The Kinetics and Mechanism of the Hydrolysis of Thiol Esters in Aqueous Solution promoted by Tetrachlorogold(III) Ions

By **Geeta Patel** and **Rosemary S. Satchell,*** Department of Chemistry, Queen Elizabeth College, Campden Hill Road, London W8 7AH
(in part) **Derek P. N. Satchell**, Department of Chemistry, King's College, Strand, London WC2R 2LS

The hydrolysis of *S*-ethyl *p*-methoxy- and of *S*-ethyl *p*-nitro-thiobenzoate is promoted by tetrachlorogold(III) and related ions. The hydrogen ion-catalysed hydrolysis is very slow by comparison. Kinetic studies show that in the promoted reactions, at suitable ambient chloride concentrations, simultaneous promotion by $AuCl_4^-$, $AuCl_3(OH)^-$, and $AuCl_3(H_2O)$ is involved. Substituent effects, activation parameters, solvent isotope effects, and the absence of a common ion effect at high chloride ion concentrations all combine to suggest that the reaction mechanism involves slow metal transfer to sulphur.

KINETIC studies of the soft metal ion-promoted hydrolysis of thiol esters using aqueous solutions of low pH [reaction (1)] have shown [1-3] that Cu^{2+}, Ni^{2+}, Pb^{2+}, and Cd^{2+} ions have little or no effect on the rate of hydrolysis whereas Tl^{3+}, Hg^{2+}, Hg_2^{2+}, and Ag^+ ions have powerful effects much greater than that of the hydrogen ion. For

$$RC_6H_4COSEt + M^{n+} + 2H_2O \longrightarrow RC_6H_4CO_2H + EtSM^{(n-1)+} + H_3O^+ \quad (1)$$

these latter ions with *S*-ethyl *p*-substituted thiobenzoates, previous results suggest for the *p*-nitro-derivative an $A_{Ac}2$-type mechanism with each ion and for the *p*-methoxy-derivative an $A_{Ac}1$ mechanism with each ion except Ag^+, where it is $A_{Ac}2$.

Tetrachlorogold(III) and related ions have been found to be very powerful promoters of the hydrolysis of thiobenzimidate esters [4] and of thiobenzamides.[5] We now report on their promotion of the hydrolysis of *S*-ethyl *p*-methoxy- and *S*-ethyl *p*-nitro-thiobenzoate.

EXPERIMENTAL

Materials.—Ethanol, perchloric acid, sodium perchlorate, and sodium chloride were of AnalaR grade and sodium tetrachlorogold(III) was a Johnson Mathey product. The *S*-esters were previous samples.[3] Deuterium oxide (99.7%) was the Goss Scientific Instruments product. All solutions (except those containing deuterium oxide) were made up with fresh, doubly distilled water.

Reaction Mixtures.—Reaction mixtures were made up by volume from stock solutions. Stock solutions of the esters were made up in ethanol which facilitates the dissolution of the ester in the final aqueous reaction mixtures which, as a result, usually contained 2% (v/v) ethanol. In addition to the ester, reaction mixtures contained known amounts of sodium tetrachlorogold(III), sodium chloride, perchloric acid, and sodium perchlorate, the latter being used to maintain constant ionic strength (usually 0.5 mol dm^{-3}). Reaction mixtures containing deuterium oxide had 98.1—99.6 atom % D.

Kinetic Arrangements.—The hydrolyses were monitored by u.v. spectroscopy in the 280—290 nm region using a Unicam SP 500 spectrophotometer. Normally the gold ions were present in at least a seven-fold excess over the *p*-nitro-ester (4×10^{-5} mol dm^{-3}) and a ten-fold excess over the *p*-methoxy-ester ($\leqslant 2.5 \times 10^{-5}$ mol dm^{-3}). Under these conditions the *p*-methoxy-ester hydrolyses showed good first-order behaviour over at least three half-lives and the *p*-nitro-ester hydrolyses over two half-lives. Values of the first-order rate constant (k_{obs}) were obtained using standard procedures. The effect on k_{obs} of variations in the gold chloride, the chloride, and the hydrogen ion concentrations and in the temperature were examined. For all systems studied values of k_{obs} were reproducible to ±2% and the contributions to the rate of hydrolysis from the hydrogen ion-catalysed and spontaneous rates were negligible. Some precipitation of gold species (probably mercaptides) occurred from reaction mixtures left for long periods, but this did not interfere with the kinetic measurements. Typical results are in Tables 1 and 2.

Products.—For each ester, preparative-scale experiments were carried out using concentration conditions as close as feasible to those used for the kinetic runs. In each case the expected benzoic acid was isolated in >80% yield. The mercaptide products were obtained as brown solids. The u.v. spectral changes observed during kinetic runs suggest that the hydrolyses proceed in effectively quantitative yield.

RESULTS AND DISCUSSION

Dissolution of sodium tetrachlorogold(III) in water leads to the rapid formation of a variety of gold species, the exact concentrations of each depending upon the ambient chloride and hydrogen ion concentrations and the temperature.[6,7] For our systems in H_2O the relevant species are $AuCl_4^-$, $AuCl_3(OH)^-$, and $AuCl_3(H_2O)$. When a deficit of either *S*-ester is added to an aqueous solution containing these gold(III) species there is no spectroscopic evidence for formation of gold–*S*-ester adducts.

Kinetics.—(i) *Variation in total* (*stoicheiometric*) *gold concentration*, $[AuCl_4^-]_S$. At constant ionic strength (I) and temperature, and at fixed values for the hydrogen ion and chloride ion concentrations, these being at least ten-fold greater than $[AuCl_4^-]_S$, plots of k_{obs} against $[AuCl_4^-]_S$ are rectilinear and pass through the origin for both esters (*e.g.* Figure 1). It follows that, under these conditions, $k_{obs} = k[AuCl_4^-]_S$. An increase in ionic strength leads to a decrease in k_{obs} (Figure 1).

(ii) *Variation in chloride ion concentration and in pH* (*Tables* 1 *and* 2). The two esters show some differences in their dependence on the chloride ion concentration.

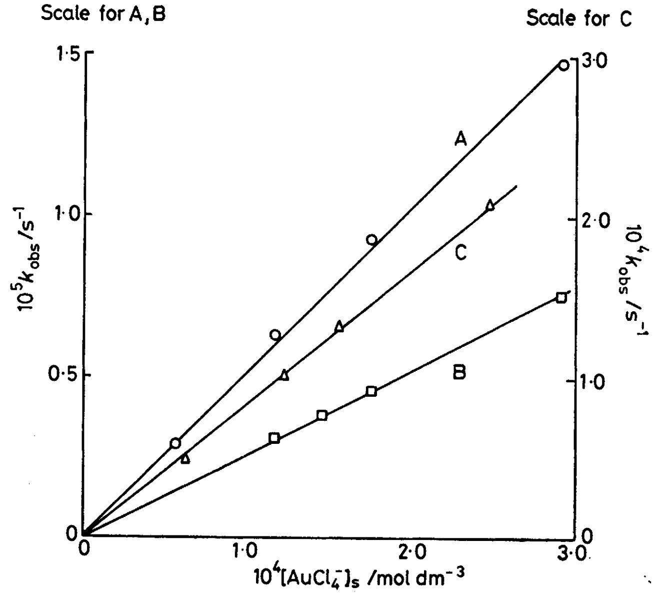


FIGURE 1 Dependence of k_{obs} on $[AuCl_4^-]_S$. A, *p*-Methoxy-ester, *t* 26.0 °C, $[Cl^-]_S$ 0.10, $[H_3O^+]_S$ 0.010, *I* 0.11 mol dm^{-3}; B, as for A but *I* 0.50 mol dm^{-3}; C, *p*-nitro-ester, *t* 60.1 °C, $[Cl^-]_S$ 0.10, 10^3 $[H_3O^+]_S$ 1.92, *I* 0.50 mol dm^{-3}

(*a*) *p*-Methoxy ester. At fixed values of $[AuCl_4^-]_S$, pH, *I*, and temperature, an increase in the concentration of added chloride ions, $[Cl^-]_S$, from 0.01 to 0.50 mol dm^{-3} has very little effect on k_{obs}, but when $[Cl^-]_S \leqslant 0.01$ mol dm^{-3} k_{obs} gradually increases as $[Cl^-]_S$ is decreased. The overall change in k_{obs} is small.

TABLE 1

Typical values of k_{obs} for the hydrolysis of *S*-ethyl *p*-methoxythiobenzoate. Concentrations in mol dm^{-3}; $[X]_S$ concentration of added X; k_{obs} in s^{-1}; solvent 2% (v/v) ethanol–water; $[Ester]_S \leqslant 2.5 \times 10^{-5}$

(i) Effect of changes in $[AuCl_4^-]_S$ ($[Cl^-]_S$ 0.10; $[H_3O^+]_S$ 0.01; *I* 0.11 and 0.50; temperature 26.0 °C)
See Figure 1

(ii) Effect of changes in $[Cl^-]_S$ at 26.0 °C ($[AuCl_4^-]_S$ 3.00×10^{-4}; *I* 0.50)

(a) $[H_3O^+]_S$ 2.17×10^{-2}

$10^3[Cl^-]_S$	1.39	2.78	5.56	13.9	139	498
10^4k_{obs}	1.45	1.12	0.941	0.845	0.780	0.778

(b) $[H_3O^+]$ 1.97×10^{-3}

$10^3[Cl^-]_S$	5.56	13.9	27.8	139
10^5k_{obs}	8.56	8.06	7.82	7.81

(c) $[H_3O^+]_S$ 9.85×10^{-4}

$10^3[Cl^-]_S$	5.56	13.9	52.1	139
10^5k_{obs}	7.94	7.84	7.88	7.83

(iii) Effect of changes in $[Cl^-]_S$ at 35.1 °C ($[AuCl_4^-]_S$ 3.08×10^{-4}; $[H_3O^+]_S$ 1.92×10^{-3}; *I* 0.51)

$10^3[Cl^-]_S$	0.524	1.05	2.62	50.0	99.9	500
10^4k_{obs}	1.99	1.87	1.81	1.54	1.54	1.54

TABLE 2

Typical values of k_{obs} for the hydrolysis of *S*-ethyl *p*-nitrothiobenzoate. Symbols and units as in Table 1; solvent 2% (v/v) ethanol–water; $[Ester]_S$ 4.1×10^{-5}; *I* 0.50

(i) Effect of changes in $[AuCl_4^-]_S$ at 60.1 °C ($[Cl^-]_S$ 0.1; $[H_3O^+]$– 1.92×10^{-3})
See Figure 1

(ii) Effect of changes in $[Cl^-]_S$ at 45.5 °C ($[AuCl_4^-]_S$ 3.01×10^{-4})
(a) $[H_3O^+]_S$ 1.97×10^{-3}

$10^3[Cl^-]_S$	13.9	52.2	139	348
10^6k_{obs}	28.9	12.5	8.02	5.96

(b) $[H_3O^+]_S$ 2.07×10^{-2}

$10^3[Cl^-]_S$	5.56	13.9	139	348
10^6k_{obs}	54.8	25.7	7.16	6.04

(c) $[H_3O^+]_S$ 5.02×10^{-2}

$10^3[Cl^-]_S$	5.56	20.9	52.3	209
10^6k_{obs}	53.6	18.6	10.6	6.68

(iii) Effect of changes in $[Cl^-]_S$ at 60.1 °C ($[AuCl_4^-]_S$ 3.12×10^{-4}; $[H_3O^+]_S$ 1.92×10^{-3}

$10^3[Cl^-]_S$	50.2	75.3	100	251	301	500
10^5k_{obs}	3.27	2.83	2.62	2.19	2.15	2.07

At the chloride ion concentrations and pH values used in our various experiments the tetrachlorogold ion undergoes [6,7] the rapid reactions shown in equations (2) and (3). The equilibrium constants imply that, at the pH

$$AuCl_4^- + H_2O \xrightleftharpoons{K_1} AuCl_3(H_2O) + Cl^- \qquad (2)$$
$$K_1\ 9.5 \times 10^{-6}\ \text{mol dm}^{-3} \text{ at 25 °C*}$$

$$AuCl_3(H_2O) + H_2O \xrightleftharpoons{K_a} AuCl_3(OH)^- + H_3O^+ \qquad (3)$$
$$K_a\ 0.25\ \text{mol dm}^{-3} \text{ at 25 °C*}$$

values used in the experiments on the variation of chloride ion concentration, > 96% of the gold is present as $AuCl_4^-$ when $[Cl^-]_S > 0.05$ mol dm^{-3}. Thus, for these conditions, we can write $k_{obs} \simeq k_1[AuCl_4^-]_f$, where f denotes the free species and k_1 the second-order rate constant for promotion by $AuCl_4^-$. When $[Cl^-]_S \lesssim 0.05$ mol dm^{-3} $AuCl_4^-$ is progressively replaced by (mainly) $AuCl_3(OH)^-$ plus some $AuCl_3(H_2O)$. Assuming that all three species contribute to the promotion we can write equation (4). Since $[AuCl_3(H_2O)]_f = K_1[AuCl_4^-]/[Cl^-]_f$ and

$$k_{obs} = k_1\,[AuCl_4^-]_f + k_2[AuCl_3(H_2O)]_f + k_3\,[AuCl_3(OH)^-]_f \qquad (4)$$

$[AuCl_3(OH)^-]_f = K_1K_a\ [AuCl_4^-]_f/[Cl^-]_f[H_3O^+]_f$, equation (4) can be rewritten as (5). For any particular

$$\frac{k_{obs}}{[AuCl_4^-]_f} = k_1 + \frac{k_2\,K_1}{[Cl^-]_f} + \frac{k_3\,K_1\,K_a}{[Cl^-]_f[H_3O^+]_f} \qquad (5)$$

reaction mixture $[AuCl_4^-]_f$, $[Cl^-]_f$, and $[H_3O^+]_f$ can be calculated using the known values of K_1 and K_a. Equation (5) predicts that, at fixed pH, a plot of $k_{obs}/[AuCl_4^-]_f$ against $1/[Cl^-]_f$ will be rectilinear with an intercept k_1 and slope $S = (k_2K_1 + k_3K_1K_a/[H_3O^+]_f)$. Typical plots are in Figure 2. By studying the effect of $[Cl^-]_S$ on k_{obs} at different pH values (Table 1) plots of equation (5) can be constructed for different values of $[H_3O^+]_f$. A plot of the resulting *S* values against $1/[H_3O^+]_f$ leads to a

---

* The temperature dependence of K_1 can be calculated from known [6] ΔH values; K_a was assumed to be little dependent on temperature.

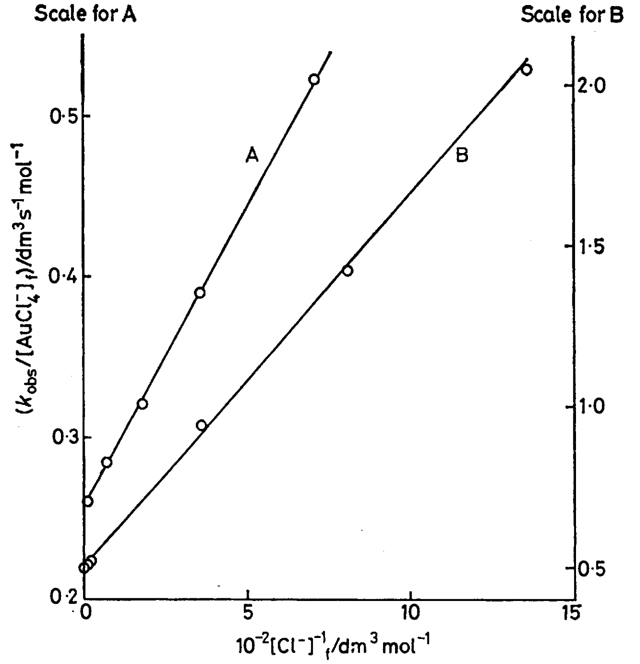


FIGURE 2 Typical plots of equation (5) for *p*-methoxy-ester. A, $10^2[H_3O^+]_S$ 2.17 mol dm^{-3}, *t* 26.0 °C; B, $10^3[H_3O^+]_S$ 1.92 mol dm^{-3}, *t* 35.1 °C

straight line with intercept k_2K_1 and slope $k_3K_1K_a$. The analysis thus leads to values for the second-order rate constants k_1—k_3. Good rectilinear plots were obtained in all cases even when $[Cl^-]_f < 10^{-3}$ mol dm^{-3}. Our kinetic data are clearly compatible with the analysis and there is no evidence for significant contributions to promotion from species such as $[AuCl_2(H_2O)_2]^+$ and $[AuCl_2(H_2O)(OH)]$ under conditions of very low chloride ion concentration.[6,7] Values of k_1—k_3 at three temperatures are in Table 3; they indicate that the increase in k_{obs} found when $[Cl^-]_S \lesssim 0.01$ mol dm^{-3} is due to the relatively great reactivity of $AuCl_3(H_2O)$ compared with those of $AuCl_4^-$ and $AuCl_3(OH)^-$.

TABLE 3

Values of the rate constants derived from equation (5). Units of k_1—k_3 are mol^{-1} dm^3 s^{-1}

k_1	k_2	k_3	t/°C
p-Methoxy-ester			
0.257	35.6	0.122	26.0
0.495	64.0	0.173	35.1
0.953	124	0.258	45.0
1.35			49.9
p-Nitro-ester			
0.0182	47.0	0.157	45.5
0.0261			49.9
0.0612			60.1
0.0981			64.7

The rate constants in Table 3 were used to calculate (by standard methods[8]) the corresponding enthalpies and entropies of activation (Table 4).

(*b*) *p*-Nitro-ester. The main difference between the behaviour of the *p*-methoxy- and the *p*-nitro-esters is that for the latter there exists no region of chloride ion concentration in which k_{obs} is completely independent of $[Cl^-]_S$: for all values of $[Cl^-]_S$, as this concentration falls, k_{obs} increases (Table 2). This result can be understood in terms of the previous analysis if, for the *p*-nitro-ester, the reactivity of $AuCl_4^-$ is significantly lower relative to those of $AuCl_3(OH)^-$ and $AuCl_3(H_2O)$ than for the *p*-methoxy-ester. The hydrolysis of the *p*-nitro-ester was, in general, much slower than that of the *p*-methoxy-derivative under the same conditions. Plots of equation (5) for the *p*-nitro-derivative are in Figure 3. For this ester our examination of the effects of change in pH was conducted at one temperature only, 45 °C (Table 2). As for the *p*-methoxy-derivative, good rectilinear behaviour is observed. The derived second-order rate constants and the activation parameters for $AuCl_4^-$ (from k_1) are in Tables 3 and 4. As can be seen, both $AuCl_3(OH)^-$ and $AuCl_3(H_2O)$ are, indeed, found to be appreciably more reactive, relative to $AuCl_4^-$, than for the *p*-methoxy-ester.

TABLE 4

Activation parameters. Units of $\Delta H^‡$ and $\Delta S^‡$ are kcal mol^{-1} (kJ mol^{-1}) and cal mol^{-1} K^{-1} (J mol^{-1} K^{-1}), respectively

	p-Methoxy-ester	*p*-Nitro-ester
$\Delta H_1^‡$	13 ± 1 (53 ± 2)	17 ± 1 (72 ± 2)
$\Delta S_1^‡$	−18 ± 2 (−77 ± 7)	−13 ± 2 (−55 ± 7)
$\Delta H_2^‡$	12 ± 1 (50 ± 2)	
$\Delta S_2^‡$	−12 ± 2 (−50 ± 7)	
$\Delta H_3^‡$	7 ± 1 (29 ± 2)	
$\Delta S_3^‡$	−40 ± 2 (−166 ± 7)	

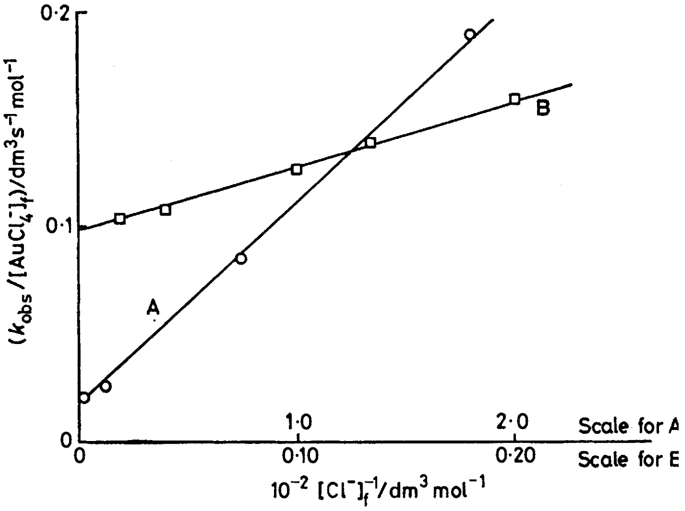


FIGURE 3 Typical plots of equation (5) for *p*-nitro-ester. A, *t* 45.5 °C, $10^2[H_3O^+]_S$ 2.07 mol dm^{-3}; B, *t* 64.7 °C, $10^3[H_3O^+]_S$ 1.92 mol dm^{-3}

(iii) *Kinetics in deuterium oxide.* The values of the equilibrium constants controlling reactions (2) and (3) are not known for solutions in deuterium oxide. It appears reasonable, however, to assume that at relatively high (>0.05 mol dm^{-3}) chloride ion concentrations and low pH (<3) the major fraction of the gold will exist as $AuCl_4^-$. For such conditions our results (Table 5) show that, for the *p*-methoxy-ester, the values of k_{obs}

TABLE 5

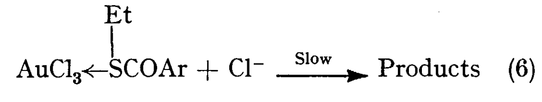
Comparison of k_{obs} in H_2O and D_2O. Concentrations in mol dm^{-3}; k_{obs} in s^{-1}; solvent 0.05% (v/v) ethanol–water; I 0.50 mol dm^{-3}

Atom % D	$10^4 \times [AuCl_4^-]_S$	$10^3[Cl^-]_S$	$10^3 \times [H_3O^+]_S$	$10^6 k_{obs}$	k_{H_2O}/k_{D_2O}
(a) $[p\text{-}MeOC_6H_4COSEt]_S$ 2.67×10^{-5}; temperature 26.0 °C					
99.6	3.40	144	1.85	90.7	0.98
0	3.45	144	1.85	89.8	
98.1	3.40	1.44	20.3	167	
0	3.45	1.44	20.3	176	1.04
(b) $[p\text{-}NO_2C_6H_4COSEt]_S$ 4.07×10^{-5}; temperature 45.5 °C					
99.6	3.40	144	1.85	9.70	0.84
0	3.45	144	1.85	8.31	
98.1	3.40	2.88	20.3	75.8	0.98
0	3.45	2.88	20.3	75.4	

in H_2O and D_2O are, within experimental error, the same. For the *p*-nitro-derivative the rate is slightly faster in D_2O. For values of pH and $[Cl^-]_S$ which, in H_2O, lead to significant contributions to k_{obs} from $AuCl_3(H_2O)$, we also find, in D_2O, no detectable isotope effect for either ester.

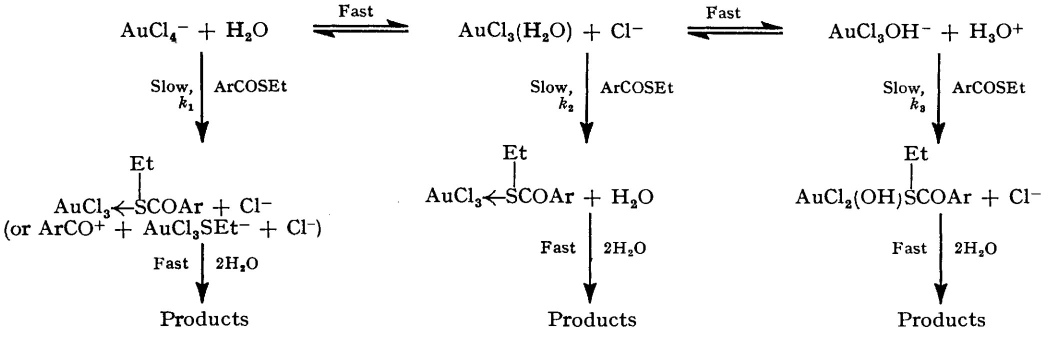
These results strongly suggest,[9] at least when $AuCl_4^-$ is the promoter, that H_2O is not involved as a nucleophile in the slow step of these ester hydrolyses.

Mechanism.—A mechanism such as that shown in outline in the Scheme seems to us most compatible with all the facts. In particular this Scheme is compatible with equation (4) and with the effects on k_{obs} of added chloride ions [equation (5)]. As we have seen, with the *p*-methoxy-ester k_{obs} becomes independent of $[Cl^-]_S$ at high chloride ion concentrations. This behaviour, and that of the *p*-nitro-ester, is compatible with the Scheme, where the only effect of $[Cl^-]_S$ is on the concentrations of the promoting ions. Were the esters to displace a chloride ion in a rapid pre-equilibrium with the gold(III) species as, for example, in equation (6), this pre-equilibrium



$$AuCl_4^- + ArCOSEt \overset{\text{Fast}}{\rightleftharpoons} AuCl_3 \leftarrow \overset{\overset{\displaystyle Et}{|}}{S}COAr + Cl^- \xrightarrow{\text{Slow}} \text{Products} \quad (6)$$

would have to lie far to the left owing to the absence of spectroscopic evidence for such adduct formation and to the first-order dependence on stoicheiometric gold(III). In this situation, unless some fortuitous compensating acceleration arose from some other source, k_{obs} would continue to fall as $[Cl^-]_S$ was increased, at all chloride concentrations, until k_{obs} became effectively zero (the rates of the spontaneous and the hydrogen ion-catalysed hydrolyses are relatively very small). This does not occur and a mechanism, such as in the Scheme, not involving pre-equilibrium chloride displacement is therefore required. In this respect the pattern of our results differs from that obtained for thiobenzimidate ester hydrolysis[4] promoted by $AuCl_4^-$, where the rapidly formed, low concentration of 1 : 1 gold–ester complex does involve displacement of chloride. It is significant that, in that system, the effect of $[Cl^-]_S$ on k_{obs} is very much greater than it is in the present system.



SCHEME

The Scheme is also in agreement[9] with the solvent isotope effect on the reaction of $AuCl_4^-$. Comments about the details of the slow step must be made in the light of (a) the observed effects on k_{obs} of substituent changes in the gold and in the ester species and (b) the activation parameters. The slow step represents a square planar substitution, possibly accompanied by decomposition of the thiol ester. Whether or not this process involves a five-co-ordinate intermediate,[10,11] the activation parameters show that it presents an overall bimolecular character. The somewhat greater reactivity of the *p*-methoxy- compared to the *p*-nitro-derivative suggests that bond forming to gold plays a dominant role, at least in promotion by $AuCl_4^-$, for which $(k_{obs})_{MeO}/(k_{obs})_{NO_2} \simeq 50$. This moderate reactivity ratio argues, in fact, against much concomitant breakdown of the ester in the slow step, when a ratio of *ca.* 10^3 and a more positive value of $\Delta S^\ddagger$ would be anticipated by analogy with related reactions.[1-3] Indeed the observed activation parameters, the ionic strength effect and the evident importance of bond-forming are all entirely in keeping with an uncomplicated square planar substitution at gold as the slow step.[10,11]

The relatively great reactivity of $AuCl_3(H_2O)$ towards both esters [compared with those of $AuCl_4^-$ and $AuCl_3(OH)^-$] probably arises[11] from a combination of its zero charge and the possibility of displacing H_2O rather than Cl^-, ($\Delta H^\ddagger$ is smaller and $\Delta S^\ddagger$ less negative). The species $AuCl_3(OH)^-$ has activation parameters with the *p*-

methoxy-ester perhaps suggestive of intramolecular attack by the hydroxy-group on the ester during the slow step. This idea is supported by the fact that the *p*-nitro-ester is nearly as reactive as the *p*-methoxy-derivative towards this gold species: intramolecular attack will be facilitated by the nitro-group.

To summarise, we can say that our results suggest that we are dealing in the present system with some form of slow metal transfer to the substrate in contrast to the pre-equilibrium mechanisms found previously for gold(III) ion promotion, and for metal ion-promoted ester hydrolysis generally.

[1/620 *Received*, 15th *April*, 1981]

REFERENCES

[1] D. P. N. Satchell and I. I. Secemski, *Tetrahedron Lett.*, 1969, 1991; *J. Chem. Soc. B*, 1970, 1306.

[2] G. Patel and R. S. Satchell, *J. Chem. Soc., Perkin Trans. 2*, 1979, 458.

[3] G. Patel and R. S. Satchell, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1403.

[4] A. J. Hall and D. P. N. Satchell, *J. Chem. Soc., Perkin Trans. 2*, 1976, 1278.

[5] A. J. Hall and D. P. N. Satchell, *J. Chem. Soc., Perkin Trans. 2*, 1975, 1351.

[6] W. Robb, *Inorg. Chem.*, 1976, **6**, 382; P. van Z. Bekker and W. Robb, *Inorg. Nucl. Chem. Lett.*, 1972, **8**, 849.

[7] B. I. Peshchevitskii, V. I. Belevantsev, and N. V. Kurbatova, *Russ. J. Inorg. Chem.*, 1971, **16**, 1007.

[8] R. S. Satchell and R. Nyman, *J. Chem. Soc., Perkin Trans. 2*, 1981, 901.

[9] P. M. Laughton and B. E. Robertson in 'Solute-Solvent Interactions', eds. J. F. Coetzee and C. D. Ritchie, Marcel Dekker, New York, 1969, vol. 1, p. 400.

[10] R. J. Puddephat, 'The Chemistry of Gold', Elsevier, Amsterdam, 1978.

[11] F. Basolo and R. G. Pearson, 'Mechanisms of Inorganic Reactions', Wiley, New York, 1967, 2nd. edn., ch. 5.