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MICELLE-INDUCED CHANGE IN THE RATE-LIMITING STEP OF SUBSTITUTED BENZOATE ESTER THIOLYSIS

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The effect of hexadecyltrimethylammonium bromide (CTAB) micelles on the acid dissociation constant of *para*-substituted benzenethiols, α-toluenethiol and *n*-heptanethiol was determined. The effect of CTAB on the rate of thiolysis by the thiols was measured using *para*-substituted *p*-nitrophenyl benzoates. The effects of micelles were analysed using a pseudophase ion-exchange (PIE) model. The Brønsted plot for ester thiolysis showed discontinuity at the pK_a of the leaving group in water and was linear in micelles. Micelles increased the Hammett ρ value for thiolysis of esters by α-toluenethiol from 2·08 to 2·68. The Hammett plot for the rection of benzenethiol with esters in water is linear with σ^- and displays a ρ value of 0·87, whereas in micelles the plot is linear with σ and presents a ρ of 2·83. Taken together, these data indicate that micelles produce a change in the rate-limiting step of thiolysis of substituted benzoate esters, leading exclusively to rate-limiting thiolate attack. In micelles thiolysis may be concerted and the effect of the aggregate on the reaction mechanism can be ascribed to the interaction of the thiolate ions, and the transition states, with the head groups as well as a medium effect.

INTRODUCTION

In addition to producing a medium effect, micelles can also modify the rate of higher molecularity reactions by concentrating reagents or maintaining reagents separated in solution.[1] For many bimolecular reactions, quantitative analysis of rate–surfactant profiles shows that the calculated second-order rate constants in the micelle are within one order of magnitude of those in water.[1,2] It would then appear that transferring the reaction site from water to the micelle produces little effect on the energetics of the reaction. Relatively small differences in the overall energy distribution at a reaction surface, however, can produce major changes in mechanism, rate-limiting steps, reaction pathways, and product distribution. Several examples of changes in reaction mechanisms have been interpreted in terms of small energy differences produced by the interactions of initial or transition states with the micelles.[3]

Detailed investigations of mechanistic effects in supramolecular aggregate such as micelles, vesicles or microemulsions critically depend on the estimated values for rate constants of the reaction occurring in the aggregate (k_m). Both the pseudophase ion-exchange (PIE) model and the Poisson–Boltzmann equation (PBE) model have been successfully applied for the calculation of k_m values.[1b] Under conditions where both models can be applied, the calculated rate constants obtained using PIE or PBE are similar,[1b,4] Mechanistic analysis based on calculated k_m values, rather than in overall rate effects, are not widely available. PIE analysis of micellar effects on ester hydrolysis has recently been carried out.[5] The increase in Hammett ρ values in the micellar pseudophase (ρ_m) was rationalized in terms of the low effective dielectric constants at the reactions site.[5] No change in the rate-limiting step occurs in the reaction of OH^- ion with esters in micelles.[5]

One particular reaction where micelles and vesicles produce remarkable kinetic effects is ester thiolysis.[6] Amphiphile aggregates increase the rate up to 10^6-fold in the thiolysis of *p*-nitrophenyl octanoate.[6] PIE analysis of the effect of positively charged vesicles and micelles on the reaction revealed that the second-order

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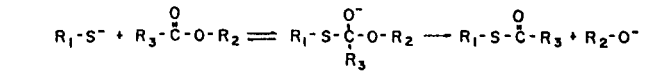

Scheme 1

rate constant in the aggregates (k_{2m}) is, at most, 50 times higher than that in water (k_{2w}). The rate enhancement is due mainly to reagent concentration at the vesicle and surface-induced pK shifts.[6] The mechanism of ester thiolysis has been extensively investigated and is presented schematically in Scheme 1.[7,8]

This paper presents a systematic investigation of the effect of hexadecyltrimethylammonium bromide (CTAB) micelles on the rate of reaction of thiols with substituted benzoate esters. Comparison of Brønsted plots for the reactions in water versus micelles revealed a mechanistic change in the aggregates. The effect of micelles on the reaction depended on the nature of the thiol. In the region of rate-limiting nucleophilic attack, the Hammett ρ values are higher in micelles. In the region of rate-limiting decomposition micelles produce a change in the rate-limiting step. Micellar effects were related to local medium effects and the interaction of the tetraalkylammonium head group with the attacking thiolate ion.

EXPERIMENTAL

The synthesis and purification of the substituted esters and the purification of CTAB have been described.[5] The following *p*-nitrophenyl esters were used: benzoate (**1**), *p*-nitrobenzoate (**2**), *p*-methylbenzoate (**3**); *p*-methoxybenzoate (**4**) and *p*-bromobenzoate (**5**). *p*-Chlorobenzenethiol, *p*-methylbenzenethiol (Aldrich Chemical), *n*-heptanethiol, benzenethiol, *p*-methoxybenzenethiol and α-toluenethiol (Connecticut Hard Rubber, Chemical Division) were purified and maintained at $-15\,^{\circ}C$ under argon. The free sulphydryl group contents of the thiols, determined by titration with 5,5′-dithiobis(2-nitrobenzoic acid),[9] showed that the compounds were pure and in the reduced form. All other reagent were of analytical grade and water was deionized and doubly glass distilled.

Kinetic measurements and pK_a determinations of the thiols were carried out using boiled water that had been allowed to cool under oxygen-free argon or nitrogen. The free sulphydryl group concentration was determined at the end of the pK_a determinations and at the end of most kinetic runs. The values for free SH were within 2% of those expected. Reproducibility of the data depends critically on the absence of oxygen since CTAB micelles increase the rate of SH oxidation.[10a]

The pK_a values of the thiols in water were determined from the effect of pH on the UV spectra. The values presented are, within experimental error, identical with those in the literature.[10b,c] In the presence of CTAB,[6a,11] the pK_{ap} values were determined, at a fixed pH (see Results, Figure 1), by measuring the absorbance of the thiolate ions at wavelengths of 250, 270, 275, 275 and 285 nm for benzene-, α-toluene-, *p*-methoxybenzene-, *p*-methylbenzene- and *p*-chlorobenzenethiol, respectively. The absorbances of the protonated and unprotonated forms were determined in 0·01 M HCl and NaOH, respectively.

Reactions were carried out as follows. A 5 μL aliquot of the ester in acetonitrile (esters **1**, **3**, **4** and **5**) or methanol (ester **2**) were added (final ester concentration 1×10^{-6}–3×10^{-6} M) to 1·5–3·0 ml of a temperature-equilibrated ($30 \pm 0{\cdot}1\,^{\circ}C$) reaction mixture. Reaction was started by adding a 5–10 μl aliquot of a stock solution of the thiol in acetonitrile to yield a final thiol concentration *ca* ten times higher than that of the ester. Rate of ester decomposition were followed in a Beckman M-25 spectrophotometer at 405 nm, the wavelength of maximum absorption of the *p*-nitrophenolate ion. First-order rate constants were calculated from linearized absorbance vs time plots. Reactions followed first-order kinetics for at least four half-lives; the reported values are the averages of at least three separate runs with a maximum deviation of 5%.

RESULTS

The reactive species in the reaction of thiols with activated esters is the dissociated thiolate ion.[7] Second-order rate constants for the reaction of thiolate ions with benzoate esters in water (k_{2w}) were calculated from the concentration dependence of the first-order rate constant (k_ψ) obtained with excess thiol. Since the benzoate esters also react with OH^- at pH values where a sufficiently high proportion of the thiol is dissociated, k_ψ was corrected for the hydrolytic path by subtracting the rate constant for the reaction of the ester with OH^- ion at the same pH (k_{OH}). Representative data are shown in Figure 1.

The second-order rate constant for the reaction was calculated from

$$k_{2w} = \frac{k_\psi - k_{OH}}{[S]} \qquad (1)$$

where [S] represents the analytical concentration of the thiolate ion calculated from the pH and the pK_a of the thiol. The values of k_{2w} are presented in Table 1.

When analysing the effect of micelles in equilibria or rates we used the PIE model, which can be applied under all conditions described here.[1b,11] Results were analysed as described in detail elsewhere,[5,11b] and therefore only the fundamental equations will be presented.

The effect of CTAB on the pK_a of a thiol was determined at a fixed pH by varying the detergent concentration.[6a,11] Representative data are shown in Figure 2. The function relating the apparent pK_a in the presence of micelles (pK_{ap}) with increase in [CTAB] is[11a]

$$K_{ap} = \frac{1 + K_{S/Br}(Br_b/Br_f)}{1 + K_{SH}C_D} \qquad (2)$$

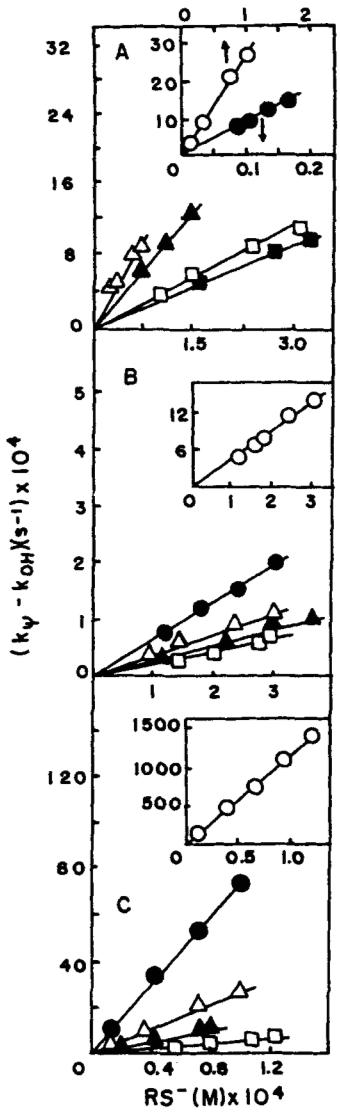

Figure 1. Effect of thiol concentration on the rate of decomposition of substituted benzoate esters. Calculated second-order rate constants for ester thiolysis in water are presented in Table 1. (A) *p*-Nitrophenyl benzoate was used as substrate, borate buffer (0·02 M), pH as indicated. Thiols: (■) *p*-chlorobenzenethiol, pH 8·60; (▣) benzenethiol, pH 8·5; (▲) *p*-methylbenzenethiol, pH 8·70; (△) *p*-methoxybenzenethiol, pH 10·04; (•) *n*-heptanethiol, pH 9·5; (○) α-toluenethiol, pH 10·04. (B) Thiolysis by benzenethiol. Borate buffer (0·02 M), pH 8·5. Esters: (△) **1**; (○) **2**; (▲) **3**; (▣) **4**; (•) **5** (C) Thiolysis by α-toluenethiol. Borate buffer (0·02 M), pH 9·50. Esters as in (B)

Table 1. Second-order rate constants (k_{2w}) for the reactions of mercaptide ions with substituted *p*-nitrophenyl benzoate esters (*p*-X-C_6H_4-CO_2-C_6H_4-NO_2-*p*)

X		Thiol	k_2 (l $mol^{-1} s^{-1}$)
CH_3O	(4)	$C_6H_5CH_2SH$	6·54
CH_3	(3)	$C_6H_5CH_2SH$	13·6
H	(1)	$C_6H_5CH_2SH$	27·8
Br	(5)	$C_6H_5CH_2SH$	72·8
NO_2	(2)	$C_6H_5CH_2SH$	1119·0
CH_3O	(4)	C_6H_5SH	0·22
CH_3	(3)	C_6H_5SH	0·27
H	(1)	C_6H_5SH	0·36
Br	(5)	C_6H_5SH	0·64
NO_2	(2)	C_6H_5SH	4·73
H	(1)	*p*-Cl-C_6H_4SH	0·30
H	(1)	*p*-CH_3-C_6H_4SH	0·86
H	(1)	*p*-CH_3O-C_6H_4SH	1·16
H	(1)	$CH_3(CH_2)_6SH$	97·2

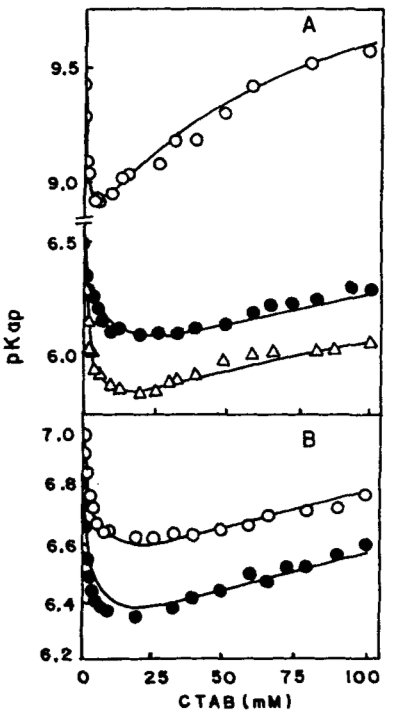

Figure 2. Effect of CTAB concentration on the apparent pK_a values of thiols. (A) (○) α-toluenethiol (5×10^{-5} M); borate buffer (0·02 M), pH 9·1. All other experiments in 0·02 M imidazole·HBr buffer. (•) Benzenethiol ($3{\cdot}63 \times 10^{-5}$ M), pH 6·6; (△) *p*-chlorobenzenethiol ($1{\cdot}47 \times 10^{-5}$ M) pH 6·8. (B) (•) *p*-methylbenzenethiol ($1{\cdot}03 \times 10^{-5}$ M), pH 6·7; (○) *p*-methoxybenzenethiol ($0{\cdot}93 \times 10^{-5}$ M), pH 6·7

Table 2. Association constants (K_{SH}), intrinsic acid dissociation constants (K_{am}) of the thiols and ion selectivity coefficients for the mercaptide–bromide exchange ($K_{S/Br}$) in micelles of CTAB calculated from the effect of [CTAB] on the apparent pK_a of the thiol

Thiol	pK_a	pK_{am}	K_{SH}	$K_{S/Br}$
p-Cl-C_6H_4SH	6·20	6·91	180	12·0
C_6H_5SH	6·50	7·01	120	10·0
p-CH_3-C_6H_4SH	6·83	7·38	130	10·0
p-CH_3O-C_6H_4SH	7·00	7·60	110	7·5
$C_6H_5CH_2SH$	9·43	10·60	150	2·75
$CH_3(CH_2)_6$-SH	10·70	11·80	3700	75·0

where $K_{S/Br}$ is the thiolate–bromide ion-exchange selectivity coefficient and K_{SH} the association constant of the undissociated thiol with the micelle; K_{SH} is expressed in inverse molar units and it interpreted as an association constant.[12] The subscripts b and f represent the species bound to the micelle and free in the intermicellar aqueous phase, respectively. C_D is the concentration of micellized detergent that is equal to the total detergent concentration (C_T) minus the critical micelle concentration (CMC) (i.e. $C_D = C_T - CMC$). The ratio (Br_b/Br_f) was calculated from C_T, CMC and ion composition as described previously.[11]

Equation (2) was fitted to the experimental data using a multiparametric computer program using K_{SH} and

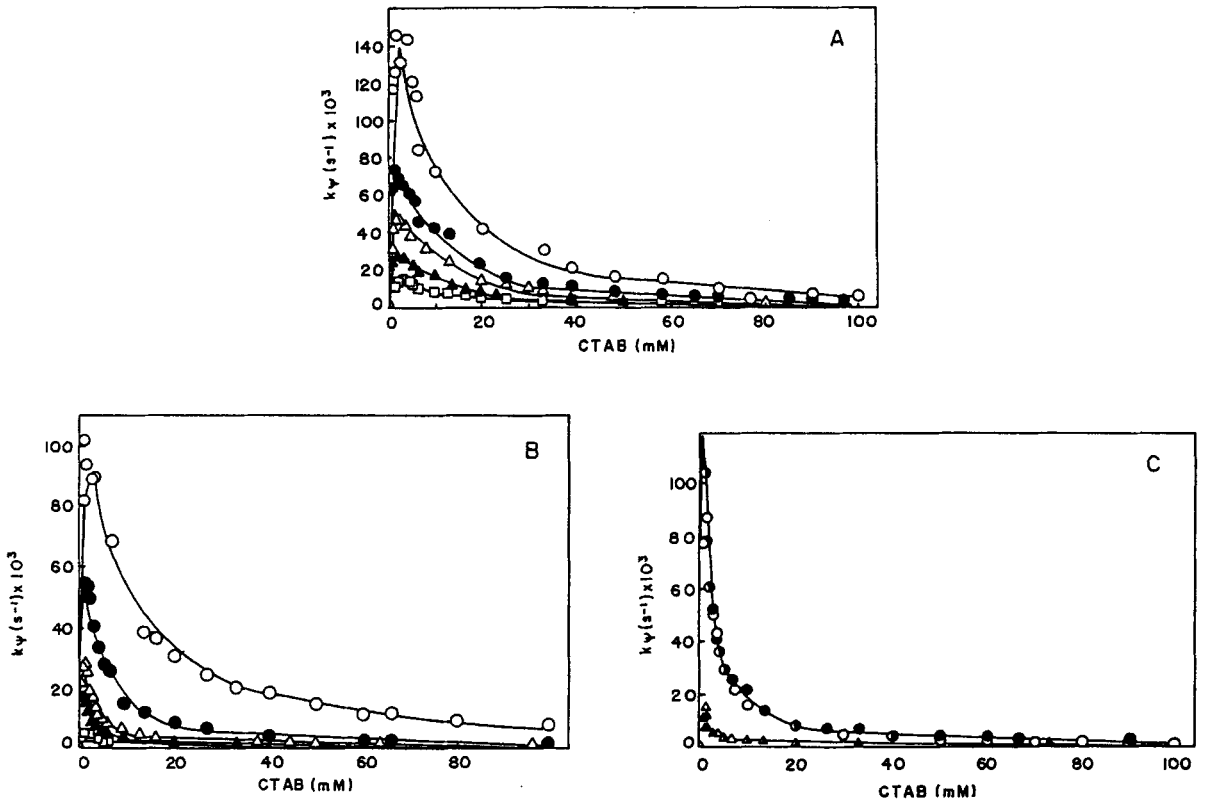

Figure 3. Effect of CTAB on the thiolysis of esters. Curves are calculated (see text). (A) Thiolysis of esters **1–5** with α-toluenethiol (BzSH), Tris–HBr buffer (0·02 M in Tris). The ester used, BzSH concentration, added NaBr and pH were, respectively: (•) **1**, $1·09 \times 10^{-4}$ M, O, pH 8·1; (□) **2**, $6·0 \times 10^{-6}$ M, 0·02 M, pH 7·3; (△) **3**, $1·09 \times 10^{-4}$ M, O, pH 8·3; (▲) **4**, $1·09 \times 10^{-4}$ M, O, pH 8·5; (○) **5**, $1·09 \times 10^{-4}$ M, O, pH 7·8. (B) Thiolysis of esters **1–5** with benzenethiol (PhSH). The ester used, PhSH concentration, buffer and pH were, respectively: (△) **1**, $3·6 \times 10^{-4}$ M, borate (0·02 M), pH 8·5; (○) **2**, $5·4 \times 10^{-5}$ M, Tris–HBr (0·02 M Tris), NaBr (0·02 M), pH 7·4; (▲) **3**, 4.87×10^{-4} M, borate (0·02 M), pH 8·5; (△) **4**, $5·84 \times 10^{-5}$ M, borate (0·02 M), pH 8·5; (•) **5**, $2·37 \times 10^{-3}$ M, Tris–HBr (0·02 M Tris), pH 8·15. (C) Thiolysis of *p*-nitrophenyl benzoate. The thiol, concentration buffer and pH were, respectively: (▲) *p*-chlorobenzenethiol, $3·26 \times 10^{-4}$ M, borate (0·02 M), pH 8·6; (△) *p*-methylbenzenethiol, $8·96 \times 10^{-5}$ M, borate (0·02 M), pH 8·5; (•) *p*-methoxybenzenthiol, $2·88 \times 10^{-4}$ M, borate (0·02 M), pH 8·5; (○) *n*-heptanethiol, $6·0 \times 10^{-5}$ M, Tris–HBr (0·02 M in Tris), pH 8·15

$K_{S/Br}$ as variable parameters. The results are presented in Table 2. With all restrictions due to this fitting procedure it should be noted that the values for both parameters are within the range of values determined experimentally for compounds of similar structure.[11b,12]

We have previously proposed that the acid dissociation constant of micelle-bound acid (K_{am}) can be expressed as[6a,11a]

$$K_{am} = \frac{[\overline{S_b}]\,[\overline{H_b^+}]}{[\overline{HS_b}]} \tag{3}$$

In equation (3) the concentrations within brackets refer to local concentrations, i.e. moles of micelle-bound reagent per litre of micellar pseudophase.[11a] HS and S represent the undissociated and dissociated thiol, respectively. From this definition and assuming that the ion product of water in the micelle is identical with that of water at the same temperature,* K_{am} can be calculated from[11a]

$$K_{am} = \frac{K_a K_{S/Br} \bar{V}}{K_{OH/Br} K_{SH}} \tag{4}$$

where $K_{OH/Br}$ is the $OH^- - Br^-$ ion selectivity for exchange at the CTAB micellar surface ($K_{OH/Br} = 0{\cdot}08$)[2,15] and $\bar{V}$ is the partial molar volume of the micellized detergent ($\bar{V} = 0{\cdot}37$ mol^{-1} l). The values of pK_a and pK_{am} for the thiols, calculated using equation (4), and the values of K_{SH} and $K_{S/Br}$ are presented in Table 2.

The effects of [CTAB] on the rate of reaction of the thiols with substituted benzoate esters are presented in Figure 3 (tables with values of rate constants can be found in Ref. 16). Note that in some of the experiments the reaction rate was decreased to suit the experimental conditions by the addition of sodium bromide. The inhibitory effect of added sodium bromide was taken into account in the equations derived from the PIE model.[1b,2,11a] The theoretical curves were calculated using the equation[11a]

$$k_\psi = [SH]_T K_a \frac{(k_{2m}/\bar{V}) K_E K_{S/Br}(Br_b/Br_f) + k_{2w}}{(1 + K_{SH}C_D)(H_f^+ + K_{ap})(1 + K_E C_D)} \tag{5}$$

The values of the ester–micelle association constants (K_E), expressed in units of mol^{-1} l and calculated from the micellar effects on spectra,[12] were those determined previously in related work (Table 3).[5] $[SH]_T$ is the total analytical concentration of added thiol and H_f^+ is the concentration of free H^+ ion calculated from the pH. In fitting the experimental data to equation (5) the only variable parameter was k_{2m}. The values of K_E, k_{2m} and the ratio k_{2m}/k_{2w} for the thiolysis reactions are presented in Table 3.

DISCUSSION

Fitting of the data presented in Figures 2 and 3 to equations (2) and (5), respectively, demonstrated that the PIE model adequately accounts for the effect of CTAB on the acid dissociation equilibrium of thiols and the thiolysis reactions. The absolute values of second-order rate constants, however, calculated using either the PIE or PBE models, rely on the definition of

* The existence kinetic evidence suggests that water at the micellar surface retains the properties of bulk solution.[13,14] There is no evidence of extensive ion dehydration at the micellar surface.[4]

Table 3. Calculated second-order rate constants in the micelle (k_{2m}) and fixed parameters used in the fitting of equation (6) to the experimental data obtained for the reaction of substituted benzoate esters (p-X-C_6H_4-CO_2-C_6H_4-NO_2-p) with thiols (RSH)

X	K_E (l mol^{-1})	R	k_{2m}(l mol^{-1} s^{-1})	k_{2m}/k_{2w}
CH_3O	800	$C_6H_5CH_2$	5·89	0·9
CH_3	2000	$C_6H_5CH_2$	16·3	1·2
H	1300	$C_6H_5CH_2$	47·2	1·7
Br	1500	$C_6H_5CH_2$	226·0	3·1
NO_2	1000	$C_6H_5CH_2$	4030·0	3·6
CH_3O	800	C_6H_5	0·0067	0·03
CH_3	2000	C_6H_5	0·019	0·07
H	1300	C_6H_5	0·046	0·13
Br	1500	C_6H_5	0·29	0·45
NO_2	1000	C_6H_5	6·8	1·45
H	1300	p-Cl-C_6H_4	0·027	0·09
H	1300	p-CH_3-C_6H_4	0·11	0·13
H	1300	p-CH_3O-C_6H_4	0·22	0·20
H	1300	$CH_3(CH_2)_6$	408·0	4·2

a reaction volume element.[1b] Thus comparisons in a series, rather than elaborate analysis on isolated values, is preferable when analysing the effects of micelles on a particular reaction. The validity of value comparisons of rate or equilibrium constants in a supramolecular aggregate assumes that the reaction sites are similar. It has been clearly demonstrated that large variations in the structure of a micelle-bound substrate cause differences in the solubilization site.[1,17,18] Since the properties of a micelle change abruptly over relatively small distances,[1,19] the changes in structure of the reactants have to be minimized. In the present case the structural variation in the reagent series is minimal, especially in the case of the substituted benzoate esters.

The mechanism of ester thiolysis has been elaborated in great detail.[7] Ester thiolysis can be represented by a reaction sequence involving the formation of an intermediate that can partition to either reactants or products (Scheme 1). The nature of the attacking thiol does not make a significant difference in the equilibrium or kinetic extra-thermodynamic relationships described for thiol acid dissociation or ester thiolysis.[7] Figure 4 shows a Brønsted plot for the thiolysis of *p*-nitrophenyl benzoate (PNPB). In water the β_{nuc} values, 0·78 for thiols with a pK lower than that of *p*-nitrophenol and 0·38 for thiols of higher pK, were similar to those described for the thiolysis of other *p*-nitrophenyl esters.[7] We have previously studied the effect of CTAB micelles on the rate of thiolysis of *p*-nitrophenyl acetate (NPA) by the same substituted thiophenols.[10] The values of k_{2w} for the reactions with NPA are very similar to those obtained here. The calculation of k_{2m}, at that time, did not take into account ion exchange. The values of k_{2m} are lower than those obtained with PNPB, consistent with other findings that show a decrease in k_{2m} as the hydrophobicity of the ester increases.[20] However, the slope of the Brønsted plot with NPA in the region of pK 6·2–7 is identical with that obtained here. The two lines intersect near pH 7·14, the pK_a of *p*-nitrophenol[21] (Figure 4). This type of non-linear Brønsted plot has been taken as evidence for an abrupt change in the structure of a transition state.[7,8] For thiols with a pK_a higher than 7 attack is rate determining and for those with a pK_a lower than that of *p*-nitrophenol the decomposition of the intermediate is the slow reaction step.[7] It has been proposed that the observation of a linear Brønsted plot, for a reaction where a change in rate-limiting step is expected on changing the pK_a of the nucleophile, can be taken as evidence for a concerted mechanism.[8]

In micelles, in contrast to the results obtained in water, the Brønsted plot was linear over a considerable pK_a range that included the pK_a of *p*-nitrophenol (Figure 4). The pK_a value of the thiol in the micelle must be clearly defined in order to analyse these results. Ionic micelles affect acid dissociation equilibria by at least two different mechanisms. The pK_a value of an

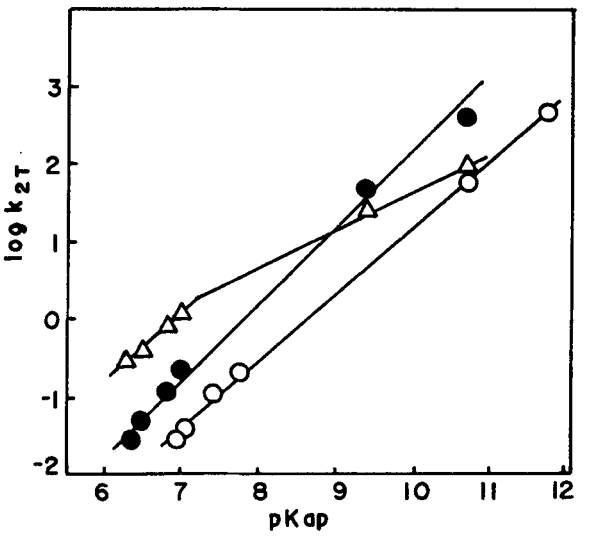

Figure 4. Brønsted plot for the reaction of *p*-nitrophenyl benzoate with thiols in (△) water and in micelles. The data for micelles was plotted against the pK_a of the thiol in water (•) or the calculated pK_{am} in micelles (○) (see text)

acid, such as HA, may be altered simply by excluding, or concentrating, H^+ ions from the surface.[1] On the other hand, the relative energy of the HA_f/A_f^- pair may be different from that of HA_b/A_b^-, producing an intrinsic difference in the acid dissociation constant.[1,22]

We chose to plot the data relating the rate of thiolysis of PNPB with different thiols in micelles using two different sets for the pK_a values of the thiols, namely those determined in water and in the micelle (pK_{am}, Table 2). Using either set of values the Brønsted plot was linear (Figure 4). These data suggest a change in mechanism when the reaction is transferred from the water to the micellar pseudophase. Another point to note is the calculated β_{nuc} value for the micellar reaction. For the reaction in micelles the calculated β_{nuc} is 0·7–0·8 depending on the value chosen to represent the pK_a of the thiol. This value of β_{nuc} is similar to that observed in water in the rate-limiting decomposition region for this reaction. Thus, from the Brønsted plot obtained in micelles it could be concluded that attack is rate limiting. However, the value of β_{nuc} can be solvent sensitive and, in the reaction of arene thiolates with *p*-nitrophenyl acetate the value of β_{nuc} in the region of rate-limiting attack is 0·7 in 95% ethanol, compared with 0·3 in water, when both *meta*- and *para*-substituted nucleophiles are considered.[23]

The fact that in micelles the Brønsted plot is linear and does not exhibit a change in slope in the region of the pK_a of the leaving group indicates that the mechanism in the aggregate is different from that in

water and is suggestive of a concerted pathway. However, the data are also consistent with either rate-limiting attack or rate-limiting decomposition of an intermediate.

Using α-toluenethiol, in the rate-limiting attack regime, Hammett plots are linear (correlation coefficient better than 0·99) both in water and in micelles (Figure 5). The value of ρ in water (ρ_w) is 2·08 and ρ_m is 2·65. Micelles, as in the case of rate-limiting OH^- ion attack on benzoate esters, increase the sensitivity of the reaction to substituent effect and $\rho_m > \rho_w$.[5] The difference in $\rho(\Delta\rho = \rho_m - \rho_w)$ for thiolysis was 0·6, a value close to that observed in the alkaline hydrolysis of esters, where $\Delta\rho$ is 0·8.[5] This increased sensitivity to polar effects in micelles has been observed with other reactions,[25] and indicates that the relative contribution of the micellar surface to charge stabilization by solvent is less than in water. A decreased effective dielectric constant has been invoked to explain some of the observed $\Delta\rho$ values.[5] In positively charged micelles both initial and transition states are surrounded by alkylammonium groups and differences in the energy of association with the head groups, or coulombic effects thereof, rather than local polarity, may be the main contribution to the higher sensistivity of micellar reactions to polar effects. Micellar activation and inhibition of the unimolecular decomposition of fluorenecarboxylates can be explained on the basis of differential coulombic interaction of the initial and transition states with the charged detergent head groups.[26]

Reaction of *p*-nitrophenyl benzoates with phenyl thiolate ion in water is rate-limited by the decomposition of the intermediate (see above). The results, in water and in micelles, expressed as a $\sigma\rho$ plot, are strikingly different from those obtained with α-toluenethiol (compare Figures 5 and 6). The Hammett plot for the reaction in water is linear with σ^- and the value of ρ_w is 0·87 which is lower than that obtained in the rate-limiting attack region. This difference in the sensitivity to polar effects is to be expected in view of the differences in rate-limiting steps in this reaction. Transfer of the reaction site from water to micelle results in two major changes, which are apparent from inspection of Figure 6. The plot is linear with σ and the value of ρ_m is 2·83, a value even higher than that obtained for ρ_m using α-toluenethiol. These results show that micelles produce a change in mechanism leading to rate-limiting attack of the thiolate ion.

CTAB micelles differently affect the basicity of alkane- and benzenethiols. The ΔpK ($pK_{am} - pK_a$) for substituted thiophenols is *ca* 0·6 while the ΔpK for α-toluenethiol and *n*-heptanethiol approaches 1·2 pH units (Table 2). These data suggest that the interaction of the charged thiolate ion with the positively charged group of the detergent may differ when the negative

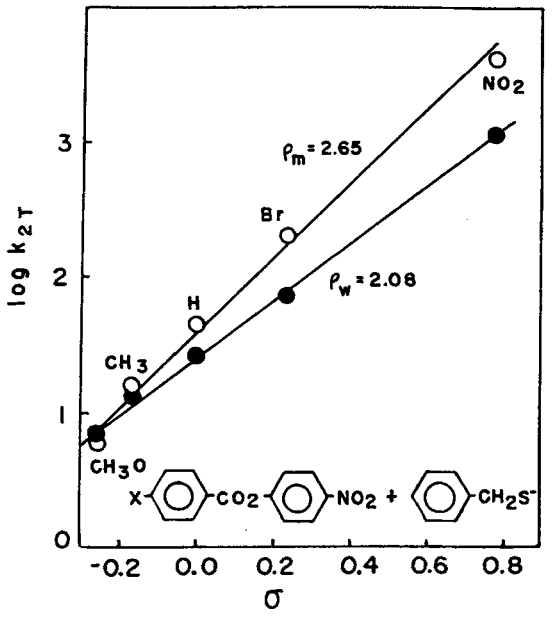

Figure 5. Hammett plot for the reaction of α-toluenethiol with *p*-X-C_6H_4-CO_2-C_6H_4-NO_2-*p* in (○) micelles and (●) water. The values of σ were taken from Ref. 24

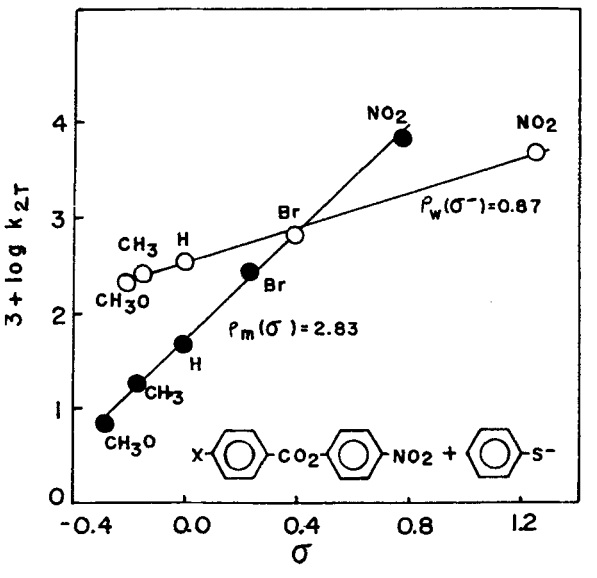

Figure 6. Hammett plot for the reaction of benzenethiol with *p*-X-C_6H_4-CO_2-C_6H_4-NO_2-*p* in (●) micelles and (○) water. The values of σ and σ^- were taken from Ref. 24

charge on sulphur can be dispersed in the phenyl ring. Data indicative of a stronger interaction of charge-dispersed anions with alkylammonium head groups has been found consistently.[1b,26] However, it would appear that alkyl thiolate ions have a stronger interaction with alkylammonium groups than phenyl thiolates. Also, the k_{2m} values for the less reactive systems are consistently lower than the k_{2w} values (Table 3). This latter fact is not related to the solubility of the thiols in the micelles or to the distribution constants of the esters. Although the determining factors for the mechanistic change cannot be pinpointed from the available data, it is suggestive that there is a correlation with differences in interactions of the initial and transition states with the alkylammonium head groups and with medium effects related to the effective dielectric constant at the micellar surface.

In conclusion, we have shown that CTAB micelles alter the mechanism of ester thiolysis. Micelles increase the sensitivity of the reaction to polar effects, while apparently maintaining the nature of the rate-determining step, in the case of α-toluenethiol. The rate-determining step in micelles is not the decomposition of the intermediate for thiolysis by α-toluenethiol. The influence of CTAB on this reaction can be related both to local medium effects and to differential coulombic interactions with the initial and transition states.

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