Kinetics of the Reaction of *p*-Nitrophenyl Acetate with Amines in the Presence of Dodecylammonium Propionate and Aerosol-OT Aggregates in Benzene

By **Omar A. El Seoud,* Abilio Martins, Leila P. Barbur, Maria J. da Silva,** and **Valentin Aldrigue,** Instituto de Química da Universidade de São Paulo, C.P. 20.780, São Paulo, Brazil

Aminolysis of *p*-nitrophenyl acetate (NPA) by dodecylamine (DA) is 53 times faster in the presence of dodecyclammonium propionate (DAP) aggregates than in pure benzene. Reaction with imidazole (Imz) and *N*-methylimidazole (MeImz) in the presence of DAP displays much more micellar catalysis. Thus addition of 0.2M-DAP to 0.08M-Imz in benzene reduced the reaction half-life from 25 h to 3 min. Addition of water decreases the reaction rates. This decrease is mainly due to DAP head-group hydration with subsequent loss of catalytic activity. Reaction between NPA and the amines, is faster in presence of DAP than Aerosol-OT(AOT). Addition of water to the amine–AOT system increases the rates. The results are discussed in terms of bifunctional catalysis by DAP and the effects of the surfactants on the reactivities of substrates solubilized in their micellar cores.

AQUEOUS detergents increase the rates of several classes of reactions.[1-3] Rate enhancements have been explained in terms of specific binding of the substrates to the micelle with subsequent reduction of the activation free energies by electrostatic and hydrophobic interactions.[1-3] Some detergents, *e.g.* Aerosol-OT (AOT) [bis-2-ethylhexyl sodium sulphosuccinate $C_8H_{17}OCO{-}CH_2{-}C(SO_3^-Na^+)H{-}COOC_8H_{17}$] and alkylammonium carboxylates, form reversed or inverted micelles in non-aqueous solvents. In these micelles, the polar head groups are packed around

---

[1] E. H. Cordes and C. Gitler, *Bio-org. Chem.*, 1973, **1**, 1.

[2] C. A. Bunton, *Progr. Solid State Chem.*, 1973, **8**, 239.

[3] J. H. Fendler and E. J. Fendler, ' Catalysis in Micellar and Macromolecular Systems,' Academic Press, New York, 1975.

a micellar ' core ' whereas the hydrophobic tails are in contact with the solvent.[4-6,*] The use of reversed micellar catalysis as a model for enzymatic catalysis rests, among other things, on their demonstrated catalytic efficiency.[3,8] In reversed micellar catalysis, the reaction takes place in the aggregate core. The polar nature of this core is a subject of much interest because it sheds some light on the change in substrate activities when they are incorporated therein.[9-11] We report here a study of the interactions of *p*-nitrophenyl acetate (NPA) with dodecylammonium propionate (DAP) and with DAP-solubilized amines and water. The study aims at elucidation of the factors affecting micellar catalysis specially the role played by solubilized water. We were also interested in comparing the results in the presence of DAP and AOT to see how the surfactant type affects the catalysis.

EXPERIMENTAL

Benzene (Merck; Uvasol) was distilled from sodium on to activated type 4A molecular sieve and stored under nitrogen. [$^2H_6$]Benzene (Aldrich; 99.5% D) was stored over activated 4A molecular sieve. Imidazole (Imz) (Merck; analytical grade) was dried *in vacuo*, MeImz and dodecylamine (DA) (Aldrich) were distilled from CaH_2. *N*-Acetylimidazole (Sigma) was used as received. AOT (Aldrich; 96%) was purified as before.[12] DAP was prepared according to the published procedure,[13] and its purity checked by its m.p. and ^1H n.m.r. spectrum. [$^2H_3$]DAP was prepared by dissolving D_2O (Aldrich; 99.8% D) in a benzene solution of DAP. The solvent was distilled under reduced pressure and the procedure was repeated several times. ^1H N.m.r. showed that deuteriation of the detergent $\overset{+}{N}H_3$ group was *ca.* 90% complete. *N*-Dodecylacetamide was prepared from acetyl chloride and dodecylamine according to the known procedure,[14] and was recrystallized from chloroform-light petroleum, m.p. 183—186°.

Special care was taken to exclude moisture during sample preparation. DAP, [$^2H_3$]DAP, or AOT were weighed, dried *in vacuo* over P_2O_5, and reweighed before making up the stock solutions. ^1H N.m.r. spectra were obtained on a Varian model XL-100 spectrometer equipped with a frequency counter and operating at $34 \pm 0.5°$. Chemical shifts were measured at 500 Hz sweep width relative to internal tetramethylsilane and were accurate to ± 0.1 Hz. I.r. spectra were obtained on a Perkin-Elmer model 457A spectrometer.

Kinetic measurements were carried out spectrophotometrically with the aid of a Zeiss PMQII spectrometer equipped with a thermostatted cell holder ($\pm 0.05°$).

Reaction kinetics were monitored by following the appearance of the liberated *p*-nitrophenol at 320 nm as a function of time. The ester concentration was $3—4 \times 10^{-5}$M. The concentration of all other reagents was always in excess, and good first-order kinetics were observed. Pseudo-first-order rate constants (k_{obs}) were evaluated from the absorbance–time data using a Hewlett–Packard model 9820 A programmable calculator.

RESULTS

Reaction with DAP.—The results of the reaction of NPA with [$^2H_3$]DAP are shown in Figure 1. The rate is negligible below the surfactant critical micelle concentration (c.m.c.),† increases sigmoidally in the c.m.c. region, then linearly as a function of increasing DAP concentration. The reaction with DAP is faster than with [$^2H_3$]DAP and the isotope effect at 0.2M-DAP, k_H/k_D, is 1.2.

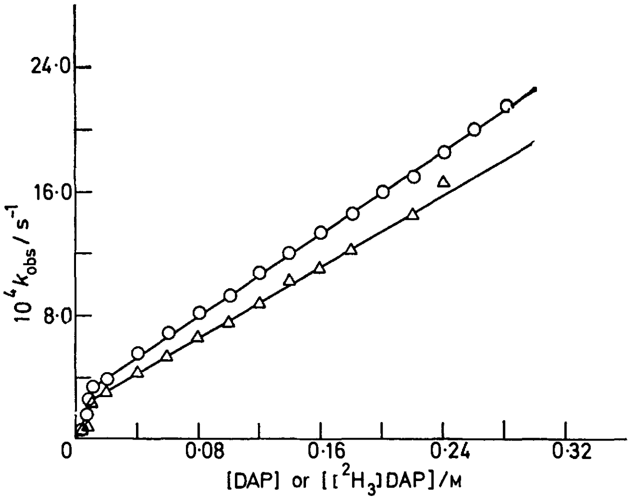


FIGURE 1 Aminolysis of NPA, ○, and [$^2H_3$]DAP, △

Reaction with Amines.—In benzene, the reaction between NPA and DA obeys the two-term equation (1). A plot of

$$k_{obs} = k_1[DA] + k_2[DA]^2 \qquad (1)$$

$k_{obs}/[DA]$ *versus* [DA] is shown in Figure 2. In the presence of DAP the reaction is faster than in bulk solvent. Equation (1) can be modified to account for the catalytic effect of

---

[*] There is a current debate about the aggregation of detergents in organic solvents. Both a single equilibrium model, *i.e.* monomer $\rightleftharpoons$ *n*-mer association, and a multiple equilibrium mode, *i.e.* monomer $\rightleftharpoons$ dimer $\rightleftharpoons \cdots \rightleftharpoons$ *n*-mer have been suggested. For alkylammonium propionates, ^1H n.m.r. chemical shifts fit either model equally well. It appears, however, that the multiple equilibrium model is gaining ground.

† The c.m.c. value used here ($3—7 \times 10^{-3}$M) [13] is an operational value determined from breaks in the graphs of the chemical shifts of the discrete protons of the surfactant *versus* its concentrations. It is interesting to note that these operational c.m.c.s correlate well with the chain length of alkylammonium carboxylates,[10,13] with solvent polarities,[5] and with the observed rate enhancements.[3]

[4] F. M. Fowkes, ' Solvent Properties of Surfactant Solutions,' ed. K. Shinoda, Dekker, New York, 1967.

[5] O. A. El Seoud, E. J. Fendler, J. H. Fendler, and R. T. Medary, *J. Phys. Chem.*, 1973, **77**, 1876; E. J. Fendler, V. G. Constein, and J. H. Fendler, *ibid.*, 1975, **79**, 917.

[6] J. B. Peri, *J. Colloid Interface Sci.*, 1969, **29**, 6; K. Kon-No and A. Kitahara, *ibid.*, 1971, **35**, 636.

[7] N. Muller, *J. Phys. Chem.*, 1975, **79**, 278; F. Y. F. Lo, B. M. Escott, E. J. Fendler, A. T. Adams, jun., R. D. Larsen and P. W. Smith *ibid.*, p. 2609; A. S. Kerts, *Surface Colloid Sci.*, 1976, **8**, 193.

[8] O. A. El Seoud, *J.C.S. Perkin II*, 1976, 1497.

[9] F. M. Menger, G. Saito, G. V. Sanzero, and J. R. Dodd, *J. Amer. Chem. Soc.*, 1975, **97**, 909.

[10] J. H. Fendler, *Accounts Chem. Res.*, 1976, **9**, 153.

[11] J. H. Fendler and L. J. Liu, *J. Amer. Chem. Soc.*, 1975, **97**, 999; M. Seno, K. Araki, and S. Shiraishi, *Bull. Chem. Soc. Japan*, 1976, **49**, 899.

[12] O. A. El Seoud and J. H. Fendler, *J.C.S. Faraday I*, 1975, 452.

[13] J. H. Fendler, E. J. Fendler, R. T. Medary, and O. A. El Seoud, *J.C.S. Faraday I*, 1973, 280.

[14] A. I. Vogel, 'A Text book of Practical Organic Chemistry,' Longman, London, 1956.

DAP as shown in equation (2), where M is the concentration

$$k_{obs} = k_1[DA] + k_2[DA]^2 + k_3[DA][M] \qquad (2)$$

of DAP in micellar form.* A plot of $k_{obs}/[DA]$ *versus* $[M]$ at constant DA concentration (0.08M) is linear as required by equation (2) (Figure 2). The slope (k_3) shows that the reaction is 53 times faster in the presence of DAP. The reaction between Imz or MeImz and NPA in benzene is negligible at 25°. We estimate that $t_{1/2}$ (0.08M Imz) is *ca.* 25 h, *i.e.* k_{obs} is $0.77 \times 10^{-5} s^{-1}$. In the presence of 0.2M-DAP the rate is much faster and increases linearly as a function of increasing the diazole concentration as shown in Table 1.

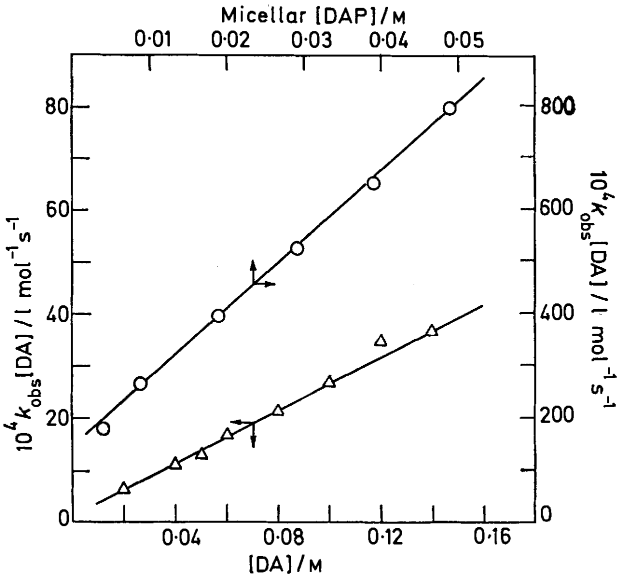


FIGURE 2 Plots of equations (1) and (2) showing aminolysis by DA in benzene, △, and micellar catalysis of the reaction of NPA with 0.08M-DA, ○

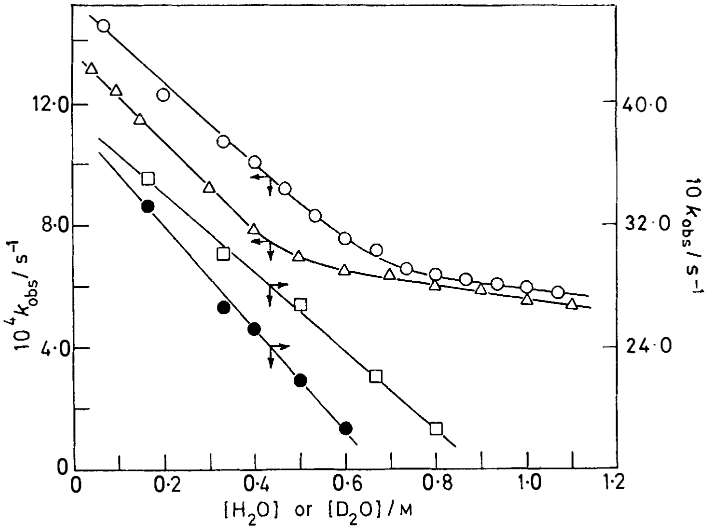


FIGURE 3 Effects of water or D_2O on the rate of reaction at a surfactant concentration of 0.2M: ○, water–DAP; △, D_2O-[$^2H_3$]DAP; □, water–0.1M-Imz–DAP; and ●, water–0.1M-MeImz–DAP

TABLE 1

Observed rate constants [a] for the NPA–amine reactions in benzene in the presence of 0.2M-DAP at 25°

[Imz] or [MeImz]/M	k_{obs}[Imz] − k_{obs}[DAP] [b]	k_{obs}[MeImz] − k_{obs}[DAP] [b]
0.02	5.0	
0.04	11.0	8.2
0.06	16.1	13.3
0.08	21.9	19.8
0.10	26.5	24.0
0.12	32.0	29.2
0.14	40.0	34.3
0.16	45.0	39.0

[a] All rate constants are multiplied by 10^4 and are given in s^{-1}.
[b] k_{obs} for 0.2M-DAP is $16 \times 10^{-4} s^{-1}$.

Effects of Water and D_2O.—Addition of water and/or D_2O decreases the observed rates. In the reaction with DAP, the rate decreases rapidly up to water concentration of 0.6M, then it decreases much more slowly. In the reaction of the ester with diazole–DAP, the rate decreases linearly as a function of increasing water concentration. The results are shown in Figure 3.

Interactions in the Presence of AOT.—The detergent itself does not react with NPA. At a fixed DA concentration (0.08M), the reaction is slower in the presence of AOT than in bulk solvent, also k_{obs} decreases as a function of increasing AOT concentration (Table 2). AOT-solubilized imidazole reacts more slowly than in the presence of DAP. Thus k_{obs} for 0.08M-Imz and 0.2M-DAP is 3.5 times faster than for 0.08M-Imz and 0.2M-AOT. MeImz reacts still slower and the rate in the presence of DAP is 84 times faster than in the presence of AOT. Addition of water to amine–AOT increases k_{obs} in all cases as shown in Table 2.

DISCUSSION

Before analysing the results, some observations about the reaction with DAP and diazole–DAP are discussed.

---

* The surfactant concentration in the micellar form (M) is given by $M = (C_D - \text{c.m.c.})/N$, where C_D is the total DAP concentration and N its aggregation number. Values of c.m.c. and N were taken from ref. 13.

The reaction rate can be conveniently followed by monitoring either the appearance of *p*-nitrophenol at 320 nm or the disappearance of the reacting ester (ν_{CO} at 1 810 cm^{-1}).*,† The production of *p*-nitrophenol and *N*-dodecylacetamide right from the start of the reaction was confirmed by t.l.c. (solvent water–dioxan 2 : 8 v/v). In the reaction with Imz–DAP, a small increase in the absorbance at 245 nm * (due to the formation of the intermediate *N*-acetylimidazole) was observed soon after adding the ester solution.† It should be noted, however, that *N*-acetylimidazole reacts rapidly with DAP producing imidazole and *N*-dodecylacetamide.* The foregoing discussion shows that the reaction under consideration is an aminolysis by the surfactant-derived dodecylamine catalysed either by DAP or by micelle-solubilized diazole.†

TABLE 2

Observed rate constants for the reaction between NPA and amines in the presence of AOT at 25°

[Amine]/M [a]	[AOT]/M	[H_2O]/M	k_{obs} [b]
1-Imz	0.20		6.3
	0.20	1.0	7.4
2-MeImz	0.20		0.2
	0.20	1.0	0.8
3-DA			1.7
	0.04		1.6
	0.08		1.4
	0.12		1.0
	0.20		0.8
	0.20	0.5	0.9
	0.20	1.0	1.1
	0.20	1.5	1.4

[a] The amines concentration was fixed at 0.08M. [b] Rate constants, in s^{-1}, were multiplied by 10^4.

Rate constants below the surfactant c.m.c. indicate a negligible reaction between NPA and DAP monomers. The sigmoidal increase in the c.m.c. region may be due to incorporation of the ester in the rapidly increasing number of micellar aggregates. The subsequent linear increase as a function of increasing DAP concentration is similar to that observed for the DAP-catalysed hydrolysis of 2,4-dinitrophenyl sulphate in the same solvent.[3] Micellar catalysis can be represented by the general equation (3) where S, M, and SM represent substrate,

$$\begin{tikzcd} S + M \arrow[r, shift left, "K"] \arrow[d, "k_o"] & MS \arrow[l, shift left] \arrow[d, "k_M"] \\ P & P \end{tikzcd} \qquad (3)$$

micelle, and micelle–substrate complex respectively, k_o and k_M are rate constants in the bulk solvent and in the micelle, K is the substrate–micelle association constant. From equation (3) the rate constant can be formulated as in equation (4).[3]

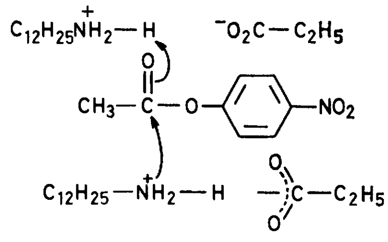
$$k_{obs} = (k_o + k_M K[M])/(1 + K[M]) \qquad (4)$$

In the reaction with DAP, k_o represents the rate of the reaction with the surfactant monomers. Assuming a constant monomer concentration above the c.m.c.,[13,16] and neglecting k_o equation (4) can be rearranged to (5).

$$\frac{1}{k_{obs}} = \frac{1}{k_M K} \cdot \frac{1}{[M]} + \frac{1}{k_M} \qquad (5)$$

Plotting the data according to equation (5) yields k_M 0.0043 s^{-1} and K 11.3 ± 0.5 l mol^{-1}. The values show that the ester does not associate completely with the micelle even at high DAP concentration. This is in agreement with the absence of a plateau (*i.e.* saturation) in Figure 1.

Rate enhancement in the presence of DAP can be explained in terms of bifunctional catalysis of the slow attack step as depicted in the Scheme.



SCHEME

The observed isotope effect indicates, not unexpectedly, synchronous proton transfer and amine attack.

The surfactant catalytic effect is more pronounced in the case of the reaction with Imz and MeImz. Thus in the presence of 0.2M-DAP the rate constant (k_{obs} — k_{obs}[DAP]) for 0.08M-Imz is 284 times greater than that in benzene. The slow step is assumed to be diazole attack on NPA, and the rate increase may be the result of the bifunctional catalysis in the Scheme. The slightly faster reaction with Imz can be attributed to its stronger association with DAP.[18] It is possible that the slower rate in benzene is due, in part, to the extensive auto-association of Imz,[19] and that the surfactant increases the rate by breaking down these aggregates. That this is not the case is shown by the observation that MeImz, which does not self-associate,[20] behaves similarly to Imz. Plots of (k_{obs} — k_{obs}[DAP]) *versus* [Imz] or [MeImz] (Table 1) yield catalytic rate constants of 0.0284 and 0.0258 l mol^{-1} s^{-1}, respectively.

---

* This experiment was carried out in dichloromethane.

† This observation is similar to that found in imidazole-catalysed NPA reaction in water. Note also that in the presence of other nucleophilic reagents such as thiols or amines, the observed reaction may be acyl transfer rather than hydrolysis because of the higher nucleophilic reactivity of thiols and amines toward acyl compounds. In the presence of moderate concentrations of such nucleophiles, the second step is fast and the attack of Imz on the acyl compound is rate determining. It seems, therefore, that the mechanism of aminolysis in the presence of DAP is similar to that in water. For details of the latter, see ref. 15.

[15] W. P. Jencks, 'Catalysis in Chemistry and Enzymology,' McGraw-Hill, New York, 1969; M. L. Bender, 'Mechanisms of Homogeneous Catalysis from Protons to Proteins,' Wiley–Interscience, New York, 1971.

[16] E. J. Fendler, J. H. Fendler, R. T. Medary, and O. A. El Seoud, *J. Phys. Chem.*, 1973, **77**, 1432.

[17] K. Kon-No, T. Matsuyama, H. Mizuno, and A. Kitahara, *Nippon Kanaku-Kaishi*, 1975, 1857.

[18] O. A. El Seoud and F. P. Ribeiro, *J. Org. Chem.*, 1976, 41, 1365.

[19] M. R. Grimmett, *Adv. Heterocyclic Chem.*, 1970, **12**, 103.

[20] L. Hunter and J. A. Marriott, *J. Chem. Soc.*, 1941, 777.

TABLE 3

Chemical shift data [a] for 0.2M-DAP and -[$^2H_3$]DAP in the presence of water and D_2O

DAP				[$^2H_3$]DAP			
[H_2O]/M	$\Delta\delta_{\overset{+}{N}H_3}$ [b–d]	$\Delta\delta_{CH_2\overset{+}{N}H_3}$ [b,c]	$\Delta\delta_{CH_2CO_2}$ [b,c]	[D_2O]/M	$\Delta\delta_{\overset{+}{N}D_3}$ [c,e,f]	$\Delta\delta_{CH_2\overset{+}{N}D_3}$ [c,e]	$\Delta\delta_{CH_2CO_2}$ [c,e]
0.22	−161.3	17.5	2.6	0.20	−174.2	19.3	2.5
0.44	−205.0	26.8	4.6	0.40	−232.8	28.3	4.1
0.60	−230.0	30.8	6.2	0.60	−256.8	33.2	6.3
0.89	−257.1	36.7	8.4	0.80	−280.2	37.4	8.0
1.11	−270.9	38.8	8.6	1.00	−291.7	38.2	8.6
1.33	−280.8	39.8	8.7	1.20	−299.6	39.2	9.0
1.78	−297.6	41.3	9.0	1.60	−310.9	40.7	9.2

[a] Reference internal tetramethylsilane, solvent [$^2H_6$]benzene, temperature 34 ± 0.5°. [b] $\Delta\delta$ = Chemical shift in the presence of water — chemical shift in its absence. [c] Chemical shifts in absence of water were 861.0, 272.2, and 244.3 Hz for the $\overset{+}{N}H_3$, $CH_2\overset{+}{N}H_3$, and $CH_2CO_2^-$ protons, respectively. [d] Due to fast proton exchange, one peak appears for the $\overset{+}{N}H_3$ and water protons. [e] Chemical shifts in absence of D_2O are 876.8, 273.1, and 244.3 for the $\overset{+}{N}D_3$ (see note *f*), $CH_2\overset{+}{N}D_3$ and $CH_2CO_2^-$ respectively. [f] The peak followed was actually due to the residual DAP (*ca.* 10%) present in [$^2H_3$]DAP.

Addition of water to either DAP or the diazole–DAP system decreases the rate. This is possibly the result of decreased acid–base catalysis due to head-group hydration, or simply to dilution of the ester in the aggregate core. Evidence that head-group hydration is more important comes from measurements of the chemical shifts of the $\overset{+}{N}H_3$, $CH_2\overset{+}{N}H_3$, and $CH_2CO_2^-$ protons in the presence of water or D_2O (Table 3). When water is added, the $\overset{+}{N}H_3$ protons shift upfield whereas the methylene protons shift downfield. As expected, the shift order is $\overset{+}{N}H_3 > CH_2\overset{+}{N}H_3 > CH_2CO_2^-$. The upfield $\overset{+}{N}H_3$ shift is due to its hydration, whereas the behaviour of the methylene groups is the result of the decreased mutual interaction, *i.e.* charge neutralization, between the CO_2^- and NH_3^+ groups because of their strong hydration. Similar behaviour has also been observed in the solubilization of other substrates.[21] Chemical shifts change rapidly up to water concentrations of 0.8M, then they change very slowly. The chemical shift variation as a function of increasing water or D_2O is parallel to that of k_{obs}[DAP] (Figure 3) and clearly demonstrates the important effect of head-group hydration on catalysis. Effect of water on the observed rate constants for the diazole–DAP system can be similarly explained.

It is possible that some NPA hydrolysis takes place at higher water concentrations. In addition to unsuccessful attempts to detect acetic acid among the reaction products (using t.l.c.), two experiments were carried out to further check this possibility. In the first experiment, DAP was varied over a narrow range (0.18—0.21M) whereas the water was kept constant near the DAP saturation point. The intercept of the graph between k_{obs} *versus* DAP concentration (six experimental points) was practically zero. In the second experiment the molar ratio water : DAP was kept constant (7.7 : 1) and the concentrations varied simultaneously. Over DAP range 0.18—0.21M the rates remained constant ±3%, *i.e.* hydrolysis is negligible indeed.†

Attention is now focused on the effect of AOT on the reaction of NPA with DA, Imz, and MeImz. In comparing AOT results with those in the presence of DAP one has to consider differences in the mechanism of solubilization and head-group participation. Solubilizates can interact with both head-groups of DAP, whereas in the case of AOT the main interaction is by hydrogen-bonding to the SO_3^- group.[21] One expects a stronger interaction between AOT and DA or Imz than with MeImz which will be distributed in favour of the bulk solvent. This partially explains the much lower rate in the case of MeImz compared with that of Imz. It also explains the rate increase in the presence of solubilized water because MeImz is now more soluble in the micellar water 'pool'.[22] Imz associates more strongly with AOT than with DAP, *e.g.* in carbon tetrachloride the ratio of the association constants is *ca.* 12 : 1.[12] Nevertheless the rate is slower than that in the presence of DAP, probably because of the absence of specific head-group catalysis in the former case.

The results of DA are interesting because not only is the reaction slower in micellar AOT than in the bulk solvent, but also the rate decreases on adding more surfactant. It seems that the amine basicity is reduced due to its strong hydrogen-bonding to AOT. Addition of water increases the rate because it causes hydration which weakens the amine–AOT bonding.

The above discussion shows the complexity of reversed micellar catalysis. It demonstrates that a rational analysis of the results has to take into account the substrate–micelle association, the participation of the head-groups, and the effect of the micelle-solubilized water.

Support for this work from the CNPq Research Foundation is gratefully acknowledged.

[7/099 *Received*, 20*th January*, 1977]

---

[21] O. A. El Seoud, E. J. Fendler, and J. H. Fendler, *J.C.S. Faraday I*, 1974, 450, 459.

[22] F. M. Menger, J. A. Donohue, and R. F. Williams, *J. Amer. Chem. Soc.*, 1973, **95**, 286.