577. *The Diffusion in Water of Some Association Colloids and Solubilised Materials.*

By N. Brudney and L. Saunders.

The diffusion of sodium cholate and potassium decanoate in water has been studied by the Gouy interference method at less than the critical concentrations for micelle formation. Small changes of integral diffusion coefficient with concentration were found with breaks in the diffusion co-efficient–concentration curve at known concentration limits. The diffusion rates of *n*-decyl and *n*-dodecyl alcohol and of lecithin solubilised in solutions of sodium dodecyl sulphate reveal monodispersion in association colloid solutions saturated with solubilised material.

EARLIER measurements [1] showed the extremely low values of the diffusion coefficients of clarified lecithin sols. Recently, variation of the diffusion coefficient with concentration for the materials used to clarify these sols has been reported.[2,3]

The Gouy method has been fully described elsewhere.[4,5] The theory of the method used in the calculation of diffusion coefficients is that outlined by Kegeles and Gosting [6] and by Gosting and Onsager [7] for single solutes, and by Akeley and Gosting [8] for mixed solutes. The complete theory of the Gouy method used in the present work has been reviewed recently by one of us.[9]

McBain [10] has recently described solubilisation as the " spontaneous passage of solute molecules of a substance insoluble in water into an aqueous solution of a soap or detergent in which a thermodynamically stable solution is formed " (for reviews see Klevens,[11] Winsor,[12] and McBain and Hutchinson [13]). The mode of solubilisation depends on the chemical nature of the material solubilised, and for the amphiphilic materials used in the work reported here the locus of solubilisation is the palisade layer of the micelle.

[1] Saunders, *J.*, 1953, 1310.
[2] Brudney and Saunders, *J.*, 1955, 2916.
[3] *Idem, J. Pharm. Pharmacol.*, 1955, **7**, 1013.
[4] Longsworth, *J. Amer. Chem. Soc.*, 1947, **69**, 2510.
[5] Saunders, *J.*, 1953, 519.
[6] Kegeles and Gosting, *J. Amer. Chem. Soc.*, 1947, **69**, 2516.
[7] Gosting and Onsager, *ibid.*, 1952, **74**, 6066.
[8] Akeley and Gosting, *ibid.*, 1953, **75**, 5685.
[9] Brudney, Ph.D. Thesis, London, 1955.
[10] McBain, *Adv. Colloid Sci.*, Vol. I, Interscience Publ. Inc., New York, 1942.
[11] Klevens, *Chem. Rev.*, 1950, **47**, 1.
[12] Winsor, " Solvent Properties of Amphiphilic Compounds," Butterworths Scientific Publ., London, 1954.
[13] McBain and Hutchinson, " Solubilisation and Related Phenomena," Academic Press Inc., New York, 1955.

EXPERIMENTAL

Materials.—Sodium cholate, potassium dodecanoate, and potassium decanoate were prepared by neutralisation of pure acids with carbonate-free alkali. Cholic acid, prepared by the method of Gauthier and Nguyen Huu Quy,[14] had $[\alpha]_D^{20}$ +34·91° (in 70% ethanol), m. p. 198·9° (Found : equiv., 411·9. Calc. for $C_{24}H_{40}O_5$: equiv., 408·6). Sodium dodecyl sulphate was prepared by the method of Dreger *et al.*[15] as modified by Burcik[16] (Found, in two samples : S, 11·1, 11·15. Calc. for $C_{12}H_{25}O_4SNa$: S, 11·2%) (no loss of wt. on continuous extraction with ether and drying). Dilute solutions of the soaps formed free-draining films and there was no maximum of turbidity on dilution of concentrated solutions. Other acids and alcohols, obtained from Eastman Kodak, were used without purification. Lecithin was prepared by a chromatographic method based on that described by Lea and Rhodes[17, 18] (to be recorded elsewhere), $[\alpha]_D^{20}$ 8·00° in ethanol (Found : N, 1·8; P, 3·8%; I. no. 71·6; sp. resistance of a 0·5% sol, 0·72 megohm cm.).

Sols were prepared with doubly distilled water and allowed to age for 24 hr. before use.

Diffusion Coefficients.—The calculation of diffusion coefficients from the Gouy interference patterns has been fully described elsewhere.[2, 4, 5, 8, 9] The length b in the Longsworth equation is described in some papers as the optical distance[4, 5, 19] and in others as the optical lever arm;[8, 9] the latter seems preferable as b is found by summing geometrical distances divided by refractive indices.

An extrapolation method for determining j_m, the refractive index term of the Longsworth equation, directly from the Gouy patterns was found satisfactory for slowly diffusing materials.

The concentrations in this paper are expressed in millimoles per l. unless otherwise stated; diffusion coefficients (D) are in cm.²/sec. at 25°. The term, integral diffusion coefficient, is applied to a value of D found by allowing a solution to diffuse into pure water.

(a) *Diffusion in water of sodium cholate and potassium decanoate.* The integral diffusion coefficients of sodium cholate together with the j_m values are shown in Table 1. In all cases, the results show that a break occurs in the diffusion coefficient–concentration (D–c) curve at about 15 millimoles/l. Above this concentration D decreased with increasing c; below $c = 15$, D varied little. The Gouy patterns obtained in these experiments were normal. The intensities of the maxima showed no such anomalies as had been observed with other association colloids.[2, 3]

For potassium decanoate (Table 1) the diffusion coefficient varies little with concentration. As with sodium cholate the patterns showed no abnormalities except for some patterns obtained with solutions containing 100 and 110 millimoles/l.; unfortunately, these could not be measured as the bottoms of the patterns were not clear.

TABLE 1. *Integral diffusion coefficients of sodium cholate and potassium decanoate.*

Concn.	j_m	10^6D	Concn.	j_m	10^6D	Concn.	j_m	10^6D	Concn.	j_m	10^6D
		Sodium cholate						Potassium decanoate			
4·6	19·5	6·42	18·0	71·7	6·15	20·0	29·9	8·90	50·0	74·5	8·66
4·8	20·6	6·41	20·0	79·5	6·08	22·5	33·6	8·87	55·0	82·2	8·66
4·6	19·2	6·42	25·0	97·3	5·45	25·0	37·0	8·90	60·0	88·0	8·62
9·4	39·8	6·45	30·0	117·5	5·24	30·0	44·8	8·79	70·0	104·0	8·51
15·0	59·5	6·45	35·0	134·0	4·73	40·0	59·7	8·65	80·0	118·0	8·46
16·5	66·0	6·31									

(b) *Diffusion of solubilised long-chain saturated alcohols.* Diffusion measurements on soap solutions containing relatively small amounts of *n*-decyl alcohol were made and continued with solutions containing more and more alcohol until the saturation concentration was reached. These results together with a measurement with *n*-dodecyl alcohol at its saturation concentration are reported in Table 2, where $D' = $ wt.-average and $D_a = $ height–area-average diffusion coefficient.

The patterns showed few anomalies in the intensities of the Gouy maxima except that the inner lines were more intense than normally expected for a pattern of this length. All the patterns obtained with solutions containing alcohol at less than the saturation concentration

[14] Gauthier and Nguyen Huu Quy, *Ann. Pharm. franc.*, 1947, **5**, 556.
[15] Dreger, Keim, Miles, Shedlovsky, and Ross, *Ind. Eng. Chem.*, 1944, **36**, 610.
[16] Burcik, *J. Colloid Sci.*, 1950, **5**, 421.
[17] Lea and Rhodes, *Biochem. J.*, 1954, **57**, xxiii.
[18] *Idem, ibid.*, 1955, **59**, v.
[19] Gosting, Hanson, Kegeles, and Morris, *Rev. Sci. Instr.*, 1949, **20**, 209.

were interpreted by the method for mixed solutes described by Akeley and Gosting.[8] Those obtained with solutions containing the saturation concentration were interpreted by the method for a single solute and these patterns gave C_t values which were remarkably constant (C_t = 1·820, 1·834, 1·837, 1·838, 1·832 for j = 3, 6, 9, 12, 15 at t = 3000 sec.).

TABLE 2. *Integral diffusion coefficients of long-chain saturated alcohols solubilised in 50 mmoles/l. of sodium dodecyl sulphate.*

Alcohol	Concn.	j_m	$10^6 D'$	$10^6 D_a$
Decyl	0·0	79·02	2·76	1·59
	2·5	79·62	2·83	2·19
	5·0	78·96	2·93	2·28
	7·5	79·98	2·81	2·25
	10·0	81·28	2·42	—
Dodecyl	5·0 *	72·44	2·44	—

TABLE 3. *Diffusion of lecithin clarified with sodium dodecyl sulphate (NaDS).*

Result no.	Concn. of lecithin in lower layer	Solutes in upper layer	j_m	$10^6 D'$	$10^6 D_a$
		Lower sol containing 20 millimoles/l. of NaDS			
1	—	—	30·49	3·80	1·06
2	2·5	—	38·82	3·62	3·42
3	5·0	—	44·77	3·50	—
4	2·5	20 NaDS	6·41	0·0898	—
5	5·0	20 NaDS	11·35	0·0890	—
6	5·0	20 NaDS +0·3 CaCl₂	10·41	0·0894	—
7	5·0 +0·3 CaCl₂	20 NaDS 0·3 CaCl₂	11·64	0·164	—
8	5·0 +0·3 CaCl₂	—	45·43	3·43	—
		Lower sol containing 50 millimoles/l. of NaDS			
9	—	—	79·02	2·76	1·59
10	2·5	—	85·78	3·25	2·20
11	5·0	—	92·19	2·97	2·84
12	7·5	—	99·63	2·98	2·91
13	10·0	—	102·80	2·98	2·94
14	12·5	—	110·70	2·99	—

An attempt to produce solutions containing more than the saturation concentrations gave emulsions which were opaque and so could not be studied by the optical method used here.

(c) *Diffusion of solubilised lecithin sols.* The results obtained with clarified lecithin sols are shown in Table 3. Concentrations of lecithin are expressed in mmoles/l. calculated from a molecular weight of monomer based on the average of a number of nitrogen determinations. In all cases, the sols were prepared by adding concentrated soap solutions to a film of lecithin which had been spread by evaporation of an alcoholic solution. The sol was shaken, made up to volume, and allowed to age for 24 hr.

The remarkably constant C_t values obtained for the integral diffusion of the long-chain alcohols at their saturation concentrations were again found with the lecithin sol. An example of the detailed results obtained with the sol saturated with lecithin is given in Table 4.

TABLE 4. *Analysis of a Gouy pattern obtained with lecithin solubilised with sodium dodecyl sulphate at the alcohol saturation concentration.*

j	C_t (1800 sec.)	C_t (2100 sec.)	C_t (3000 sec.)	j	C_t (1800 sec.)	C_t (2100 sec.)	C_t (3000 sec.)
1	1·219	1·130	0·947	6	1·218	1·129	0·946
2	1·220	1·132	0·948	7	1·219	1·130	0·946
3	1·216	1·127	0·944	8	1·221	1·132	0·948
4	1·217	1·128	0·946	9	1·220	1·129	0·946
5	1·218	1·130	0·945	10	1·217	1·132	0·947

	C_t (1800)	C_t (2100)	C_t (3000)
Mean C_t	1·2185	1·130	0·946
Standard deviation	0·00156	0·00173	0·00125
Standard error of mean	0·00049	0·00055	0·00039
$10^6 D$	3·51	3·50	3·50

Mean diffusion coeff. = 3·50 × 10^{-6}.

DISCUSSION

The results obtained for sodium cholate are interpreted as follows. Below 15 mmoles/l., the solution is composed of simple electrolytes, *i.e.*, dissociated cholate and sodium ions. At 15 mmoles/l., small aggregates of low stability are formed. Above 15 millimoles/l., and with increasing concentration, the concentration of aggregated cholate ions increases, and the aggregates become increasingly stable. These aggregates are thought not to be true micelles, but far more simple structures such as ion pairs or small groups of ions. Actual micelle formation [20] begins in sodium cholate solutions at about 40—44 mmoles/l. This concentration was not reached in the course of this work.

Ekwall [21, 22] has observed an abrupt change in many of the physical property–concentration curves of sodium cholate at about 15 mmoles/l. Measurements of equivalent conductance, solubilisation properties, hydroxyl-ion activity, and partial molal volume, when plotted against concentration, gave curves which showed a distinct break, similar to the D–c curve at 15 mmoles/l. Ekwall termed this concentration the first concentration limit of the sodium cholate solution and showed further concentration limits at 45, the critical micelle concentration, and 100 mmoles/l. He showed that the physical properties of this and other association colloids do not vary in a continuous manner with concentration below and above the critical micelle concentration but that there are also other concentration limits. The present work and that on the diffusion of other association colloids [2, 3] corroborate Ekwall's theories.

Sodium cholate solutions are thought to be somewhat different in structure from the solutions of other association colloids, *e.g.*, the long-chain soaps. For instance, with potassium decanoate there is only a small fall in diffusion coefficient at the concentration limits, though there is a considerable fall with sodium cholate. This difference is thought to be due to the difference in the size and shape of the anions. The break in the D–c curve for the cholate at 15 mmoles/l. shows clearly that some change in the structure of the solution occurs at that point but the particles in the solution do not differ sufficiently to give a heterogeneous Gouy pattern which could be interpreted by the mixed solute method. The value of C_t in all of the patterns measured was constant.

Potassium decanoate shows (Table 1) small but noticeable breaks in the D–c curve at the Ekwall concentration limits : he found limits at 25 and 55 mmoles/l., and the D–c curve shows breaks at 25 and 60 mmoles/l. of potassium decanoate. Ekwall infers that association of the decanoate ion commences at 25 mmoles/l., with small aggregates and continues to 97 mmoles/l. at which point micelles are formed. However, over the whole concentration range, the diffusion coefficient decreased by only about 5.0×10^{-7}. This is a very small fall in diffusion coefficient if aggregation is indeed taking place throughout this concentration range. It is suggested that aggregates of low stability, such as ion pairs, or small groups of ions may be formed, particularly at the concentration limits, but these are definitely not micelles. When micelles are formed in soap solutions, the Gouy patterns show considerable anomalies in the intensities of their maxima.[2]

The outstanding result with solubilised materials is the apparent homogeneity of the solution at the saturation concentration of additive. Below this concentration the solutions gave interference patterns which indicated the presence of at least two different diffusing entities (for these measurements it has been assumed that there are only two types of diffusing particles). At the saturation concentration, however, the patterns were the same as for single-solute diffusion; this means that at the saturation concentration all the dissociated soap anions are drawn into the mixed alcohol–soap micelles. Further, since the Gouy patterns at this concentration were easily interpreted by a single-solute type of calculation, these micelles must be of comparatively uniform structure throughout the solution.

On the whole, the results (see Table 2) have shown very little variation of diffusion coefficient with the concentration of added alcohol. This is ascribed to the very great

[20] Ekwall, *Acta Acad. Aboensis, Math. Phys.*, 1951, **17**, No. 8, 1 ; *Chem. Abs.*, 1953, **47**, 24.
[21] *Idem, J. Colloid Sci.*, 1954, Suppl. 1, 66.
[22] *Idem, Kolloid Z.*, 1954, **136**, 37.

electrical effect across the boundary when 50 mmoles/l. of sodium dodecyl sulphate diffuses into water; this obscures any effects due to the additive. A measurement in which a solution containing 50 mmoles/l. of this sulphate together with 10 mmoles/l. of *n*-decyl alcohol diffused into a solution containing 50 mmoles of sodium dodecyl sulphate per l. gave D' 4.07×10^{-7}, showing that large colloidal particles were present. When the boundary between these two solutions was formed with the solution containing the alcohol below that without alcohol, there was a tendency for mixing to occur, the alcohol–soap solution being the less dense. The positions of the two solutions were therefore reversed in forming the boundary, and the diffusing column with alcohol–soap solution above the soap solution gave interference patterns whose fringes were displaced *above* the optic axis. These patterns could be interpreted by the single-solute method.

Decyl and dodecyl alcohol at their saturation concentrations have been found to have the same effect upon D for a soap solution of given concentration, supporting the theory that the alcohols are solubilised in the palisade layer of the micelle where chain length would have little effect on micellar size. These results show that substances of chemically similar nature can cause the same change in D for a soap solution. This would seem to cast some doubt on the work of Stigter *et al.*[23], whose dye solubilisation method for measuring self-diffusion coefficients assumes that the dye has no effect on D because different dyes give the same value for micellar mobility.

Table 3, giving values of D for lecithin–soap solutions, shows that, as with the alcohols, when the saturation concentration is reached the solution becomes homogeneous and contains only one type of solute particle. The solution of sodium dodecyl sulphate saturated with lecithin gave normal interference patterns which yielded extremely consistent results when interpreted by the single-solute diffusion method.

The standard error of the mean C_t values (Table 4) compares favourably with that for single-solute diffusion (*e.g.*, Saunders[5] using pure glycine found a standard error of 0.002). This illustrates clearly the homogeneous nature of the soap solutions containing the saturation concentration of lecithin. The results in Table 3 show that as the lecithin concentration is increased, the D_a values approach the D' values, that is the solutions become less heterogeneous as more lecithin is solubilised. Results nos. 4 and 5 of Table 3, in which the electrical effect at the boundary is eliminated by equal concentrations of sodium dodecyl sulphate on both sides, show that large colloidal particles are present in the lecithin–soap solutions. The micellar volume calculated from the Stokes–Einstein equation is about 8×10^7 Å^3.

An attempt was made to decrease the diffusion coefficient of the solubilised lecithin still further by adding calcium chloride. The concentration chosen, 0.3 mmoles/l., has been found[24] to increase considerably the surface force between a lecithin sol and water. Added calcium chloride had little effect on the integral diffusion coefficient of the lecithin–sodium dodecyl sulphate sols, probably because of the relatively large concentration of soap present.

SCHOOL OF PHARMACY, UNIVERSITY OF LONDON.

[23] Stigter, Williams, and Mysels, *J. Phys. Chem.*, 1955, **59**, 330.
[24] Elworthy and Saunders, *J.*, 1955, 1166.