Structure and Hydration of Nonionic Detergent Micelles. A High Resolution Nuclear Magnetic Resonance Study[1a,b]

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Abstract: Proton chemical shifts, progressive saturation, and high resolution spin–lattice relaxation times (T_1) were measured at 220 MHz for three *p-tert*-octylphenoxy(polyethoxy)ethanols, with average polar chain lengths of 9–10, 12–13, and 30 ethoxy groups. Bulk detergents, aqueous solutions above and below the critical micelle concentration, and solutions in dioxane, ethylene glycol, and benzene were studied. Chemical shifts were assigned to the various groups in the detergent molecule. The band corresponding to the CH_2 signals of the polyethoxy chain is partially resolved into several peaks in the aqueous solutions. Based on the relative chemical shifts and on the differences in relaxation times, some of these peaks can be assigned to CH_2 groups occurring in various locations along the polyethoxy chain and having different local environments. The interior of the micelle is liquid-like and is not penetrated by solvent to any significant extent. The methylene and the internal methyl groups of the hydrocarbon chain are actually in a less polar environment in the micelle than in the bulk detergent. The opposite is true for the polyethoxy chain. Contact with solvent seems to begin in the region of the first ethoxy group following the phenyl group and gradually increases toward the other end of the chain. The mobility of the segments increases in the same direction. Water molecules in the region between the polyethoxy chains appear to be partially immobilized.

Detergent molecules in solution associate reversibly and cooperatively into large aggregates, termed micelles, above a certain concentration, called the critical micelle concentration (cmc).[2] Studies of micelles in water are more numerous, but micelles have also been studied in many aqueous solvent mixtures[3–5] and have recently been shown to occur in a wide variety of nonaqueous solvents.[6] It is generally accepted[2–6] that the nonpolar tails of the detergent molecules comprise the interior of the micelle, while the polar head groups, charged or uncharged, are located on the exterior, maintaining contact with the solvent and keeping the micelle in solution. "Inverted micelles" are known to form in hydrocarbon solvents only.[7,8] While micellar association has its own intrinsic interest, it is also important as a relatively simple model system for hydrophobic interactions in globular proteins[3–6] and for lipid–lipid and lipid–protein interactions in complex systems such as biological membranes.[9,10]

The following important questions, among others, arise in detailed studies of micelles: (a) that of the arrangement and relative mobility of the various parts of the detergent molecules in the micelle, (b) that of the extent to which these parts come into contact with the solvent.[2,11] Conventional physical methods supply little information regarding these questions. A much more powerful approach is provided by various nmr techniques.

Some nmr studies have been reported in the past on both ionic[12–16] and nonionic[17–19] detergent solutions. These studies were concerned with the detergent proton signals,[12,13,19] the water proton signals,[14,15] or both.[18] Studies of proton chemical shifts of solubilized aromatic hydrocarbons[20,21] in micelles, and of ^{19}F chemical shifts of partially fluorinated ionic and nonionic detergents in solutions,[16,17] led to the conclusion that there is considerable penetration of these micelles by water molecules.[16,17,21] Spin–lattice relaxation times (T_1) of the water protons in solutions of sodium alkyl sulfates were interpreted in terms of possible penetration of these micelles by water.[14,15] However, T_1 measurements of the protons of an alkyl(polyethoxy)-ethanol, a nonionic detergent, led to the conclusion that there is no significant water penetration of these micelles even at the level of the alkyl CH_2 group closest to the polyethoxy chain,[19] in contrast to interpretations of the chemical shifts for the same detergent.[18]

We studied the chemical shifts and T_1 of the various groups of protons in several nonionic detergents of the

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(2) (a) P. Mukerjee, *Advan. Colloid Interface Sci.*, 1, 241 (1967); (b) P. Mukerjee and K. Mysels, "Critical Micelle Concentrations of Aqueous Surfactant Systems," National Bureau of Standards, Washington, D. C., NSRDS-NBS 36, 1970.

(3) P. Mukerjee and A. Ray, *J. Phys. Chem.*, 67, 190 (1963).

(4) (a) A. Ray and G. Némethy, *J. Phys. Chem.*, 74, 809 (1971); (b) A. Ray and G. Némethy, *Biochemistry*, submitted for publication.

(5) A. Ray, Abstracts, 164th National Meeting of the American Chemical Society, New York, N. Y., Division of Colloid and Surface Chemistry, Aug 1972.

(6) (a) A. Ray, *J. Amer. Chem. Soc.*, 91, 6511 (1969); (b) A. Ray, *Nature (London)*, 231, 313 (1971); (c) A. Ray, *Fed. Proc., Fed. Amer. Soc. Exp. Biol.*, 30, 1270 (1971); (d) A. Ray, *J. Amer. Chem. Soc.*, submitted for publication.

(7) I. J. Heilweil, *J. Colloid Sci.*, 19, 105 (1964).

(8) P. Becher, "Nonionic Surfactants," M. J. Schick, Ed., Marcel Dekker, New York, N. Y., 1967, p 511.

(9) J. L. Kavanau, "Structure and Function of Biological Membranes," Vol. I, Holden-Day, San Francisco, Calif., 1965.

(10) H. T. Tien and A. L. Diana, *Chem. Phys. Lipids*, 2, 55 (1968).

(11) D. Stigter and K. Mysels, *J. Phys. Chem.*, 59, 45 (1955).

(12) J. C. Eriksson, *Acta Chem. Scand.*, 17, 1478 (1963).

(13) T. Nakagawa and K. Tori, *Kolloid-Z.*, 194, 143 (1964).

(14) (a) J. Clifford and B. A. Pethica, *Trans. Faraday Soc.*, 60, 1453 (1964); (b) *ibid.*, 61, 182 (1965).

(15) J. Clifford, *Trans. Faraday Soc.*, 61, 1276 (1965).

(16) N. Muller and R. H. Birkhahn, *J. Phys. Chem.*, 71, 957 (1967).

(17) N. Muller and F. E. Platko, *J. Phys. Chem.*, 75, 547, 942 (1971).

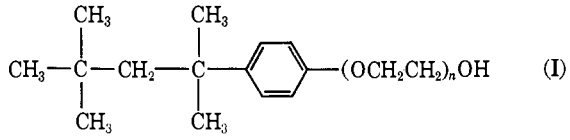
(18) L. M. Corkill, J. F. Goodman, and J. Wyer, *Trans. Faraday Soc.*, 65, 9 (1969).

(19) C. J. Clemett, *J. Chem. Soc. A*, 2251 (1970).

(20) J. C. Eriksson and G. Gillberg, *Acta Chem. Scand.*, 20, 2019 (1966).

(21) J. E. Gordon, J. C. Robertson, and R. L. Thorne, *J. Phys. Chem.*, 74, 957 (1970).

alkylphenoxy(polyethoxy)ethanol class, used earlier in our laboratory in other studies.[4] We compared the detergents in the bulk liquid and in aqueous micellar solutions and studied one detergent in a few organic solvents, in order to obtain comparative data for various solvent environments. The structure of the three detergents used is as follows[22]



(I)

where n is the average number of ethoxy units in the molecule. The abbreviation OPE_n will be used throughout the paper. The presence of polydispersity of chain length (n) and its probable effect on the micelles was discussed elsewhere.[4a] For conciseness' sake, we will refer to various parts of the molecule as follows: the "terminal" methyl groups, those of the $(CH_3)_3C$ group; the "internal" methyl groups, those located on the carbon next to the aromatic ring; the "first" ethoxy group, the one located next to the aromatic ring; the "last" ethoxy group, the one located next to the hydroxyl group.

Experimental Section

Triton X-100 (OPE_{9-10}), Triton X-102 (OPE_{12-13}), and Triton X-305 (OPE_{30}), supplied by the Rohm and Haas Co., were used without further purification. Bulk liquid samples of the first two were free of water. The sample of OPE_{30} contained 31% water by weight. The water content was obtained from nmr measurements by determining the ratio of the signal areas corresponding to the protons of the ethoxy chain and of water, if any.

Deuterium oxide of at least 99.8% isotopic purity was obtained from Thomson and Packard, ethylene-*1,1,2,2-d*$_4$ glycol from Merck, Sharp, and Dohme of Canada Ltd. Benzene and chloroform of spectroquality grade and dioxane of chromatoquality grade, supplied by Matheson Coleman and Bell, were used. Solutions were made up by weight.

Proton chemical shifts were measured on a Varian HR220 spectrometer at 220 MHz. Values listed are averages over several measurements, at a probe temperature of 18°. All observed chemical shifts, δ, were corrected for the differences in the volume diamagnetic susceptibility[23] of the sample (χ_s) and the external reference (χ_r). The correction terms are listed in Table I. χ_s was experimentally determined by high resolution nmr. The method of variation of field orientation, originally suggested by Becconsall,[24,25] was used. It utilizes the difference of the bulk susceptibility contribution to the total magnetic field in a cylindrical sample with the geometrical axis oriented either perpendicular or parallel to the static field H_0. Indicating the chemical shifts, measured in ppm, in the two cases with $\delta_\perp$ and $\delta_{||}$, respectively, the following relationship can be derived.

$$\chi_s = \chi_r + \frac{(\delta_s - \delta_r)_\perp - (\delta_s - \delta_r)_{||}}{2\pi} \qquad (1)$$

Chloroform was used as reference, with $\chi_r = -0.740 \times 10^{-6}$ at 20°.[26] Measurements of $\delta_{||}$ were made on a Varian HR220 spectrometer, those of $\delta_\perp$ on a Varian A60. The same probe temperature, 18°, was set in both instruments. The validity of the method was checked on pure 1,4-dioxane. The measured value of the bulk susceptibility (Table I) coincides exactly with the value calculated from the literature data.[26,27] Some measurements were also checked on a Bruker HFX-90 spectrometer. Reproducibility was better than 0.001 esu.

Progressive saturation measurements were carried out at 220 MHz. The signal intensities were measured under conditions of slow passage through the resonance frequency as a function of the logarithm of the applied radiofrequency power.[28] The width at half-height of the signals was measured at 60 and 220 MHz at radiofrequency fields well below the saturation value.

A Fourier transform spectrum for monomeric OPE_{9-10} was obtained at the Varian Associates Laboratories, Analytical Instruments Division, Palo Alto, Calif.

Samples used for relaxation time (T_1) measurements were deoxygenated in several freeze–vacuum pump–thaw cycles and were sealed under nitrogen. The T_1 values of individual lines were measured at the nmr facilities of the Johnson Research Foundation, on a Varian HR-220 spectrometer modified for the use of the Fourier transform technique.[29-31] The "inversion-recovery" method was used, employing a $\pi-\tau-\pi/2-\tau'$ pulse sequence,[32,33] where τ is the delay time between the radiofrequency pulse of π with which the magnetization is inverted and the monitoring pulse of $\pi/2$ which excites the free induction decay signal. In time τ, the magnetization returns practically to its equilibrium value. For each line, T_1 was evaluated from the slope in the plot of the logarithm of the longitudinal magnetization *vs.* τ.

Table I. Volume Diamagnetic Susceptibilities[a]

System	Concn	$\chi_s \times 10^6$, esu	Correction term,[b] ppm
Detergent samples			
OPE_{9-10}	Liquid	−0.702	0.16
OPE_{12-13}	Liquid	−0.697	0.18
OPE_{30}	69% (wt)	−0.725	0.06
Micellar solutions in H_2O			
OPE_{9-10}	0.104 *M*	−0.728	0.05
OPE_{12-13}	0.103 *M*	−0.728	0.05
OPE_{30}	0.140 *M*	−0.728	0.05
Dioxane	Liquid	−0.612	0.54
Water	Liquid	−0.720[c]	0.08

[a] Determined in this study, unless indicated. The precision of the χ_s values is ±0.001 esu. [b] Correction for differences in the volume diamagnetic susceptibility (see text). [c] Reference 18.

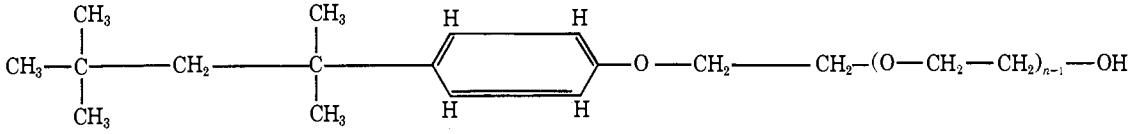
Results and Discussion

Diamagnetic Susceptibilities. Values measured for the liquid detergents and their aqueous solutions at 18° are listed in Table I. The method described above, applied to the ethoxy and the terminal methyl proton signals, gave identical values for the susceptibilities within experimental error. This indicates that possible local differences of the diamagnetic susceptibility in the hydrophobic core and the hydrophilic exterior part of the micelles are at most of the order of 10^{-9} esu.

The diamagnetic susceptibility of the aqueous detergent samples is slightly higher than that of pure water (Table I). According to the Wiedmann–Frantz law of additivity,[34a] however, it should be slightly lower. The reason for this discrepancy is not clear.

(22) C. R. Enyeart, "Nonionic Surfactants," M. J. Schick, Ed., Marcel Dekker, New York, N. Y., 1967, p 50.
(23) W. C. Dickinson, *Phys. Rev.*, **81**, 717 (1951).
(24) Cited by K. D. Bartle, D. W. Jones, and S. Marič̆ic, *Croat. Chem. Acta*, **40**, 227 (1968).
(25) D. H. Live and S. I. Chan, *Anal. Chem.*, **42**, 791 (1970).
(26) G. W. Smith, "A Compilation of Diamagnetic Susceptibilities of Organic Compounds," Research Laboratories, General Motors Corp., Warren, Mich., 1960, GMR-317.
(27) A. Weissberger and E. S. Proskauer, "Organic Solvents, Physical Properties and Methods of Purification," 2nd ed, Interscience, New York, N. Y., 1955.
(28) A. S. Mildvan and M. Cohn, *Advan. Enzymol.*, **33**, 1 (1970).
(29) I. J. Love and R. E. Norberg, *Phys. Rev.*, **107**, 46 (1957).
(30) A. Abragam, "Principles of Nuclear Magnetism," Oxford University Press, New York, N. Y., 1961, p 114.
(31) R. R. Ernst and W. A. Anderson, *Rev. Sci. Instrum.*, **37**, 93 (1966).
(32) R. L. Vold, J. S. Waugh, M. P. Klein, and D. E. Phelps, *J. Chem. Phys.*, **48**, 3831 (1968).
(33) E. L. Hahn, *Phys. Rev.*, **76**, 145 (1949).
(34) (a) J. A. Pople, W. G. Schneider, and H. J. Bernstein, "High Resolution Nuclear Magnetic Resonance," McGraw-Hill, New York, N. Y., 1959, p 18; (b) p 205; (c) pp 201–203, 480.

Table II. Chemical Shifts δ of the Detergents in the Bulk and in Aqueous Micellar Solution, Expressed in ppm, with Respect to $CHCl_3$ as External Reference[a]



Substance								
Bulk detergent								
OPE_{9-10}	6.64	5.66	6.04	0.51	0.12	3.31	3.59	3.80
OPE_{12-13}	6.62	5.65	6.02	0.50	0.11	3.30	3.58	3.79
OPE_{30} (69%)	6.63	5.67	6.04	0.49	0.12		[3.64–3.70][b]	
Dioxane (liquid)								3.74
Aqueous solutions								
OPE_{9-10}	6.65	5.70	6.07	0.51	0.13	3.32	3.55	[3.59–3.70]
OPE_{12-13}	6.64	5.69	6.06	0.50	0.12	3.31	3.54	[3.60–3.70]
OPE_{30}	6.64	5.68	6.06	0.49	0.13			[3.60–3.69]
Dioxane								3.59

[a] The sign of δ is taken as positive in the direction of increased electron screening. Estimated precision, 0.01 ppm. All values are corrected for volume magnetic susceptibility. [b] Numbers in brackets indicate the positions of the extreme peaks in the partially resolved main ethoxy band.

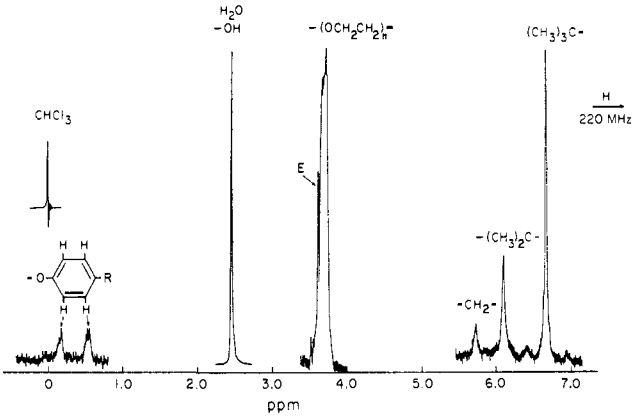


Figure 1. Proton resonance spectrum of OPE_{9-10} in micellar solution in H_2O at a detergent concentration of 0.104 M (7.1% (w/v) = 0.002 mol fraction = 430 times critical micelle concentration[4a]). All assignments are indicated. See the text for a discussion of peak E. The signal of chloroform, used as external reference, is shown above the spectrum. All spectra in this and the following figures are corrected for differences in the volume diamagnetic susceptibilities.

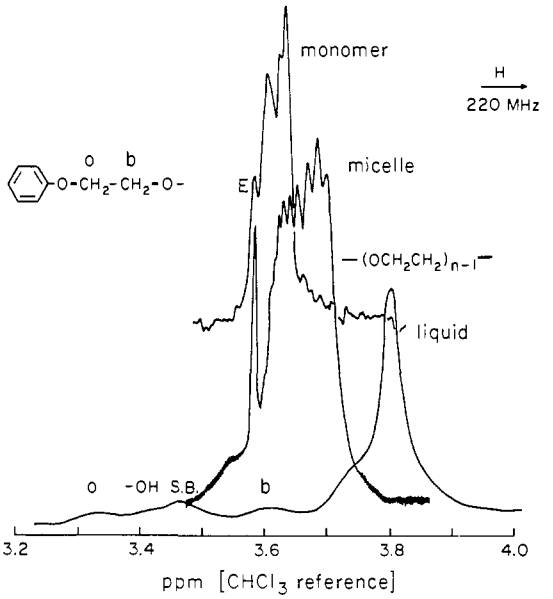


Figure 2. Comparison of the main ethoxy band of OPE_{9-10} in the bulk liquid and in aqueous solutions at high and low concentrations (micelle and monomer, respectively). The spectrum of the micellar solution is the same as in Figure 1. The monomer signal was taken at a detergent concentration of 1.3×10^{-4} M. For the liquid, all ethoxy signals are shown. The assignment of the bands marked a and b is discussed in the text. S.B. = side band. Corrected chemical shifts of the liquid and micelle signals are based on chloroform as external reference. For the monomer, no external reference was used (see text).

Chemical Shifts in Aqueous Micelles and in the Bulk.[35] Corrected chemical shifts for all three detergents are listed in Table II. An example of a complete spectrum is shown in Figure 1. Assignments were based on relative signal areas and on general considerations of electron shielding effects.[34,36] The combined error of the observed chemical shifts (±0.005 ppm) and of the susceptibility determinations is estimated as ±0.01 ppm for the entries in the table.

In the pure detergents, the ethoxy proton signals consist of a main unresolved asymmetric band and of two small signals at lower fields (Figure 2). For OPE_{9-10}, the area of each small peak (a and b in Figure 2), determined graphically, is about 7% of the total area assigned to ethoxy signals; *i.e.*, it corresponds to two protons. These two peaks are assigned to the two methylene groups of the first ethoxy unit. Their low field shift can be attributed to the diamagnetic anisotropy effect of the phenyl group.[37]

In aqueous micellar solution, the main band is shifted considerably to lower field; it is resolved partially into several overlapping resonances (Figure 2). Of the two small peaks, a is unchanged, while b (assigned to the CH_2 group further from the phenoxy group) is downfield shifted by 0.04 ppm only. The comparison of the shifts for the two first CH_2 groups, together with their difference with respect to the main band, suggests that the extent of contact with water in the micelles, after being very low for the first CH_2

(35) P. Laszlo, *Progr. Nucl.. Magn. Resonance Spectrosc.*, 3, 280 (1967).

(36) F. A. Bovey, "Nuclear Magnetic Resonance Spectroscopy," Academic Press, New York, N. Y., 1969.

(37) This assignment was substantiated by measurements under similar conditions on two alkyl(polyethoxy)ethanols, $C_{12}H_{25}(OCH_2CH_2)_nOH$, with n = 6 and 9. The positions of the main ethoxy band and of the OH band are very close to those for OPE_{9-10}, but the two small signals at lower field (a and b) are absent: A. Ray, to be published.

group, increases relatively faster in the region containing the first few ethoxy groups than in the region in which the further ethoxy groups are located. Generally, when a group containing a proton, not engaged in hydrogen bonding, is transferred from a less to a more polar environment, solvent effects cause a downfield shift if changes in the diamagnetic anisotropy of the two solvents can be neglected.[38,39]

The main ethoxy bands of all three detergents are compared in Figure 3. The total width of the band is the same within experimental error. However, the shape varies strongly with an increase in the chain length; only the intensity of the peaks in the lower field region of the band increases. This suggests that the ethoxy groups in the part of the molecules far from the nonpolar part, and therefore presumably located on the outside of the micelle, are exposed to a similar local environment, different from the first few ethoxy groups, but essentially the same for all the additional groups in the two higher homologs. We refer here primarily to the degree of exposure to the solvent as local environment.

The lowest field peak (denoted E) coincides in all three detergents and has the same chemical shift as that of dioxane in dilute aqueous solution (Table II). Its area in the OPE_{9-10} signal corresponds to not more than two protons. We assign it to the last methylene group (next to the terminal hydroxyl), fully hydrated on the outside of the micelle.

On the other hand, the chemical shift of bulk liquid dioxane is intermediate between those of the ethoxy bands of micellar and of bulk liquid detergents (Table II). It seems that even ethoxy groups not fully solvated by water in the micelle are in a more polar environment than that occurring in pure dioxane. The latter would be an approximate analogy for tightly packed and unsolvated polyethoxy chains. Further, the environment of the polyethoxy chains in the bulk liquid detergent is less polar than is pure dioxane, due to the randomly located alkyl groups in the former.[40]

The chemical shifts of the alkyl and phenyl protons are independent of the ethoxy chain length, either in pure detergents or in the micelles (Table II). The comparison of the chemical shifts in the micellar solution with those for the bulk detergents shows that the proton signals of the terminal methyl groups and of the phenyl group remain unchanged (within experimental error), while the signals of the methylene group and of the internal methyl groups are slightly upfield shifted. Thus we can conclude that there is no water or very little in the interior of the micelle. The environment of the alkyl groups in the micelles appears to be even less polar than in the pure liquid.[40] In the latter, the polyethoxy chains provide a partially polar environment.

Chemical Shift of the Monomer in Aqueous Solution. The chemical shift of the OPE_{9-10} main ethoxy band was determined with the Fourier transform method, in D_2O at a concentration about half the critical micelle concentration found in H_2O solutions.[4a] Five hundred transients were accumulated. The band is narrower than that in micellar solution (Figure 2). We assume that peak E has the same chemical shift as in the micelle. This is reasonable since the latter peak was assigned to the fully solvated last methylene group. Its environment ought not change with dilution. The assumption is supported by comparison with aqueous dioxane solutions and by the T_1 measurements on the micellar solution (see below). The band is narrower than that for micelles, in that the signals are downfield shifted toward band E, indicating an increase in the polarity of the environment. This behavior is consistent with our earlier interpretation, in which we postulate that the peaks on the left of the band in the micelle are signals of the more fully solvated ethoxy groups. Their environment must be similar to that of all ethoxy groups in the monomer.

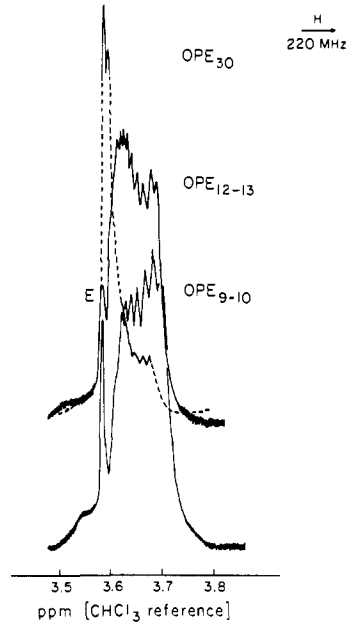


Figure 3. Comparison of the main ethoxy band of the three detergents, in micellar solution in water. The signal for OPE_{9-10} is identical with that shown in earlier figures, that for OPE_{12-13} was taken at a concentration of 0.103 M (8.4% (w/v) = 0.002 mol fraction = 400 times critical micelle concentration[4a]), that for OPE_{30} at 0.070 M (11.2% (w/v) = 0.001 mol fraction = 130 times critical micelle concentration[4a]). The signal for OPE_{30} is shown in part dashed only for ease in distinguishing the curves in the figure.

Several signals seem to appear in the monomer band, too, indicating some nonuniformity of the various ethoxy groups. This might be due to differences of the chemical environment along the chain, accentuated by the high sensitivity of the 220-MHz instrument, but the data do not warrant a more detailed analysis.

Chemical Shifts in Nonaqueous Solvents. The chemical shifts for OPE_{9-10} were determined in dilute solutions, using chloroform as external reference (Table III and Figure 4). The concentration in ethylene-d_4 glycol is below the critical micelle concentration (0.08 M at 25°).[6] The bulk susceptibilities of all solutions in organic solvents were computed from the Wiedmann–Frantz additivity law. At these detergent concentrations, the correction terms are practically identical with those for the pure solvents.

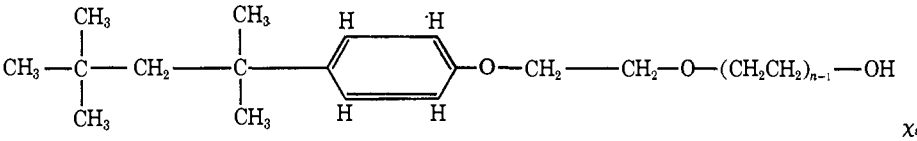
The chemical shifts of the alkyl protons are either identical within experimental error (terminal methyl

(38) A. D. Buckingham, T. Schaeffer, and W. G. Schneider, *J. Chem. Phys.*, 32, 1227 (1960).

(39) J. J. Jacobs, R. A. Anderson, and J. R. Watson, *J. Pharm. Pharmacol.*, 23, 786 (1971).

(40) The opposite medium effects seen for the diverse parts of the detergent molecule are analogous to the observations by Eriksson on an ionic detergent.[9] Similar changes were found by Corkill, *et al.*,[18] for the ethoxy chain of a related nonionic detergent.

Table III. Chemical Shifts of OPE_{9-10} in Various Solvents, Expressed in ppm, with Respect to $CHCl_3$ as External Reference[a]



Solvent	Concn, M									$\chi_s \times 10^{6}$ [b]
Water (micelle)	0.104	6.65	5.70	6.07	0.51	0.13	3.32	3.55	[3.59–3.70][d]	−0.728[c]
Liquid	1.0	6.64	5.66	6.04	0.51	0.12	3.31	3.59	3.80	−0.702[c]
Dioxane	0.011	6.65	5.62	6.03	0.53	0.06	Obscured by dioxane signal			−0.612[c]
Ethylene-d_4 glycol	0.017	6.63	5.61	6.00	*h*	*h*			3.80–3.82	−0.698[e]
Benzene	0.010	7.04	6.16	6.52	*f*	*f*			[4.33–4.46]	−0.611[g]
Line width ($\Delta\nu_{1/2}$) in water (Hz)		3.5 ± 0.5		7 ± 1						

[a] See footnote *a* to Table II. [b] Used for the bulk susceptibility corrections. [c] This work. [d] See footnote *b* to Table II. [e] It was assumed that the value given for the protonated molecule[26] is applicable here. [f] Obscured by benzene signal. [g] Reference 18. [h] Not resolved from noise.

Table IV. Relaxation Time T_1 (msec) and Saturating Radiofrequency Power Levels for Aqueous Micelles in D_2O at 220 MHz

Detergent	OPE_{9-10}		OPE_{12-13}	OPE_{30}	OPE_{9-10}
Concn, M	0.104	0.052 and 0.104	0.103	0.070	0.052
Temp, deg	39	18	18	18	18
	T_1[a]				rf power, dB[b]
$C(CH_3)_3$	270	200	195	185	34.5
CH_2	150	150	150	150	38
$C(CH_3)_2$	130	105	115	115	37
H	370	330	320	320	39
H H	310	260	270	270	41
H					
O					
CH_2	360	210			41
CH_2	415[c]	190[c]			*d*
O					
CH_2	460–580	290–370	315–410	340–470	36.5 to 31
$CH_2)_{n-1}$	Peak E: 850[c]	600[c]			26
OH					

[a] Precision: ±20 msec, except where indicated otherwise. [b] Precision: ±0.5 dB. [c] Precision: ±50 msec. [d] See ref 42.

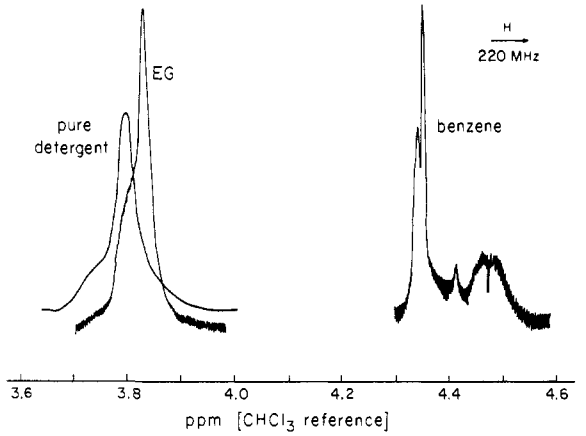


Figure 4. Comparison of the main ethoxy band of OPE_{9-10} in the liquid state and in organic solvents. The signal for the pure detergent is identical with that shown in Figure 2. Concentrations are listed in Table III.

groups) or altered very little in the bulk and in the organic solvents, except for benzene. They are all somewhat downfield shifted with respect to the signals in aqueous micelles. This supports the arguments made above regarding the latter solution. The chemical shift of the ethoxy band in ethylene-d_4 glycol is very similar to that in the bulk liquid.

In benzene, all signals are strongly upfield shifted. This, as well as the splitting of the ethoxy band (Figure 4), suggests that there are variations in the interactions of various segments with neighboring benzene rings of the solvent. Differences in the broadenings observed in the ethoxy region suggest differences in the mobility along the chain.

Progressive Saturation Measurements. In order to get a qualitative insight into the dynamic structure of aqueous micelles, we carried out progressive saturation measurements[28] in CW on individual peaks of micellar OPE_{9-10} in D_2O. Under conditions of slow passage,[28,41] the saturating value of the applied radiofrequency field is related to the spin–lattice (T_1) and spin–spin (T_2) relaxation times by the relation $(\gamma H_1)^2 \cdot T_1T_2 = 1$, where γ = the nuclear magnetogyric ratio. The applied fields, required to yield maximal signal amplitudes for the various detergent signals, are listed in the last column of Table IV. The saturating field is highest for the "central" part of the detergent molecule,

(41) A. Carrington and A. D. McLachlan, "Introduction to Magnetic Resonance," Harper and Row, New York, N. Y., 1967.

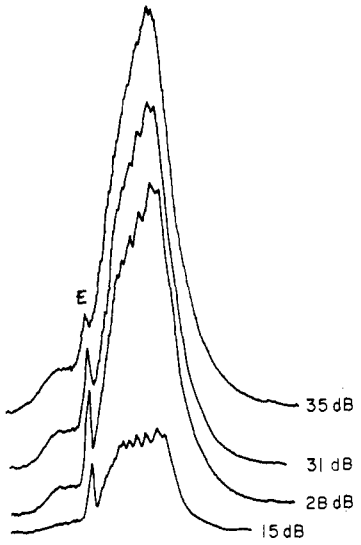


Figure 5. Progressive saturation of the main ethoxy signal of OPE_{9-10} (0.052 M) in micellar solution in D_2O. Signals are shown at various saturating radiofrequency levels, expressed in dB of rf power.

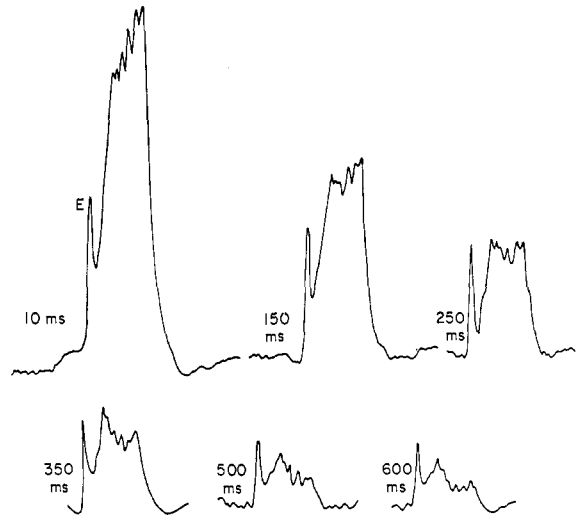


Figure 6. Illustrative examples for the measurements of T_1 on the main ethoxy band of OPE_{9-10} (0.052 M) in micellar solution in D_2O. Signals are shown for various values of the delay time τ between the π and the $\pi/2$ pulses. They represent the differences between the magnetization at equilibrium ($\tau \rightarrow \infty$) and at time τ.[44] It is to be noted that various components of the band have different relaxation times.

between the alkyl methylene group and the first ethoxy group.[42] The field is lower (and hence T_1T_2 higher) for the terminal methyl groups. Presumably, this reflects the high rotational freedom of the symmetrical terminal *tert*-butyl group. Except for the first one, the methylene groups of the ethoxy chain require a lower saturating field than the alkyl methylene group. This can be due to the rigidity of the strongly branched alkyl group. The shape of the main ethoxy band changes considerably with increase of the radiofrequency power level (Figure 5). This strongly suggests different mobilities or packing densities, or both, of the various groups contributing to the band (*cf.* T_1 measurements). No accurate measurements for each component of the band were possible. However, we could estimate that the saturating power level decreases from 36.5 to 31 dB from the left to the right side of the band, with exception of the E peak for which a much lower value was found. This too supports the earlier assignment of peak E to the last methylene group of the ethoxy chain.

Because of the intrinsic limitations of this method,[43] it served merely as a qualitative auxiliary study to the direct determination of the T_1 values, to be reported next.

T_1 Measurements in Aqueous Micelles. Spin–lattice relaxation times, T_1, for micellar solutions in D_2O at 18° are shown in Table IV. Detergent concentrations were 100 to 500 times higher than the critical micelle concentrations. This ensured that the data represent relaxation times in the micellar form only.

Within experimental error, T_1 values for all alkyl and phenyl proton signals are identical in all three detergents. The high T_1 for the terminal methyl groups (as compared with the other alkyl signals) confirms our conclusion (*cf.* saturation measurements) about the higher rotational mobility of the terminal group. The small value of T_1 for the alkyl methylene group, as compared with those for the ethoxy groups, also agrees with the saturation data.

The longitudinal relaxation of the CH_2 groups of the first ethoxy unit is intermediate between those of the alkyl CH_2 and that of the rest of the polyethoxy chain. Presumably, the mobility of the portion of the polyethoxy chain next to the phenoxy group is rather restricted. Mobility increases faster in the region around the second ethoxy group than for the further ethoxy groups, in parallel with the changes in exposure to water, as indicated by the chemical shifts. The line widths confirm this conclusion; the first two methylene signals are broad, indicating stronger immobilization, in contrast to the narrow signals or the components of the main ethoxy band.

As seen in Figure 6 for OPE_{9-10}, the shape of the main ethoxy band changes as a function of the delay time τ between the π and the $\pi/2$ pulses. This means that various groups contributing to this band have different relaxation times. Individual T_1 times for the single peaks in the band could not be determined because of the partial overlaps. However, it is clear from Figure 6 that there is a progressive decrease of T_1 from the low to the high field side of this band. The range of values is listed in Table IV. The T_1 for peak E is much longer than for the rest of the band. These results are consistent with the earlier conclusions about the behavior of the polyethoxy chain. T_1 increases slightly as the polyethoxy chain lengthens, suggesting increased mobility and/or looser packing in the higher homologs.

When τ is very large, several more very closely spaced peaks can be distinguished in the low field region of the band than in the static signal. Even though the most mobile ethoxy units have very similar environment and mobility, one may detect minor differences in the chemical shifts of some of them with the help of

(42) The determination of the saturating field for the second CH_2 group was difficult because of the partial overlap of its resonance with the main ethoxy band.

(43) J. Reuben, D. Fiat, and M. Folman, *J. Chem. Phys.*, **45**, 311 (1966).

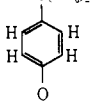
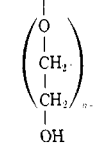
(44) R. Freeman and H. D. W. Hill, *J. Chem. Phys.*, **54**, 3367 (1971).

Fourier transform techniques, under proper experimental conditions.

With a rise in temperature from 18 to 39°, T_1 increases for all peaks of OPE_{9-10}, except those of the internal alkyl groups (Table IV). This indicates that the spin–lattice relaxation is mainly determined by a motional mechanism with a correlation time τ_c of about 10^{-9} to 10^{-10} sec (*i.e.*, about $1/(2\pi\nu_0)$, where ν_0 = 220 MHz) for the internal alkyl groups and shorter for all others.[28,30,34b] This mechanism is interpreted as provided essentially by the rotation of the various groups about single bonds.[45] These results confirm the "liquid-like" nature of the micellar core, suggested by several investigators.[46,47]

We repeated the T_1 measurements for OPE_{9-10} with various amounts of H_2O added to the solution. In this experiment, a shortening of T_1 is expected for those groups which are in contact with the solvent. This effect arises from intermolecular magnetic dipole–dipole interactions and is due to the higher magnetogyric ratio of the proton.[34c] Because of the technical difficulties associated with the limited dynamic range of the computer used for the Fourier transform operation,[48] we could not raise the H_2O concentration above 20%. Even there, measurements were difficult for the small signals of the phenyl protons. However, measurements on the alkyl and the main ethoxy band signals are fairly accurate (Table V).

Table V. Relaxation Time T_1 (msec) in Aqueous Micelles of OPE_{9-10} (0.104 *M*) as a Function of D_2O–H_2O Composition (t = 18°, 220 MHz)[a]

	% H_2O added		
	0	12	20
$C(CH_3)_3$	200	220	190
CH_2	150	150	160
$C(CH_3)_2$	105	110	110
			
O			
CH_2			
CH_2	190		160
	290–370	285–335	165–230
Peak E:	600	520	520

[a] Precision: ±20 msec; for peak E, ±50 msec.

T_1 was not altered for the alkyl protons. This confirms that there is no (or very little) penetration of water into the nonpolar interior of the micelle. T_1 is noticeably shortened for the ethoxy chain. As H_2O is added in successive portions, the relaxation time of the signals on the low field side of the band (signals with higher T_1 values) is shortened at first. The rest of the band is affected only at higher HDO concentrations. This result, too, confirms the assignment of the low field signals in the band to the more mobile ethoxy units which are at the same time more exposed to the solvent, *i.e.*, the ones near the hydroxy terminal.

Our conclusions about the lack of penetration of water into the micelle and about the temperature dependence of T_1 for the polyethoxy chain agree completely with the results of Clemett,[19] obtained by the same methods for an alkyl(polyethoxy)ethanol.

The lack of strong variation of T_1 for peak E appears contradictory. However, it might be explained on the basis of the mechanism of solvent–solute magnetic dipole–dipole interactions. It is known that the magnitude of these interactions depends both on the distance of closest approach of protons in the two molecules and on their relative diffusional coefficient.[30] High relative mobility of water in the vicinity of the last methylene group would explain the constancy of T_1.

On the other hand, this requires the postulation of more effective magnetic dipole–dipole interactions between water protons and those of the other ethoxy groups, in order to explain the strong observed dependence on H_2O concentration. This could happen if water molecules were less mobile near these groups. Such an interpretation is in accord with several studies in which it was suggested that water is kinetically bound to nonionic micelles.[16,18,49,50] The proposals were based on hydrodynamic measurements[49,50] and on studies of proton chemical shifts[18] and proton relaxation times.[16]

Conclusions

The main results can be summarized as follows. The high mobility of the terminal methyl group (as seen from the saturation and the relaxation time measurements) confirms that the interior of the micelle is liquid like. Both the chemical shifts and the absence of variation of T_1 when H_2O is added show that no water (or very little) penetrates into the interior part of the micelle, composed of the alkyl groups. This region actually is less polar than the environment of the alkyl groups in the pure liquid detergent.

On the other hand, almost all ethoxy regions are in a polar environment in the micelle, as seen from the chemical shifts. The large difference in the chemical shift of the first and subsequent ethoxy groups shows that contact with water begins in the region of the first ethoxy group. However, the local environment of the ethoxy groups continues to change as one moves along the polyethoxy chain, as indicated by the large spread of chemical shifts of the main ethoxy band. Chemical shifts show that in the higher homologs, the environment of the added ethoxy groups appears to be practically constant. Saturation and T_1 measurements indicate an increase in chain mobility along the ethoxy chain, going toward the hydroxyl terminal. Comparison of the micelle, monomer, and dioxane chemical

(45) One might use the T_1 data at 18 and 39° to evaluate activation energies. The data in Table IV give the following values: terminal methyl group 2.5 kcal/mol, "peak E" methylene group 3 kcal/mol, other methylene groups of the polyethoxy chain 4 kcal/mol. However, we must point out that the activation energies estimated in this manner for micellar systems may be meaningless in either of two possible cases: (i) if the "extreme narrowing condition" ($\omega_0\tau_c \ll 1$, where τ_c is the correlation time of the motion) is not obeyed; (ii) if there is more than one relaxation mechanism, due to anisotropy. This can be checked by estimating the ratio T_1/T_2, which should be near unity if either of the two cases occurs. In our case, evaluating $T_2 = (\pi\Delta\nu)^{-1}$ (Table III) gives ratios between 2 and 3 for the alkyl peaks.

(46) E. D. Goddard, C. A. J. Hoeve, and G. C. Benson, *J. Phys. Chem.*, 61, 593 (1957).

(47) K. Shigehara, *Bull. Chem. Soc. Jap.*, **38**, 1700 (1965).

(48) A. G. Redfield and K. Gupta, *J. Chem. Phys.*, **54**, 1418 (1971).

(49) L. M. Kushner and W. D. Hubbard, *J. Phys. Chem.*, **58**, 1163 (1954).

(50) P. M. Elworthy, *J. Pharm. Pharmacol.*, **12**, 260 (1960).

shifts in water suggests that the last methylene group (corresponding to peak E) is fully exposed to solvent in the micelle. T_1 measurements in D_2O–H_2O mixtures provide some evidence for a partial immobilization of water molecules between the polyethoxy chains on a micelle.

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Radical Ions of *tert*-Butylphenylacetylene. Mechanism of Their Unconventional Dimerization and Structures of the Four Isomeric Protonated Dimers

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Abstract: The reduction of *tert*-butylphenylacetylene in THF by metallic potassium at −70° yields radical anions of that hydrocarbon which, under those conditions, undergo an unconventional dimerization. The dimers result from the addition of one radical anion to the para position of the phenyl group of another. Such a reaction yields dimeric dianions of quinonoid structure possessing a labile H atom on the quinonoid ring. Subsequent protonation or deuteration resulting from the addition of H_2O or D_2O produces four isomeric para-substituted benzene derivatives having the labile ring H replaced by another H (or D) atom on the α carbon, *viz.*, the hydrocarbons IH, IIH, IIIH, and IVH. The four isomers were separated and identified by their nmr and mass spectra, their structure being confirmed by ozonolysis. The mechanism of this dimerization was elucidated. In addition to the dimers, a small amount of carbanions $Ph\bar{C}{=}CH(t\text{-Bu})$ is formed through the protonation of the dianions of *tert*-butylphenylacetylene by THF. These yield on the addition of H_2O or D_2O the respective β-*tert*-butylstyrenes. The reduction performed at room temperature mainly yields a completely protonated benzyl-type carbanion, *viz.*, $Ph\bar{C}H \cdot CH_2(t\text{-Bu})$; *i.e.*, the protonation by THF becomes the dominant reaction.

It has been reported elsewhere[1] that the low temperature (*ca.* −80°) reduction of *tert*-butylphenylacetylene (BPA) by potassium results in the formation of its radical anion, $BPA\cdot^-$. Its esr spectrum is exceedingly simple; it consists of a doublet, a = 7.15 G, resulting from the coupling to para proton, split into triplets, a = 2.8 G, presumably arising from the coupling to the ortho protons. The narrow width of that spectrum, about 13 G only, implies that about 50% of the spin density is localized in the C≡C system. The fate of these radical ions, when kept at *ca.* −70° in prolonged contact with potassium, is elucidated in the present communication. The products of the reaction were isolated and identified. They arise from protonation by the solvent of the dianions (BPA^{2-}) formed by further reduction of $BPA\cdot^-$ and from an unconventional dimerization of the radical ions resulting in the precursors of four distinct dimers, all of which were isolated and identified.

Low-Temperature Reduction of *tert*-Butylphenylacetylene

About 2×10^{-2} *M* tetrahydrofuran solution of *tert*-butylphenylacetylene,[2] cooled to *ca.* −70°, was contacted with a freshly prepared potassium mirror kept at the same temperature. The reduction, performed in an all glass, vacuum tight apparatus, proceeded for about 6 hr. The resulting reddish solution, after being decanted from the mirror, was divided into two approximately equal portions. One of them was protonated with deaerated water while the other deuterated with D_2O; thereafter each solution was acidified. All of these operations were performed under vacuum, keeping the reagents at −70°.

The acidified solutions were warmed up to room temperature and the solvent was distilled off under vacuum. The residue was three times extracted with 5 ml of hexane and once with benzene. The combined extracts were freed from the solvents by vacuum distillation and then fractionated on a preparative gas chromatographic column (20% Carbowax on Chromosorb G). The separation was clearcut and eventually two monomeric and four dimeric fractions were collected.

Identification of the Monomeric Products of Low-Temperature Reduction

The monomeric products were unambiguously identified as the unreacted *tert*-butylphenylacetylene and

(1) G. Levin, H. D. Connor, P. Caluwe, and M. Szwarc, submitted for publication.

(2) Prepared according to the method of B. S. Kupin and A. A. Petrov, *Zh. Obshch. Khim.*, 31, 2958 (1961).