-MeO and *p*-H compounds, $k_{\text{obs}}^{\text{D}_2\text{O}}/k_{\text{obs}}^{\text{H}_2\text{O}} < 1$ (Table 1), when compared with the value⁵ $k_{\text{obs}}^{\text{D}_2\text{O}}/k_{\text{obs}}^{\text{H}_2\text{O}} = 1.3$ for the A1 mechanism of acetal I (Table 2), are also qualitatively compatible with AS_E2 mechanisms for the former compounds. Solvent isotope effects are not particularly well understood for *S*-substrates, or for strongly acidic media⁸ but values less than 1 do suggest some contribution from slow proton transfer.

Various pieces of evidence therefore concur in pointing to an AS_E2 mechanism for the most reactive dithianes with perhaps some shift towards an A2-like mechanism as the reactivity of the dithianes fall. This picture is in harmony with some relevant previous work. Thus for a series of substituted benzaldehyde *S,S*-diethyl acetals the mechanism was considered⁵ gradually to change from a simple A1 process with a transition state such as II, involving a strongly *S*-bound proton and considerable cleavage of the C–S bond, for the acetals with the most electron-releasing groups (R), to a transition state III with less strongly



S-bound proton, and less C–S cleavage, for the (least reactive) acetals for which proton transfer and formation of the carbocation are least favourable. Cyclic acetals have always been found^{1,9} to be notably less reactive than their open-chain analogues towards acid catalysed hydrolysis both in the *O,O*- and the *S,S*-series. Different reasons have been proposed, and there has been much debate about the mechanisms involved for cyclic acetals.¹ We suggest that the lower reactivity arises from a combination of more difficult protonation and C–S cleavage. If

this is so, the trend observed⁵ for the benzaldehyde *S,S*-diethyl acetals make an AS_E2 mechanism reasonable for our present cyclic compounds. 1,3-Dioxolanes derived from substituted benzophenones IV also display¹⁰ AS_E2 mechanisms whereas



acetals ArCH(OEt)₂ do so less markedly.¹¹ A change in the balance between the ease of protonation and of leaving group departure presumably controls the change from A1 to AS_E2 character. Slow proton transfer to sulfur has been postulated more than once in acid catalysed *S*-ester hydrolysis,¹² and its previous apparent absence¹ in *S*-acetal hydrolysis is very surprising.

For relatively very unreactive acetals for which the stability of the carbocation is very low, the departure of the leaving group may require assistance from a nucleophilic attack at carbon by one, or more, water molecules; alternatively, the very reactive carbocation may react so rapidly with water that the water molecule becomes involved before the cation is fully formed. Both circumstances correspond to an effectively A2 mechanism of hydrolysis, which we suggest for the 1,3-dithiane of *para*-nitroacetophenone. This type of mechanism has been proposed before for unreactive *O,O*-acetals.^{1,13} It is noteworthy that in the first two systematic studies of Brønsted acid catalysed *S,S*-acetal hydrolysis we have had to call on all the main mechanisms postulated for *O,O*-acetals.¹

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