Interactions and Reactions in Reversed Micellar Systems

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Received August 19, 1975

The chemical approach to biological problems through investigations of models rests upon the ability of the chosen system to mimic some functions of the biological ensemble. Surfactants in aqueous media have been extensively used as model systems. Surfactants are amphipathic molecules which have distinct hydrophobic and hydrophilic regions. Over a narrow concentration range, defined as the critical micelle concentration, or cmc, surfactants dynamically associate to form large molecular aggregates, called micelles.

Rates of numerous organic and inorganic reactions are affected by micelles in aqueous solutions.[1] Catalysis or inhibition is the consequence of substrate solubilization in the micellar pseudophase. Rate effects can be attributed to electrostatic, hydrophobic, electrophilic, and/or nucleophilic interactions with the resultant alteration of the free energy of activation for the overall process. Interest in micellar chemistry has been prompted by the proposed similarities between the structures of globular proteins and spherical micelles and between micellar and enzymatic catalyses. Additionally, mechanistic information obtained at interfaces is more representative of complex biochemical reactions than that studied in dilute aqueous solutions. Although micelles in water have provided useful models for utilizing binding energies for decreasing free energies of activation, the observed rate enhancements and specificities have been, in most cases, unimpressive.[1] The scarcity of well-documented micelle-induced reaction stereospecificity has been equally discouraging. The flexibility and dynamic nature of the monomer–micelle–substrate system, water penetration and solubilizate-induced structural changes, are the reasons for the relatively poor ability of micelles in aqueous solutions to mimic enzymes. Efforts to enhance the effectiveness of micellar catalysis have included investigations of multicharged[2] and functional micelle forming surfactants[3] as well as polyions attached to macromolecular backbones.[4]

An alternative medium for approximating the effects of selective substrate partitioning and binding, mono- and multifunctional catalyses, and changes in the effective microenvironment of the reactants is provided by surfactant aggregates in nonpolar solvents. Such surfactant aggregates have been termed reversed or inverted micelles since their polar groups are concentrated in the interior of the aggregate while their hydrophobic moieties extend into, and are surrounded by, the bulk apolar solvent.[5] Significantly, considerable amount of water can be solubilized by reversed micelles. This surfactant-solubilized water is often referred to as a water pool.

Reversed micellar solutions are homogeneous and optically transparent. The most important difference between aqueous and reversed micelles is that substrates do not penetrate appreciably into the former, but, if polar, they are localized in the hydrophilic cavities of reversed micelles. Interactions between the substrate and the polar headgroups of the surfactant, between the substrate and the solubilized water, and between the solubilized water and the surfactants can be quite strong and specific. Substantial rate enhancements or retardations are, therefore, expected. The available data on reactions in reversed micellar systems fully substantiate this expectation (Table I).[6-17] The present Account summarizes the

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Table I
Effects of Reversed Micelles on Reaction Rates

Reaction	Reversed micellar system	k_ψ/k_S[a]	k_ψ/k_{H_2O}[b]	Comments	Ref
Hydrolysis of *p*-nitrophenyl dodecanoate	Hexadecyltrimethylammonium bromide–hexanol–water			Catalysis in reversed micelle-solubilized water pool, $k_{\psi(max)} = 4.33 \times 10^{-3}\ s^{-1} \approx k_\psi$(CTAB)	6
Imidazole-catalyzed hydrolysis of *p*-nitrophenyl acetate	Sodium bis(2-ethylhexyl)sulfosuccinate in octane + H_2O		0.02	Retardation is the consequence of preequilibrium partitioning and unfavorable orientation	7
Aminolysis of *p*-nitrophenyl acetate	Tetra-*n*-hexylammonium benzoate in toluene			Rate effects are highly specific	8
Mutarotation of 2,3,4,6-tetramethyl-α-D-glucose	Alkylammonium carboxylates in benzene and in cyclohexane	380–863	15–39	Substrate favorably oriented in polar cavity where concerted proton transfer facilitates ring opening	9
Decomposition of 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide ion (Meisenheimer complex)	Dodecylammonium propionate in benzene	$(2–6) \times 10^4$	690–1860	Substrate favorably oriented in polar cavity where concerted proton transfer assists C–O bond cleavage	10
	Hexadecyltrimethylammonium butanolate in benzene	1			
	Phosphatidylcholine in benzene	1533	45	Addition of water increases rate enhancement	
	Phosphatidylethanolamine in benzene	5.1×10^4	1450	Addition of water does not affect rate enhancement	
Aquation of $[Cr(C_2O_4)_3]^{3-}$	Alkylammonium carboxylates in benzene		$(1–5.4) \times 10^6$	Rate enhancement depends on the concentrations of the surfactant and added H_2O	11
Aquation of $[Co(C_2O_4)_3]^{3-}$	Dodecylammonium propionate in benzene + 0.11 M H_2O		1450		11
Aquation of $[Co(CN)_5N_3]^{3-}$	Dodecylammonium propionate in benzene + 0.11 M H_2O				
trans-$[Cr(C_2O_4)_2(H_2O)_2]^- \rightarrow$ *cis*-$[Cr(C_2O_4)_2(H_2O)_2]^-$	Alkylammonium carboxylates in benzene with 0.010–0.11 M H_2O or D_2O		5–30	Rate enhancement and isotope effects depend on the concentration of added water	12
Solvolysis of 2,4-dinitrophenyl sulfate	Alkylammonium carboxylates in benzene		21–70	General-acid, general-base, and micellar catalysis contribute to rate enhancement	13
Vitamin $B_{12}a + L^c \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}}$ Vitamin $B_{12}L + H_2O$	Dodecylammonium propionate and sodium bis(2-ethylhexyl) sulfosuccinate in benzene		$10^2–10^4$	Rate enhancement is dependent on ligand, surfactant, and solubilized-water concentrations	14
Hemin + CN^-	Poly(oxyethylene(6))–nonylphenol in benzene containing 0.2% v/v CH_3OH		$k_\psi/k_{CH_3OH} = 960$	Formation of hemin monomer predominates in micelles (dimers in H_2O)	15
Dissociation of ethylpyridinium charge-transfer complex	Dodecylammonium propionate in methylene chloride containing different amounts of water			K_d depends on surfactant and solubilized water concentration. In 0.20 M DAP it increases logarithmically with increasing water concentration	16
Phospholipase-catalyzed hydrolysis of phosphatidylcholine in the presence of Ca^{2+}	Phosphatidylcholine in diethyl ether–methanol 95:5 (v/v)			Complex kinetics, rate depends on concentrations of substrate, water, and Ca^{2+}	17

[a] k_ψ/k_S = rate in reversed micelle relative to that in bulk organic solvent. [b] k_ψ/k_{H_2O} = rate in reversed micelle relative to that in water. [c] L = glycine, sodium azide, and imidazole.

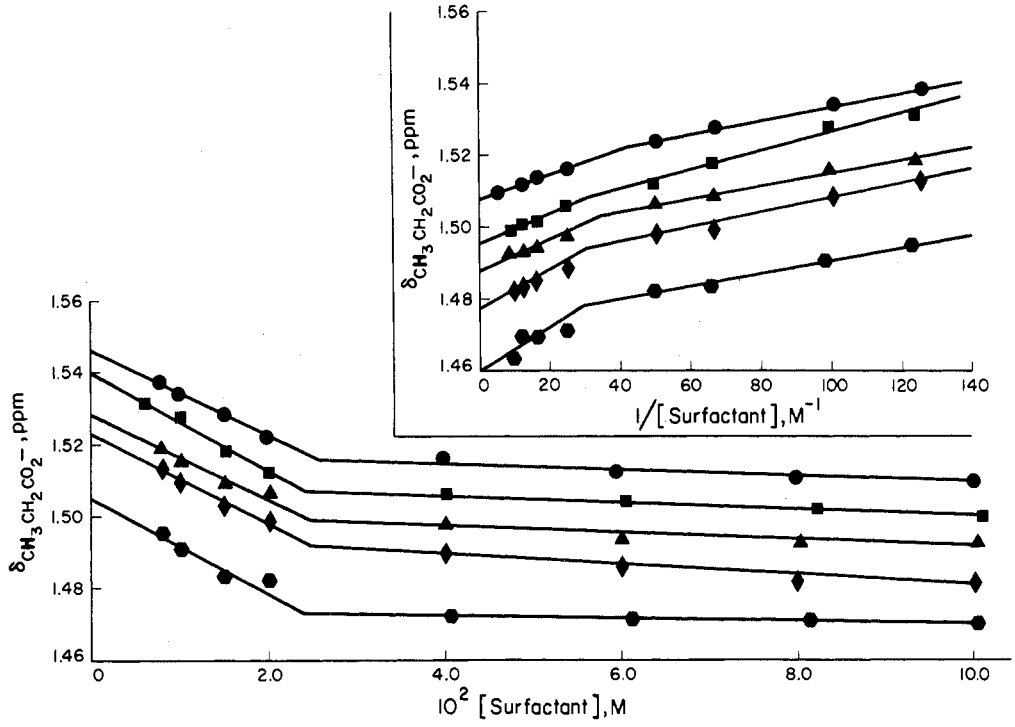

Figure 1. Chemical shift of the $CH_3CH_2CO_2^-$ protons as functions of surfactant concentration in carbon tetrachloride at 33 °C: ●, butylammonium propionate; ■, hexylammonium propionate; ▲, octylammonium propionate; ♦, decylammonium propionate; ■, dodecylammonium propionate.

behavior of surfactants in nonpolar solvents, the consequences of substrate and water solubilization, and the observed rate effects in reversed micelles. Major emphasis will be placed on results obtained in our own laboratories.

Behavior of Surfactants in Nonpolar Solvents

Information on the physical chemical properties of surfactants in nonpolar solvents is meager. Until recently, theories for aggregation were based on models derived for aqueous micelles.[18] Thus, an equilibrium between monomers and micelles was assumed, with the concentration of the monomer remaining essentially constant above the critical micelle concentration. At the onset of the discussion, the profound influence of a third component, an added solubilizate or an unrecognized impurity, should be emphasized. This, even at low concentrations, dramatically alters the solubilities and aggregation properties of surfactants in nonpolar solvents. Effects of an additive are complex and, as yet, unpredictable. Surfactant—nonpolar bulk solvent—added water systems have received the most attention. In many instances water promotes the formation of larger and more stable reversed micelles. Indeed, in the absence of traces of water, aggregation is sometimes precluded.

In our laboratories we have utilized ^{1}H NMR spectroscopic techniques for the investigation of alkylammonium carboxylates[19-22] and poly(oxyethylene)–nonylphenols[23] in nonpolar solvents. At sufficiently high concentrations, the ^{1}H NMR spectra of the surfactants consist of single weight-averaged resonances for the magnetically discrete protons of the monomeric and aggregated species, indicating that association is rapid on the NMR time scale. Chemical shifts of the different protons as functions of stoichiometric surfactant concentrations generally show discontinuities (Figure 1). Although theoretically not entirely valid (vide infra), breaks in plots analogous to that in Figure 1 have been taken to represent "operational critical micelle concentrations".[19-22] Such operational critical micelle concentrations for butyl-, hexyl-, octyl-, decyl- and dodecylammonium propionates in benzene were found to decrease logarithmically with increasing chain lengths of the alkylammonium group.[19] Conversely, values for octylammonium propionate, butyrate, hexanoate, nonanoate, dodecanoate, and tetradecanoate in the same solvent increase logarithmically with increasing chain lengths of the carboxylate group.[20] Equally interesting is the observed linear relationship between the operational critical micelle concentrations and both the macroscopic (expressed in terms of reciprocal dielectric constant) and microscopic [given in terms of $E_T(30)$] solvent polarities for alkylammonium propionates in DMAC, $CDCl_3$, CH_2Cl_2, C_6H_6, and CCl_4.[21] Apparently, aggregation properties of surfactants in nonpolar solvents depend on both the solute and the solvent.

The number of monomers involved in most surfactant aggregates in nonpolar solvents is relatively

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small,[18-23] and the monomer $\rightleftharpoons$ n-mer type association is unlikely to represent the behavior of surfactants.[24] Indeed Muller has demonstrated that the observed concentration dependence of the ^{1}H NMR chemical shifts for alkylammonium carboxylates in benzene[19-21] fits either a single or a multiple equilibrium model[25] equally well. The multiple equilibrium model assumes the stepwise formation of aggregates in an indefinite association:

$$\text{monomer} \overset{K_1}{\rightleftharpoons} \text{dimer} \overset{K_2}{\rightleftharpoons} \text{trimer} \overset{K_3}{\rightleftharpoons}$$

$$\text{tetramer} \ldots . \overset{K_n}{\rightleftharpoons} n\text{-mer}$$

Distribution of the different aggregates depends on the stoichiometric surfactant concentration. At higher surfactant concentration larger aggregates are formed than at lower concentration. The multiple equilibrium model deemphasizes the concept of critical micelle concentration[24] but it allows fruitful discussions of average aggregation numbers and distribution of aggregates at given surfactant concentrations.

Aggregation of dodecylammonium propionate in benzene and in cyclohexane has been recently examined in detail by vapor-pressure osmometry.[26] In this method, the values obtained for the number- and weight-averaged molecular weights and weight fractions of monomers have been utilized at different stoichiometric surfactant concentration for distinguishing between the different types of self-association.[27,28] The data were analyzed in terms of monomer–n-mer, monomer–n-mer–m-mer (1,2,4; 1,2,6; 1,2,8), and two types of indefinite self-associations. In type I (indefinite self-association), the presence of all associating species and the equality of all equilibrium constants ($K_1 = K_2 = K_3 \ldots . = K_n$) are assumed. In type II (indefinite self-association), equilibrium constants are also assumed to be equal, but odd species (trimers, pentamers, etc.) are presumed to be absent. Very significantly, the monomer–n-mer, the monomer–n-mer–m-mer, and the type II (indefinite self-association) models fail to describe the observed data, while the fit with type I (indefinite self-association) is remarkably good.[26] Examination of the temperature dependence revealed that the self-association is enthalpy controlled and that the equilibrium constant for it decreases with increasing temperature, as expected if dipole–dipole interaction is the predominant force governing reversed micelle formation.[26] Vapor-pressure osmometry is clearly a superior technique for establishing unequivocally the aggregation behavior of surfactants in nonpolar solvents.

An important consequence of the indefinite self-association model, particularly when the average aggregation number is small, is that changes in physical properties with increasing surfactant concentrations are expected to be gradual, with no apparent breaks. The observed breaks in the ^{1}H NMR plots, defined as operational cmc's, may be due to changes in the relative concentrations of the monomers or oligomers with respect to the other species present. It is somewhat unexpected and puzzling that there are well-defined breaks and that the operational critical micelle concentrations correlate so well with the chain length of alkylammonium carboxylates,[19,20] with the solvent polarities,[21] and with the rate enhancements.[5-16]

Additional information on the behavior of surfactants in nonpolar solvents has been deduced recently from fluorescence lifetime measurements.[23] Nonionic poly(oxyethylene)–nonylphenols fluoresce upon excitation. At concentrations smaller than 0.02 M, the decay of fluorescence of poly(oxyethylene(6))–nonylphenol, $CH_3(CH_2)_8C_6H_4(OCH_2CH_2)_6OH$ (Igepal CO-530), in cyclohexane is of single exponential form with a lifetime of 21 ns. At surfactant concentrations greater than 0.03 M, however, the decay takes the form of two exponents, with lifetimes of 21 and 9 ns. Significantly, the appearance of the shorter decay coincides with the independently determined operational cmc and the lifetimes of the two decays remain unchanged in the concentration range of 0.03–0.10 M.[23] The longer decay has been assigned to monomeric Igepal CO-530, while the shorter one is due to the aggregated surfactant.[23] The observation of two distinct fluorescence decays for Igepal CO-530 in cyclohexane above the operational cmc has two important implications. Firstly, the appearance of aggregates in relation to the presence of monomers is sufficiently distinct to cause two well separated consecutive decays. Secondly, the aggregate $\rightleftharpoons$ monomer equilibrium is slower than the time scale of observation for the fluorescence decay. This information, in combination with the ^{1}H NMR experiments, places the lifetime of the monomers in the presence of higher aggregates between 10^{-5} and 10^{-8} s.

In early works, reversed micelles were considered to be spherical, with the polar groups located in their interior.[18] It is more likely, however, that aggregates containing only small numbers of monomers associate to form lamellar micelles, with the polar and hydrophobic groups being placed end to end and tail to tail, with water and organic solvents between them.[29a] Addition of water and/or other solubilizates causes the micelle to swell and to assume a different shape.

Nature of Surfactant-Entrapped Water

Controlled amounts of surfactant-entrapped water in nonpolar solvents provide a unique medium for interactions and reactions of polar substrates. Water is predominantly localized at the polar groups of surfactant aggregates. ^{1}H NMR experiments on 0.20 M dodecylammonium propionate in methylene chloride have substantiated this contention.[16] Plots of the observed chemical shifts of the magnetically discrete surfactant protons vs. the concentration of solubi-

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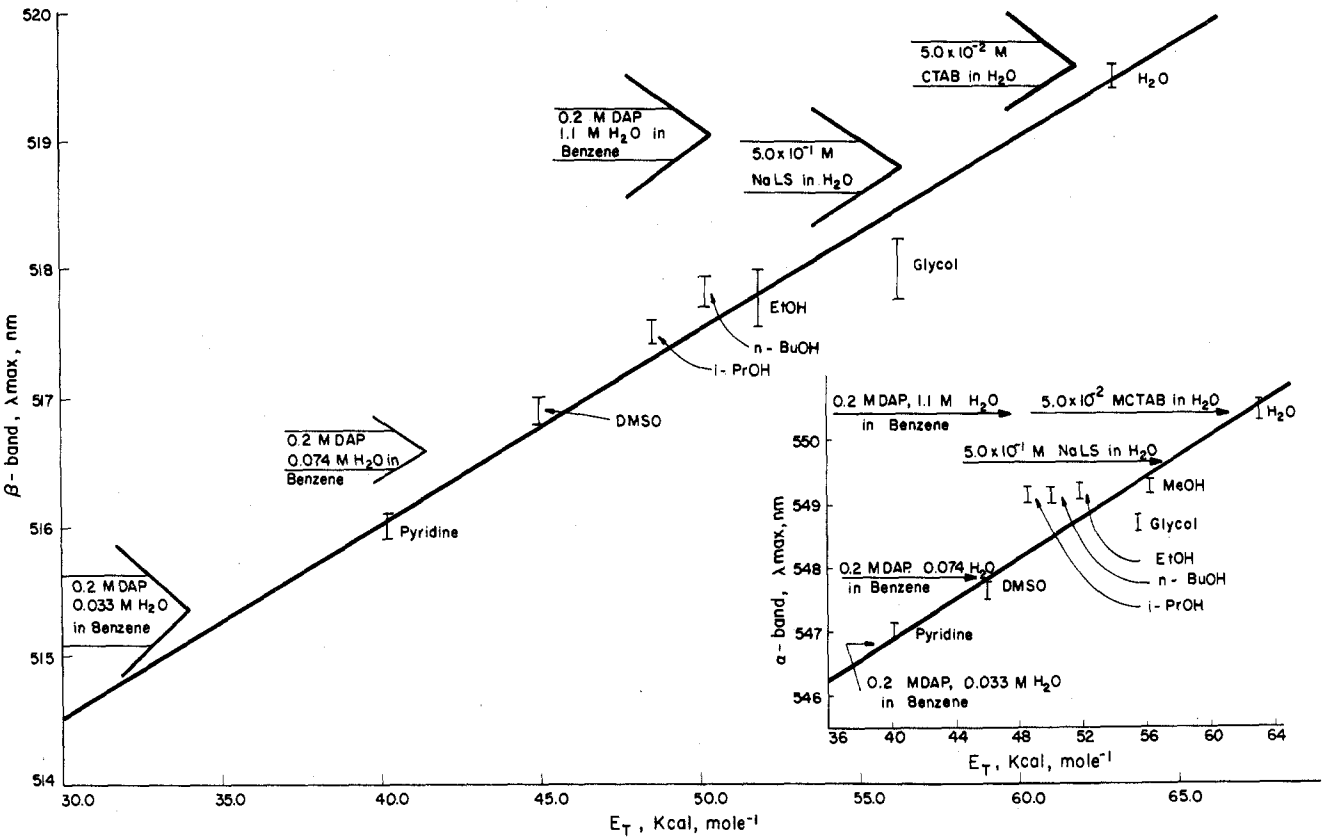

Figure 2. Correlation between absorption maxima of the α and β bands of vitamin B_{12} and solvent polarity parameter E_T.

lized water result in a considerable upfield shift of the NH_3^+ protons and in a somewhat smaller downfield shift of the $CH_2NH_3^+$ and $CH_2CO_2^-$ protons while other surfactant protons are unaltered. The effective polarity, acidity, and microscopic viscosity of the surfactant-entrapped "water pools" are expected to be substantially different from those in bulk water. The ionic strength of surfactant-entrapped water can be usually large. Indeed, a resemblance to the ionic environment of crystals has been proposed.[18] In view of its importance, research is being increasingly directed toward the elucidation of the properties of this unique reaction medium.

Both macroscopic and microscopic solvent polarities and dipole moments[29b] have been examined in selected systems. Thus, the dielectric constants of sodium bis(2-ethylhexyl) sulfosuccinate aggregates in hexane containing up to 16.7% solubilized water were found to resemble that of octane.[7] More meaningful information was obtained, however, by determination of the absorption maxima of pyridine 1-oxide along with the fluorescence quantum yields in sodium bis(2-ethylhexyl) sulfosuccinate solubilized water pools in octane. Based on these latter criteria the effective polarities of the probes varied in the range which corresponded to those between methanol and water.[7] We have examined the microscopic polarities of dodecylammonium propionate and poly(oxyethylene-(6))–nonylphenol solubilized water in methylene chloride, benzene, and cyclohexane by utilizing absorption and fluorescence spectroscopic measurements on 1-ethyl-4-carbomethoxypyridinium iodide,[16] vitamin B_{12},[14] and hemin[15] as extrinsic probes. The most salient fact emerging from these studies is that the concentration of added water, i.e., the size of the water pool, determines the effective polarity. Figure 2 illustrates the solvent dependency of the absorption maxima of the α and β bands of vitamin B_{12}.[14] Using this correlation as a ruler, effective polarities in different micellar environments in which vitamin B_{12} is solubilized have been assessed in terms of $E_T(30)$ values. It is seen that at low concentrations of solubilized water the effective environment of vitamin B_{12} is appreciably less polar than pyridine. Conversely, in large solubilized water pools as well as in aqueous micelles the substrate is in a medium which is not too dissimilar from water.[14] It should be pointed out, however, that such large molecules as vitamin B_{12} or hemin substantially alter the structure of the reversed micelles. Vitamin B_{12} is in fact surrounded by some 300 molecules of dodecylammonium propionate and hemin is wrapped around by approximately 2000 molecules of poly(oxyethylene(6))–nonylphenol.[14,15] These aggregates should be compared to reverse micelles which in the absence of other solubilizates have average aggregation numbers of 2–10.

The effective polarity and, more generally, the nature of solubilized water are not uniform. The water initially solubilized by sodium bis(2-ethylhexyl) sulfosuccinate in benzene has a higher apparent density than that obtained on addition of greater amounts of water,[29a] implying stronger binding of the initial water molecules than of the ones subsequently incorporated. Similar conclusions have been drawn from determinations of heats of water solubilizations.[30] The presence of two types of water was established in phosphatidylcholine-reversed micelles in diethyl

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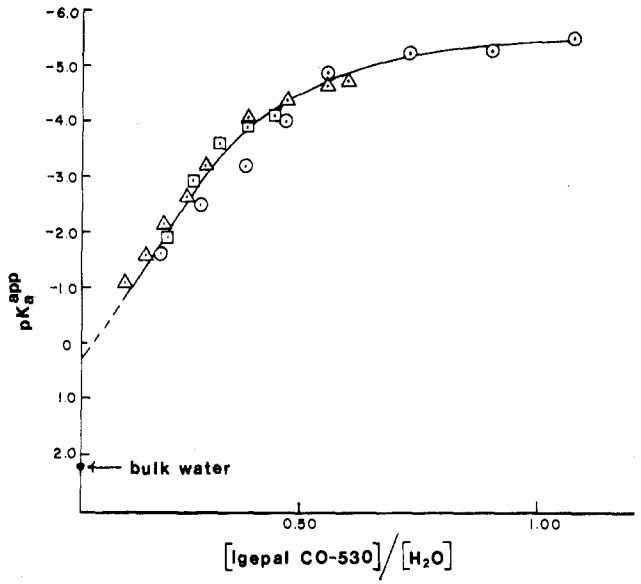

Figure 3. pK_a^{app} values for malachite green in benzene as a function of [Igepal CO-530]/[H_2O]. ○, 0.55 M H_2O; △, 1.1 M H_2O; and □, 1.65 M H_2O.

ether.[31] The first 6–8 molecules of water per lipid molecule are bound to the polar head groups and their motion is restricted. Additional water molecules occupy the core of the micelle, and their properties resemble bulk water. The two types of water coexist, but exchange between the two states is fairly rapid. These conclusions were based on investigating (a) the infrared bands of the OH and HOD stretchings, (b) the ^1H NMR chemical shifts and relaxation times, (c) the fluorescence intensities and polarization of *N*-dansylphosphatidylethanolamine, and (d) the visible spectra of cobalt chloride under a variety of experimental conditions.[31] Results of pulse radiolytic generation of hydrated electrons and their subsequent scavenging in sodium dioctyl sulfosuccinate solubilized water in heptane may be interpreted analogously.[32] Decreasing the size of the water pool results in decrease of electron yields and scavenging efficiency. More importantly, below a critical concentration of water, hydrated electrons are not detected. At this point all the water molecules are strongly solvating the sodium ions in the micellar core.[32] Quenching of the fluorescence due to micellar Igepal CO-530 in cyclohexane by water molecules also shows a pronounced discontinuity at a water concentration which is four times the stoichiometric concentration of the surfactant.[23] This result implies the initial hydration of Igepal CO-530 by four molecules of water.

Evidence for differences in the acidity of the reversed micellar core has been recently obtained from titrations of solubilized dyes.[33,34] Bromophenol blue, thymol blue, methyl orange, and malachite green have been entrapped in water pools solubilized by Igepal CO-530 in benzene. Addition of increasing concentration of $HClO_4$ alters the absorbances of the indicators in a manner analogous to that observed in aqueous titrations. From appropriate plots, pK_a^{app} values for bromophenol blue, thymol blue, methyl orange, and malachite green have been determined in the 0.50 M Igepal CO-530–benzene–0.55 M water system to be −2.50, −5.00, −3.98, and −5.20, respectively.[34] These values have been calculated by assuming that all acid is localized in the "water pools" and they are expressed in terms of H_0 scale.[35] These pK_a^{app} values are up to seven units lower than the corresponding pK_a values in water (bromophenol blue = 4.07, thymol blue = 1.65, methyl orange = 3.41, malachite green = 2.26).[34] Preferential proton concentration into the 0.55 M water pools can only account for a decrease of two units in pK_a^{app} values (as indicated by the intercept of the dotted line in Figure 3). Evidently Igepal CO-530 restricted volumes of water provide an apparently basic environment for the indicators. One important factor in altering the apparent acidity of the indicators is the ratio of the surfactant to solubilized water. This point is nicely illustrated for malachite green in Figure 3. It is seen that the pK_a^{app} values obtained at different surfactant and solubilized water concentrations fall on a smooth curve.

For charged surfactant aggregates in nonpolar solvents the addition of acid or base results in charge neutralization. Thus, infrared titrations revealed the neutralization of dodecylammonium propionate in benzene to dodecylammonium propionic acid.[33] Determination of ratios of propionate to propionic acid as a function of added $HClO_4$ at 0.10 M dodecylammonium propionate concentration in benzene allowed the calculation of pK_a^{app} values for 2,5-, 2,4-, and 2,6-dinitrophenols, 2,4,6-trinitrophenol, bromophenol blue, bromophenol red, malachite green, and vitamin $B_{12}a$ in 0.55 M water pool.[33] In contrast to results in Igepal CO-530, dissociation constants of these indicators in dodecylammonium propionate reversed micelles do not appreciably differ from those in bulk water. Acidities of each reversed micellar system need, therefore, to be examined individually.

Interaction of Solubilizates

Substrate partitioning between surfactant-trapped and bulk water, differential interactions, and reactivities are factors responsible for rate enhancements by reversed micelles. Polar substrates are expected to be localized in water pools. ^1H NMR experiments have amply substantiated this expectation.[9,16,36–39] Of all the chemical shifts of the magnetically discrete protons of dodecylammonium propionate, butanoate, and benzoate, only the NH_3^+, $CH_2NH_3^+$, $^-O_2CCH_2$, and $^-OCAr(H_{2,6})$ protons are affected by the addition of 2,3,4,6-tetramethyl-D-glucose.[9] The dependence of the chemical shifts on the glucose concentration was found to decrease with increasing separation from the ionic head groups. These results are

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compatible, of course, with the solubilization of the sugar at the polar core of the reversed micelle.[9] Similarly, addition of Me_2SO, methanol, pyrazole, 2-pyridone, and tetrabutylammonium perchlorate to dodecylammonium propionate aggregates in benzene, deuteriochloroform, and dichloromethane affects the NH_3^+ protons of the surfactant most.[37,38] The predominant interaction of ethylpyridinium bromide with micellar dodecylammonium propionate in methylene chloride is also at the polar core.[16] Imidazole, methanol, and pyrazole have also been shown to be localized in the cavities of reversed micellar sodium bis(2-ethylhexyl) sulfosuccinate.[39]

Positions of pyrenebutyric and pyrenesulfonic acid in dodecylammonium propionate aggregates in cyclohexane have been assessed by studying the quenching of their fluorescence.[40] Two types of quenchers were used. Potassium bromide, a polar quencher, is taken up in the surfactant-solubilized water pools. Carbon tetrachloride, a nonpolar quencher, is distributed in bulk cyclohexane. The fluorescence lifetime of ionized pyrenebutyric acid, solubilized by dodecylammonium propionate in cyclohexane, is efficiently quenched by carbon tetrachloride, but it is unaffected by potassium bromide. The excitation energy of pyrenesulfonic acid in the same system, on the other hand, is quenched by carbon tetrachloride and by potassium bromide, but rate constants for quenching by the latter depend on the size of the water pool.[40] These results imply that pyrenebutyric acid is lined up along the alkyl chains of the surfactant such that its carboxylate group is close to the micellar core but its aromatic moiety is near the bulk hydrocarbon solvent. The hydrocarbon layer of the dodecylammonium propionate surfactant is sufficiently thick to prevent energy transfer from the pyrene ring to the ionic quencher, localized in the micellar interior. Pyrenesulfonic acid, having no alkyl chain, is pulled in closer to the micellar core, presumably by dipole-dipole attractions between the micellar headgroups and the sulfonate ions; thus energy transfer occurs with both quenchers.[40]

Free energies of transfer, ΔF_t, of amino acids from dodecylammonium propionate trapped water in hexane to bulk water have recently been determined.[41] The data can be clearly divided into two groups: hydrophobic and charged or polar amino acids. Within each group ΔF_t values increase in the order of alanine < proline < valine < phenylalanine ≈ isoleucine ≈ leucine and glycine < arginine < glutamic acid < histidine < aspartic acid. More significantly, values of ΔF_t ranged from −2000 to +500 cal/mol.[41] Such a selectively in the amino acid uptake substantiates the proposed micellar model for the prebiotic compartmentalization of amino acids and nucleotides.[42]

The extent of substrate binding depends on the polarity of the substrate, the nature and concentration of the surfactant, the amount of cosolubilized water, and the polarity of the bulk nonpolar solvent. At present there are insufficient data for establishing relationships among these parameters. Qualitatively it appears that in a given system the more polar the solubilizate the greater the binding constant. Conversely, for a given solubilizate and micelle, the less polar the bulk solvent the greater the substrate–micelle interaction. The accumulation of considerably more data on the properties of surfactant aggregates in nonpolar solvents and on the magnitude and size of solubilizate interactions therein is clearly required in order to rationalize the observed reaction rate effects.

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Catalysis in Reversed Micellar Systems

Rates of several reactions are dramatically enhanced when the reactants are localized in the polar cavities of reversed micelles (Table I). It is seen that rates in the presence of micelles are greater than in either the bulk organic solvent or bulk water. Rate enhancements, therefore, cannot be attributed simply to favorable partitioning of substrates between the polar micellar cavity and the nonpolar bulk solvent. To date the most spectacular catalysis has been observed for the aquation of the tris(oxalato)chromium(III) anion. The aquation is up to 5.4 million times faster in the restricted water pool of octadecyltrimethylammonium tetradecanoate than that in bulk water.[11] Even more significantly, there are only modest rate enhancements of the reaction if either the metal or the ligand is replaced (Table I).[11] Reversed micellar systems mimic well, at least in this instance, the magnitude and specificity of enzymatic catalysis.

The kinetic rate profile of the catalysis can assume several forms (Figure 4). The simplest situation is the occurence of saturation kinetics with respect to both the surfactant and the substrate (Figure 4A). This behavior has been observed for the mutarotation of 2,3,4,6-tetramethyl-α-D-glucose,[9] for the decomposition of Meisenheimer complexes,[10] and for the trans → cis isomerization of sodium bis(oxalato)diaquachromate(III).[12] For bimolecular reactions, just as in case of aqueous micelles,[1] rate maxima can often be seen. Maximum rate acceleration occurs in a region of surfactant concentration at which all of the substrate is incorporated into the micelle-entrapped water pools and additional detergent solubilizes only the nucleophile, thereby rendering it inactive. Ligand-exchange reactions of vitamin B_{12} in micelle-solubilized water pools represent a typical example for this behavior (Figure 4B).[14] The net stoichiometry of the reaction needs also to be considered. Increasing surfactant concentrations decreases the rate constant for the aquation of tris(oxalato)chromate(III) anion in a water pool whose size remains constant (Figure 4C).[11] This kinetic profile is explicable in terms of decreasing effective water concentrations per micelle with increasing surfactant concentrations at a constant water concentration. Finally, surfactants may act as general acid and/or general base catalysts or indeed they can participate in the overall reaction as electrophiles or nucleophiles. The kinetic manifestation of these type of interactions is a linear increase in the rate constant with increasing surfactant concentrations. Solvolysis of 2,4-dinitrophenyl sulfate in the polar cavities of reversed micellar alkylammonium carboxylates in benzene is catalyzed both by the general-acid and the general-base components of the surfactants in addition to micellar catalysis (Figure 4D).[13]

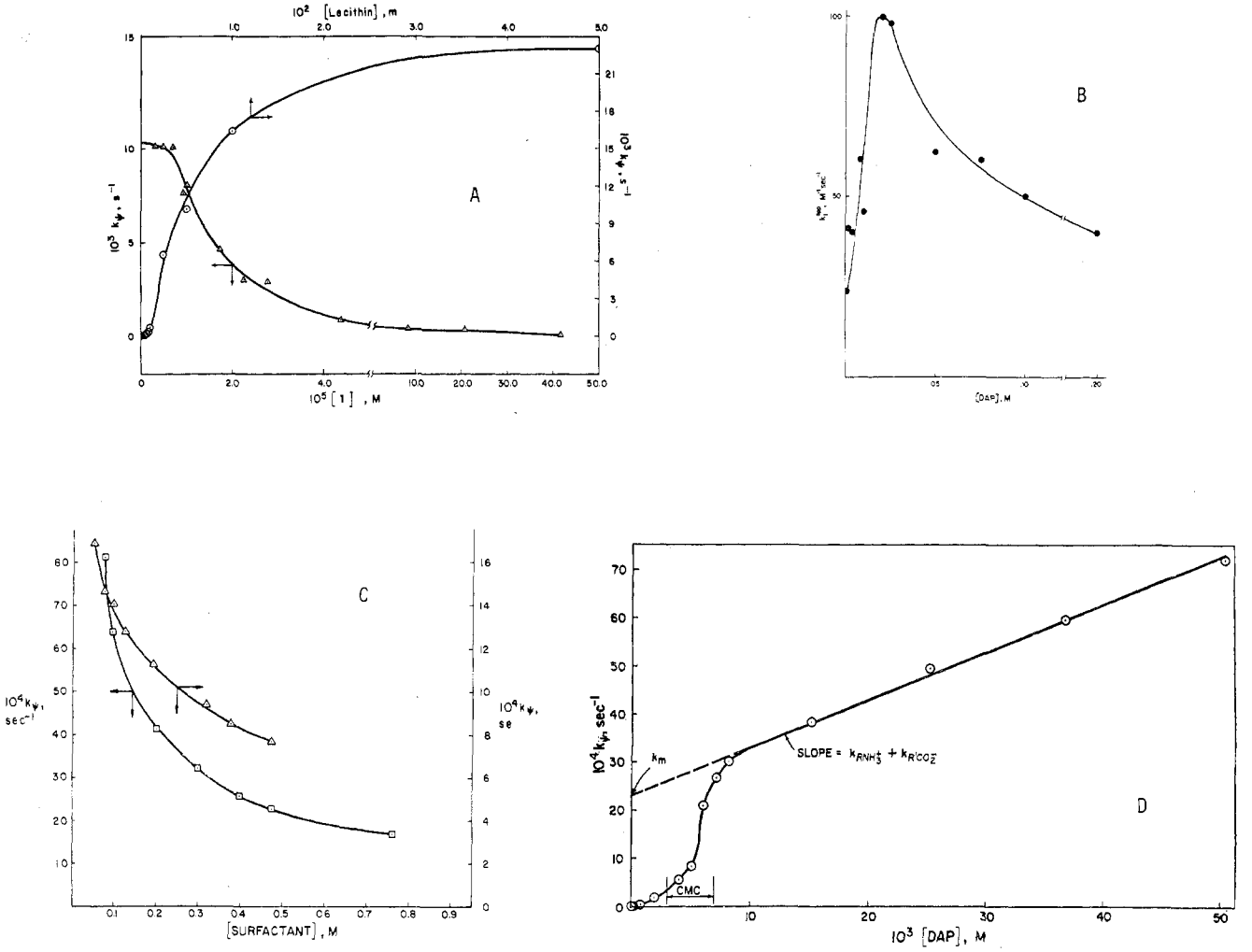

Figure 4. (A) Rate constants, k_ψ, for the decomposition of 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide ion (I) in benzene at 24.5 °C as a function of phosphatidylcholine at [I] = 5.5×10^{-6} M (○) and as a function of the concentration of I at [phosphatidylcholine] = 5.0×10^{-3} M. (B) Rate constant for the anation of vitamin B_{12}a by glycine in 0.010 M water solubilized by dodecylammonium propionate as a function of the surfactant concentration at 25 °C. (C) Rate constants for aquation of $Cr(C_2O_4)_3^{3-}$ to *cis*-$Cr(C_2O_4)_3(H_2O)_2^-$ by dodecylammonium propionate (△) and octadecylammonium tetradecanoate (□) solubilized 1.1×10^{-1} M water in benzene as functions of the surfactant concentration at 25.0 °C. (D) Rate constants for the solvolysis of 2,4-dinitrophenyl sulfate in benzene at 39.8 °C as a function of dodecylammonium propionate.

Rate enhancements in reversed micelles have been rationalized in terms of favorable substrate partitioning into and binding at the polar regions of the micelle where, in case of alkylammonium carboxylates, bond breaking can be assisted by concerted proton transfer. The observed rate enhancements for the mutarotation of tetramethyl-α-D-glucose,[9] for the decomposition of Meisenheimer complexes,[10] and for the aquation of tris(oxalato)chromate(III) anion[11] in alkylammonium carboxylate reversed micelles provided the grounds for this rationalization. Lack of rate enhancement by hexadecyltrimethylammonium butanoate,[10,11] a surfactant which cannot transfer protons, supported this proposal. Although concerted proton transfer appears to be the predominant mechanism for micellar catalysis, it is by no means the only one. Substantial rate enhancements are also elicited by phosphatidylcholine as well as by nonionic poly(oxyethylene)–nonylphenols,[11,15] neither of which can transfer protons. The unique nature of cosolubilized water is responsible for catalysis in these systems. Indeed the magnitude of rate enhancements is drastically altered upon changing the concentrations of added water.

Effects of increasing the chain lengths of reversed micelle forming surfactants have only been investigated for the trans → cis isomerization of sodium bis(oxalato)diaquachromate(III)[12] and for the solvolysis of 2,4-dinitrophenyl sulfate.[13] An increase in the alkyl chain length of both the ammonium and carboxylate ions of alkylammonium carboxylate enhances the catalytic efficiency of the trans → cis isomerization of the chromium(III) complex in benzene. However, rates are affected to a greater extent by changes in the latter than by those in the former. Logarithmic plots of the rate constants vs. ΔpK's (amine pK − carboxylic acid pK) are linear.[12] Since the ΔpK's reflect the tightness of the ion pairs, and consequently the electron density, and therefore acidity of the ammonium ion, these results substantiate the predominant role of proton transfer in the catalysis. Rate constants for the general acid and the general base catalyzed solvolysis of 2,4-dinitrophenol also increase logarithmically as functions of increasing chain lengths in the alkylammonium carboxylates.[13]

The number of parameters influencing catalysis in reversed micellar systems far exceed those affecting

rate enhancements in aqueous micelles.[1] We are only at the beginning of our understanding of these factors, and as yet cannot rationalize all the specific rate effects, let alone predict them.

Conclusion

The current status of investigations on reversed micelles as selective catalysts has been delineated in the present Account. Reversed micelles merit attention since in their polar regions they can bind substrates fairly strongly in specific orientations and configurations. In addition to providing a playground for doing fascinating chemistry, they bear resemblance to the active sites of enzymes as well as to biomembranes. Additionally there are many industrial applications which are proprietary information. Reversed micellar systems are utilized for the selective concentration of corrosion-inducing acidic and basic substances, for the solubilization of polar dyes, for photographic processes, and for polymerizations. It is evident that only very few of the potential applications have been explored. If we have stimulated academic and industrial scientists to enter into this exciting area of research, our efforts in writing this summary have been amply rewarded.

Thanks are due to my coworkers whose names are given in the references and without whom this work would have been impossible. We are grateful to the National Science Foundation, the U.S. Energy Research and Development Administration, and The Robert A. Welch Foundation for support of these investigations.

Relaxation in Collisions of Vibrationally Excited Molecules with Potentially Reactive Atoms

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Received July 11, 1975

The details of the molecular collisions that bring about macroscopic chemical and physical change are now being closely examined by experimentalists and theoreticians. The outcome of these encounters is controlled by the electrostatic forces which are in operation while all the atoms are close together and by the positions and momenta of the nuclei at the "start" of each collision. Unfortunately, spectroscopic methods cannot be used to study these forces in the unstable regions that are important in molecular collisions, and consequently the form of the electronic potential must be inferred from less direct evidence. Measurements of thermal rate constants provide little information, apart from indicating the magnitude of any potential energy barrier to the process. More revealing are studies of (i) how *specifically* energy is distributed among the degrees of freedom of the collision products, and (ii) how *selective* excitation of the reactants can promote particular results—for example, chemical reaction.

To describe the results of kinetic experiments of this more detailed kind, and to relate them to the rate constants of "conventional kinetics", *cross sections* are frequently used. Thus, for collisions between X and Y in quantum states denoted by n at a relative velocity u_R, $\sigma_{n,n'}(u_R)$ corresponds to the cross section for formation of species in final states n' (u_R' will be fixed by energy balance) and the rate at which these *selected* collisions yield these *specific* products is given by

$$d[\text{products}]_{n'}/dt = \sigma_{n,n'}(u_R)u_R\{[X][Y]\}_n \qquad (1)$$

so that $\sigma_{n,n'}(u_R)u_R$ clearly takes the form of a rate coefficient.

The results of bimolecular collisions fall into three general categories: X and Y may scatter elastically, i.e., $n = n'$ and $u_R = u_R'$; inelastically, i.e., $n \neq n'$, $u_R \neq u_R'$; or reaction may occur, in which case the atomic groupings as well as the quantum states change during the course of the collision. The simplest system where all three outcomes are possible is that where an atom (A) collides with a diatomic molecule (BC), and only collisions of this kind will be considered in this article. These may be considered *potentially reactive* when AB, AC, or ABC are known to exist as stable molecules.

Ideally one would like to determine cross sections for reactive, inelastic, and elastic events for various combinations of u_R and n, but in practice only partial, and partially averaged, information has been obtained up to the present time. The infrared chemiluminescence experiments of Polanyi's group[1] have provided perhaps the most detailed information of this kind. Analysis of the vibration–rotation spectrum emitted spontaneously by the products of simple exoergic reactions yields the relative rates at which these emitting states are populated. Where the

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