Catalysis by Surfactant and Phospholipid Reversed Micelles in Nonpolar Solvents. Decomposition of Meisenheimer Complexes[1]

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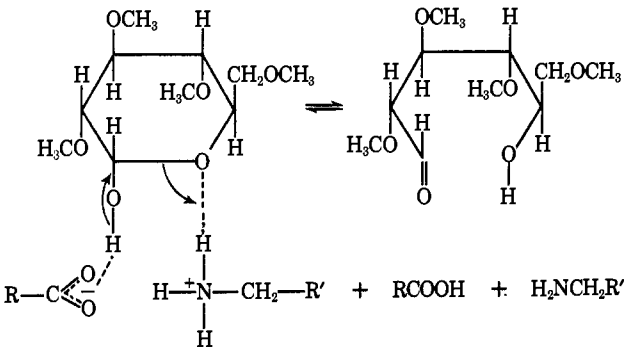
Abstract: The rate constant for the decomposition of sodium 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide (**1**), k_ψ, in benzene in the presence of dodecylammonium benzoate (DABz) aggregates is greater by factors of 62,900 and 1800 than that in pure benzene or in water. Dodecylammonium propionate and dodecylammonium butyrate aggregates are equally effective catalysts. Decomposition of the methoxyl adduct of 1-methoxy-2,4-dinitronaphthalene (**2**) is enhanced to a greater extent than that of **1**. The catalysis is dependent upon the concentrations of **1**, DABz, and added dimethyl sulfoxide, and it is explicable in terms of solubilization of **1** in the polar cavity of micellar DABz where breaking of the carbon–oxygen bond is assisted by proton transfer to the leaving methoxyl group. Phosphatidylethanolamine (**3**) and lecithin (**4**) also enhance the rate of decomposition of **1** in benzene. Catalysis by **3** is even greater than by DABz and the catalytic mechanism is rationalized analogously. Since **4** cannot transfer protons to the substrate **1**, its catalytic effectiveness is considerably smaller than that of **3**. Added water causes additional rate enhancements for the decomposition of **1** in benzene in the presence of **4** but not of **3**. Enhanced water activity in the micellar cavity as well as its size and geometry and the orientation of substrates with respect to the headgroups affect the extent and mechanism of catalysis by reversed micelles in nonpolar solvents.

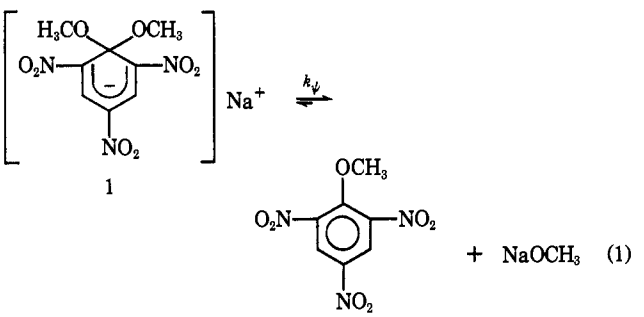
Surfactant aggregates in nonpolar solvents[2] represent novel and in many respects unique microenvironments since they, like the active sites of many enzymes, contain a cavity with polar functional groups capable of binding substrates fairly rigidly in specific orientations.[3] Additionally, it is possible to solubilize known amounts of water in the interior of reversed micelles[2] as well as to investigate the effects of size, activity, and structure of the cavity on catalyses and interactions.[3]

Recently we have reported that micellar dodecylammonium carboxylate surfactants enhance the rate of 2,3,4,6-tetramethyl-α-D-glucose mutarotation in benzene and in cyclohexane by factors of up to 860 and that these catalyses are significantly greater than those due to hydronium ions or water in aqueous solutions.[4] Pmr investigations of the chemical shifts of the surfactant protons as a function of 2,3,4,6-tetramethyl-D-glucose concentration established the most significant interactions to be between the substrate and the ammonium protons and the protons on the carbon atoms α to the carboxylate ion of the surfactants. Consequently, it was postulated[4] that 2,3,4,6-tetramethyl-D-glucose is solubilized in the polar interior of the reversed micelle where hydrogen bond formation both between the dodecylammonium ion and the heterocyclic oxygen atom and between the 1-hydroxyl group and the carboxylate ion of the surfactant can facilite ring opening.

As a continuation of these studies, we now report data on the unimolecular decomposition of an ionic



compound solubilized in the interior of dodecylammonium carboxylate and poly(oxyethylene) nonylphenol aggregates in nonpolar solvents. We have chosen the decomposition of the symmetrical Meisenheimer complexes **1** and **2** as our models since the



effects of aqueous micelles on Meisenheimer complex equilibria have been studied[5,6] and since the mechanism of their nucleophilic aromatic substitution is well established.[7]

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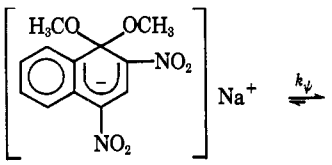
Table I. Decomposition of 1,1-Dimethoxy-2,4,6-trinitrocyclohexadienylide Ion (1) in Benzene Containing DMSO in the Presence of Surfactants at 24.5° [a]

10^4[surfactant], M [b]	10^3k_ψ, sec^{-1}: 0.05% DMSO	0.10% DMSO	0.20% DMSO	0.30% DMSO	0.50% DMSO	1.00% DMSO	2.00% DMSO
0.00[c]	0.0150	0.0145					
0.10		0.016					
0.20		0.022					
0.50		19.8					
0.75		62.9					
1.00	195	75.9					
2.50	713	193					
2.50[d]	850	495					
5.00	943	377	109	41.7	7.36	3.52	1.27
5.00[e]	345	168					
7.50	888	407	143	69.2	18.0	6.25	2.37
10.0	851	449	151	80.5	23.5	8.67	3.27
25.0	638	327	175	105	48.9	15.3	7.73
50.0	568	285	178	106	53.3	21.2	14.0
75.0	451	308	145	93.5	50.7	21.5	11.4
100	391	241	137	87.5	50.5	21.5	9.67

[a] Concentration of 1 = 5×10^{-5} M; concentration of DMSO in v/v; k_ψ values are the mean of 3 runs, each within ±6%. [b] Dodecylammonium benzoate (DABz) unless stated otherwise. [c] Decomposition of 1 in pure benzene. [d] Dodecylammonium butyrate, DAB. [e] Dodecylammonium propionate, DAP.



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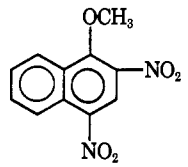

+ $NaOCH_3$ (2)

Naturally occurring phospholipids also form reversed micelles in nonpolar solvents.[8-10] We have, therefore, extended our kinetic investigation of reaction 1 to these systems and report that both lecithin and phosphatidylethanolamine catalyze reaction 1.

Experimental Section

Reagent grade benzene, cyclohexane, chloroform, and carbon tetrachloride were dried and stored over Linde Type 5A molecular sieve. Preparation and characterization of sodium 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide (1) and the analogous sodium salt of the methoxy adduct of 1-methoxy-2,4-dinitronaphthalene (2) have been described.[11] Dodecylammonium propionate (DAP), dodecylammonium butyrate (DAB), dodecylammonium benzoate (DABz), and hexadecyltrimethylammonium butyrate (CTABu) were prepared and analyzed by standard techniques.[4,12] Igepal CO-530, poly(oxyethylene(6) nonylphenol (General Aniline and Film Corp.), was used as obtained.

L-α-Lecithin (β,γ-diacylphosphorylcholine) and phosphatidylethanolamine were prepared from fresh egg yolks and purified by standard techniques.[8,13] Purities were established by thin-layer chromatography on 0.25 mm thick 8 in. × 8 in. Absorbasil-5 plates using chloroform–methanol–glacial acetic acid–water, 65:35:5:5 (v/v), solvent system and iodine to develop the plates. The purified phospholipids showed only a single spot and their R_f values, lecithin = 0.50 and phosphatidylethanolamine = 0.65, agreed with authentic samples and with those quoted in the literature.[8,13]

Decomposition of 1 and 2 was followed spectrophotometrically at 495 nm in the thermostated cell compartment of a Beckman Kintrac VII spectrophotometer. Runs were initiated by injecting known volumes (10–20 μl) of the complexes dissolved in benzene–dimethyl sulfoxide to thermostated solutions of the surfactants or phospholipids dissolved in the nonpolar solvents. Solutions of the phospholipids were prepared daily and their purity was established for each solution by thin-layer chromatography. Pseudo-first-order rate constants, k_ψ, were obtained from good linear plots of the logarithm of the change in absorbance *vs.* time.

Absorption spectra of the starting materials and products were recorded on a Cary 14 spectrophotometer with appropriate blanks.

Results

Decomposition of 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide ion (1) in pure benzene is extremely slow ($k_\psi = 1.5 \times 10^{-5}$ sec^{-1}) and within an order of magnitude is independent of the concentration of complex 1 and added DMSO. In the presence of dodecylammonium carboxylate surfactants dramatic rate enhancements are observed and k_ψ values become dependent on the concentrations of surfactants, of DMSO, and of 1. Table I presents rate constants for the decomposition of 1 at constant complex concentration (5×10^{-5} M) as functions of surfactant and DMSO concentration. Table II gives the data for k_ψ at constant surfactant and DMSO concentration as a function of the concentration of complex 1. Table III presents data for the decomposition of 1 in benzene

Table II. Effects of Complex 1 Concentration on k_ψ in Benzene at 24.5° [a]

10^5[1], M	10^3k_ψ, sec^{-1}	10^5[1], M	10^3k_ψ, sec^{-1}
0.597	70.9	6.00	53.4
0.943	68.1	8.00	38.9
1.313	70.5	1.48[b]	425
2.96	66.0	13.6[b]	477
4.00	60.6		

[a] In the presence of 5.0×10^{-5} M DABz containing 0.10% DMSO (v/v); mean of two runs, each within ±6%. [b] In the presence of 2.5×10^{-3} M DABz containing 0.01% DMSO (v/v); mean of two runs, each within ±5%.

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(10) K. P. Henrikson, *Biochim. Biophys. Acta*, **203**, 228 (1970).
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Table III. Rate Constants for the Decomposition of 1 in Benzene in the Presence of Igepal CO-530 at 24.5° [a]

10^2[Igepal CO-530], M [b]	10^3k_ψ, sec^{-1}	10^2[Igepal CO-530], M [b]	10^3k_ψ, sec^{-1}
0.00	0.0145	30.0	10.78
1.00	0.0194	40.0	14.10
2.00	0.0253	50.0	16.71
3.00	0.0437	60.0	19.16
4.00	0.0516	70.0	19.27
5.00	0.0761	80.0	20.27
10.0	2.26	90.0	19.97
20.0	6.00	100.0	19.62

[a] Concentration of 1 = 1.0×10^{-4} M; containing 0.10% DMSO (v/v); values are the mean of 2 runs, each within ±6%. [b] Critical micelle concentration of Igepal CO-530 in benzene is $(3\text{–}4.5) \times 10^{-2}$ M: O. A. El Seoud, C. J. Chow, E. J. Fendler, and J. H. Fendler, unpublished results.

in the presence of nonionic Igepal CO-530. Rate constants for the decomposition of the methoxyl adduct of 1-methoxy-2,4-dinitronaphthalene (2) in benzene, at a constant concentration of 2 and DMSO as a function of [DABz], M, are given in Table IV. Decomposition of 1 in benzene was found not to be affected by hexadecyltrimethylammonium butyrate (CTABu). k_ψ values in 0.010 M CTABu in benzene at 24.5° were identical, within experimental error, with those obtained in pure benzene.

Table IV. Rate Constants for the Decomposition of 2 in Benzene in the Presence of DABz at 24.5° [a]

10^4[DABz], M	10^3k_ψ, sec^{-1}	10^4[DABz], M	10^3k_ψ, sec^{-1}
1.00	13.89	75.0	843
2.50	26.75	100	670
5.00	83.78	200	492
7.50	84.25	300	396
10.0	275	400	355
25.0	405	500	318
50.0	732		

[a] Concentration of 2 = 1.0×10^{-4} M; containing 0.10% DMSO (v/v).

Effects of phosphatidylethanolamine (3) and lecithin on the rate of decomposition of 1 in benzene are given in Tables V and VI. Tables VII and VIII present data on the effects of lecithin on k_ψ in chloroform and carbon tetrachloride, respectively.

Table V. Decomposition of Complex 1 in the Presence of Phosphatidylethanolamine (3) in Benzene at 24.5° [a]

10^4[3], M	10^4[1], M	10^3k_ψ, sec^{-1}
1.0	1.0	0.632
10.0	1.0	10.6
25.0	1.0	14.5
50.0	1.0	43.7
50.0	1.0	45.5 [b]
75.0	1.0	108
100	1.0	377
50	0.5	739
50	5.0	9.92

[a] Containing 0.10% DMSO (v/v). [b] Containing 4.0×10^{-2} % added water (v/v).

The decomposition of 1 and 2 in water and in alcohol has been demonstrated to result in the quantitative formation of the parent aromatic ethers (eq 1 and 2).[11] We have quantitatively determined the absorption spectra of 1, 2,4,6-trinitroanisole, picric acid, and the decomposition products of 1 under identical conditions in the presence of surfactants and phospholipids in benzene containing 0.1% DMSO (v/v). In all cases the absorption spectra of the *in situ* decomposition product of 1 corresponded only to those obtained from 2,4,6-trinitroanisole. Equation 1 describes, therefore, the quantitative stoichiometry of the decomposition of 1 in nonpolar solvents in the presence of these

Table VI. Decomposition of 1,1-Dimethoxy-2,4,6-trinitrocyclohexadienylide ion (1) in Benzene in the Presence of Lecithin and in the Presence of Lecithin Solubilized Water at 24.5° [a]

10^4[lecithin], m [b]	10^3k_ψ, sec^{-1}
0	0.015
1.00	0.009
2.50	0.048
5.00	0.159
7.50	0.336
10.0	0.726
25.0	6.53
50.0	10.2
50.0 [c]	7.70, 8.09, 4.61, 3.00, 2.90, 0.897, 0.425, 0.385, 0.015
50.0 [d]	17.5, 25.5, 45.6, 139, 212, 234
100.0	16.4
500.0	23.0

[a] All solutions contained 0.10% DMSO (v/v); [1] = 5.05×10^{-6} M, unless specified otherwise. [b] Calculated taking 0.73 g/l lecithin = 1.10×10^{-3} m: P. H. Elworthy, *J. Chem. Soc.*, 139 (1960). [c] Concentrations of 1 are 0.919×10^{-5}, 1.05×10^{-5}, 1.75×10^{-5}, 2.23×10^{-5}, 2.79×10^{-5}, 4.38×10^{-5}, 8.75×10^{-5}, 2.17×10^{-4}, and 4.34×10^{-4} M, respectively. [d] Solutions contained 2.0×10^{-2}, 4.0×10^{-2}, 6.0×10^{-2}, 8.0×10^{-2}, 1.0×10^{-1}, and 1.2×10^{-1} % added water (v/v), respectively.

Table VII. Rate Constants for the Decomposition of 1 in the Presence of Lecithin in Chloroform at 24.5° [a]

10^3[lecithin], M	10^5[1], M	10^3k_ψ, sec^{-1}
1.00	1.00	>1000 [d]
1.00	5.0	15.7
1.00	20	2.27
5.00	10	38.6
5.00	20	22.6
5.00	20	20.9 [b]
5.00	20	24.0 [c]
10.0	20	609

[a] Containing 0.10% DMSO (v/v), and 0.75% ethanol (v/v). [b] In the presence of 4×10^{-2} % added water (v/v). [c] In the presence of 8×10^{-2} % added water (v/v). [d] Too fast to follow.

Table VIII. Rate Constants for the Decomposition of 1 in the Presence of Lecithin in Carbon Tetrachloride at 24.5° [a]

10^3[lecithin], M	10^5[1], M	10^3k_ψ, sec^{-1}
1.00	20	6.37
5.00	5	1006
5.00	10	96.5
5.00	20	16.6
5.00	20	21.0 [b]
5.00	20	41.0 [c]
10.0	20	113

[a] Containing 0.10% DMSO (v/v). [b] Containing 4×10^{-2} % added water (v/v). [c] Containing 8×10^{-2} % added water (v/v).

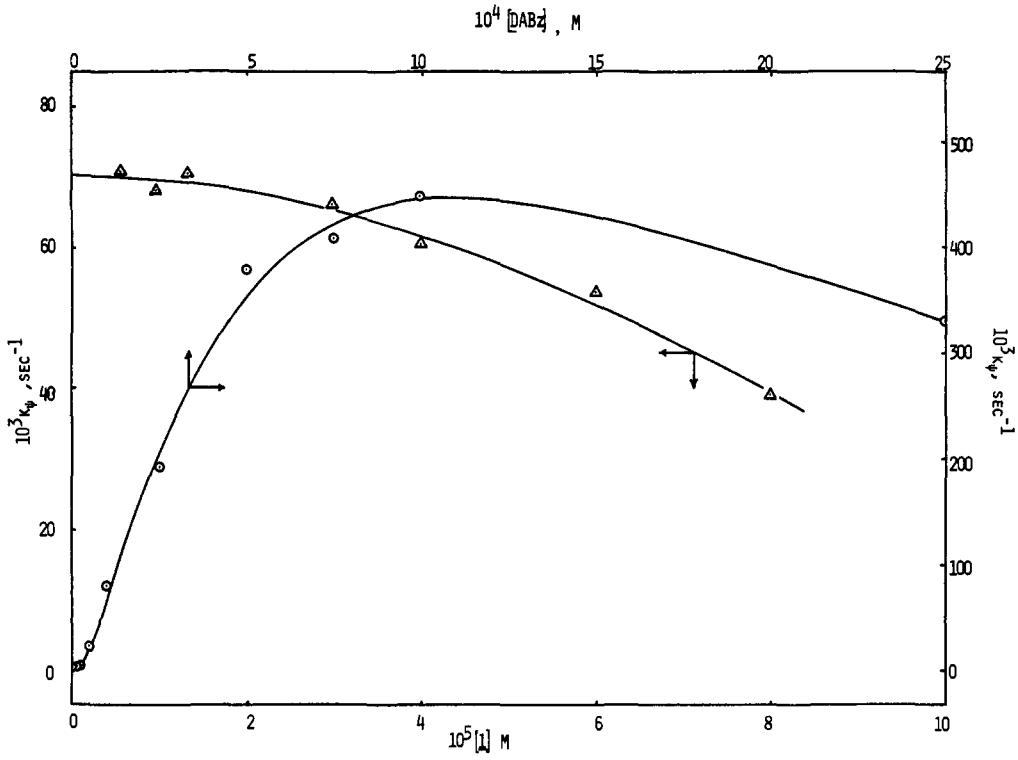

Figure 1. Rate constants, k_ψ, for the decomposition of 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide ion (**1**) in benzene at 24.5° as a function of DABz concentration at [**1**] = 5.0×10^{-5} M (⊙), and as a function of [**1**] at [DABz] = 5.0×10^{-5} M (△).

synthetic and naturally occurring surfactant aggregates.

Discussion

Catalysis by Dodecylammonium Carboxylate Surfactants. At any constant complex (**1**) and solvent composition dodecylammonium carboxylates enhance reaction 1 in benzene dramatically. The order of catalytic efficiency is dodecylammonium butyrate (DAB) > dodecylammonium benzoate (DABz) > dodecylammonium propionate (DAP) (Table I). The catalytic efficiency decreases with increasing substrate (**1**) and DMSO cosolvent concentrations (*vide infra*). Increasing concentrations of DABz, at constant concentrations of **1** and DMSO, cause very sharp rate enhancements up to a maximum after which the rate decreases. At the rate maximum in 0.05% DMSO (v/v) the rate constant for the decomposition of **1** in the presence of DABz (k_ψ = 943×10^{-3} sec^{-1}) is greater by factors of 62,900 and 1800 than that in pure benzene (k_ψ = 1.5×10^{-5} sec^{-1}) or in pure water (k_ψ = 5.08×10^{-4} sec^{-1}).[5,6] Rate enhancements, therefore, cannot be attributed simply to partitioning of **1** between the polar micellar cavity and apolar benzene. The decrease in k_ψ values with increasing [DABz], at high surfactant concentration, may be the consequence of changes in micellar structure and/or interactions. Lack of structural information at this high surfactant concentration does not allow quantitative discussion of this behavior at present.

Rate constants for the decomposition of **1** in benzene, at constant concentrations of surfactant and DMSO, decrease with increasing substrate concentration (Table II) presumably as the consequence of saturation of the binding sites in the micellar cavity. Hence, saturation-type kinetics are observed with respect to both the surfactant and the substrate (Figure 1). In this respect, catalysis by reversed micelles in nonpolar solvents resembles those observed in aqueous micellar systems.[14-16]

Decomposition of the methoxyl adduct of 1-methoxy-2,4-dinitronaphthalene (**2**) in benzene is also catalyzed by DABz (Table IV). Unfortunately, rate constants for the decomposition of **2** at high surfactant and low substrate and DMSO concentrations (conditions under which maximum rate enhancement is expected) are too fast for measurement under our experimental conditions. Maximum rate enhancements by DABz in benzene for **1** and **2** therefore cannot be directly compared. At comparatively high substrate concentration ([**2**] = 1.0×10^{-4} M) the surfactant-rate profile for the decomposition of **2** in the presence of DABz is similar to that observed for **1** (Table IV). At the rate maximum (k_ψ = 843×10^{-3} sec^{-1}) the decomposition of **2** in benzene in the presence of DABz is faster by a factor of 480 than that in pure water (k_ψ for the decomposition of **2** in water = 1.76×10^{-3} sec^{-1}).[11] At the same substrate concentration, the corresponding ratio for **1**, k_ψ DABz in benzene/k_ψ in water, is 78. Based on these rate ratios, complex **2** appears to be a better substrate for catalysis by reversed micellar DABz than substrate **1**. One may speculate that the more bulky **2** is held more rigidly in the micellar cavity than **1**.

Kinetic rate profiles for the decomposition of **1** in benzene in the presence of DABz at different DMSO

(14) E. H. Cordes and R. B. Dunlap, *Accounts Chem. Res.*, **2**, 329 (1969).
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concentrations are qualitatively similar (Table I). With increasing DMSO concentration, rate enhancements, however, become progressively smaller and the rate maximum shifts to higher surfactant concentration. This reduction of catalytic efficiency with increasing DMSO concentration may well be the consequence of decreased micelle–substrate interactions, *i.e.*, inhibition by DMSO. Micelle–substrate interactions in aqueous solutions[15] and in nonpolar solvents for the catalysis of 2,3,4,6-tetramethyl-α-D-glucose by dodecylammonium carboxylates[4] have been described

$$\begin{array}{ccc} M + S & \overset{K}{\rightleftharpoons} & MS \\ \downarrow k_o & & \downarrow k_m \\ P & & P \end{array} \qquad (3)$$

where k_o and k_m are the rate constants in the bulk and micellar phase, respectively; M, S, and MS represent the micelle, substrate, and micelle–substrate complex, and K is the binding, or association, constant. The observed pseudo-first-order rate constant for the reaction, k_ψ, is given by

$$k_\psi = (k_o + k_m K[M])/(1 + K[M]) \qquad (4)$$

which can be rearranged to

$$(k_\psi - k_o)/(k_m - k_\psi) = (K/N)(C_D - \text{cmc}) \qquad (5)$$

where C_D and cmc are the stoichiometric and critical micelle concentrations of the surfactant.[17]

Rate constants for the decomposition of **1** in benzene in the presence of DABz at different DMSO concentrations gave good straight lines when plotted according to eq 5 (Figure 2). It is seen that the slopes of these lines, *i.e.*, K/N values, decrease with increasing DMSO concentrations (Table IX). If the aggregation

Table IX. Calculated Substrate Micelle Association Parameters for Reaction 1 in Benzene in the Presence of DABz[a]

% DMSO, v/v	$10^{-4}K/N$, M^{-1}	$10^{-3}K$, M^{-1}	10^4cmc, M
0.05	47.0	94	0.88
0.10	25.5	51	1.5
0.20	19.5	39	2.7
0.30	12.0	24	3.8
0.50	3.25	6.5	3.8
1.00	2.50	5.0	3.0
2.00	1.00	2.0	2.7

[a] Using eq 5, see Discussion.

number for DABz in benzene is taken as 5,[18] binding constants and critical micelle concentrations can be calculated (Table IX). Increasing concentration of DMSO appears to significantly decrease the association between **1** and DABz. DMSO can either competitively bind to the surfactant or stabilize complex **1**[19] or indeed influence the overall kinetics by both of these processes. The magnitude of the binding constant is substantial, although its absolute value may be in error since the aggregation number may well be influenced appreciably both by the substrate and by

(17) Consult ref 15 for the assumptions made in the derivation of eq 3–5.

(18) J. H. Fendler, E. J. Fendler, R. T. Medary, and O. A. El Seoud, unpublished results.

(19) J. H. Fendler and J. W. Larsen, *J. Org. Chem.*, 37, 2608 (1972).

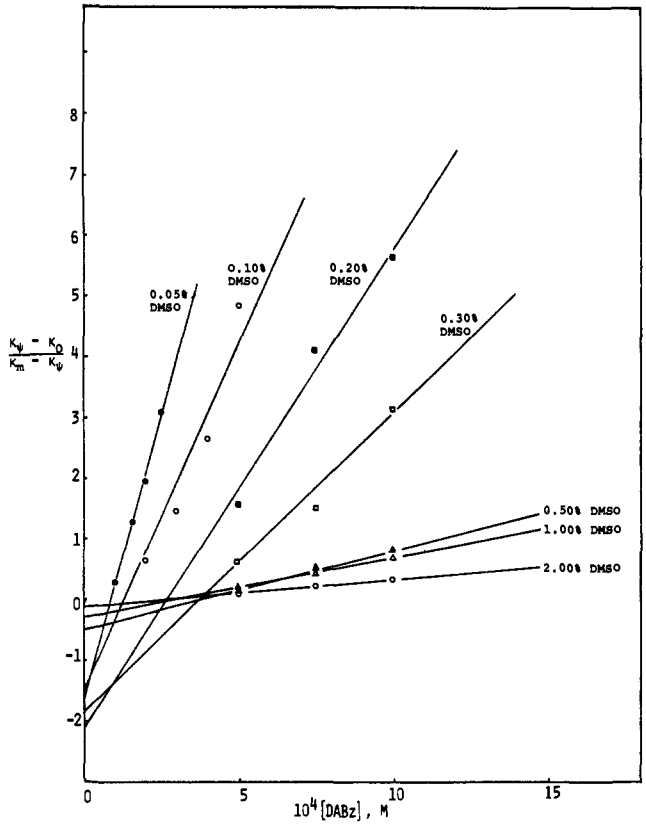
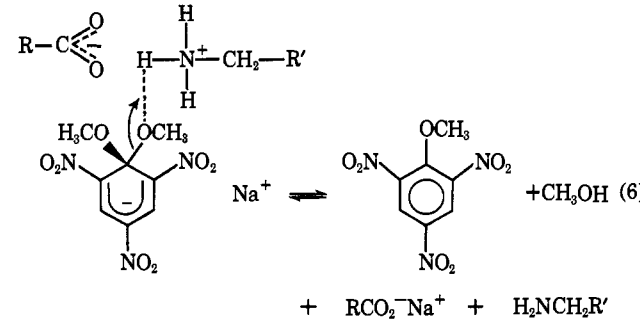


Figure 2. Binding constants plots, according to eq 5, for reaction 1 in benzene in the presence of DABz at different DMSO concentrations.

DMSO. Similarly, the calculated cmc values may be in error partly because they are taken from intercepts and partly because of the uncertainties in N.

The mechanism for the rate enhancement of reactions 1 and 2 by dodecylammonium carboxylates in benzene is likely to be explicable in terms of favorable orientation of complexes **1** and **2** in the polar micellar cavity where breaking of the carbon–oxygen bond is assisted by transfer of a proton to the leaving methoxyl group (eq 6). Lack of catalysis in benzene by micellar hexa-



decyltrimethylammonium butyrate (see Results), for which proton transfer from the ammonium ion to the methoxyl group is not possible, is consistent with this postulated mode of catalysis. The fact that nonionic Igepal CO-530 enhances the rate of decomposition of **1** by factors of 1800 and 40 with respect to those in benzene and in water, respectively (Table III), suggests that factors other than facilitated proton transfer, such as enhanced water activity, can contribute significantly to the catalyses observed in reversed micellar systems.

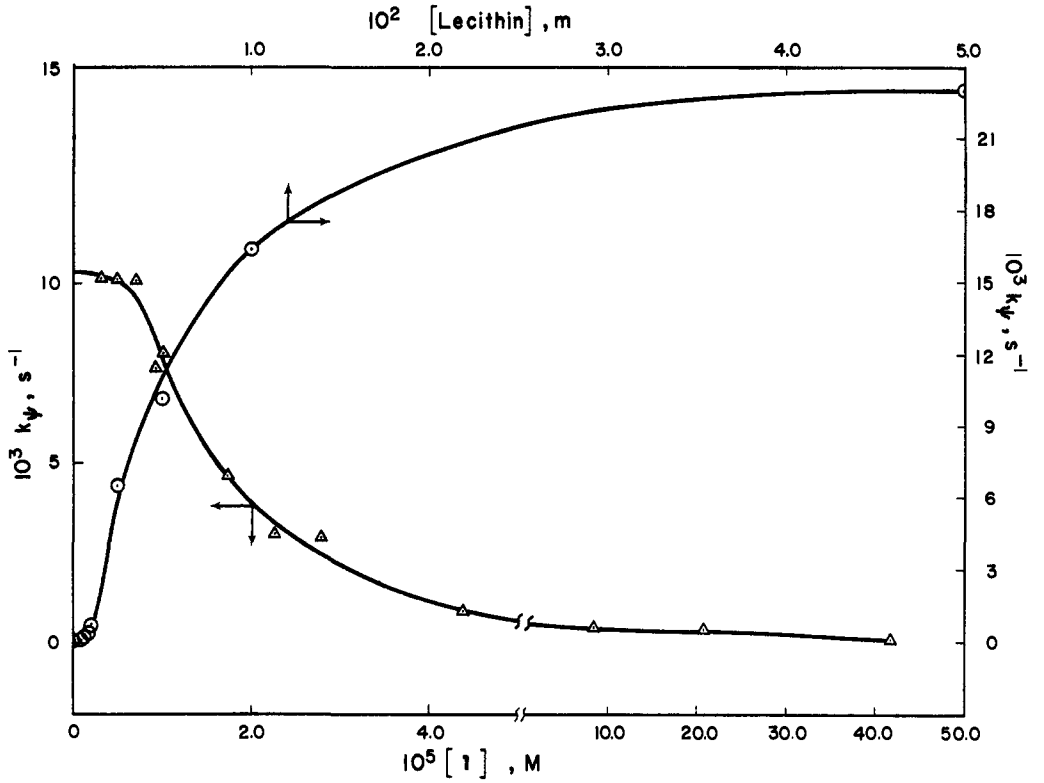
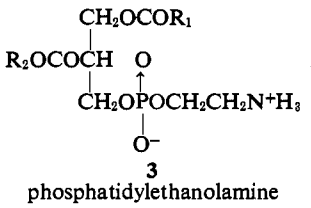
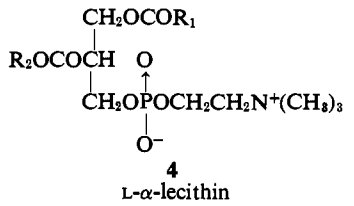


Figure 3. Rate constants, k_ψ, for the decomposition of 1,1-dimethoxy-2,4,6-trinitrocyclohexadienylide ion (**1**) in benzene at 24.5° as a function of lecithin concentration at [**1**] = 5.05×10^{-6} M (⊙), and as a function of the concentration of **1** at [lecithin] = 5.0×10^{-3} M (△).

Catalysis by Phospholipids. The present work represents the first observation of catalysis by phospholipid micelles in nonpolar solvents. Phosphatidyl-



3
phosphatidylethanolamine



4
L-α-lecithin

ethanolamine (**3**) is analogous to dodecylammonium carboxylates in that it can transfer protons from the ammonium ion. L-α-Lecithin, β,γ-diacylphosphorylcholine (**4**), on the other hand, resembles CTABu in that it cannot transfer protons in this manner. If proton transfer is the only mode of catalysis, rate constants for the decomposition of **1** should be enhanced by **3** but not by **4**. In actual fact, both **3** and **4** catalyze reaction 1 in benzene, although catalysis by the former is considerably greater than by the latter. The magnitude of the catalysis by **3** is, in fact, such that under our experimental conditions we could not observe the maximum rate enhancement. We had no other alternative than to work at relatively high substrate concentration since rate enhancements, just as in the case of dodecylammonium carboxylates, are functions of phospholipid, substrate, and DMSO concentration.

Rate constants for the decomposition of **1** in benzene in the presence of phosphatidylethanolamine (**3**) are given in Table V. At 1×10^{-4} M substrate concentration the rate in the presence of **3** is 25,130- and 754-fold faster than that in pure benzene and that in pure water, respectively. At 8.0×10^{-5} M substrate concentration, the corresponding rate enhancements by DABz are 2590- and 78-fold (Table IV). Assuming similar kinetic behavior for the catalysis by DABz and **3**, one can estimate that at 5×10^{-5} M substrate concentration **3** enhances the rate of decomposition of **1** by factors of *ca.* 6×10^5 and 2×10^4 with respect to that in pure benzene and in pure water. Clearly, phosphatidylethanolamine is a more powerful catalyst for the decomposition of **1** than the dodecylammonium carboxylate surfactants. It is significant that added water causes no additional rate enhancement (Table V). The mechanism for the catalysis of reaction 1 in benzene by **3** can be rationalized analogously to that postulated for the synthetic surfactants (eq 6).

Catalysis by lecithin in benzene is qualitatively similar to that observed for dodecylammonium carboxylates and phosphatidylethanolamine (Table VI). The kinetics obey the Michaelis–Menten equation with respect to both lecithin and substrate (Figure 3). Treating the data (in Table VI) according to eq 5 gave a good linear plot (not shown) from which, assuming N = 73,[8] $K = 1.9 \times 10^4$ M^{-1} and cmc = 9.4×10^{-4} M have been calculated. The good agreement between the independently obtained value for the cmc of lecithin in benzene (1.1×10^{-3} m)[8] lends credence to the assumptions made in the derivation and use of eq 5.

The magnitude of the catalysis is, however, considerably smaller than that observed either with the dodecylammonium carboxylate surfactants or with **3**. Even at 5×10^{-6} M substrate concentration, the rate constant for reaction 1 is enhanced "only" by factors of 1530 and 46 with respect to benzene and water. Similar "meager" catalysis has been observed with Igepal CO-530 (Table III). When the concentration of **1** is increased

to 8.75×10^{-5} M, k_ψ in benzene in the presence of **4** is similar to that in pure water (Table VI). Under similar conditions **3** enhanced the rate by a factor of 754 with respect to water (*vide infra*). More significant is that addition of water, known to be solubilized in the interior of lecithin micelles formed in benzene,[20] causes additional rate enhancements at a given lecithin concentrations (Table VI). The profile for this rate enhancement is also sigmoidal; maximum catalysis (at 1.2×10^{-1} % water) occurs when the micellar interior presumably is saturated with water. Since lecithin forms rather tight monohydrates,[8-10] it is likely that in spite of drying it *in vacuo* we did not completely eliminate water in our "dry" solutions of lecithin in benzene. Since no proton transfer can occur with lecithin, catalysis of reaction 1 by **4** can be, at least in part, ascribed to the significantly increased activity of water[2] trapped in the interior of the inverted lecithin micelle. The rate profile as a function of added water substantiates this mode of catalysis. An added complication, however, is the difference in size between alkylammonium carboxylate and lecithin micelles. Aggregation numbers in benzene for the former are in the range of 3–7,[3] while that for lecithin is 73.[8] Although the presence of the substrate, DMSO, and water is likely to alter the absolute value of these aggregation numbers, their relative difference is still predictably large.

Recent pmr investigations established the formation of small ($N \approx 3$) lecithin micelles in chloroform and in carbon tetrachloride.[9] If micellar size also influences catalytic efficiency, neglecting solvent effects, one would expect greater catalytic efficiency of lecithin for reaction 1 in chloroform and in carbon tetrachloride than in benzene. This is in fact the case (Tables VII and VIII).

(20) W. V. Waller and R. G. Hayes, *Biochim. Biophys. Acta*, **249**, **528** (1971).

At 2×10^{-4} M substrate concentration, rate constants for the decomposition of **1** in chloroform and carbon tetrachloride are factors of 1200 and 226 faster than that in pure water. The presence of ethanol (as a stabilizer) in chloroform is likely to contribute to the overall rate enhancement. Once again addition of water causes further rate enhancements.

Conclusion

Cationic micellar hexadecyltrimethylammonium bromide and nonionic poly(oxyethylene(15)) nonylphenol decrease the rate of decomposition of **1** in water by factors of 12 and 3.7, respectively, and anionic sodium dodecyl sulfate does not affect it.[5] Clearly, both dodecylammonium carboxylates and phospholipids catalyze the decomposition of ionic Meisenheimer complexes in nonpolar solvents to a considerably greater extent than micelle forming surfactants in aqueous solutions. The present data suggest that polar substrates are solubilized in the hydrophilic cavity of reversed micelles where hydrogen bond formation, proton transfer, and enhanced water activity facilitate product formation. Additional factors, such as the geometry of substrates and headgroups on the surfactants, size of the micelles and of the cavity, and polarity of the bulk solvent and of the substrate, are likely to influence the extent and mechanism of the catalysis. We are currently investigating the effects of these factors on rate enhancements by reversed micelles in nonpolar solvents for a variety of reactions.

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