

MICELLAR CATALYSIS OF ORGANIC REACTIONS. PART 34. NUCLEOPHILIC AROMATIC SUBSTITUTION REACTIONS IN MICELLES WITH BULKY HEAD GROUPS

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Observed second-order rate constants for the hydroxydechlorination of 1-chloro-2,4-dinitrobenzene (2), 2-chloro-3,5-dinitrobenzoate ions (3) and 4-chloro-3,5-dinitrobenzoate ions (4) in micelles of cetyltrialkylammonium bromide ($C_{16}H_{33}NR_3Br$, where $R = Me, Et, n\text{-}Pr$ and $n\text{-}Bu$) are reported. For substrate 2, the observed catalysis increased as the size of the micellar head group was increased. This was shown to be primarily due to an increase in the rate of reaction in the micellar pseudo-phase (k_2^M). For substrates 3 and 4, the observed catalysis decreased as the size of the micellar head group was increased. Much smaller changes in k_2^M were observed in these reactions, which lead to a dianionic intermediate which is more sensitive to polarity effects at the micelle surface than is the monoanionic intermediate formed from 2. These results support the contention that as the size of the micellar head group is increased, water is squeezed away from the micelle surface, resulting in a less polar reaction environment.

INTRODUCTION

Recently there has been considerable interest in reactions carried out in the presence of micelles containing bulky head groups. For example, the effects of micelles of cetyltrialkylammonium salts, $C_{16}H_{33}NR_3^+Br^-$ (1), where $R = Me$ (CTAB) (a), Et (CTEAB) (b), $n\text{-}Pr$ (CTPAB) (c) and $n\text{-}Bu$ (CTBAB) (d), on the S_N2 reactions^{1,2} of hydroxide ions with methyl naphthalene-2-sulphonate, on the unimolecular decarboxylation of 6-nitrobenzisoxazole-3-carboxylate and on the cyclization of 3-halopropoxyphenoxide ions^{3,4} have been studied. It has been concluded that as the size of the head group is increased, from the trimethyl (1a) to the triethyl (1b), tripropyl (1c) and the tributyl (1d) derivative, water is squeezed out from the micelle surface, creating a reaction medium of lower polarity.

We have previously studied⁵ the effects of micelles of 1a on the S_NAr reactions of a number of substrates leading to both monoanionic and dianionic intermediates. It has been shown that the magnitude of catalysis is larger for reactions leading to monoanionic than for those leading to dianionic intermediates. This difference in the magnitude of catalysis has been explained in terms of the differing polarity of the reaction medium. In water and in the micellar aggregates and the differing sensitivity of these reactions to the polarity of the environment. Further, we have also shown that the

magnitude of catalysis by micelles of 1a is dependent on the orientation of the aromatic substrate within the micelle.⁶ We now report kinetic studies of the basic hydrolysis of 1-chloro-2,4-dinitrobenzene (2) 2-chloro-3,5-dinitrobenzoate ions (3) and 4-chloro-3,5-dinitrobenzoate ions (4) in these micelles, to determine whether the magnitude of catalysis is affected by an increase in the size of the micellar head group. We chose these reactions to allow a study of the effects of the orientation of the substrate in the micelle and the charge developed in the rate-determining transition state on the magnitude of catalysis in these micelles.

RESULTS AND DISCUSSION

Second-order rate constants for the hydroxydechlorination of substrates 2–4 in micelles 1b–d are given in Tables 1–3. The data for the reactions in micelle 1a are available in the literature.^{6,7} On the basis of the pseudo-phase ion-exchange (PPIE) model of micellar catalysis,^{6,8–10} the magnitude of observed catalysis is dependent on a number of parameters, including the binding constant of the substrate to the micelle (K_s), the exchange constant of the nucleophile (hydroxide ion) with the micellar counterion (bromide) ($K^{OH/Br}$) and the actual rate constant for reaction in the micellar pseudo-phase (k_2^M). In addition, for the above micelles it has been reported¹ that the critical micelle concentration

Table 1. Second-order rate constants ($10^3 k_2$) for the hydroxy-dechlorination of 1-chloro-2,4-dinitrobenzene (**2**) at 30.0°C (0.01 M sodium hydroxide; analytical wavelength 360 nm)

[CTA] micelle (mM)	R = Et (1b)	R = <i>n</i> -Pr (1c)	R = <i>n</i> -Bu (1d)
0	0.27	0.27	0.27
0.5	1.35	7.85	13.3
1.0	11.1	18.2	24.8
2.0	27.0	35.0	38.1
3.0	32.9	41.2	49.1
4.0	37.6	45.2	55.0
6.0	36.8	47.5	57.1
8.0	38.1	46.1	63.7
10.0	33.7	—	—
12.0	31.7	43.1	54.6
16.0	26.6	39.7	54.9

Table 2. Second-order rate constants ($10^2 k_2$) for the hydroxy-dechlorination of 2-chloro-3,5-dinitrobenzoate ions (**3**) at 48.0°C (0.01 M sodium hydroxide; analytical wavelength 373 nm)

[CTA] micelle (mM)	R = Et (1b)	R = <i>n</i> -Pr (1c)	R = <i>n</i> -Bu (1d)
0	0.04	0.04	0.04
0.5	0.664	1.61	1.64
1.0	2.28	2.12	1.96
2.0	2.51	2.21	1.96
3.0	2.72	1.92	1.95
4.0	2.32	1.77	1.71
6.0	1.84	1.57	1.45
8.0	1.73	1.40	1.41
12.0	1.28	1.17	1.23
16.0	1.05	0.99	1.12

Table 3. Second-order rate constants ($10^2 k_2$) for the hydroxy-dechlorination of 4-chloro-3,5-dinitrobenzoate ions (**4**) at 48.0°C (0.01 M sodium hydroxide; analytical wavelength 442 nm)

[CTA] micelle (mM)	R = Et (1b)	R = <i>n</i> -Pr (1c)	R = <i>n</i> -Bu (1d)
0	0.42	0.42	0.42
0.5	11.6	13.2	10.7
1.0	17.7	16.0	12.2
2.0	18.7	15.2	11.2
3.0	17.5	13.4	10.6
4.0	16.3	11.0	9.27
6.0	14.2	10.2	7.35
8.0	11.2	9.02	7.05
12.0	9.48	6.85	4.30
16.0	7.37	6.00	5.02

(cmc) and the fraction of head groups neutralized (β) vary with the size of the head group. Both of these parameters affect the observed rate of reaction in the presence of micelles; in particular, the smaller the value of β , the lower is the concentration of ions at the micelle surface and hence the lower is the concentration of hydroxide ions at the surface.

Hence it is not sufficient merely to determine the magnitude of the observed catalysis of these reactions. It is also necessary to estimate the values of the above parameters to determine the origin of any variation in the magnitude of catalysis. This is usually done by a computer simulation of the variation of the observed rate constants for a range of detergent concentrations, as described previously.⁵⁻⁷ In this case we used the β values of these micelles quoted by Bacaloglu *et al.*¹ and optimized the cmc values to obtain the best fit of the experimental data. It appears that compared with the neutral substrate **2**, the anionic substrates **3** and **4** lower the cmc of all the micelles, possibly as a result of seeding micelle formation. As shown by Bacaloglu *et al.*¹ the cmc decreased as the size of the head group increased. For all of the micelles, the value of $K_{OH/Br}^{OH/Br}$ used for each compound was fixed at that found previously^{6,7} for the reaction in micelles of **1a**. The data derived from this treatment are given in Table 4.

For substrate **2** it can be seen that the observed catalysis, i.e. the ratio of the optimum rate in the presence of the detergent to that in water, increased as the size of the head group increased. The rate of reaction in the micellar pseudo-phase (k_2^M) is greater than the rate of reaction in water for all of the micelles. Also, k_2^M increased as the size of the head group was increased. The increase in the observed catalysis is due primarily to this increase in k_2^M , which may well be explained by the increased nucleophilicity of hydroxide ions as water

Table 4. Derived data for the reactions of substrates **2-4** in micelles of surfactants **1a-d**

Substrate	Surfactant	Cat.	β	K_s (M ⁻¹)	$10^4 k_2^M$	Cmc (M)
2^a	CTAB (1a)	80	0.8	70	9.5	0.0006
	CTEAB (1b)	141	0.7	170	8.4	0.0006
	CTPAB (1c)	176	0.6	87	19.3	0.0004
	CTBAB (1d)	236	0.4	22	118	0.0002
3^b	CTAB (1a)	70	0.8	1225	2.5	0.0003
	CTEAB (1b)	68	0.7	832	2.0	0.0003
	CTPAB (1c)	55	0.6	1174	1.9	0.0002
	CTBAB (1d)	49	0.4	571	3.6	0.0001
4^c	CTAB (1a)	48	0.8	2750	13.3	0.0003
	CTEAB (1b)	45	0.7	1546	12.7	0.0003
	CTPAB (1c)	38	0.6	1969	11.2	0.0002
	CTBAB (1d)	29	0.4	1147	15.7	0.0001

^a Using $K_{OH/Br}^{OH/Br} = 14$; $k_2^W = 2.7 \times 10^{-4}$.

^b Using $K_{OH/Br}^{OH/Br} = 10$; $k_2^W = 4.0 \times 10^{-4}$.

^c Using $K_{OH/Br}^{OH/Br} = 10$; $k_2^W = 4.2 \times 10^{-3}$.

is squeezed out from the micelle surface. The positive effect of this increase in k_2^M (six fold from the propyl to the butyl micelle) is larger than the unfavourable effect of the decrease in β which results in a decrease in the concentration of hydroxide ions at the micelle surface. The values of K_s are misleading because of the variation of the cmc of the different micelles. A reduction in the cmc results in a decrease in the K_s value for a given set of data because of the presence of micelles at lower concentrations. The raw kinetic data in Table 1 show that the optimum rate in micelles **1b**, **c** and **d** occurs at similar CTA concentrations (6–8 mM) but the lower cmc of micelle **1d** results in an artificially low value of K_s in that micelle Table 4. In all cases the substrate is solubilized much better than in CTAB (**1a**), for which the optimum rate was found at about 20 mM.⁷

For the anionic substrates **3** and **4** the observed catalysis decreased as the size of the micellar head group increased. The rate of reaction in the micellar pseudo-phase (k_2^M) is less than the rate of reaction in water for both compounds in all of the micelles. Hence we conclude that the favourable effect of an increase in the nucleophilicity of hydroxide ions as the size of the micellar head group is increased is overshadowed in these reactions by the unfavourable effect of increased repulsions between the two anions. This effect is expected to increase as the ion solvating power of the medium is decreased, as predicted by the Hughes–Ingold solvent effect.¹¹ Hence it becomes more important as the size of the micellar head group is increased and water is squeezed out from the micellar surface. The decrease in the observed catalysis in these reactions of compounds **3** and **4** as the size of the micellar head group is increased is also due to the unfavourable effect of the decrease in β .

For compound **3** the k_2^M value is larger (94%) for reaction in the butyl micelle than in the propyl micelle. For compound **4** there is less variation (ca 40%) in the value of k_2^M in the different micelles. This possibly reflects the fact that for this substrate the reaction centre is more buried within the micellar interior⁶ than that for the reaction of either substrate (**2** or **3**) and hence is less sensitive to polarity changes at the micelle surface.

These results support the contention^{1–4} that water is squeezed away from the micelle surface as the size of the head group is increased, resulting in a decrease in the polarity of the reaction medium.

EXPERIMENTAL

Materials. The detergents were prepared by the reaction of the appropriate tertiary amine with cetyl bromide in propan-1-ol at reflux. The product was iso-

lated after removal of the solvent under vacuum. Dry diethyl ether was added to the residue and the white precipitate was collected and recrystallized first from ethyl acetate and then from a mixture of ethanol and diethyl ether. For **1b**, m.p. 170–171 °C (lit.¹² m.p. 169–171 °C); **1c**, m.p. 87–88 °C (lit.¹² m.p. 85–87 °C); **1d**, m.p. 74 °C (lit.¹² m.p. 70–72 °C). The identity and purity of the products were confirmed by electrospray mass spectrometry using a VG Bio-Q triple quadrupole mass spectrometer (VG Bio Tech, Altringham, Cheshire, UK) using a mobile phase of methanol–water (1 : 1) containing 1% acetic acid. The mass spectra had principal ions corresponding to the desired quaternary ammonium salts. Under these conditions, the tertiary amine reactant was protonated and consequently showed up in the mass spectrum. The reaction time was adjusted to obtain complete reaction, as indicated by the absence of reactant amine in the mass spectra.

The substrates were all commercially available. Distilled water was further purified by a Milli-Q system (millipore) to achieve a resistivity of 18 MΩ cm.

Kinetics. Stock solutions (0.01 M) of the substrates, were prepared in HPLC-grade acetonitrile. Stock solutions of NaOH (0.5 M) and the detergents (20 mM) were prepared in purified water. Rate measurements were carried out at the temperatures indicated in the tables using a cuvette kept at constant temperature in the cell compartment of a Varian 635 UV–visible spectrophotometer. Solutions for kinetic studies were prepared by mixing appropriate volumes of NaOH and detergent, with dilution as required. The mixed solutions were placed in cuvettes and allowed 30 min to reach thermal equilibrium in the constant-temperature cell holder. The temperature within the cuvette was measured with a Jenco Thermistor thermometer. A sample of the stock solution of the required substrate (20 μl) was then added and the contents were mixed thoroughly to initiate the reaction. The rate of change of absorbance at the desired wavelength (see tables) was followed by means of a National VP 6511 A $x-t$ recorder. Reactions were followed to infinity (ten half-lives) where possible, or alternatively for very slow reactions or for consecutive reactions an infinity value was calculated by using a computer program designed to give the best straight-line fit to data collected over at least two half-lives. Rate constants were all obtained in duplicate and average results (within ±2%) are presented in the tables. Good agreement was obtained between rate constants and infinity measurements obtained by the two methods.

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