Determination of Association Constants of Cyclodextrin-Nonionic Surfactant Inclusion Complexes by a Partition Coefficient Method

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Abstract. The partition behavior of isotopic labeled nonionic surfactants between carbon tetrachloride and an aqueous solution containing β-cyclodextrin (β-CD) was studied with a liquid scintillation counting technique. The association constants of the inclusion complexes were determined at different temperatures. It was found that the nonionic surfactants form 1 : 1 inclusion complexes with β-CD. The results demonstrated that the smaller the HLB values of the nonionic surfactants, the greater the association constants with β-CD, and that for the same surfactant the association constant is higher at lower temperatures.

1. Introduction

Cyclodextrins (CDs) are cyclic oligosaccharides consisting of 6, 7, or 8 glucose units, called α-, β-, and γ-CD, respectively. One of their most important properties is their ability to form inclusion complexes with various lipophilic compounds [1–3]. The inclusion complexes formed between surfactants and cyclodextrins have been studied using a number of physical methods, including conductivity [4–10], UV-visible spectroscopy [11–15], fluorescence spectroscopy [13–15], NMR [14, 15], and surface tension [16, 17]. The partition coefficient method was used to determine the stoichiometries and association constants of inclusion complexes of organic molecules with cyclodextrins [18, 19]. In this paper the partition coefficient method was also employed to determine stoichiometries and association constants of complexes of the (temperature $135 \pm 5\,°C$, pressure of reaction ≤ 40 MPa) and SP (^{14}C-hexadecanol : PO = 1 : 129, weight ratio) was obtained. Second, under the

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Table I. The values of HLB and content (RPC) of EO in nonionic surfactants (calculated from the Griffin function [23])

Surfactants	SP161	SP165	SP1613	SP1617
HLB values	13.3	10.0	6.0	5.0
RPC of EO	75	50	30	25

same conditions, ethylene oxide (EO) was added to the reactor which contained SP, SP16 {SP (l : 129) : EO = 1 : 6, weight ratio} was obtained. Third, under the same conditions, PO was added to the reactor, which contained SP16, SP161, and SP165, SP1613, and SP1617 were obtained, respectively. For example, SP161 indicates SP (1 : 129) : EO : PO = 1 : 6 : 1, weight ratio).

The HLB values of the surfactants calculated from the Griffin function [23] and relative percentage contents (RPC) of EO in each surfactant are listed in Table I.

2. Methods

A Beckman 9800 scintillation detector was used to measure the concentrations of isotopic labeled nonionic surfactants in this study. The scintillating solution consisted of toluene (as solvent) 2,5-diphenyloxazole (as the first scintillant, 4 g/L) and 1,4-di-[2″-(5′-phenyloxazolyl)]-benzene (as the second scintillant, 0.2 g/L) [20–23].

3. Results and Discussion

A 10-mL portion of an aqueous solution of isotopic labeled nonionic surfactants (0.1 mg/L, below their CMCs) and β-CD in varying concentrations was equilibrated with 10 mL CCL$_4$ in a 25-mL flask for 4 days. The organic phase was separated from the pre-equilibrated phases, and a 1-mL aliquot of organic phase was added to the sample cell which containing 9 mL scintillating solution, and the prepared solutions were stored in cool and dark conditions until measurement. Using the expression P (the partition coefficient) $= M^w/M^o = M^t - M^o/M^o (M^t, M^o$ and M^w are the total amount of surfactant in this system, the amount in the organic phase and aqueous phase, respectively), we obtained the partition coefficients under different conditions (see Table II).

The determination of association constants of nonionic surfactants with cycloclextrin by partition coefficient is based on the increase in P with increasing cyclodextrin concentration. In most studies concerning inclusion complex formation between surfactant and cyclodextrin, a 1 : 1 stoichiometry was assumed,

$$S + CD \rightleftharpoons S \cdot CD \qquad K_a = \frac{[S \cdot CD]}{[S][CD]} \tag{1}$$

Table II. Effect of β-CD on the partition coefficient $(P_t)^a$ of the triblock polyether nonionic surfactants

Surfactants		Concentration of β-CD (mmol/L)						
		0	0.8513	0.9125	0.9502	0.9779	1.000	1.018
SP161	(30 °C)	0.1251	0.3739	0.3918	0.4029	0.4110	0.4174	0.423
	(35 °C)	0.1312	0.3802	0.3980	0.4091	0.4172	0.4237	0.4290
	(40 °C)	0.1391	0.3974	0.4158	0.4273	0.4358	0.4425	0.4480
SP165	(30 °C)	0.1014	0.3373	0.3543	0.3648	0.3725	0.3786	0.3837
	(35 °C)	0.1152	0.3661	0.3842	0.3953	0.4035	0.4100	0.4154
	(40 °C)	0.1243	0.3826	0.4012	0.4126	0.4210	0.4278	0.4334
SP1613	(30 °C)	0.0831	0.4382	0.4637	0.4792	0.4910	0.5002	0.5086
	(35 °C)	0.1073	0.5246	0.5546	0.5728	0.5867	0.5976	0.6075
	(40 °C)	0.1211	0.5517	0.5826	0.6013	0.6157	0.6269	0.6372
SP1617	(30 °C)	0.0714	0.4228	0.4479	0.4629	0.4728	0.4843	0.4919
	(35 °C)	0.0961	0.5199	0.5502	0.5684	0.5827	0.5940	0.6033
	(40 °C)	0.1193	0.5873	0.6208	0.6409	0.6567	0.6692	0.6795

[a] The values are the averages of six determinations. Error limits are 0.045%.

where S, CD, S · CD, and K_a are the surfactant, the cyclodextrin, the inclusion complex (1 : 1), and the association constant, receptively. However, more information about the stoichiometry of the complexes formed is available from the following:

$$[S]_{aqu} \rightleftharpoons [S]_{org} \qquad P_o = \frac{[S]_{aqu}}{[S]_{org}} \tag{2}$$

$$[S]_{aqu} + \alpha CD \leftrightarrow S \cdot CD_\alpha$$

$$K_a = \frac{[S \cdot CD_\alpha]}{[S]_{aqu}[CD]^\alpha} = \frac{[S \cdot CD_\alpha]}{P_o[S]_{org}[CD]^\alpha}. \tag{3}$$

Here, α is the stoichiometric ratio between the surfactant and the cyclodextrin, P_o is the partition coefficient between water and the organic phase and K_a is the association constant. The measured partition coefficient can be divided into one part describing the partitioning in the cyclodextrin:

$$P_t = P_o + \frac{[S \cdot CD_\alpha]}{[S]_{org}}, \qquad P_t = \frac{[S]_{aqu} + [S \cdot CD_\alpha]}{[S]_{org}}; \tag{4}$$

P_t is the partition coefficient of the surfactant between an aqueous solution of cyclodextrin and the organic phase.
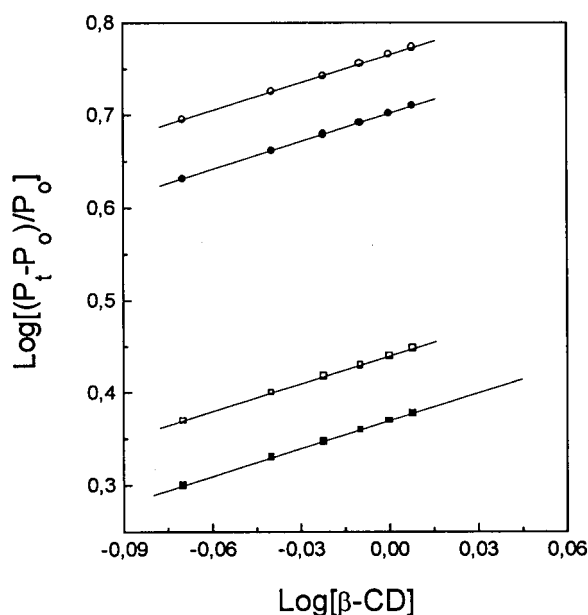
Figure 1. Log$((P_t - P_o)/P_o)$ vs. log[β-CD]. Plot of Equation (5) for the determination of the stoichiometry and association constant between surfactants and β-CD at 30 °C (■: SP161; □: SP165; ●: SP16; ○: SP1617).

If we rearrange Equation (4), inserting it into Equation (3), and converting it into the logarithmic form we get

$$\log\left(\frac{P_t - P_o}{P_o}\right) = \log K_a + \alpha \log[CD]. \tag{5}$$

Plotting the term on the left in Equation (5) against the logarithm of the total concentration of β-CD gives a straight line for four surfactants (see Figures 1–3). From the slope we get the stoichiometric ratio α which is in all cases one. This means that the surfactants form only 1 : 1 inclusion complexes with β-CD under the given experimental conditions. K_a can be evaluated from the y-intercept. Since the cyclodextrin concentration was given in mmol/L, K_a must be multiplied by a factor 1000 to give the results in Table III.

The formation constants between β-CD and isotopic labeled triblock polyether nonionic surfactants were also investigated at 35 and 40 °C, and the results are listed in Table III.

Figures 1–3 illustrate that the smaller the HLB values of triblock polyether surfactants, the greater the association constants with β-CD. These results mean that the HLB values and content of EO affect the association constants of surfactant with β-CD. It is also found that the association constant is higher at the lower temperatures (see Table III).
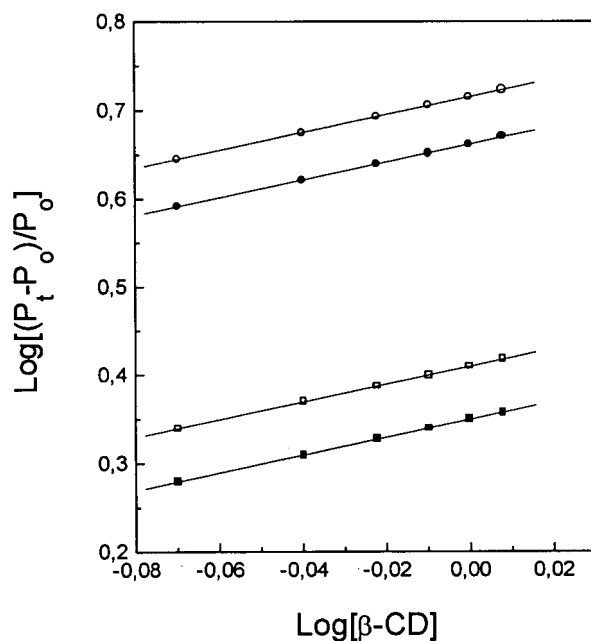
Figure 2. $\text{Log}((P_t - P_o)/P_o)$ vs. $\log[\beta - \text{CD}]$. Plot of Equation (5) for the determination of the stoichiometry and association constant between surfactants and β-CD at 35 °C (■: SP161; □: SP165; ●: SP16; ○: SP1617).
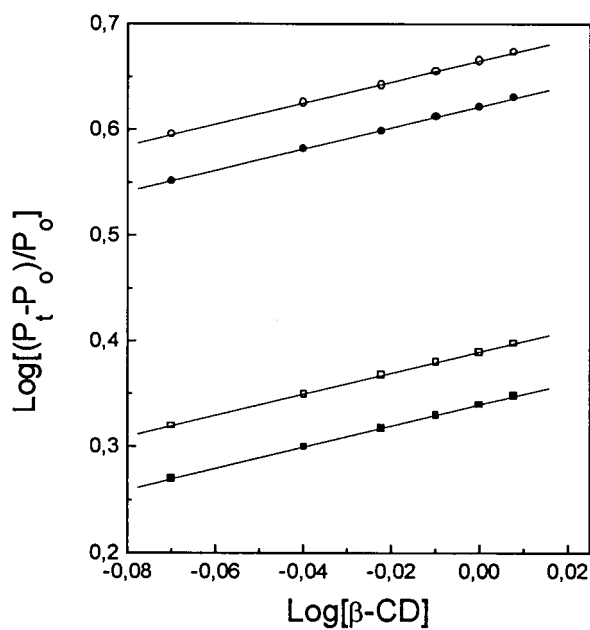

Figure 3. $\text{Log}((P_t - P_o)/P_o)$ vs. $\log[\beta - \text{CD}]$. Plot of Equation (5) for the determination of the stoichiometry and association constant between surfactants and β-CD at 40 °C (■: SP161; □: SP165; ●: SP16; ○: SP1617).

Table III. Association constants (K_a)[a], stoichiometric ratios (α)[b] and intercepts[b] for inclusion complexes of β-CD with the triblock polyether nonionic surfactants

Systems	30 °C			35 °C			40 °C		
	K_a	α	Int	K_a	α	Int	K_a	α	Int
SP161 + β-CD	2339 ± 42	0.98	0.3690	2234 ± 35	1.01	0.3490	2183 ± 33	1.00	0.3361
SP165 + β-CD	2748 ± 31	0.99	0.4389	2565 ± 41	1.02	0.4088	2450 ± 31	1.07	0.3846
SP1613 + β-CD	5029 ± 45	1.08	0.7015	4586 ± 45	1.12	0.6623	4183 ± 44	1.09	0.6211
SP1617 + β-CD	5818 ± 39	1.12	0.7648	5185 ± 36	1.13	0.7139	4622 ± 43	1.10	0.6651

[a] The standard state is 1 mol/L.
[b] The slopes (stoichiometric ratios) and the intercepts are averages of six determinations. Error limits are 0.050%.

4. Conclusion

The interaction of β-CD with surfactant can be determined by partition coefficient measurements. Adding β-CD to a solution of isotopic labeled nonionic surfactant results in an increase in partition coefficients of surfactants between the aqueous phase and $CC\beta_4$. This indicates that the surfactants and β-CD form inclusion complexes in the aqueous phase. The association constants and stoichiometric ratios have been determined. The results demonstrate that the stoichiometric ratios $\alpha \approx 1$ and the association constants are dependent on the HLB values of the surfactants. For the same surfactant, the association constant with β-CD is greater at lower temperatures.

References

1. J. Szejtli: *Cyclodextrins and their Inclusion Complexes*. Academia Kiado, Budapest (1982).
2. J. Szejtli: *Cyclodextrin Technology*. Kluwer Academic Press, Dordrecht (1988).
3. J. Szejtli: *Inclusion Compounds*, Vol. III, p. 331. Academic Press, London/San Diego (1984).
4. T. Okubo, H. Kitano, and N. Ise: *J. Phys. Chem.* **80**, 2661 (1976).
5. J. Georges and S. Desmettre: *J. Colloid Interface Sci.* **118**, 192 (1987).
6. D.J. Jobe, R.E. Verall, R. Palepu, and V. Reinsborough: *J. Phys. Chem.* **92**, 3582 (1988).
7. R. Palepu, J.E. Richardson, and V.C. Reinsborough: *Langmuir* **5**, 218 (1989).
8. T. Okubo, Y Maeda, and H. Kitano: *J. Phys. Chem.* **93**, 3721 (1989).
9. K.J. Sakaki, S.D. Chrisian, and E.E. Tucker: *J. Colloid. Interface Sci.* **134**, 412 (1990).
10. W.C. Cromwell, K. Bystrom, and M.R. Eftink: *J. Phys. Chem.* **89**, 326 (1985).
11. W. Guo, B.M. Fung, and S.D. Christian: *Langmuir* **8**, 446 (1992).
12. V.K. Smith, T.T. Ndou, A.M. DeLaPena, and I.M. Warner: *J. Incl. Phenom.* **l0**, 471 (1991).
13. Q.X. Guo, Z.Z., Li, T. Ren, X.Q. Zhou, and Y.C. Liu: *J. Incl. Phenom.* **17**, 149 (1994).
14. V.K. Smith and T.T. Ndou: *Applied Spectrosc.* **46**, 659 (1992).
15. U.R. Dharmawardana, S.D. Christian, E.E. Tucker, R.W. Tayor, and J.F. Scamehorn: *Langmuir* **9**, 2258 (1993).
16. M. Tuncay and S.D. Christian: *J. Colloid Interface Sci.* **167**, 181 (1994).
17. R.-H. Lu, J.C. Hao, H.Q. Wang, and L.H. Tong: *J. Colloid interface Sci.* **192**, 37 (1997).
18. J. Andreaus, J. Draxler, and A. Hermetter: *J. Colloid. Interface Sci.* **l93**, 8 (1997).
19. Y. Nakar, K. Yamamoto, K. Terada, and H. Horibe: *Chem. Pharm. Bull.* **30**, 1796 (1982).

20. A. Dayer: *An Introduction to Liquid Scintillation Counting*. Heyden & Son, London (1974).
21. M. Tschurlovits, V. Rajner, and D. Rank: *Appl. Radiat. Isot.* **42**, 891 (1990).
22. J.-T. Bu, W.-H. Chen, Z.-X. Wen, and Q.-J. Xue: *J. Disp. Sci. and Technol.* **19**, 535 (1998).
23. W.C. Griffin: *J. Soc. Cosmetic Chemists* **1**, 311 (1949).