Pure & Appl. Chem., Vol. 50, pp. 617-625.
Pergamon Press Ltd. 1978. Printed in Great Britain.

0033-4545/78/0701-0617 $02.00/0

KINETICS OF ORGANIC REACTIONS IN MICELLES

E. H. Cordes

Department of Chemistry, Indiana University, Bloomington, Indiana 47401, U.S.A.

Abstract - Those features of micellar organization and structure most pertinent to the understanding of micellar catalysis of organic reactions are briefly reviewed. Of crucial importance are the properties of the micelle-water interface: marked hydrophobicity and hydrophilicity as manifested in binding of both organic molecules and ions to the micellar surface; a surface dielectric constant near 35; the high concentration of charged groups at the micellar surface; a water activity near unity; and the presence of functional groups. Those factors contributing to micellar catalysis are reviewed. For nonfunctional micelles, effects are either the consequence of the nature of the reaction medium (activity coefficient effects), the concentration of reactants (entropy effects) or both. Pertinent examples are cited including decarboxylations, phosphate ester hydrolyses, fading of dyes, and addition of cyanide ion to pyridinium ions. Finally, theoretical treatments of micellar catalysis are briefly reviewed, pointing out that equations derived by Berezin and by Romsted account satisfactorily for many features of micelle catalysis.

INTRODUCTION

The interface formed at the polar head groups of micelles in the presence of a surrounding aqueous environment provides an unusual microenvironment in which chemical reactions may occur. During the past decade, there have been a number of studies concerned specifically with the characteristics of reactions occurring at the micellar surface. The extensive literature generated has been the subject of several detailed reviews (1-4).

The purposes of the present review are the following. First, to review those aspects of the chemistry of the micellar surface which are particularly important for the understanding of organic reactions occurring thereon. Second, to outline the salient features of the kinetics of organic reactions at the micelle surface, with particular emphasis on the source of the rate enhancements observed. Third, to provide a theoretical picture which accounts for these features. Finally, to relate, where possible, the chemistry of reactions at the micellar surface to those of reactions occurring in related microenvironments. No attempt is made to be comprehensive. Rather, I have chosen to focus attention on a modest number of reaction types, which illustrate clearly the underlying principles involved. Moreover, I have chosen to focus attention on the simplest of systems. Thus, two important systems for micellar catalysis, functionalized micelles and inverted micelles, are not discussed. Similarly, the modest literature dealing with stereochemical control of reactions in micelles and the utilization of micelles for synthetic purposes are not considered.

PROPERTIES OF THE MICELLE-WATER INTERFACE

Above the critical micelle concentration, ionic surfactants in water form aggregates of various sizes, shapes, and dispersity. The simplest micelles, formed from ordinary surfactants such as sodium dodecyl sulfate or hexadecyltrimethylammonium chloride, contain 50-100 molecules of surfactant. Such small micelles are nearly monodisperse (5,6); other micellar systems have been shown to be polydisperse (5-7). Small micelles are frequently considered to be spherical in shape; however, geometrical considerations associated with micelle formation require that they be ellipsoids of revolution (8). Several lines of evidence, however, suffice to indicate that the axial ratio of micelles is ordinarily not greater than 6:1 (9-11). Certain micelles undergo a transition to large rod-shaped structures at sufficiently high concentrations of certain salts.

Most reactions of interest in this review occur at the interface between the micelles and the surrounding water solvent. Consequently, the properties of that interface are of importance to us. A number of related systems in aqueous solution also possess interfaces which may

provide a microenvironment for chemical reactions related in some respects to that of the micellar surface. Included in this category are the surfaces of polysoaps, globular proteins, microemulsions and inverted micelles, liposomes, and biological membranes. Where pertinent, comparisons between properties of these surfaces and of chemical reactions occurring on them will be developed.

The crucial aspects of the chemistry of the interface formed between micelles and water, and the related interfaces mentioned above, are the following: hydrophobicity, hydrophilicity, polarity, charge, water activity, segmental and rotational mobilities of groups located at the surface, and the presence of functional groups which may participate directly in chemical reactions as, for example, nucleophiles. Needless to say, these properties are interdependent but each shows up in one or more facets of reaction kinetics at the micellar surface.

One of the most salient and important features of the micellar surface is the fact that it is amphipathic. Just as a surfactant molecule can be considered to be a one-dimensional amphipathic construct, the micellar surface can be viewed as a two-dimensional amphipathic structure. This shows up in the fact that both hydrophobic organic molecules and hydrophilic ions may associate with micelles and be localized at the micellar surface (1). In fact, a large number of reactions studies in micellar systems involve two substrates: one an organic molecule and the other an ion. Examples are the acid catalyzed hydrolysis of acetals, the basic hydrolysis of esters, alkaline fading of triphenylmethyl dyes, and addition of ions to pyridinium ions.

The amphipathicity of the micellar surface is a property shared with the surfaces of proteins and membranes. For example, it is well known that serum albumin has high affinity for nonpolar molecules such as steroids and also interacts strongly with ions. Similarly, membranes have high affinity for both classes of substances. The structural basis of the amphipathic character of the protein surface has been clearly defined as a consequence of extensive x-ray diffraction structure determinations. The surface is dotted with exposed cationic and anionic groups which are separated, to some extent, by exposed hydrophobic side chains of amino acid residues. Consequently, a molecule may encounter quite distinct environments depending on what specific site on the protein surface it probes. The structural basis of the amphipathic nature of the micellar surface is not so easy to understand. The surface is, in the simplest model, heavily occupied by the charged groups, their counterions, and solvating water molecules. It is not clear why an organic molecule should be attracted to such an environment. Most likely this uncertainty derives from the fact that this model is too simple. More realistically, one should view the micellar surface as rough so that a molecule absorbed on to the surface will be exposed to the first two or three methylene groups of the surfactant chains. This model is made attractive by the fact that micelles are highly dynamic structures, in rapid equilibrium with their monomeric constituent molecules. Moreover, as we shall see, individual molecules within the micelle have abundant freedom of motion. A dynamic, rough-surfaced, micelle provides a suitable structural model for accounting for the amphipathic character of the micellar surface.

The polarity of the micellar surface has been probed by two means. Mukerjee and Ray employed the position of the charge transfer band between pyridinium ions and iodide as a measure of the dielectric constant of the ionic micellar surface (12). They derived a value near 35. Thus, the polarity of the micellar surface is considerably less than that of the aqueous environment and is more nearly comparable to that of ethanol. A second approach relies on the position of the fluorescence maxima of absorbed dyes such as 1-anilino-naphthalene-7-sulfonate. The position of the fluoresence maxima can be correlated with the Kosower Z values (13, 14); representative data is provided in Table 1 (3). This data is in essential agreement with the conclusions of Mukerjee and Ray: the micellar surface is significantly less polar than that of water but somewhat more polar than that of ethanol. Note specifically that the polarity of the micellar surface is comparable to that at the surface of simple globular proteins and the membrane of the erythrocyte.

The surface of micelles formed from ionic surfactants is highly charged. A simple arithmetical calculation suggests that the concentration of charged groups at the micellar surface is 3-5 M. About 80% of these charges are neutralized directly through the incorporation of counterions into the micellar surface, forming the Stern layer. The remainder of the counterions form the diffuse Gouy-Chapman layer. The existence of a substantial net charge at the micellar surface provides a large drop in electrical potential across the Stern layer and attracts ions of opposite charge, a conclusion of importance in understanding reaction kinetics at the micellar surface.

There are three lines of evidence strongly suggesting that the activity of water at the surface of ionic micelles is not very different from that in the bulk solvent. First, it was noted some years ago that the rate of pH-independent hydrolysis of long-chain alkyl sulfates is unchanged when these substrates form micelles (15). Since this reaction involves the attack of water on the phosphate ester, the conclusion cited above follows.

A related observation has been recently made by Menger (16). He has established that the

TABLE 1. Estimation of the polarity of binding sites from the emission maximum of bound 1-aminonaphthalene-7-sulfonate.[a]

1,7-ANS bound to	Protein Concentration (mg/ml)	ν_F X 10^4 (cm^{-1})	Z (Estimated)
Glutamate dehydrogenase	1.20	2.193	84
Chymotrypsinogen	0.9	2.198	84
Hexokinase	0.19	2.193	84
Adenosine deaminase	0.2	2.227	81
Aldolase	3.0	2.212	82.5
Lysozyme	1.0	2.155	88
Hemoglobin-free erythrocyte membranes	1.0-2.0	2.214	82.5
Hexadecyltrimethylammonium bromide (15 mM)	-	2.174	85.5
Tetradecyldimethylbenzyl ammonium chloride (50 mM)	-	2.183	84.5
Triton X-100 (5 mM)	-	2.183	84.5

[a]Modified from Ref. 3

rate of pH-independent hydrolysis of p-nitrophenyl carbonate, a reaction thought to involve two molecules of water in the transition state, is only slightly depressed when it occurs on the surface of ionic micelles compared to bulk water. A direct effort was made to measure the activity of water at the micellar surface by comparing the extent of hydration of N-alkyl-3-formylpyridinium ions in water and in the presence of micelles into which it is incorporated. The results fail to indicate a significant difference in the extent of hydration in the two environments (17), added support for a near normal water activity at the micellar surface. Finally, Bunton has observed that the rate of attack of water on triphenylmethyl cationic dyes is uninfluenced by the presence of micelles (18). Our conclusion is also consistent with the results of several studies indicating that the extent of hydration of counterions incorporated into the Stern layer is about the same as that for the same ions existing free in the bulk aqueous solvent (19-21).

The interior of a micelle is viewed as being much like a liquid hydrocarbon droplet. Fluoresence (22,23) and esr (24) measurements on the rate of rotational reorientation of probe molecules in micelles indicates that this is substantially true even though their motion is significantly restricted relative to that in pure organic solvents of low viscosity. This conclusion is consistent with results of measurements of spin-lattice relaxation times for several carbon atoms of alkyltrimethylammonium surfactants in the monomeric and micellar states (25). Upon micellation, significant restrictions on segmental and rotational mobilities for all carbon ions are observed. The restrictions are most marked for those carbon atoms at the micellar surface and diminish as one moves down the chain away from the ionic head group. Despite the restrictions on mobilities, the values of the spin-lattice relaxation times indicate a rather fluid environment, both in the micellar interior and at the surface. The fluid nature of the micellar surface may provide insight concerning the fact that there are relatively few well-defined examples of stereochemical control of organic reactions in micelles.

Finally, a large number of surfactants have been constructed through chemical synthesis which bear reactive functionalities. These frequently include nucleophilic groups which are active against esters. Such studies have been frequently undertaken in an effort to generate realistic models for enzymes, such as chymotrypsin, which carry out direct nucleophilic attack on their substrates. It is in fact true that micelles formed from surfactants containing nucleophilic functionalities are frequently exceptionally effective catalysts for the hydrolysis of esters (26-30).

This brings to a conclusion our consideration of properties of the micellar surface. As noted above, it has been established that micelles are frequently catalytically active toward organic reactions. With this background in hand, it is now appropriate to turn to consideration of this catalytic action.

CONTRIBUTING FACTORS IN MICELLAR CATALYSIS

Aside from inherent interest in micelles as catalytic entities, a good deal of consideration of micellar reactions as models for certain aspects of enzyme catalyzed reactions has been developed. The same statement is also true for catalysis of organic reactions by polysoaps. In many respects, micelles fail as models for enzyme catalyzed reactions. Functional micelles have been developed which match certain enzymatic reaction velocities but nonfunctional micelles are much less effective catalysts. Neither functional nor nonfunctional micelles exhibit the degree of specificity associated with enzymatic reactions and neither class of micellar reaction is subject to the kind of control to which enzymes are. Nonetheless, in one important respect, nonfunctional micelles are suitable models for enzymatic catalysis. Enzymes and micelles derive a significant portion of their catalytic ability from the same sources. This matter has been discussed in revealing detail by Jencks (31).

The fact that micelles are catalysts for a number of reactions is equivalent to saying that there is a decrease in the standard free energy of the transition state relative to reactants in the aqueous phase. The question is: to what factor or factors may one attribute this diminution in standard free energy difference between reactants and transition state? In dealing with reactions in homogeneous systems, it is customary to discuss this question in terms of the Brönsted-Bjerrum equation:

$$\delta\Delta G^{\ddagger} = RT \ln \frac{f^{\ddagger}}{f_A f_B} \qquad (1)$$

In terms of this equation, one analyzes rate changes in terms of effects on activity coefficients for substrate and transition state. While this is a straightforward procedure, for the most part, for homogeneous systems there are two significant difficulties in carrying out such analysis for reactions occurring on the surface of a micelle or, for that matter, on the surface of an enzyme. First, an important contributor to catalysis in micellar or enzymatic systems for second-order and higher-order reactions derives from a decrease in entropy of the reactants by virtue of their binding to the catalyst surface. That is to say, if the substrates are confined to the micellar surface the volume available to them is much decreased from that available in the bulk aqueous phase. This is equivalent to recognizing that the two or more reactants will be much more concentrated with respect to each other as a consequence of the binding reactions. This entropic contribution to the reaction rate is not easily understood in terms of the Brönsted-Bjerrum equation. Second, the activity coefficient of a molecule in the micellar phase may not be revealing in attempting to account for an increase in reaction rates. This derives from the fact that there may well be different microenvironments for different parts of the absorbed molecule. The fact that an organic substrate, for example, associates with micelles with an equilibrium constant greater than unity requires that its activity coefficient decreases on going from the aqueous phase to the micellar phase. However, the overall decrease in the activity coefficient of the reactant may be accompanied by an <u>increase</u> in the activity coefficient at the site of chemical reaction. This consideration is true for both enzymatic and micellar reactions. It, too, is not evident on the basis of the Brönsted-Bjerrum equation.

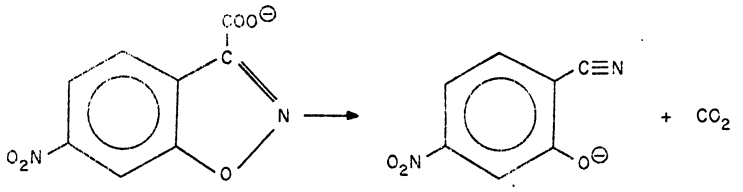
Understanding of catalysis for organic reactions in the presence of micelles requires that one separate the two factors indicated above: the entropic contribution reflecting concentration effects and the effects on the relative activity coefficients at the site of reaction for substrates and transition states, a consequence of the nature of the microenvironment in which the reaction occurs. Perhaps the simplest means of accomplishing this end is to begin by considering unimolecular reactions for which the entropic contribution cannot be important. Rate changes, whether it be catalysis or inhibition, must necessarily reflect the changes in the nature of the medium in which the reaction occurs. If one assumes that all of the substrate is in the micelle and that activity coefficients for both substrate and transition state in the aqueous phase are unity, the extent of catalysis is given by the simple equation:

$$K/K_o = f^A/f^{\ddagger} \qquad (2)$$

in which the activity coefficients refer to the micellar system. Clearly, catalysis may result from destabilization of the reactant, an increase in f^A, or stabilization of the transition state, reflected in a decrease in $f^{\ddagger}$.

As a pertinent example of micellar catalysis for a unimolecular reaction, let us consider the

decarboxylation of 5-nitrobenzisoxazole-3-carboxylate, a reaction probed in considerable detail by Bunton and his coworkers (32-34):



5-nitrobenzisoxazole-carboxylate (3)

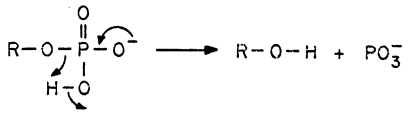
This reaction is catalyzed by cationic, nonionic, and zwitterionic surfactants.

The decarboxylation of 5-nitrobenzisoxazole-3-carboxylate is a reaction in which a negative charge localized in the substrate is delocalized in the transition state. Consequently, it might be anticipated that the reaction would be accelerated in less polar environments. The work of Kemp and Paul, prior to the initiation of studies in micellar systems, established that this is the case (35). Consequently, the most logical explanation for the fact that micelles are effective catalysts for this reaction is substrate destabilization in the less polar environment provided by the micellar surface. This destabilization is most probably electrostatic in nature since considerations indicated above suggest that the carboxylate function is probably not significantly desolvated at the micellar surface. This reaction shows one additional notable feature: the rates are modestly increased upon the addition of certain salts. This is contrary to the observations made for many bimolecular reactions in micellar systems for which salts are almost uniformly inhibitory. In this particular case the catalytic effect of added salts must reflect some alteration in the shape and properties of the micelles.

Kunitake et al. have investigated the polysoap-catalyzed decarboxylation of the same substrate (36). Partially laurylated poly(4-vinylpyridine) and poly(2-ethyl-1-vinylimidazoles) are more effective as catalysts for this reaction than are simple cationic surfactants. The addition of hydrophilic salts elicits complex kinetic behavior. Such salts first diminish then, at higher concentrations, increase the rate of the polysoap-dependent decarboxylation. Like the micellar reaction, catalysis observed in the presence of polysoaps probably reflects destabilization of the carboxylate moiety of the substrate by the nonpolar environment. Bovine serum albumin was observed by the same workers to be noncatalytic for this reaction (36).

Klotz and coworkers have observed that partially laurylated polyethyleneimines are even more potent catalysts for 5-nitrobenzisoxazole-3-carboxylate decarboxylation (37). A maximum catalytic effect of 1300-fold was observed. The reaction obeys the Michaelis-Menten kinetics pattern typical of enzymatic reactions.

A second example of micellar catalysis which must derive from medium effects, as opposed to entropic ones, is provided by the unimolecular hydrolysis of phosphate esters. Phosphate ester monoanions hydrolyze via unimolecular elimination of a metaphosphate ion:



(4)

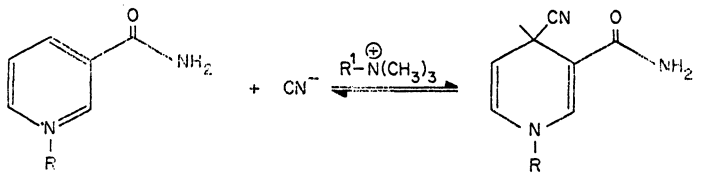
Although phosphate monoanions are readily incorporated into micelles formed from cationic surfactants, this does not result in an appreciable alteration in the rate of hydrolysis (38). Those phosphate ester dianions in which the leaving group contains strong electron attracting groups also hydrolyze via unimolecular elimination of metaphosphate. In this case, however, cationic micelles are good catalysts for hydrolysis (38-40). For example, the rate of hydrolysis of 2,5-dinitrophenyl phosphate dianion is approximately 25 times more rapid in the presence of an optimal concentration of hexadecyltrimethylammonium bromide than in water. The loss of the metaphosphate anion from a phosphate ester dianion involves a dispersal of two negative charges. Consequently one may argue that the catalytic driving force involves destabilization of the substrate relative to the transition state by the relatively nonpolar micellar surface, an explanation essentially the same as that invoked in the case of decarboxylation reactions. This conclusion is consistent with the fact that the rate of hydrolysis of phosphate ester dianions is significantly increased with a decrease in solvent polarity in the absence of micelles.

These examples of catalysis by micelles for unimolecular reactions indicate that the utili-

zation of binding forces between substrate and micelle can bring reactive functionalities of the substrate into an environment in which reactivity is augmented. We now turn attention to the case of bimolecular reactions in which not only medium effects but entropic effects resulting from concentration of reactants may be important.

In one of the earliest thorough studies of micellar catalysis, Duynstee and Grunwald established that rate and equilibrium constants for addition of hydroxide ion to stable triphenylmethyl cationic dyes, such as Crystal Violet, is subject to catalysis by cationic surfactants (41). This conclusion has been confirmed and amplified in several subsequent investigations (42-45). Facilitation of this reaction may reflect (i) concentration of hydroxide ion in the presence of the cationic dye by the cationic micellar surface and (ii) destabilization of the cationic dye by the cationic micellar surface. That the latter effect is important is suggested by two considerations. First, equilibrium constants for incorporation of the cationic dye and the corresponding alcohol into the micellar phase indicate a strong electrostatic effect in this process. The magnitude of the effect is about the same as that for the equilibrium constant for addition of hydroxide ion to the cationic dyes in the presence of micelles (41). Second, Bunton has established that addition of amines to the tri-p-anisyl cation is catalyzed by surfactants (42). That the former effect is important is strongly suggested by the observation that the addition of hydroxide ion to Crystal Violet in the presence of cationic surfactants is subject to strong inhibition by other anions, presumably the consequence of competition between hydroxide ion and these anions for binding sites at the micellar surface (see below) (45). Thus, the observed catalysis may be ascribed to electrostatic substrate destabilization as well as to the concentration of the reactive nucleophile in the presence of the substrate.

A closely related example is provided by the case of catalysis of the addition of cyanide ion to pyridinium ions (46):



(5)

As the data in Table 2 indicate, both rate and equilibrium constants for this reaction are markedly increased in the presence of cationic surfactants. Moreover the extent of the increases in rate and equilibrium constants is magnified by increasing substrate hydrophobicity and surfactant hydrophobicity (46). Here again catalysis may reflect the selective destabilization of the cationic head group by the cationic micelle as well as the concentration of cyanide ions in the vicinity of the substrate through electrostatic interactions with the micellar surface.

TABLE 2. Rate and association constants for the addition of cyanide ions to a series of N-substituted 3-carbamoylpyridinium ions in the presence of a series of n-alkyltrimethylammonium bromides in water at 25°

Substrate	Surfactant			
	Decyl	Dodecyl	Tetradecyl	Hexadecyl
Octyl				0.21; 135
Decyl			1.10; 530	1.35; 710
Dodecyl		2.5; 1100		5.8; 4000
Tetradecyl	0.28; 330		6.6; 3600	10.4; 4500
Hexadecyl		6.4; 4500		13.3; 4800

[a]Surfactant concentration of 0.02 M throughout. The entries in the table are second-order rate constants in units of M^{-1}. sec^{-1} followed by association constants in units of M^{-1}. From Ref. 46.

The effect of the hydrophobic character of substrate and surfactant is particularly noteworthy. Basically what happens is that binding interactions between substrate and catalyst are employed to destabilize the substrate. In this respect, the catalysis strongly resembles that of enzymes. As the length of the chain of the substrate increases from 8 to 16

carbon atoms, the rate of the reaction increases 64-fold and the equilibrium constant 355-fold (Table 2). The former figure corresponds to utilization of 38% of the available binding energy to facilitate the reaction and the latter figure corresponds to utilization of 54% of the available binding energy to increase the affinity of substrate for cyanide (31). Finally, it has been established that this reaction is also subject to catalysis by bilayers formed from biological surfactants (46) and to marked catalysis by polyelectrolytes (47).

A KINETIC MODEL FOR MICELLAR CATALYSIS

It has been tempting to provide an explicit quantitative explanation to account for the principal features of micelle catalyzed reactions. These include the shape of rate-concentration profiles, dependence of catalytic parameters on the nature of the surfactant, particularly on the length of the hydrocarbon chain which determines the cmc, dependence of catalytic parameters on the hydrophobicity of the substrate, and inhibition of the reaction by salts.

The first kinetic model for micelle catalyzed reactions was proposed by Menger and Portnoy (48):

$$\begin{array}{ccc} D_n + S & \overset{K}{\rightleftharpoons} & D_n \cdot S \\ \downarrow k_w & & \downarrow k_m \\ \text{products} & & \text{products} \end{array} \qquad (6)$$

Employing certain simplifying assumptions, this kinetic scheme provides the following rate law:

$$k_{obs} = \frac{k_w + k_m K C_m}{1 + K C_m} \qquad (7)$$

in which K is the equilibrium constant for association of substrate, S, with micelles, D_n and C_m is the concentration of micelles: $C_m=(C_D-cmc)/N$, C_D being the total surfactant concentration and N the micelle aggregation number. This equation predicts a sigmoidal increase in rate constant with increasing surfactant concentration. Such behavior is seen for unimolecular reactions in the presence of micelles and this simple equation gives a good account of the data. On the other hand, reactions which are second-order, or higher order, usually exhibit an optimal rate at some surfactant concentration above which the rates decrease with increasing concentration. This fact has led to a search for a more satisfactory kinetic treatment for these more complex cases.

An important advance was made by Berezin and coworkers who treated the case of reaction of two uncharged organic molecules (49). The equation which they derived is:

$$k_{app} = \frac{k_m P^n C_D V + k_w (1 - C_D V)}{1 + C_D V (P-1)^n} \qquad (8)$$

in which V is the molar volume of the surfactant, P is the partition coefficient of the substrate between the two phases, and the other quantities have been identified earlier. This equation accounts well for data which it was intended to explain. On the other hand, it is not readily applicable to the understanding of some of the features of reactions between ions and organic molecules.

Perhaps the most generally satisfactory theory is that developed by Romsted in the author's laboratory (50). Romsted's theory depends on the following assumptions. First, one can write an equilibrium constant for the interaction of the substrate with the micelles. This assumption is common to all kinetic treatments of micellar catalysis but may fail in cases in which micelle structure and properties change as a function of some parameter in the reacting system. Second, and crucial, is the assumption that the Stern layer is always saturated with respect to counterions. In this respect, the Romsted treatment differs from all previous ones. This assumption is equivalent to the statement that the ground state for ions is the ion bound to the micellar surface, and not the ion free in the bulk phase. This assumption is introduced into the kinetic treatment in the form of an equilibrium constant describing counterion exchange on the micellar surface:

$$I_m + X_w \overset{K}{\rightleftharpoons} I_w + X_m \qquad (9)$$

in which I is taken to be a reactive and X an unreactive counterion.

Mathematical analysis yields the following equation to describe the rate constants for second-order reactions in the micellar phase:

$$k = \frac{k_m \beta S K_a (C_D - cmc)}{[K_a(C_D - cmc) + 1][I_t + X_t K]} + \frac{k_w}{[K_a(C_D - cmc) + 1]} \quad (10)$$

in which β is the degree of binding of counterions to the Stern layer and S is the molar density of micellar phase. In the case of first order reactions this simply reduces to the equation of Menger and Portnoy (eq. 7).

The utility of 10, lies largely in the fact that it accounts quantitatively for the basic features of reaction kinetics in micellar systems. Let us briefly consider a few examples; more detailed analyses are available (50,51). First, one of the repeated observations for second-order reactions in the presence of micelles is that plots of observed rate constants against surfactant concentration pass through maxima. Computer-generated plots based on eq. 10 mimic this behavior (50,51). This fact can be understood in terms of two competing effects, both of which are integrated into eq. 10. On the one hand, with increasing surfactant concentration, the relative concentrations of organic substrate and ionic reactant in the Stern layer increase rapidly; this tends to accelerate the reaction, accounting for the ascending limb of the curve. On the other hand, increasing surfactant concentration (for ionic surfactants) requires that the unreactive counterion concentration also increase while the reactive ion concentration remains constant. Since there are a limited number of ionic binding sites in the Stern layer, this requires that the concentration of the reactive ion in the vicinity of bound organic substrate decrease. This accounts for the descending limb observed at high surfactant concentrations.

Second, it has been observed in a number of cases that increasing substrate hydrophobicity results in larger maximal rate increases which are attained at progressively lower surfactant concentrations (Table 2 for example). Computer-generated plots based on eq. 10 reproduce this behavior very nicely (50). The increase in substrate hydrophobicity is reflected in eq. 10 in terms of an increase in K_a, the equilibrium constant for incorporation of the organic substrate into the Stern layer. The greater the binding constant, the less surfactant required to incorporate the substrate into the micellar pseudophase. This leads to faster rate increases as a function of surfactant concentration. In turn, this means that less unreactive counterion will be present, accounting for the fact that greater maximal rate increases are observed.

Third, it is frequently observed that increasing surfactant hydrophobicity also leads to greater maximal rate increases which are attained at lower surfactant concentrations (Table 2 for example). This is accounted for in just the same way as that employed above: increasing hydrophobicity (in substrate or surfactant) leads to increases in K_a and hence, to a greater concentration of reactive ion in the Stern layer. Hence, eq. 10 accounts well for this observation, too.

Fourth, a particularly nice success of eq. 10 is that it accords with the important observation of Bunton and Wolfe (52) that second-order rate constants for specific acid catalyzed hydrolysis of p-nitrobenzaldehyde diethyl acetal in the presence of sodium dodecyl sulfate decrease with increasing acid concentration. Note that eq. 10 predicts that the observed second-order rate constants are inversely related to the reactive ion concentration, accounting for the observation. This realization was first stated by Berezin and his coworkers (53).

Finally, there are many examples of inhibition of reactions in micellar systems through increasing concentrations of unreactive counterions; the extent of inhibition increases with increasing affinity of the unreactive counterion for the Stern layer. This phenomenon finds a ready explanation in terms of eq. 10 since a competition between reactive and unreactive ions for sites in the Stern layer, and hence in the vicinity of bound organic substrate, has been built into the model explicitly (eq. 9).

These examples should suffice to indicate that the theory of Romsted, and to a significant extent that of Berezin, is adequate to account for the salient features of micellar catalysis in a qualitative way at least. No one would argue that the theoretical treatments available are the last word; quite the contrary, it seems certain that improvements will be forthcoming regularly. However, in addition to providing chemically rational explanations for the dependence of the kinetics of these reactions on a number of variables, the equations derived are of predictive value. Efforts to examine these predictions will certainly lead to additional insight into reaction kinetics in micellar systems.

REFERENCES

1. J.H. Fendler and E.H. Fendler, Catalysis in Micellar and Macromolecular Systems, Academic Press, New York, 1975.
2. C.A. Bunton, Solid State Chem., 8, 239 (1973).

3. E.H. Cordes and C. Gitler, Prog. Bioorg. Chem., 2, 1 (1973).
4. E.H. Cordes, ed., Reaction Kinetics in Micelles, Plenum, New York, 1973.
5. P. Mukerjee, J. Phys. Chem., 76, 565 (1972).
6. N. Muller, J. Phys. Chem., 79, 287 (1975).
7. J.M. Corkhill and T. Walker, J. Colloid Interface Sci., 39, 621, (1972).
8. C. Tanford, J. Phys. Chem., 76, 3020 (1972).
9. D.G. Oakenfull and D.E. Fenwich, J. Phys. Chem., 78, 1759 (1974).
10. E.E. Schrier, M. Pottle, and H.A. Scheraga, J. Amer. Chem. Soc., 86, 3444 (1964).
11. W.P.J. Ford, R.H. OHeweil, and H.C. Parreira, J. Colloid Interface Sci., 21, 522 (1966).
12. P. Mukerjee and A. Ray, J. Phys. Chem., 67, 190 (1963); 70, 2144 (1966).
13. D.C. Turner and L. Brand, Biochemistry, 7, 3381 (1968).
14. C. Gitler, unpublished observations.
15. J.L. Kurz, J. Phys Chem., 66, 2239 (1962).
16. F.M. Menger, personal communication.
17. J. Albrizzio and E.H. Cordes, unpublished observations.
18. C.A. Bunton and S.K. Huang, J. Org. Chem., 37, 1790 (1972).
19. H. Gustavsson and B. Lindman, J. Amer. Chem. Soc., 97, 3923 (1975).
20. J. Oakes, J.C.S. Faraday II, 69, 1321 (1973).
21. I.D. Robb and R. Smith, J.C.S. Faraday I, 70, 287 (1974).
22. M. Shinitzky, A.C. Dianoux, C. Gitler, and G. Weber, Biochemistry, 11 2106 (1971).
23. U. Khuanga, B.K. Selinger, and R. MacDonald, Australian J. Chem., 29, 1 (1976).
24. J. Oakes, J.C.S. Faraday II, 68, 1464 (1972).
25. E. Williams, B. Sears, A. Allerhand, and E.H. Cordes, J. Amer. Chem. Soc., 95, 4871 (1973).
26. T. Kunitake and Y. Okahata, J. Amer. Chem. Soc., 98, 7794 (1976).
27. T. Kunitake, Y. Okahata, and T. Sakamoto, J. Amer. Chem. Soc., 98, 7800 (1976).
28. I.M. Klotz, G.D. Roger, and I.S. Scarpa, Proc. Natl. Acad. Sci, 68, 263 (1971).
29. A.K. Yatsimirskii, K. Martinek, and I.V. Berezin, Dokl. Akad. Nauk. SSSR, 194, 840 (1970).
30. Y. Okahata, R. Ando, and T. Kunitake, J. Amer. Chem. Soc., 99, 3067 (1977).
31. W.P. Jencks, Advan. Enzymol., 43, 219 (1975).
32. C.A. Bunton, M. Minch, and L. Sepulveda, J. Phys. Chem., 75, 2707 (1971).
33. C.A. Bunton, M.J. Minota, J. Hidalgo and L. Sepulveda, J. Amer. Chem. Soc., 95, 3262 (1973).
34. C.A. Bunton and M.J. Minch, Tet. Lett. 3881 (1970).
35. D.S. Kemp and K. Paul, J. Amer. Chem. Soc., 92, 2553 (1970).
36. T. Kunitake, S. Shinkai, and S. Hirotsu, J. Org. Chem., 42, 306 (1977).
37. J. Suk, I.S. Scarpa, and I.M. Klotz, J. Amer. Chem. Soc., 98, 7060 (1976).
38. C.A. Bunton, E.J. Fendler, L. Sepulveda, and K.H. Yang, J. Amer. Chem. Soc., 90, 5512 (1968).
39. G.J. Buist, C.A. Bunton, L. Robinson, L. Sepulveda, and M. Stam, J. Amer. Chem. Soc., 92 4072 (1970).
40. C.A. Bunton, L. Robinson, and L. Sepulveda, J. Org. Chem, 35, 108 (1970).
41. E.F.J. Duynstee and E. Grunwald, J. Amer. Chem. Soc., 81, 4540, 4542 (1959).
42. C.A. Bunton, S. Chan, and S.K. Huang, J. Org. Chem., 39, 1262 (1973).
43. C.A. Bunton and S.K. Huang, J. Org. Chem., 37, 1790 (1972).
44. C.A. Bunton and C.H. Park, J. Org. Chem., 41, 40 (1976).
45. J. Albrizzio, A. Archila, T. Rodulfo, and E.H. Cordes, J. Org. Chem., 37, 871 (1972).
46. J. Baumrucker, M. Calzadilla, M. Centeno, G. Lehrmann, M. Urdaneta, P. Lindquist, D. Dunham, M. Price, B. Sears, and E. H. Cordes, J. Amer. Chem.,Soc., 94, 8164 (1972).
47. N. Ise and T. Okubo, J. Amer. Chem. Soc., 95, 4031 (1973).
48. F.M. Menger and C.A. Portnoy, J. Amer. Chem. Soc., 89, 4968 (1967); 90, 1875 (1968).
49. K. Martinek, A.P. Osipov, A.K. Yatsimirskii, V.A. Dadali, and I.V. Berezin, Tet. Letters 1279 (1975); K. Martinek, A.K. Yatsimirskii, A.P. Osipov, and I.V. Berezin, Tetrahedron, 29, 963 (1973).
50. L.S. Romsted, Micellization, Solubilization, and Microemulsions (K.L. Mittal, ed.) Vol. 1, p. 509, Plenum Press, New York, 1977.
51. L.S. Romsted, Ph.D. Thesis, Indiana University, 1975.
52. C.A. Bunton and B. Wolfe, J. Amer. Chem. Soc., 95, 3742 (1973).
53. I.V. Berezin, K. Martinek, and A.K. Yatsimirskii, Russ. Chem. Rev., 42, 787 (1973).