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Physicochemical Foundations of Micellar Catalysis

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The structure and the properties of micelles of surface-active substances in aqueous solution are briefly surveyed. Attention is paid mainly to solubilisation and methods for investigating the location of solubilised molecules. Kinetic concepts of micellar catalysis are examined and compared. The role of various factors (concentration effect, orientation, shift in pK_a of reactants, change of environment) in the micellar effects observed in organic reactions is analysed. A list of 113 references is included.

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I. INTRODUCTION

Research on the effect of surface-active agents on the kinetics of organic reactions in aqueous solution has recently become a separate branch of physical organic chemistry. Interest in this problem has arisen mainly from the fresh opportunities both for controlling the rates of chemical reactions and for studying their mechanism[1,2].

The presence of a surface-active agent usually produces a 10–100-fold acceleration or deceleration of the reaction; in individual cases reaction velocities are increased by factors of 10^3–10^4.[1-4] It has now been finally established that these effects are due to the presence not of individual molecules but of association complexes (micelles) containing a large number of molecules of the surface-active agent. This fact has been responsible for the appearance of the term "micellar catalysis".

Micellar catalysis is also of interest to biochemists, for several aspects of this phenomenon exhibit features recalling the mechanism of the action of enzymes[5-8].

Surface-active agents may also be used in organic syntheses[1,2], e.g. in reactions between water-insoluble substances in aqueous solution (the most important application of this is emulsion polymerisation[9,10]).

Micellar catalysis may also be assumed to play some part in the bactericidal action of surface-active agents mixed with other bactericidal preparations. An example is the dependence of the time of destruction of *Bacillus coli* bacteria by a solution of phenol (0.54%) on the concentration of a dialkyl sulphosuccinate anionic surface-active agent (Aerosol MA).[11] The efficiency of the phenol is greatly increased by the formation of micelles in the solution of the surface-active agent (when the critical micelle concentration (c.m.c.) is reached), after which it passes through an optimum. As will be shown subsequently, both these features are characteristic of micellar catalysis.

The number of papers on the kinetics of chemical reactions in the presence of micelles of surface-active compounds began to increase sharply after 1960, and now exceeds fifty (excluding papers on emulsion polymerisation). An exhaustive survey of work on micellar catalysis

(up to 1970) was made by E. and J. Fendler[2], who reviewed systematically all available published information on the mechanisms of the catalysed reactions. The present paper attempts to discuss the physicochemical basis of micellar catalysis†. Attention will be paid mainly to explaining the kinetics of chemical reactions occurring in the presence of the micelles of surface-active compounds and to establishing the rôle of the principal factors—the close approach (concentration) of reactants attached to the micelle, their mutual orientation, the change in the environment, and with ionic micelles the effect of the micellar charge on the transition state in the reaction—causing the change in reaction velocity in the presence of micelles. An analysis of these factors must take into account the structure of the micelles and the laws governing their formation and interaction with other solutes. The first part of the Review will therefore report the necessary information on the physicochemical properties of aqueous solutions of surface-active agents.

II. PHYSICOCHEMICAL PROPERTIES OF AQUEOUS SOLUTIONS OF SURFACE-ACTIVE AGENTS

Among the many aspects connected with the problem of the physicochemical properties of aqueous solutions of surface-active agents[12-15] we shall consider only those which are directly related to micellar effects in the kinetics of chemical reactions.

1. Formation and Structure of Micelles in Aqueous Solutions of Surface-active Agents

Surfactant molecules possess well defined diphilic properties: i.e. they contain both hydrophobic and hydrophilic groups. They usually have the structure RX, where R is a hydrocarbon chain containing 8–18 carbon atoms, an alkylaromatic radical, or other type of hydrophobic residue, and X is a hydrophilic group. Depending on the nature of X surface-active agents can be divided into non-ionic, anion-active, and cation-active. In the last case the hydrophilic residue is usually a quaternary ammonium, pyridinium, or phosphonium group; the anion-active compounds contain a sulphate, sulphonate, phosphate, or carboxylate group; in non-ionic surfactants X represents a polyoxyethylene residue. Zwitterionic surface-active compounds constitute a special class[13].

Surface-active substances are characterised by several specific features—(i) the ability to lower the surface tension in solutions by adsorption and orientation at interfaces, (ii) very low maximum concentration of the molecular form in solution, (iii) formation of micelles above a certain concentration (critical micelle concentration, c.m.c.), and (iv) ability to solubilise water-insoluble substances within and on the surface of the micelles—all of which are closely interrelated[12,14]. The last two properties are of interest in connection with micellar catalysis, and will be considered in greater detail below.

In fact the formation of micelles takes place in a narrow range of surfactant concentrations around the c.m.c. and is accompanied by a sharp change in several properties of the solution (light scattering, viscosity, electrical conductivity, surface tension, solvent power for certain substances, etc.), which is used for determining the c.m.c. The "experimental" value of the c.m.c. may depend significantly on the property and on the method of measurement; when a third component (e.g. a dye) is used, its presence may cause a shift in the c.m.c. [16]

Theoretical statistical-mechanical models of micelle formation[17,18] are by no means perfect, and merely enable the presence of a minimum in the dependence of the free energy of the system on the aggregation number to be established. Nevertheless, the rôle of several factors which lead to micelle formation can be traced on the basis of these models. The main driving force causing the association of surfactant molecules is the hydrophobic interaction of their hydrocarbon chains.

The following generalisations apply to micelle formation. The shorter the hydrocarbon chain the smaller the decrease in free energy of the system resulting from aggregation and the higher the concentration at which the surfactant molecules have the same chemical potential in the dissolved state and in the micelle, and hence the higher the critical micelle concentration. Factors that diminish the electrostatic repulsion of the hydrophilic groups favour micelle formation. Thus increase in the concentration of gegenions considerably lowers the c.m.c. of ionic surfactants. With the non-ionic compounds micelle formation is promoted by rise in temperature, which diminishes the hydration of their hydrophilic groups. Higher alcohols also lower the surface charge density on an ionic micelle and diminish the c.m.c. On the other hand, methanol and similar compounds (dioxan, ethylene glycol), which do not penetrate a micelle to the same extent, have a weak effect on the c.m.c., raising it in high concentrations by decreasing the energy of hydrophobic interaction between the hydrocarbon chains of the surfactant molecules.

Enlargement of the micellar aggregates, i.e. separation of the surfactant as a macrophase, is prevented by hydration of the hydrophilic group, steric factors, entropy losses, and electrostatic repulsion of head groups in the case of ionic surfactants. In terms of the general theory of the thermodynamic stability of two-phase disperse systems the stability of micelles is probably determined by two factors—sufficiently low interfacial tension and its rapid increase with decrease in particle radius[19].

Micelle formation can be regarded thermodynamically as resembling the formation of a new phase, with the c.m.c. as saturation concentration[12]. However, the resulting micelles do not coalesce into a continuous phase, but are uniformly distributed in the aqueous medium, forming a "pseudophase". Micelle formation actually possesses several properties characteristic of phase separation. Many properties of surfactant solutions undergo an abrupt change at the critical micelle concentration (see above). The increase in solubility of certain substances in surfactant solutions above the c.m.c. can be regarded as similar to dissolution of the substance in a separate phase. At the Kraft point—the temperature above which micelle formation is possible—the first derivative of the solubility of the surfactant with respect to temperature exhibits a discontinuity, which is also characteristic of one type of phase transition. The variation in the c.m.c. caused by various substances can be regarded, on the basis of the pseudophase model of micelle formation, as variation in the true solubility of the surfactant.

† Several aspects of this problem have already been touched upon in monographs[6,7] or have formed the subject of separate reviews[1,5], many conclusions from which we shall use in the subsequent discussion. The relation between micellar catalysis and processes involving macromolecular catalysts (both synthetic polymers and biopolymers—enzymes) was subjected to detailed examination by Morawetz[5].

Another approach is to describe micelle formation as an equilibrium process using the law of mass action. On this model a sharp change in the properties of the system can be expected only if a sufficiently large number of molecules are bound into the micelle[12,20].

Micelles are dynamic structures having times of formation and destruction of a few milliseconds[21]. Ionic micelles usually comprise roughly 50–100 surfactant ions. In dilute solutions they are supposed to be spheroidal with the polar groups on the surface and the hydrophobic chains at the centre. A spherical micelle is shown diagrammatically in Fig. 1. The ionic "head" groups in the diphilic surfactant molecules and some of the gegenions form a compact Stern layer[22], in which about 60–70% of the micellar charge in neutralised. The remaining gegenions form a diffuse Gouy–Chapman layer. The mean surface potential (the ζ-potential) of the micelle can be estimated from the electrophoretic mobility, although the exact value of ζ depends to some extent on the model used for interpreting the experimental data. It usually varies in the range 50–100 mV. A critical examination of the estimation of surface potential from the shift in pK_a of dyes adsorbed on the micelle showed[23] that the potential measured is rather higher than the ζ-potential but less than the total potential difference between micelle and water.

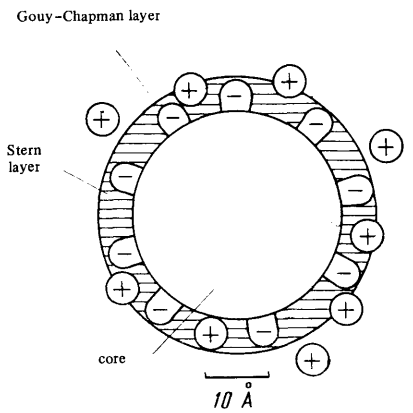


Figure 1. Schematic representation of a micelle of an ionogenic surfactant according to Stigter[22] (micelle of sodium dodecyl sulphate shown as example).

The behaviour of ionic surfactants is greatly complicated by interaction between micelles and gegenions. The concentration of the latter in the aqueous phase can be supposed to remain almost constant and equal to the concentration of molecularly disperse surfactant (i.e. to the c.m.c.[24]) in the vicinity of the critical micelle concentration, but further increase in surfactant concentration is accompanied by an increase in the concentration of gegenions in the water. This tends to depress the c.m.c. and the surface potential of the micelle, and also increase the size and change the shape of the micelles[12,15].

The micellar surface is not uniform[25]. Nuclear magnetic resonance data[26] indicate that some of the hydrocarbon chains are turned towards the solvent, or at least come into contact with it periodically. It must also be borne in mind that micelles contain a considerable quantity of water, e.g. 33–46 vol.% in those of sodium dodecyl sulphate[27]. The water is probably located not only in the surface layer but also in the hydrophobic core of the micelle, the content decreasing with distance from the polar head group into the interior of the micelle[28,29]. On the whole it may be supposed that the micellar surface is a polar environment differing in properties from water itself. For example, the effective dielectric constant of the micellar surface was estimated as 36[30] from the position of the charge-transfer band in the surface layers of micelles formed by dodecylpyridinium iodide.

The hydrophobic core of a micelle is closely similar to a liquid hydrocarbon in properties, although rather more ordered. Results obtained by means of a fluorescent probe group[31] indicate that the core closely resembles a liquid hydrocarbon in nature, although the microviscosity is considerably higher in micelles than in hydrocarbons. The whole micelle, although evidently possessing some solid character[32], is more in the liquid state. This last view is consistent with the facts (*a*) that micelle-forming ions are able to form mixed micelles with various additives[12], and (*b*) that solubilisation takes place in micellar systems. This process resembles in many respects the extraction of organic substances from an aqueous phase, with the micelles acting as the second phase.

2. Distribution of Simple Substances between Aqueous and Micellar Phases

A specific feature of solutions of surface-active agents is their ability to dissolve within the micelles substances that are sparingly soluble in water, with the formation of thermodynamically stable isotropic solutions[12,33,34]. This explains the sharp increase in solubility of certain substances when the critical micelle concentration is reached in a surfactant solution (the phenomenon of solubilisation). With further increase in the surfactant concentration the solubility increases in proportion to the latter, mainly because of the increase in the total number of micelles in unit volume. Solubilisation is affected by the many factors which in turn influence the properties of micelles (temperature, presence of foreign non-electrolytes, concentration of gegenions), and is further complicated by the effect of the solubilised substance itself on the micelles[35]. Nevertheless, data on solubilisation can be analysed with some caution by means of a simple model, in which micelles are regarded as a separate phase from the rest of the solution[36].

We postulate that a solute A is distributed between micellar and aqueous phases in conformity with the simple distribution law:

$$[A]_M/[A]_W = P_A \qquad (1)$$

Here and subsequently the subscripts "M" and "W" denote quantities relating to micellar and aqueous phases respectively. The total concentration of A, averaged over the volume of the whole system, is

$$[A]_0 = [A]_M CV + [A]_W(1 - CV), \qquad (2)$$

which with (1) gives

$$[A]_0/[A]_W = 1 + (P_A - 1)CV, \qquad (3)$$

where C is the surfactant concentration (molarity) less the c.m.c., and V is the molar volume of the surfactant, the factors CV and $1 - CV$ being the fractions by volume of micellar and aqueous phases respectively. Provided that the distribution (1) is satisfied at concentrations up to S_W, the solubility of A in pure water, its solubility $S_{M,W}$ in the

presence of the surfactant is related to S_W by Eqn. (3), which can be conveniently written

$$S_{M,W}/S_W = 1 + K_A C, \quad (4)$$

where the constant K_A is given by

$$K_A = (P_A - 1)V \quad (5)$$

and thus has the dimensions (M^{-1}) of an ordinary binding constant. From general considerations, however, Eqn. (1) would be satisfied only for dilute solutions. Therefore Eqn. (4) is applicable only to sufficiently sparingly soluble substances, whose saturated solutions can still be regarded as dilute.

(*a*) Determination of binding constants of solutes with micelles

Binding constants of type K_A are convenient measures of efficiency of solubilisation. Examples of the use of solubilisation data for various substances to determine their binding constants with micelles can be found in Refs. 36–40. Fig. 2[4] shows plots of Eqn. (4) illustrating the typical dependence of the solubility of several *p*-nitrophenyl carboxylates on surfactant concentration. A more general method applicable to substances whatever their solubility is to determine their binding with the micelles by gel filtration[40]. However, this method is restricted to fairly large partition coefficients ($P \geqslant 10$).

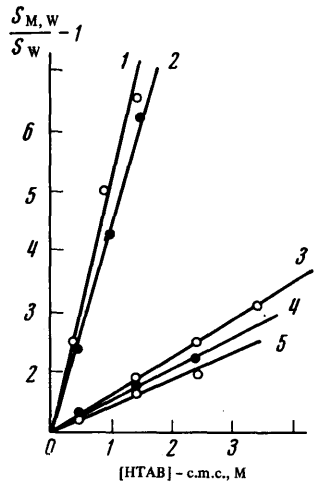


Figure 2. Effect of hexadecyltrimethylammonium bromide on solubility of *p*-nitrophenyl carboxylates: 1) heptanoate; 2) β-phenylpropionate; 3) salicylate; 4) butyrate; 5) αα-dimethylpropionate[4].

The binding constant of a substance with a micelle can readily be found also when the variation in some molecular property on passing from water to the micellar medium can be followed. Such properties may be the visible and ultraviolet spectra[41], the nuclear magnetic resonance[42] and electron spin resonance[43] spectra, or also e.g. the reactivity towards solvolysis[37,38,44]. Since their variation is connected with the change in the microenvironment in the vicinity of the molecule undergoing solubilisation, data of this type can be used to solve the important problem of the arrangement of the solubilised molecule in the micelle.

(*b*) Location and orientation of solubilised molecules in micelle

A solute can be arranged in various ways in the micelle: it may pass completely inside the hydrophobic core, or penetrate a particular depth into the surface layer; it can be adsorbed on the surface of the micelle or—what is most probable for molecules containing polar substituents—be oriented with the polar portion of the molecule situated in the surface layer and the non-polar portion directed into the micelle. In order to solve the problem of where a solubilised molecule had entered—into the hydrophobic core or into the hydrated surface layer—it was usual to compare the spectra (ultraviolet, e.s.r., n.m.r.) observed in the presence of the detergent with the spectra in water and in an organic solvent (hydrocarbon, alcohol). However, the interpretation of such results is usually complicated, because the observed effects may depend on various factors.

An instructive example is the investigation of the polarity of the sorption centre in the enzyme α-chymotrypsin, on which the colorant proflavin is bound. The "red shift" of the visible absorption spectrum of proflavin on interaction with the enzyme was interpreted as resulting from the low polarity of the sorption site in the protein globule, since the same shift occurs in aqueous dioxan[45]. It has since been shown[46], however, that the shift in λ_{max} of proflavin is determined not by the dielectric constant of the medium but by the refractive index. Thus the shift relative to water ($\epsilon = 81$ and $n_D = 1.33$) is the same in dioxan (2.4 and 1.42) and in formamide (109.5 and 1.44). Detailed analysis of the spectral changes undergone by proflavin in various systems suggests[46] the presence of orientation interaction in its complex with chymotrypsin on excitation of the colorant molecule, and hence that the corresponding sorption site in the enzyme is highly polar.

Parallel studies by several methods of the arrangement of solubilised molecules in the micelle[47,48], giving consistent results, are therefore especially valuable. In general aliphatic molecules or side-chains are immersed in the hydrophobic core of the micelle[12,49]; aromatic molecules or parts thereof are probably (but not always[50]) situated in the surface layer of cationic micelles[49], but in the hydrophobic core of anionic and non-ionic[50,51] micelles. Molecules with polar substituents (alcohols, phenols, acids, amines, etc.) are oriented with their polar groups in the surface layer and the non-polar portions immersed in the core[12,47]; ions are adsorbed on the surface of the micelles[12,22].

The efficiency of chemical interaction between solubilised molecules should obviously be strongly dependent on their mutual orientation. The arrangement of solubilised molecules in the micelle must therefore be examined in rather greater detail.

The most widely used method for investigating the microenvironment of solubilised molecules is n.m.r. spectroscopy‡, for the chemical shifts of protons and

‡ The lifetime of solubilised molecules in micelles has also been estimated from n.m.r. spectral data. That of the benzene molecule in micelles of sodium dodecyl sulphate was determined[42] as ~ 10^{-4} s from the broadening of the n.m.r. band of benzene on solubilisation.

especially fluorine-19 atoms are fairly sensitive to the medium. Muller and Birkhahn[52] suggested as a quantitative measure of the closeness of the environment of a molecule to a liquid hydrocarbon the function

$$Z=(\delta_M-\delta_W)/(\delta_{HC}-\delta_W) \quad (6)$$

where δ_M, δ_W, and δ_{HC} are the chemical shifts of hydrogen or fluorine atoms in the test molecule solubilised by micelles and in aqueous and hydrocarbon solutions. The quantity Z can obviously be calculated also from ultraviolet, visible, or e.s.r. spectroscopic data. The Table gives values for benzene and certain derivatives in the presence of a number of surfactants. Sufficiently reliable interpretation of Z is evidently possible only in comparative experiments examining the variation in Z resulting from variation in some parameter of the system, whereas the absolute value of Z may firstly contain a systematic error[28] and secondly be a non-linear function of the composition of the medium.

Values of Z for aromatic molecules solubilised by micelles of various surfactants[51].

Surface-active agent	Z	Substance
Polyoxyethylene dodecyl ether	0.06-0.16	benzene
Hexadecyltrimethylammonium bromide	0.18	benzene
Sodium dodecyl sulphate	0.20-0.22	radicals I and II
Sodium laurate	0.52	trifluoromethylbenzene
Sodium decanoate	0.29-0.33	benzene
Sodium decanoate + 1 M NaCl	0.55	benzene

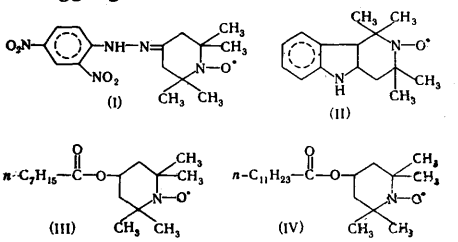
Important information on the nature of solubilisation can be obtained simply by comparing the position of the chemical shift of the solubilised molecule with the position in aqueous and hydrocarbon solutions. Such investigations[49] suggest that aromatic molecules are arranged in the surface layer of the cationic micelles n-hexadecyltrimethylammonium bromide, whereas aliphatic molecules and aliphatic side-chains of aromatic molecules enter the hydrocarbon core. The shielding constants of the fluorine nuclei in *para*-substituted fluorobenzenes (with formyl, acetyl, methoxyl, trimethoxymethyl, and diethoxymethyl as substituents) show that these molecules are arranged in the micelles of sodium dodecyl sulphate in such a way that the hydrogen bonds with water are preserved[53]. From this it might be concluded that these molecules are located in the surface layer of the micelle, but since water may be partly enclosed also in the inner regions of the micelle (see above), they may nevertheless be immersed to some extent in the hydrophobic core.

The permeability of micelles for molecules of substances possessing no well defined hydrophobic properties can be studied by means of the n.m.r. spectra of fluorine present in the surfactant (sodium 12,12,12-trifluorododecyl sulphate)[54]. Glycerol, glycine, and urea hardly penetrate the hydrocarbon core of the micelle at all; methanol and acetamide enter only to a slight extent; and ethanol, acetone, and dioxan freely enter the inner regions of the micelles.

The ultraviolet and visible spectra of solubilised molecules can be used only with aromatic compounds. Reigelman et al., in their pioneering work[50], were the first to pose the problem of determining the site of a solubilised molecule in a micelle. In their view four modes of solubilisation—penetration into the hydrocarbon core, deep immersion in the surface layer, shallow immersion in the surface layer, and adsorption on the micelle surface—must be distinguished. They investigated the nature of solubilisation in micelles of three types of surfactants—anion-active (potassium laurate), cation-active (dodecylammonium chloride), and non-ionic (Brij 35—oxyethylated dodecanol). From an analysis of the fine structure and the positions of the maxima in the spectra of several aromatic compounds they concluded that solubilised molecules are arranged in the same way in all three types of micelles: ethylbenzene penetrates into the hydrocarbon core; naphthalene, anthracene, and *trans*-azobenzene are deeply immersed in the surface layer; *o*-nitroaniline effects shallow penetration of the surface layer; and dimethyl phthalate is adsorbed on the surface of the micelles.

A more quantitative result was obtained by Rehfeld[41], who studied the solubilisation of benzene in the presence of sodium dodecyl sulphate. The spectrum of the solubilised benzene, whose concentration in the micelle was 0.47 ppm, was roughly equivalent to the spectrum of a solution of benzene in hydrocarbons and dodecanol or methanol at a concentration of 0.5 ppm. Certain differences in the spectra were due, according to this author, to various non-equivalent positions of the benzene molecule in the micelle, between which dynamic equilibrium was rapidly established.

Investigations using electron spin resonance require that the molecule undergoing solubilisation shall contain a "paramagnetic label", for which purpose iminoxyl radicals have been widely used[55]. The e.s.r. spectra of the "label" enable at least the following information to be obtained—concentration of radicals, polarity of solvent surrounding the radical, rotational mobility of radical, and degree of aggregation of radicals§.



Solubilisation of the radicals (I)–(IV) by micelles of sodium dodecyl sulphate has been investigated by Waggoner and his coworkers[57]. Since both ends of radicals (I) and (II) can be watched (one end by means of the e.s.r. spectra and the other by the ultraviolet spectra), these workers attempted to distinguish three situations—adsorption on the micelle surface, radial orientation in the micelle, and submersion in the hydrocarbon core—but the results were consistent with none of these static models of solubilisation. It was therefore concluded that the observed parameters were mean values resulting from rapid exchange between the different positions, and on the average the radicals were in a fairly polar environment. Data on radicals (III) and (IV) also indicate that the solubilised molecules are subject to relatively rapid rotational motion.

Information on the nature of the bonding of solubilised molecules by micelles was obtained also by studying the effect of salts on solubilisation. Additions of salts lower the degree of solubilisation of octanol and benzaldehyde by

§ A critical survey has been published[56] of factors complicating the interpretation of e.s.r. spectra of solubilised radicals.

hexadecylpyridinium[58], and of dimethyl phthalate by potassium laurate and Triton X[59] (oxyethylated octylphenol). This indicates that solubilised molecules of these substances interact with polar groups of the surfactant molecules. On the other hand, the solubilisability of octane and benzene by hexadecylpyridinium increases in the presence of salts[58], which is interpreted as a change in structure of the micelles produced by the salts, although this phenomenon can probably be explained as an ordinary salting-out effect.

The above brief review shows that the interrelation between the molecular structure of organic compounds and their arrangement and orientation in the micelle on solubilisation cannot yet be regarded as adequately studied. A future kinetic study of organic reactions occurring in micelles may reveal fine effects of micellar structure and the orientation of solubilised molecules.

(*c*) Nature of interactions during solubilisation and free energy of transfer from water into the micelle

Hydrophobic and ionic interactions with non-polar and charged groups of the solubilised molecules are responsible for binding to micelles[12,33,34,60]. In the case of aromatic molecules interaction between charged groups in the micelle surface and the π-electron system of the aromatic ring also plays a part[49]. We give some very rough estimates of the partition coefficient P to be expected for various types of molecules. We start from the usual relation for the equilibrium constant

$$P = e^{-\frac{\Delta\mu_0}{RT}} \qquad (7)$$

where $\Delta\mu_0$ is the change in the standard chemical potential of the partitioned substance on passing from water to the micelle.

If a molecule is bound to a micelle mainly by hydrophobic interactions, $\Delta\mu_0$ can be either calculated theoretically[61,62] or estimated from data on the free energy of transfer of the molecule from water to a non-aqueous solvent, e.g. octanol[60,63]. The correctness of such estimate is confirmed in particular by data[36] showing that the partition coefficients of several dyes between the micelles of a non-ionic surfactant (Triton X-100) and water are close to the values for these dyes between octanol and water. We have found that the increment in the free energy of transfer of an aliphatic or a phenylalkyl group from water into the micelle of a cation-active surfactant (hexadecyltrimethylammonium bromide) is practically equal to the increment for transfer of the same group from water to n-octanol[4] (0.6–0.7 and 2.9 kcal mole^{-1} for a methylene group and for benzene respectively). The latter value yields for benzene $P \simeq 100$; experimental data give calculated values of $P = 75$ and 280 for sodium dodecyl sulphate[41] and for hexadecyltrimethylammonium bromide[64].

The contribution of the electrostatic interaction of an ion or an ionic group in a molecule with the micellar charge of an ionogenic surfactant can be estimated from the expression for the electrostatic free energy $Ze\Psi$, where Z is the ionic charge, e the electronic charge, and Ψ the surface potential of the micelle[12]. If Ψ is expressed in millivolts, as is usual, the contribution of electrostatic interaction to the partition coefficient can be written $\exp(-Z\Psi/25.2)$ (at 20°C).[65] With the usual values of the ζ-potential of 50–100 mV (see above) this factor is 10–50. However, the actual potential at the site of a solubilised molecule is usually higher than the ζ-potential[23].

The energy of interaction with dipolar molecules, even those possessing large dipole moments (e.g. Zwitterionic amino-acids), is probably insignificant, and for systems of this type (interaction of amino-acids with macroions) is comparable with RT.[66]

III. KINETICS OF CHEMICAL REACTIONS IN THE PRESENCE OF MICELLES OF SURFACE-ACTIVE AGENTS

In the discussion of the kinetics of micellar reactions the micelle M is most often regarded[2] as an additional species, which on combination with a reactant A can change its reactivity both in a unimolecular reaction and on reaction with another substance B dissolved in water:

$$\begin{array}{ccc} A + M & \overset{K}{\rightleftharpoons} & AM \\ \downarrow k_W[B] & & \downarrow k_M[B] \\ \text{Products} & & \text{Products} \end{array} . \qquad (8)$$

The association constant in (8) has its usual significance ($K = [AM]/[M][A]$), while k_W and k_M are the conversion rate constants of A in water and in the micelle. The effective reaction rate constant measured experimentally (as the ratio of the rate of the process to the total concentration of the reactant: $k_{exp} = v/[A]_0$) depends in this case on the surfactant concentration:

$$k_{exp} = \frac{k_W + k_M[M]}{1 + K[M]} . \qquad (9)$$

provided that $[M] \gg [AM]$. The concentration of the micelles is given by the ratio $[M] = C/N$, where N is the aggregation number.

According to the principles discussed in Section II, however, the binding of the reactant molecules to the micelles involves physically a partition of the substance between micellar and aqueous phases rather than association in the stoichiometric proportions 1 : 1. In other words, the kinetic scheme of the reaction must be written differently:

$$\begin{array}{ccc} (A)_W & \overset{P}{\rightleftharpoons} & (A)_M \\ \downarrow k_W[B] & & \downarrow k_M[B] \\ \text{Products} & & \text{Products} \end{array} \qquad (10)$$

where the partition coefficient P is given by Eqn. (1). When the surfactant concentration greatly exceeds the reactant concentration, the two approaches lead to formally indistinguishable kinetic equations. A formula for the effective rate constant based on scheme (10) was probably first given by Grunwald[67]:

$$k_{exp} = \frac{k_W + k_M P \varphi_M}{1 + P\varphi_M} \qquad (11)$$

where the volume fraction of the micellar phase $\varphi_M \ll 1$. Since $\varphi_M = [M]NV$, a relation can easily be established between the equilibrium constants in Eqns. (9) and (11):

$$K = P \cdot N \cdot V \qquad (12)$$

Equations (9) and (11) are quite correct for first-order reactions, but there are fundamental objections to their application to higher-order reactions. With a bimolecular reaction, in fact, the constant k_M in these equations has the significance of a rate constant for interaction of one reactant, attached to the micelle, with the other, unattached reactant, uniformly distributed throughout both phases. However, the latter condition can hardly be satisfied in general, since the second reactant may also

interact with the micelle, and will then have different concentrations in aqueous and micellar phases. In this case, moreover, the fractions of the second reactant in aqueous and micellar phases would depend on the concentration of micelles, so that in principle Eqns. (9) and (11) give an incorrect dependence of k_{exp} on the surfactant concentration. This is evident from the monotonic increase in k_{exp} with the volume fraction of the micellar phase indicated by Eqn. (9): actually, the dependence of k_{exp} on C observed experimentally for a bimolecular reaction usually passes through a maximum[1]. The occurrence of an optimum surfactant concentration is easily explained (see below) if the distribution of the second reactant is taken into account.

The situation is simpler in the particular case in which the second reactant has a very high concentration (in comparison with the surfactant) or is a component of a buffer solution. Its concentrations in micellar and aqueous phases then remain almost constant but are unequal and are independent of the surfactant concentration. As a consequence, Eqns. (9) and (11) give a correct formal description of the dependence of k_{exp} on the surfactant concentration. In comparing the constants k_M found by means of these equations with the constants k_W, however, we must bear in mind that the former are effective values, since they contain the ratio of the concentrations of the second component in water and in the micelle.

The effect of micelles on the kinetics of bimolecular reactions when both reactants are bound to the micelle has been discussed qualitatively by Heitmann[68]. A quantitative treatment of this concept and its experimental verification have been undertaken by the Reviewers[4,69], and will be considered in detail below.

1. Kinetic Concept of Micellar Effects in a Bimolecular Reaction

Regarding a surfactant solution above the critical micelle concentration as a two-phase system, in conformity with the above discussion, we can express the observed reaction velocity v, averaged over the whole volume of the system, in terms of the reaction velocities in micellar and aqueous phases v_M and v_W:

$$v = v_M CV + v_W(1 - CV) = k_{exp}\,[A]_0[B]_0. \qquad (13)$$

Assuming that the law of mass action is satisfied in each phase, we obtain

$$\left.\begin{aligned} v_M &= k_M[A]_M[B]_M \\ v_W &= k_W[A]_W[B]_W \end{aligned}\right\}. \qquad (14)$$

The relation between the total concentrations of the reactants $[A]_0$ and $[B]_0$ and their true concentrations in the corresponding phases is established by means of Eqns. (1) and (2) for each reactant. This involves the postulate that the equilibrium distribution of the reactants between the phases is not displaced by the occurrence of the chemical reaction. The justification is that the exchange of molecules between the phases occurs very rapidly (see above). From Eqns. (1), (2), (13), and (14) it follows that

$$k_{exp} = \frac{k_M P_A P_B CV + k_W(1 - CV)}{(1 + K_A C)(1 + K_B C)} \qquad (15)$$

where the constants K_A and K_B are defined by formula (5).

Molecules of the same kind can in general be differently arranged and oriented in the micelle (above). The observed effective rate coefficient k_M is therefore in fact "averaged" over the volume of the micelle. We consider as a limiting case the situation in which the observed reaction velocity includes not only the rates in micellar and aqueous phases but also the rate of a reaction between solubilised and unsolubilised reactants:

$$v = k_M[A]_M[B]_M CV + k'_M[A]_M[B]_W CV + k''_M[A]_W[B]_M CV + k_W[A]_W[B]_0(1 - CV)$$

whence we obtain

$$k_{exp} = \frac{(k_M P_A P_B + k'_M P_A + k''_M P_B)CV + k_W(1 - CV)}{(1 + K_A C)(1 + K_B C)}$$

This equation is similar in form to (15), and when P_A, $P_B \gg 1$ (strong binding of reactants) and $k_M \simeq k_M' \simeq k_M''$ it shows approximately the same dependence of k_{exp} on P_A, P_B, and C as does Eqn. (15).

In the case of dilute surfactant solutions, in which the volume fraction of the micellar phase is small, Eqn. (15) can be simplified to

$$k_{exp} = \frac{k_M P_A P_B CV + k_W}{(1 + K_A C)(1 + K_B C)}. \qquad (16)$$

This equation¶, first given in Ref. 69, enables the nature of micellar effects to be analysed as functions of the relation between the "elementary" rate constants in the two phases and the binding constants of the reactants. We shall consider some important particular cases.

Case 1. Both reactants are weakly bound to or are repelled from the micelle: i.e. P_A, $P_B \leqslant 1$. Then K_A and K_B vary from zero to $-V$, and when $C < 0.1$ M (corresponding to dilute surfactant solutions) we have

$$k_{exp} \cong k_M P_A P_B CV + k_W. \qquad (17)$$

In this case an appreciable increase in k_{exp} in comparison with k_W is possible only with $k_M \gg k_W$, since $CV \ll 1$. In rare cases, however, k_M exceeds k_W hundredfold, but usually $k_M \simeq k_W$ (see below). Even in the most favourable case (when $P_A \simeq P_B \simeq 1$ and at higher surfactant concentrations of ~ 0.1 M), therefore, k_{exp} is able to exceed k_W only about fourfold, since for the usual surfactants V is around $0.3\ M^{-1}$.[4,6,70] Evidently this case is in general of no special interest.

Case 2. One reactant is strongly bound to the micelle, while the other is weakly repelled from it. This implies e.g. that $P_A \gg 1$, while $P_B \leqslant 1$. In this case Eqn. (16) can be simplified to

$$k_{exp} = \frac{k_M P_A P_B CV + k_W}{1 + P_A CV} \qquad (18)$$

since from (5) we have $K_A \simeq P_A V$. If the reactant B is very strongly repelled from the micelle $P_B \simeq 0$, or the reaction rate constant in the micelle is small $k_M \simeq 0$, the micelles inhibit the reaction, since in this case k_{exp} would fall with increase in C:

$$k_{exp} \approx \frac{k_W}{1 + P_A CV}. \qquad (19)$$

If, however, $P_B \simeq 1$, it follows from (18) that $k_{exp} \simeq k_W$ in the absence of a specific effect of the micelles on the reaction, i.e. with $k_M \simeq k_W$, and therefore the reaction

¶ When the reactant concentrations are far smaller than the surfactant concentration, the concept of a distribution of the reactants between micellar and aqueous phases and the less rigorous hypothesis of association of reactants with micelles give the same results. We have already seen this for a first-order reaction. The mathematics for a second-order reaction is similar.

velocity is almost independent of the presence of the surfactant. But when $k_M > k_W$, or conversely $k_M < k_W$, increase in C produces an increase or conversely a decrease in k_{exp}, in conformity with the equation

$$k_{exp} \approx \frac{k_M P_A CV + k_W}{1 + P_A CV} \qquad (20)$$

and in both cases k_{exp} reaches the limiting value k_M.

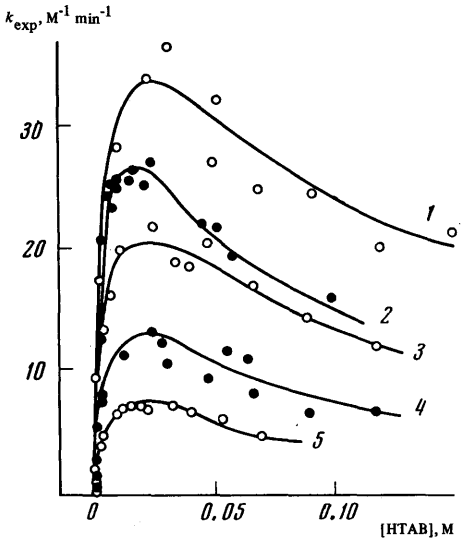


Figure 3. Dependence of experimental rate constant for reaction between fluoro-2,4-dinitrobenzene and the methyl ester of *N*-benzoyl-L-histidine on surfactant concentration at various temperatures (°C): 1) 55; 2) 48; 3) 40; 4) 32; 5) 25.[71]

Case 3. The case in which both reactants are strongly bound to micelles is of especial interest. Considerable acceleration of the reaction is now possible in the presence of surfactant micelles even if they have no specific influence on reaction velocity. The reason is that the reactants become concentrated in the micellar phase. When P_A, $P_B \gg 1$, Eqn. (16) can be written

$$k_{exp} = \frac{\bar{k}_M K_A K_B C + k_W}{(1 + K_A C)(1 + K_B C)} \qquad (21)$$

where

$$\bar{k}_M = k_M / V. \qquad (22)$$

If the reaction hardly occurs at all in the micelle ($k_M \simeq 0$), the micelles have an inhibiting effect, since k_{exp} falls monotonically with increase in C:

$$k_{exp} \cong \frac{k_W}{(1 + K_A C)(1 + K_B C)} . \qquad (23)$$

In all the remaining cases in which reaction is accelerated in the presence of micelles, the dependence of k_{exp} on C passes through a maximum (Fig. 3 illustrates a typical case). The physical significance of the presence of an optimum is that increase in the volume of the micellar phase is accompanied both by an increase in the quantity of substance passing into it from water and by a decrease in the concentration of this substance in the micellar phase. The first process tends to accelerate the reaction by increasing the relative proportion of the more rapid micellar reaction, and it predominates at low surfactant concentrations, while the quantity of substance passing into the micelles is small. The second process—dilution of the reactants in the micellar phase—slows down the reaction, and predominates at high surfactant concentrations, when the reactants are mainly present in the micellar phase.

This aspect can be analysed in greater detail for the most important particular case, in which the reaction velocity in the aqueous phase can be neglected. Putting $\bar{k}_M K_A K_B C \gg k_W$, we can then simplify Eqn. (21), and obtain the formula[4]

$$C_{opt} = (K_A K_B)^{-1/2} \qquad (24)$$

for the optimum surfactant concentration, corresponding to the maximum value of k_{exp}. The maximum acceleration of the reaction is then

$$(k_{exp}/k_W)_{max} = \frac{k_M}{k_W} \frac{K_A K_B}{V(\sqrt{K_A} + \sqrt{K_B})^2} . \qquad (25)$$

The ratio k_M/k_W represents the change in reactivity when the reactants are transferred from water into the micelle, and hence the specific effect of the micelles on the transition state of the reaction. The factor following the ratio on the right-hand side of (25) represents the "trivial" acceleration produced by the localisation of the reactants in the micelle.

2. Shift in pK_a of Ionogenic Reactant in presence of Surfactant Micelles

Acceleration or retardation of a reaction may also be caused by a shift in the pK_a of an ionogenic reactant in the presence of micelles. General consideration has already been given[4] to the kinetics of a bimolecular reaction involving an ionogenic reactant. Taking into account the dissociation of the reactant

$$AH \overset{K_a}{\rightleftharpoons} A^- + H^+ \qquad (26)$$

and assuming that the reactive form is, for instance, the anion

$$A^- + B \xrightarrow{k_W^0} \text{Products} \qquad (27)$$

we can write the effective rate constant of the reaction in the form

$$k_W = k_W^0/(1 + [H^+]_W/K_a) . \qquad (28)$$

Formally the same relation applies in the presence of a surfactant:

$$k_{exp} = k_{exp}^0/(1 + [H^+]_W/K_{a,exp}), \qquad (29)$$

where

$$k_{exp}^0 = \frac{\bar{k}_M^0 K'_A K_B C + k_W^0}{(1 + K'_A C)(1 + K_B C)} \qquad (30)$$

and

$$K_{a,exp} = K_a \frac{1 + K'_A C}{1 + K_A C} . \qquad (31)$$

Here K_A and K'_A are the binding constants of undissociated and ionic forms of the reactant A, and K_B is the binding constant of reactant B. Analysis of Eqn. (29) yields for

the maximum acceleration of the reaction the expression[4]

$$(k_{exp}/k_W)_{max} = \frac{k_M}{k_W}\frac{K_A K_B}{V(\sqrt{K_A}+\sqrt{K_B})^2}\frac{K'_A}{K_A} \quad (32)$$

As with the simpler equation (25), the second factor on the right-hand side represents the localisation of the reactants (substance B and the non-ionic form of A) into the micellar phase. The last factor on the right-hand side of Eqn. (32) represents the effect of the shift in the pK_a of the ionogenic reactant in the presence of the micelles, as can be seen from Eqn. (31), whence it follows that $K_{a,exp}/K_a$ tends to K'_A/K_A at sufficiently high values of C. With a cationic micelle, which would obviously bind the anion A^- more strongly than the non-ionic form A, we have $K'_A > K_A$, so that the shift in pK_a makes an additional contribution to the acceleration of the reaction in the presence of micelles (this effect is discussed in greater detail in Ref. 4).

3. Determination of Binding Constants of Reactants with Micelles from Kinetic Data. Experimental Determination of Second-order Rate Constant in Micellar Phase

It is a simple matter to analyse the dependence of the rate of a first-order reaction on C, for which purpose we convert Eqn. (11) to the form

$$k_{exp} = \frac{k_M P_A C V + k_W}{1 + P_A C V} \quad (33)$$

on the assumption that $\varphi_M = CV$. The value of k_M can then be found as the limiting dependence of k_{exp} on C at high C, and the binding characteristic of the reactant PV as the reciprocal of the abscissa for which $k_{exp} - k_W$ has half its limiting value. Graphical methods, based on the linearisation of Eqn. (33), are normally used[2] to evaluate k_M and PV.

Binding constants of reactants with micelles and the true reaction rate constant in the micellar phase can also be found for a bimolecular reaction. We shall consider this for one of the most important particular cases of micellar catalysis†, when $k_M K_A K_B C \gg k_W$. For this purpose we write (21) in the form

$$C/k_{exp} = \alpha + \beta C + \gamma C^2, \quad (34)$$

where

$$\alpha = 1/k_M K_A K_B,$$
$$\beta = \alpha(K_A + K_B),$$
$$\gamma = \alpha K_A K_B. \quad (35)$$

A graphical method is convenient for determining α, β, and γ from experimental data. The value of α is then the intercept made on the vertical axis by the curve representing the dependence of C/k_{exp} on C according to Eqn. (34). With α determined, the experimental results are conveniently plotted as the linear equation

$$\frac{C/k_{exp} - \alpha}{C} = \beta + \gamma C \quad (36)$$

which follows from (34). The intercept on the vertical axis and the slope of the straight line obviously give β and γ respectively. Finally, knowing α, β, and γ, we can use Eqns. (35) to calculate the required quantities K_A, K_B, and k_M.

A study[71] of the effect of cationic micelles of hexadecyltrimethylammonium bromide on the aminolysis of fluoro-2,4-dinitrobenzene by *N*-benzoyl-L-histidine has shown[71] agreement between the binding constants of the reactants with the micelles K_A and K_B found by the above method from kinetic data and measurements in an independent experiment on the solubilisation of the reactants by the micelles. Such agreement proves the correctness of the above kinetic concept of micellar effects in bimolecular reactions.

The molar volume V of the surfactant must be known in order to calculate the true rate constant k_M of a bimolecular (but not a unimolecular) reaction in the micellar phase from the measured effective value $\bar{k}_M$. This independent parameter must be known also in order to calculate partition coefficients P from experimental binding constants K. Certain difficulties arise as a consequence, since the molar volume V occurring in Eqn. (5) or (22) is in fact an effective quantity, representing that portion of the surfactant molecule which forms the region of the micelle where the reactants are actually solubilised and the chemical reaction takes place. However, difficulties already arise in estimating the total molar volume of the surfactant. The estimation usually starts[4,6,40] from the density of the micelles calculated from the partial specific volume of the surfactant above the critical micelle concentration, which varies from 0.9 to 1.1 g ml^{-1} for different surfactants[70]. On this basis an estimate of the total molar volume of the surfactant in the micelles which started from a density of ~ 1.0 g ml^{-1} might have been regarded as quite acceptable. However, this density applies to the "dry" surfactant, and does not allow for the hydration of the micelles, which is very considerable (see above). Nevertheless, the use of such a value for the density of the micelles probably does not lead to serious errors.

As example we estimate the size of micelles of the well studied sodium dodecyl sulphate[22,25]. The probable radius of the hydrocarbon core of its spherical micelles is 16.6 Å, the thickness of the Stern layer 4.6 Å, and the aggregation number 62. Hence the volume of the whole micelle is 4.0×10^4 Å^3,[5] or the molar volume of the surfactant in the micelles is 0.4 M^{-1}. Using the molecular weight 288 and density of the "dry" surfactant in the micelles 1.1 g ml^{-1},[70] we find that the corresponding molar volume is 0.26 M^{-1}. Since sodium dodecyl sulphate micelles contain 33 vol.% of water[27], the molar volume of the hydrated surfactant in the micelles is 0.39 M^{-1}, almost identical with the estimate obtained above from the dimensions of the micelles.

Estimating the effective molar volume is a more complicated task. All the reactions that have hitherto been studied in the presence of micelles involve polar molecules, which on solubilisation are probably located in the surface layers of the micelles. In most cases the reaction is assumed to occur in some surface region of the micelle, which covers the Stern layer and a further 3–4 methylene groups of the hydrocarbon chain in the surfactant molecule[1]. In the case of sodium dodecyl sulphate this means that ~ 4 Å must be added to the 4.6 Å thickness of the Stern layer. The volume of such a layer is 3.6×10^3 Å^3, which gives a molar volume of 0.32 M^{-1}, only slightly less than the above estimate of the total molar volume of the surfactant. It may be expected that this difference will also be small in the remaining cases.

† A general analysis of Eqn. (21) has been given previously[71]. The general equation (16) is analysed similarly to (21).

4. Micellar Catalysis in Reactions of the *n*th Order

The contribution made by concentrating the reactants to accelerating the reaction should increase with increase in the kinetic order of the reaction. We can show this for the *n*th-order reaction

$$n\mathrm{A} \rightarrow \text{Products}, \qquad (37)$$

When the concentrating effect in the micellar phase is strongly marked ($P_A \gg 1$), while the surfactant concentration is not too large ($CV \ll 1$), the effective reaction rate constant $k_{exp} = v/[A]_0^n$ is given by[8]

$$k_{exp} = \frac{k_M P_A^n CV + k_B}{(1 + P_A CV)^n}. \qquad (38)$$

With $n = 1$ the dependence of k_{exp} on the surfactant concentration tends to the limiting value k_M. With other values of n this function has a maximum. With sufficiently large accelerations, when the rate of reaction in the aqueous phase can be neglected $k_M P_A^n CV \gg k_W$, the optimum surfactant concentration is‡

$$C_{opt} = 1/P_A V(n-1). \qquad (39)$$

At this surfactant concentration the maximum acceleration reaches[8]

$$(k_{exp}/k_W)_{max} = \frac{k_M}{k_B} \cdot \frac{(n-1)^{n-1}}{n^n} P_A^{n-1}. \qquad (40)$$

Equation (40) shows that two factors—change in reactivity of A on passing from water to the micellar phase and the concentrating of A into the micelle—are responsible for accelerating the reaction. The first factor k_M/k_W depends on the mechanism of the reaction and the orientation of the reactants in the micelle; the second factor is determined [not] only by the partition coefficient of the substance between micelle and water but also by the order of the reaction. Values of P usually lie in the range 10^2–10^3. Then the maximum acceleration due solely to the concentration effect, i.e. with $k_M/k_W = 1$, is shown by Eqn. (40) to lie in the range 10–10^2 for a bimolecular reaction, and 10^3–10^5 for a termolecular reaction.

Since the factor $(n-1)^{n-1}/n^n$ in Eqn. (40) varies only slightly with n, the involvement of each new species in the reaction (i.e. unit increase in the order of the reaction) increases the efficiency of micellar catalysis approximately P-fold. This was confirmed by studying the effect of micelles of sodium dodecyl sulphate on the kinetics of the hydrolysis and the formation of benzylideneaniline[8]

$$C_6H_5NH_2 + C_6H_5CHO \rightleftharpoons C_6H_5N{=}CHC_6H_5 + H_2O. \qquad (41)$$

At pH < 9 this reaction is acid-catalysed, whereas at pH 9–12 its progress is independent of pH. Hence the efficiency of micellar catalysis when the reaction order varies from 1 to 3 could be followed by studying the rates of forward and reverse reactions in various pH ranges. Micelles of sodium dodecyl sulphate were found to produce a 3-fold retardation of the pseudounimolecular (pH-independent) hydrolysis of benzylideneaniline, whereas the pseudobimolecular reaction (acid-catalysed hydrolysis) underwent 20-fold acceleration. The effect of micelles on the bimolecular formation of benzylideneaniline was in turn 3-fold acceleration, but the termolecular (acid-catalysed) reaction was accelerated 125-fold. Thus the efficiency of micellar catalysis increases by factors of 40–60 with unit increase in the order of the reaction. This is consistent with the above kinetic concept, since the partition coefficients of the reactants lie in the same range (P = 30–80).[8]

The facts cited in this Review together with the detailed investigation of the effect of surfactant micelles on the kinetics of several other reactions[1,2] demonstrate that the kinetic concept of micellar catalysis that has been developed has the following merits: (i) the dependence of reaction velocity on surfactant concentration can be correctly described for reactions of different kinetic orders; (ii) the binding constants of reactants with the micelle can be calculated from kinetic data, and the reaction rate constant in the micellar phase can be estimated with satisfactory accuracy; and (iii) the acceleration of the reaction due to the concentrating of reactants in the micelle can be predicted and calculated theoretically.

IV. NATURE OF MICELLAR CATALYSIS

Two types of physicochemical factors—(1) change in reactivity of reactants on transfer from water to the micellar phase and (2) the concentrating of reactants into the micellar phase (Eqn. 25) in the case of reactions of the second and higher orders—can be distinguished as responsible for the efficiency of micellar catalysis. The above effect of the shift in the pK_a of an ionogenic reactant is essentially of the second type, since it represents the preferential concentrating of one ionic form relative to the other. Effects of the first type are characterised by the ratio of the rate constants k_M/k_W and may be caused by the environment (including electrostatic interaction of the transition state of the reaction with the surface charge of the micelle) and by orientation of the reactants in the micelle. The contribution of the concentration effect in accelerating reaction is determined mainly by the strength of ionic and hydrophobic interactions between reactant molecules and micelles (by the partition coefficients of the reactants).

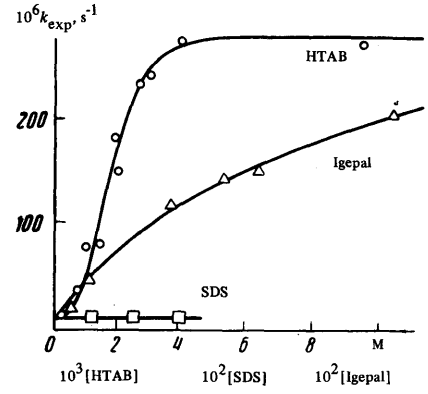
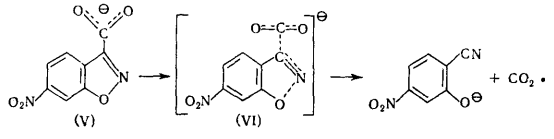


Figure 4. Effect of various surfactants on rate of decarboxylation of the 6-nitrobenzisoxazole-3-carboxylate anion (42).[72]

The most reliable information on the effect of micelles on the true reaction rate constant in the micellar phase

‡ Equations essentially equivalent to (38) and (39) were probably first given in Ref. 9, in connection with the kinetics of emulsion polymerisation.

will be provided by the study of *unimolecular reactions*, when k_M can be found without any assumptions concerning V (see above). Unfortunately, very little work has been done on such reactions. Data obtained by Bunton and Minch[72] on the effects of hexadecyltrimethylammonium bromide (HTAB), the non-ionic surfactant Igepal (an oxyethylated alkylphenol), and sodium dodecyl sulphate (SDS) on the kinetics of the decarboxylation of the anion (V) are plotted in Fig. 4. These workers assume[72] that the catalytic effect of the first of these surfactants is due to the action of the positive charge of the micelle in stabilising the anionic transition state (VI), in which the charge is more delocalised than in the initial species (V):



(42)

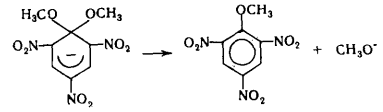
In our view this interpretation is not entirely satisfactory, since firstly it does not explain the catalytic action of a non-ionic surfactant, and secondly it is not entirely clear why a more delocalised charge on the substrate should be subject to stronger electrostatic interaction with the micelle. Probably in this case direct electrostatic interaction with the micellar charge is manifest only in binding the reactant to the micelles. This is indicated by our treatment of the kinetic data (Fig. 4) by means of Eqn. (33). Closely similar values of k_M were obtained for the quaternary bromide and Igepal (2.9×10^{-4} and 3.0×10^{-4} s^{-1}). On the other hand, the binding constants of the initial reactant with the corresponding micelles actually differ substantially (1400 and 20 M^{-1} respectively). The lack of effect of sodium dodecyl sulphate on the reaction is clearly due to electrostatic repulsion of the reactant from the anionic micelle. With cationic and non-ionic micelles the most probable factor tending to increase k_M in comparison with k_W is in our view replacement of the aqueous environment by the comparatively non-polar environment of the micelle. The direction and the magnitude of the observed effect ($k_M/k_W \simeq 100$) are fully consistent with those to be expected for processes involving delocalisation of the charge, and may be due both to stronger hydration of the localised charge in water and to stronger dispersion interaction of the delocalised charge with its environment in the micelle[73,74].

The breakdown of the 2,6-dinitrophenyl phosphate dianion[75]

$$ArOPO_3^{2-} \rightarrow [ArO^- \ldots PO_3^-] \rightarrow ArO^- + PO_3^- \qquad (43)$$

is an analogous process. In the presence of hexadecyltrimethylammonium bromide the reaction is accelerated, with $k_M/k_W = 29$ and $K = 1250$ M^{-1}. The substrate remains almost completely unattached to micelles of a non-ionic surfactant, let alone to an anionic agent; this may explain the lack of effect of non-cationic surfactants on the reaction velocity. The considerable contribution of electrostatic attraction to the efficiency of binding of a doubly charged ion (see above) may be responsible for the absence of binding. However, as in the preceding example, electrostatic interaction between reactant and micellar charge has only a very slight effect on the reaction in the micellar phase. An indication of this is the "competitive" inhibition of micellar catalysis produced by the introduction of gegenions leading to neutralisation of the surface charge on the micelle: i.e. the binding constant decreases, but the rate constant k_M remains almost constant. It is interesting that micelles do not catalyse hydrolysis of the *p*-nitrophenyl phosphate monoanion or the glucose 6-phosphate dianion, which involves transfer of a proton to the resulting negative charge and hence is not accompanied by delocalisation of charge in the transition state.

E. and J. Fendler studied the effect of surfactants on the kinetics of the unimolecular decomposition of Meisenheimer complexes[76]. They examined in greatest detail the reaction



(44)

which is retarded in the presence of hexadecyltrimethylammonium bromide and Igepal, but whose rate is unaffected by sodium dodecyl sulphate. This latter fact is easily explained by electrostatic repulsion of the reactant from the anionic micelle. Although the data given[76] are unfortunately insufficient for detailed analysis of the kinetics, nevertheless even qualitative comparison of the effects observed with different surfactants indicates that here, too, interaction of the substrate with the micellar charge has no decisive effect on the reaction rate constant in the micelle k_M.

The above facts suggest that in general, when the sole difference between initial and transition states is the degree of delocalisation of the charge, the rate constant k_M is mainly affected merely by the change in reaction medium when the reactant passes into the micellar phase. A specific effect of the micellar charge on the rate of a unimolecular reaction can probably be expected only when ionisation occurs in the transition state, as e.g. in the hydrolysis of t-butyl chloride[73].

Most *bimolecular reactions* studied hitherto involve the interaction of appreciably hydrophobic neutral molecules with ions. They comprise mainly the acid and alkaline hydrolysis of carboxylic esters, phosphoric and sulphuric esters, acetals and orthoesters, Schiff bases, and aryl and alkyl halides, as well as nucleophilic substitution of the latter compounds with anions. Data on the effect of micelles on the kinetics of these reactions have been assembled in Ref. 2. The recently investigated reduction of iminoxyl radicals by iron(II) ions[77,78] and the reaction of benzene with the hydrated electron[79] are of the same type. Micellar effects on these processes exhibit several characteristic general features, although there are exceptions[1,2,80]. The reaction is usually accelerated by a surfactant whose micelles are oppositely charged to the reactant ion; when micelles and reactant ions bear like charges, the reaction is inhibited. Non-ionic surfactants generally have no significant influence on the rates of these reactions. The efficiency of ionic surfactants is in turn greatly diminished by increasing the concentration of gegenions.

The simplest explanation of the regularities observed is that a hydrophobic reactant is attached to a micelle by hydrophobic interactions, independently of the charge on the latter. If the second reactant is oppositely charged to the micelle, it also becomes bound to the latter, and thus the reactants are concentrated, which is responsible for accelerating the reaction. If, however, the ion bears a like charge to the micelle, it is repelled from the latter, and reaction is retarded owing to separation of the reactants (Eqn. 19). Since the binding of ions is determined by the surface potential of the micelle, the lowering of the potential with increasing concentration of gegenions tends to diminish the attachment of a reactant ion and hence decreases the efficiency of micellar catalysis.

A fundamental difficulty is encountered when Eqn. (16) is used to analyse the kinetics of these reactions. In fact increase in surfactant concentration is accompanied by an increase in the concentration of gegenions and thus a fall in the surface potential, which entails a decrease in the binding constant for the ionic reactant and a consequent divergence between theoretical and experimental variations of k_{exp} with C (Fig. 5). At large values of C this disregarded effect may be very considerable[8]. The method sometimes used, of maintaining a constant total concentration of gegenions[81], is not entirely correct, since these ions attach to the micelles, so that their concentration in the aqueous phase, which should have been maintained constant, falls with increase in C.

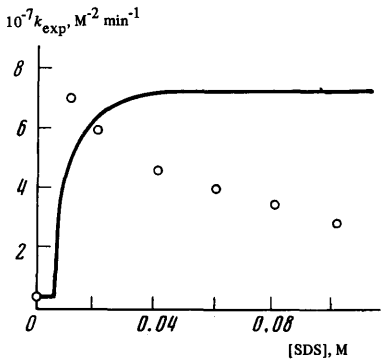
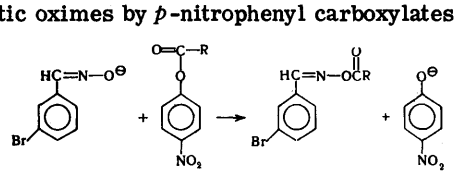


Figure 5. Dependence of experimental rate constant for the acid hydrolysis of benzylideneaniline on concentration of sodium dodecyl sulphate[8]. The theoretical curve has been drawn on the assumption that the surface potential of the micelle remains constant with increase in the surfactant concentration.

The above kinetic concept of micellar catalysis has formed the basis for a most detailed study[4] of the acylation of aromatic oximes by p-nitrophenyl carboxylates



(45)

in the presence of hexadecyltrimethylammonium bromide. Analysis of the experimental results by means of Eqn. (29) shows that the acceleration of the reaction due to the shift in the pK_a of the oxime is about 15-fold. The effect of concentrating the reactants—ester and undissociated form of oxime—in the micellar phase varies from 60 for the acetate to 2000 for the heptanoate. The two effects enable substantial accelerations to be achieved, up to 17 000 in the case of the salicylate.

An extremely interesting dependence of k^0_M/k^0_W on the structure and dimensions of the aliphatic portion of the hydrocarbon radical R has been found in the latter investigation[4] (Fig. 6). Since the mechanism of reaction (45) should not depend on the size of R, so that the same change in reactivity on transfer of the reactants to the micellar phase should be produced by the environment and by interaction with the micellar charge, the most probable reason for the observed dependence of the ratio on the size of the side-chain R may be *orientation of the reactants in the micelle*.

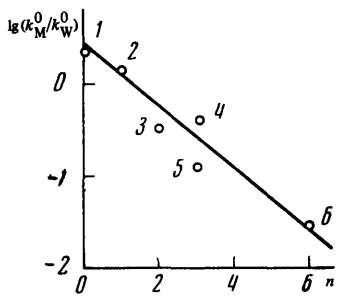


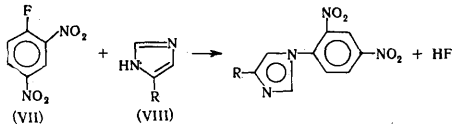
Figure 6. Dependence of logarithm of ratio of rate constants in micellar k^0_M and aqueous k^0_W phases for the acylation of m-bromobenzaldehyde oxime on number n of methyl and methylene groups in acyl portion of p-nitrophenyl carboxylate acylating agent: 1) salicylate; 2) acetate; 3) β-phenylpropionate; 4) $\alpha\alpha$-dimethylpropionate; 5) butyrate; 6) heptanoate[4].

A semi-quantitative interpretation of this effect is that ions and aromatic molecules are sorbed in the surface layer of the quaternary ammonium micelles, whereas the aliphatic chains on solubilisation by the micelle are immersed in the hydrophobic core. Thus increase in size of the aliphatic portion R will secure an orientation of the ester molecule such that both R and the ester group will be drawn into the hydrophobic core of the micelle. This, of course, would prevent its interaction with the oxime ion. It may be postulated as a first approximation that every methyl or methylene group makes a roughly constant positive contribution, equal to the incremental free energy of transfer of this group from the hydrophobic core to the hydrated surface layer, to the free energy of activation of the reaction in the micellar phase. The validity of such a view is indicated by the linear relation between $\lg(k^0_M/k^0_W)$ and the number n of methyl and methylene groups in the radical R (Fig. 6), whose slope gives +0.43 kcal $mole^{-1}$ (for each methylene or methyl group) as the increment in the free energy of transfer.

This phenomenon is remarkable in indicating the possibility of specificity in micellar catalysis. Indeed this is a case not of "trivial" specificity due to the concentration effect (the stronger the binding the greater the acceleration) but of finer "tuning" of the catalyst, when substantially different acceleration effects are obtained with similarly bound substrates.

The situation with regard to research on micellar catalysis in bimolecular reactions involving only uncharged molecules is far worse, although this particular case is far easier to analyse theoretically because of the absence of effects due to variation of the surface potential. A reaction of this type—between fluoro-2,4-dinitrobenzene

(VII) and the methyl ester of *N*-benzoyl-L-histidine (VIII) [sic]



(46)

has been used[71] to solve the important problem of activation energy in micellar catalysis. "Experimental" values E_{exp}, obtained from the temperature dependence at some constant value of C

$$E_{exp} = -R\left(\frac{\partial \ln k_{exp}}{\partial (1/T)}\right)_C \qquad (47)$$

have normally been employed. However, this quantity is equal to the true activation energy of the reaction occurring in the micellar phase only for a unimolecular reaction, provided that limiting values of k_{exp} are used at sufficiently large values of C. In all other cases E_{exp} is composite (as will be shown below), and therefore its value must be interpreted with caution. From the decrease in E_{exp} in the presence of hexadecyltrimethylammonium bromide, which catalyses the alkaline hydrolysis of chloro-2,4-dinitrobenzene, and its increase when the same reaction was inhibited in the presence of sodium dodecyl sulphate, it was concluded[37] that the transition state of the reaction is stabilised by the surface charge of the micelle during catalysis, and destabilised during inhibition. However, it is then difficult to explain why E_{exp} passes through a minimum with increase in C in the catalysis of the alkaline hydrolysis of fluoro-2,4-dinitrobenzene by the quaternary bromide[38], whereas it increases with increase in C during micellar catalysis of the alkaline hydrolysis of *p*-nitrophenyl diphenyl phosphate[82]. Similarly, the lower value of E_{exp} for the acid hydrolysis of sodium dodecyl sulphate as compared with that of sodium ethyl sulphate led to the conclusion that the transition state is stabilised by the anionic micelle of this surfactant (whose rate of hydrolysis exceeds that of sodium ethyl sulphate by a factor of 60)[83]. But it then remains obscure why the acid hydrolysis of the surfactant is characterised by the same value of E_{exp} before and after the c.m.c.[84] Yet all these facts can be explained perfectly satisfactorily by using the above simple concepts of the approach or separation of ionic and hydrophobic reactants. From Eqn. (21) with $\bar{k}_M K_A K_B C \gg k_W$ and Eqn. (47) it follows that

$$E_{exp} = E_M + \frac{\Delta H_A}{1 + K_A C} + \frac{\Delta H_B}{1 + K_B C} \cdot \qquad (48)$$

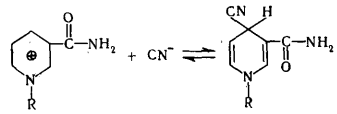
The composite quantity E_{exp} is seen to include also the heats of binding of the reactants by the micelles and to depend on C. For reaction (46) between uncharged reactants it was found that $E_M \simeq E_W$, and the very considerable decrease in E_{exp} observed is due to negative heats of binding of the reactants[71].

The binding by micelles of reactants containing no charged groups is due mainly to hydrophobic interactions. Therefore cation-active, anion-active, and non-ionic surfactants should act as catalysts, with the action of ionic surfactants unaffected by the concentration of the gegenions. This occurs in the case of reaction (46),[71] and also for the reaction of aniline with chloro-2,4-dinitrobenzene or fluoro-2,4-dinitrobenzene[85].

However, very considerable specific electrostatic effects are nevertheless possible in the micellar catalysis of reactions between uncharged molecules. An example is the reaction of (VIII) or other imidazole derivative with *p*-nitrophenyl carboxylates[71]. These reactions are accelerated by hexadecyltrimethylammonium bromide, retarded by sodium dodecyl sulphate, and slightly dependent on the concentration of a non-ionic surfactant. Catalysis by the quaternary bromide is sharply depressed in the presence of gegenions. At the present time it is difficult to establish whether these effects are due to orientation of the reactant in the micelle or are a direct effect of the surface charge of the micelle on the transition state of the reaction. In any case, the presence of such effects indicates the existence of extremely untrivial ways in which surfactant micelles influence the kinetics of organic reactions.

V. EFFECT OF MICELLES ON REACTION EQUILIBRIUM

The influence of micelles on ionic equilibria is well known. The effect of surfactant micelles has been most fully studied on the dissociation constants of acids and bases[2,23]. The shift in pK_a produced by ionic surfactants can in general be satisfactorily described on simple electrostatic concepts, of the type applied by us to the kinetics of ion–molecule reactions. The shift usually reaches 1–2[2,23], corresponding to the observed 10–100-fold acceleration of such reactions. The most considerable changes in ionic equilibrium constants have probably been found in the reaction



(49)

where the equilibrium constant increases by a factor of 25 000 in the presence of hexadecyltrimethylammonium bromide[86].

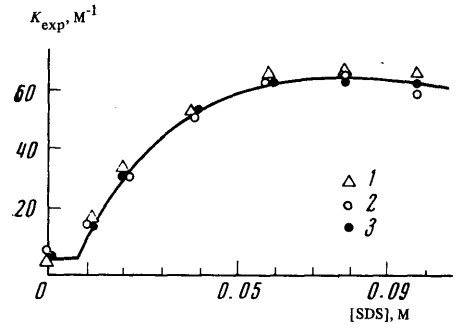


Figure 7. Effect of sodium dodecyl sulphate on experimental equilibrium constant for the formation of benzylideneaniline: 1) values calculated from equilibrium concentration of benzylideneaniline; 2) ratios of rate constants of forward and reverse reactions at pH 7; 3) ratios at pH 10.[8]

An example of the displacement of a non-ionic equilibrium[8] is the effect of sodium dodecyl sulphate on the equilibrium constant of the formation of benzylideneaniline by reaction (41). Fig. 7 illustrates the dependence of the experimental equilibrium constant on the surfactant concentration. These results were discussed on the basis of

a rapidly established distribution of reactants between aqueous and micellar phases. The experimental equilibrium constant

$$K_{exp} = \frac{[AB]_0}{[A]_0[B]_0} \quad (50)$$

is then related[8] to the surfactant concentration by the formula

$$K_{exp} = K_W \frac{1 + K_{AB}C}{(1 + K_AC)(1 + K_BC)} \quad (51)$$

where K_A, K_B, and K_{AB} are binding constants of the reactants with the micelles and K_W is the equilibrium constant in water. The true equilibrium constant in the micellar phase is

$$K_M = \frac{[AB]_M}{[A]_M[B]_M} = \frac{[AB]_0}{[A]_W[B]_W} \cdot \frac{P_{AB}}{P_AP_B} = K_W \frac{P_{AB}}{P_AP_B}. \quad (52)$$

The binding constants of the reactants with the surfactant micelles were found from Eqn. (51) by analysing the dependence of K_{exp} on C (Fig. 7). The results were almost identical with independent measurements using the gel filtration of the reactants in an aqueous solution of the surfactant[8]. This demonstrates the validity of the theoretical equation (51). Moreover, it was found that $K_M \leqslant K_W$. Despite a more than tenfold increase in the experimental equilibrium constant K_{exp} (Fig. 7), the true equilibrium constant in the micellar phase K_M is thus roughly equal to K_W (or even less). This phenomenon is directly analogous to the acceleration of reactions by the localisation of the reactants.

In view of these facts the term "micellar catalysis" is not entirely correct, since a "true" catalyst should not displace an equilibrium appreciably[87]. Nevertheless, this term has become established and is a quite happy choice, for it reflects the facts firstly that a surfactant has a substantial effect on reaction velocities when added in low concentrations ($\leqslant$0.01 M) and secondly that the surfactant is not used up in the reaction.

ADDENDUM

A considerable number of studies of micellar effects in various organic reactions have been published since the appearance of the review[2]. Some of them are covered in the present Review (see above), but several investigations, not specially concerned with physicochemical aspects, have not been mentioned. Among them we may note the following—alkaline decolorisation of triphenylmethane dyes[88-90], hydrolysis of carboxylic esters[91-93] and ethers[94], hydrolysis and aminolysis of phenyl sulphates[95], acylation of thiols[96], interaction of the hydroxide ion with tetranitromethane[97] and of the cyanide ion with 3-carbamoylpyridinium ions[98], azo-coupling[99], deamination of amines[100] and hydroxylamines[101], decarboxylation[102], addition of cyanide to haemin[103], reactions of Cl_2^- and hydroxyl radicals[104,105], activation of complex ions[106], and other reactions[107,108]. Catalysis by "reversed" micelles in non-aqueous solvents is especially interesting. The mutarotation of 2,3,4,6-tetramethyl-α-D-glucose in benzene and in cyclohexane[109], the aquation of complex ions in benzene[110], and other reactions[111-113] have been studied in such systems.

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