A Volumetric Study of β-Cyclodextrin/Hydrocarbon and β-Cyclodextrin/Fluorocarbon Surfactant Inclusion Complexes in Aqueous Solutions

Lee D. Wilson and Ronald E. Verrall*

Department of Chemistry, Thorvaldson Building, University of Saskatchewan, 110 Science Place, Saskatoon, SK S7N 5C9 Canada

Received: April 30, 1997; In Final Form: August 5, 1997[⊗]

The apparent molar volumes ($V_{\phi,S}$) of a homologous series of hydrocarbon (hc) ($C_xH_{2x+1}CO_2Na$, $x = 2$, 5−9, 11, 13) and perfluorocarbon (fc) ($C_xF_{2x+1}CO_2Na$, $x = 1$, 3, 4, 6−9) surfactants (S) have been determined in water and in binary solvent (H_2O + β-cyclodextrin (β-CD)) systems at 25 °C. The apparent molar volumes of β-CD ($V_{\phi,CD}$) in water and in binary (H_2O + S) systems containing hc and fc surfactants have also been obtained. The results show that the magnitudes of $V_{\phi,S}$ and $V_{\phi,CD}$ are greater in ternary solutions than in the binary aqueous systems. The apparent molar volumes at infinite dilution (V_ϕ°) of β-CD and of the surfactants in ternary solutions are observed to depend on the following factors: (i) the magnitude of the binding constant (K_i), (ii) the alkyl chain length of the surfactant, (iii) the mole ratio of the host to guest species, (iv) the host/guest stoichiometry, and (v) the physicochemical properties of the surfactant. The volumetric properties of the ternary systems have been analyzed in terms of the complexed and uncomplexed species by application of Young's rule. The formation of β-CD/surfactant complexes having 1:1 and 1:1 plus 2:1 stoichiometries were successfully modeled using two-site and three-site models, respectively.

Introduction

Cyclodextrins (CDs) have attracted considerable interest because of their ability to form stable inclusion complexes with a wide variety of inorganic and organic guest molecules in aqueous solution.[1,2] The hydrophobic effect has been implicated as one of the key factors contributing to the relatively strong, noncovalent complexes that are formed between β-CD and apolar guest molecules.[3] β-CD shows amphiphilic[4] character due to an apolar cavity and a hydrophilic annulus consisting of a number of hydroxyl groups. Consequently, unusual solvation effects may occur and, indeed, have been reported in studies of β-CD/guest complexes in mixed (water/organic) solvents.[5] X-ray studies[6] of β-CD hydrate indicate that the cavity interior contains several water molecules that are often referred to as being "high energy" or "entropically unfavorable" because of an incomplete intermolecular hydrogen-bonding network. Interfacial studies have shown that water next to an interface possesses different properties from that in the bulk phase.[7] However, the critical role played by the hydration sheath of β-CD and other oligosaccharides during complex formation is still not fully understood. Lemieux et al.[8] have proposed that the "polar-gate" mechanism is a useful model for describing intermolecular interactions between carbohydrates and proteins. They argue that the hydrophilic/lipophilic balance of a carbohydrate can be modified by a conformational change of the sugar ring which alters the degree of intramolecular H-bonding. Ultrasonic relaxation studies[9] indicate that the conformational mobility of the pyranosyl rings of β-CD increases upon inclusion of a guest molecule due to disruption of interglycosidic H-bonding. In a recent thermodynamic and NMR investigation of β-CD, Marini et al.[10] proposed that some type of "relaxational" process was involved in the dehydration of β-CD. It is apparent from these reports that host/guest complex formation in aqueous solution should occur with extensive desolvation and resolvation of the host, guest, and complexed species. Consequently, a better understanding of solvation and the relative roles of solute−solute and solute−solvent interactions in these systems should provide improved insight into the processes that lead to the formation of these strongly bound, noncovalent complexes.

SCHEME 1: Solvation, Desolvation, and Solvent Reorganization Processes Associated with the Formation of Host/Guest Complexes of Various Stoichiometries in Aqueous Media[a]

$$\beta\text{-CD} \cdot n H_2O + S \cdot m H_2O \overset{K_{1:1}}{\rightleftharpoons} \beta\text{-CD/S} \cdot r H_2O + H_2O_{n+m-r}$$

$$2\,\beta\text{-CD} \cdot n H_2O + S \cdot m H_2O \overset{K_{2:1}}{\rightleftharpoons} \beta\text{-CD}_2\text{/S} \cdot p H_2O + H_2O_{2n+m-p}$$

[a] β-CD = β-cyclodextrin and S = surfactant.

Volumetric studies have been shown to provide useful information concerning the role of solvent in biochemical and physicochemical processes, for example, protein folding,[11] DNA−ligand interactions,[12] and micelle formation and solubilization[13] of third components. The process of forming CD/inclusate complexes resembles several important biochemical processes such as antigen−antibody, DNA−ligand, enzyme−substrate, and protein−carbohydrate binding.[5] Scheme 1 is a generalized description of the hydration changes that can occur due to the formation of host/guest complexes of different stoichiometries. It is apparent that macroscopic volume changes occurring during the complexation process should contain information which may be used to assist in the elucidation of the relative contributions of molecular level solvation phenomena, such as the hydrophobic effect and cooperative solvent effects. Notwithstanding these facts, there have been only a few volumetric studies of CD/inclusate complexes.[14−18]

This paper presents the results of a comprehensive apparent molar volume study of the complexes formed between β-CD and a homologous series of hydrocarbon (hc) ($C_xH_{2x+1}CO_2Na$, $x = 2$, 5−9, 11, 13) and fluorocarbon (fc) ($C_xF_{2x+1}CO_2Na$, $x =$ 1, 3, 4, 6−9) surfactants (S), in the premicellar region, using

* To whom correspondence should be addressed. Telephone: 306-966-4669. Facsimile: 306-966-4730. E-mail: Verrallr@sask.usask.ca.

[⊗] Abstract published in *Advance ACS Abstracts,* October 1, 1997.

S1089-5647(97)01460-0 CCC: $14.00

high-precision density data. The apparent molar volumes of the guest and host species have been determined in both water and in ternary (H_2O + CD + S) aqueous solutions. The study of a homologous series of surfactants of increasing alkyl carbon chain length (n_x) provides an opportunity to analyze the degree of expulsion of water from the β-CD cavity as well as to ascertain the relative degree of carbon chain coiling within β-CD as n_x increases in each homologous series of surfactant. The latter may be inferred from a comparison of the results for the two surfactant series since fc chains usually exist in an all-trans conformation, whereas hc chains do not. Finally, the utility of applying model equations, based on Young's rule,[19] to account for the volumetric behavior of the CD/S complexes of different stoichiometries is assessed.

Experimental Section

Instrumentation. Density measurements were carried out with a high-precision densimeter (Model O2D Sodev Inc.). Temperature control to 25 ± 0.001 °C was maintained by using a closed loop Sodev temperature controller (Model CT-L, Sodev Inc.). The densimeter was calibrated by using the densities of water (0.997047 g cm^{-3})[20] and nitrogen gas[21] as primary standards. The estimated precision in the density measurements was found to be $\pm 2 \times 10^{-6}$ g cm^{-3} or better.

Materials. The water content of β-CD was determined using a Karl Fischer titration procedure and was taken into account in the calculation of concentrations. β-CD (Aldrich) was twice recrystallized from Millipore water, but no difference in the density data was detected compared to that of unpurified β-CD. As well, reproducible apparent molar volume (AMV) data were obtained using β-CD from different lot numbers. The majority of hc surfactants ($C_xH_{2x+1}CO_2Na$, x = 2, 5−9, 11, 13) (99%) were obtained as sodium salts from Sigma except for the heptanoic (Sigma) and nonanoic (BDH) compounds which were prepared by converting the acids to the sodium salts using standard procedures. These salts were recrystallized from acetone/methanol mixtures and washed in a Soxhlet extractor with acetone. All fc surfactants ($C_xF_{2x+1}CO_2Na$, x = 1, 3, 6−9) were obtained as the acid (Fluorochem, 99%), converted to the sodium salt, and recrystallized from methanol/chloroform mixtures. The salts were dried to constant weight in a vacuum at 50 °C. The water used to make solutions was obtained from a Millipore-Super-Q system, and the solution pH was adjusted to 10.5 with NaOH to minimize protonation of the carboxylate anion ($pK_b \approx 9$) and dissociation of the β-CD hydroxyl protons ($pK_a \approx 12$).[1]

Models and Calculations. AMV data were calculated using the following expression

$$V_\phi = \frac{M}{d} - \frac{10^3(d - d_0)}{mdd_0} \quad (1)$$

where d and d_0 are the densities of the solution and solvent, respectively, M is the relative molar mass of solute, and m is the concentration in molality units. The solvent in the binary solutions is water (W) whereas in ternary solutions it is either (W + S) or (W + CD). For the determination of $V_{\phi,S}$ in ternary systems, the binary solvent was 0.013 m β-CD and the concentration of surfactant (C_S) was varied but always kept below the critical micelle concentration (cmc). A choice of 0.013 m β-CD was made because of the limited water solubility of β-CD and to allow for the investigation of a sufficient range of C_S below the 1:1 host/guest ratio. In the case of the determination of $V_{\phi,CD}$ in ternary systems, the binary solvent (W + S) consisted of a fixed C_S, where $C_S \leq$ cmc, and the concentration of β-CD (C_{CD}) was varied. All stock solutions were freshly prepared by weight and serially diluted. The error bars shown for AMV data represent the sum of estimated errors in solution density (δd) and concentration (δm). In ternary solutions, error arising from the uncertainty in the density of the binary solvent (δd_0) was also taken into account.

TABLE 1: Apparent Molar Volume Data for Sodium Alkyl Carboxylates in Water and Aqueous β-CD Solutions at pH 10.5 and 298 K

surfactant	$V^\circ_{\phi,S}$ (cm^3 mol^{-1}) water	$V^\circ_{\phi,S}$ (cm^3 mol^{-1}) aqueous β-CD[a]	$\Delta V^\circ_{\phi,S}$ (cm^3 mol^{-1})[b]
$C_3H_5O_2Na$, SP	53.8	53.9	≈0
$C_6H_{11}O_2Na$, SHex	100.9	110.2	9.3
$C_7H_{13}O_2Na$, SHep	116.6	130.7	14.1
	116.8[c]		
$C_8H_{16}O_2Na$, SO	133.0	151.2	18.2
	132.4[c]		
$C_9H_{17}O_2Na$, SN	148.6	170.3	21.7
	148.3[c]		
$C_{10}H_{19}O_2Na$, SDec	165.1	188.6	23.5
	164.2[c]		
$C_{12}H_{23}O_2Na$, SDodec	196.9	225.0	28.1
	195.8[d]		
$C_{14}H_{27}O_2Na$, ST	226.7	270.0	43.3
	226.4[c]		

[a] Concentration of aqueous β-CD approximately 1.3×10^{-2} m in all cases. [b] $\Delta V^\circ_S = V^\circ_{\phi,S}(\beta\text{-CD(aq)}) - V^\circ_{\phi,S}(\text{water})$. [c] Reference 39. [d] Reference 40.

The volumetric contributions for complexes exhibiting different stoichiometries were estimated by using model equations based on Young's rule,[19] as shown below.

$$V_\phi = X_d V_{\phi,d} + X_{1:1} V_{\phi,1:1} \quad (2)$$

$$V_\phi = X_d V_{\phi,d} + X_{1:1} V_{\phi,1:1} + X_{2:1} V_{\phi,2:1} \quad (3)$$

where X_d, $X_{1:1}$, and $X_{2:1}$ are the mole fractions of the dispersed component (surfactant or β-CD), 1:1 complex, and 2:1 complex, respectively, and $V_{\phi,d}$, $V_{\phi,1:1}$, and $V_{\phi,2:1}$ are the AMV of the dispersed species, 1:1 complex, and 2:1 complex, respectively. Equations 2 and 3 represent the two-site (2-S) and three-site (3-S) models which can be cast in terms of either $V_{\phi,S}$ or $V_{\phi,CD}$, and the equilibrium binding constants ($K_{1:1}$ and $K_{2:1}$) can be related to the mole fractions of the dispersed and complexed species through standard equilibrium relations. The simulation of volumetric data for ternary solutions was carried out using a nonlinear least-squares (NLLS) fitting program employing a Marquardt−Levenberg algorithm. K_i and $V_{\phi,i}$ were used as adjustable parameters whereas $V_{\phi,d}$ was estimated from experimental AMV data at infinite dilution in water. In the 3-S model, the Newton−Raphson method was employed to obtain the concentration of dispersed species.[22] The "best fit" of the experimental data was obtained by minimizing the sums of the squares of the residuals (SSR), $SSR = \sum_i[(V_{\phi,calc})_i - (V_{\phi,expt})_i]^2$, where $V_{\phi,calc}$ and $V_{\phi,expt}$ are the calculated (according to eqs 2 or 3) and experimental AMV, respectively. Estimates of the AMV at infinite dilution for β-CD and surfactants in water were obtained from linear least-squares regression analysis of AMV against concentration or square root of the concentration, respectively.

Results and Discussion

Surfactant Volumes: $V_{\phi,S}$. Tables 1 and 2 show the abbreviations used for the various hc and fc surfactants, respectively, and the values obtained for their apparent molar volumes at infinite dilution ($V^\circ_{\phi,S}$) in H_2O and 0.013 m aqueous β-CD.

TABLE 2: Apparent Molar Volume Data for Perfluorinated Sodium Alkyl Carboxylates in Water and Aqueous β-CD Solutions at pH 10.5 and 298 K

surfactant	$V^\circ_{\phi,S}$ ($cm^3\ mol^{-1}$) in H_2O	$V^\circ_{\phi,S}$ ($cm^3\ mol^{-1}$) β-CD[a]	$\Delta V^\circ_{\phi,S}$ ($cm^3\ mol^{-1}$)[b]
$C_2F_5O_2Na$, SPFA	56.9	60.8	3.9
	57.2[c]		
	57.28[e]		
$C_4F_7O_2Na$, SPFB	104.7	117.7	13.0
	104.9[c]		
	105.00[e]		
$C_5F_9O_2Na$, SPFP	128.5	142.9	14.4
	128.5[c]		
$C_7F_{13}O_2Na$, SPFH	175.9	196.7	20.8
	175.9[c]		
$C_8F_{15}O_2Na$, SPFO	200.6	225.1	24.5
	199.3[c]		
	199.23[e]		
$C_9F_{17}O_2Na$, SPFN	225.1	260.0	34.9
	225 ± 2[d]		
$C_{10}F_{19}O_2Na$, SPFD	249.0[f]	290.0	41.0

[a] Concentration of aqueous β-CD approximately 1.3×10^{-2} *m* in all cases. [b] $\Delta V^\circ_S = V^\circ_{\phi,S}(\beta\text{-CD(aq)}) - V^\circ_{\phi,S}(\text{water})$. [c] Reference 41. [d] Reference 42. [e] Reference 43. [f] Extrapolated from density data at concentrations from 0.5−2.0 m*m*.

TABLE 3: Group Contributions to the van der Waals Volume (V_W), Molar Volume (V_M),[a] and the Apparent Molal Volume at Infinite Dilution[b] (V°_ϕ) for *n*-Alkyl Fluorocarbon and Hydrocarbon Compounds at 298 K

group	V_W ($cm^3\ mol^{-1}$)	V_M[a] ($cm^3\ mol^{-1}$)	$V^{\circ b}_\phi$ ($cm^3\ mol^{-1}$)
CH_3	13.7[c]	32.7[e]	26.2[c]
			27.1[g]
CH_2	10.2[c]	16.2[d]	15.7[c]
			15.7[g]
CF_3	21.3[c]	55.7[d]	39.1[c]
			45.7[g]
CF_2	15.3[c]	22.9[d]	23.6[c]
			23.9[g]
			23.57[h]
COO^-	12.2[c]	21.8[f]	17.8[c]
Na^+	1.25[f]		−6.6[c]

[a] Calculated from density data of neat alkane and perfluoroalkane liquids. [b] Obtained from density measurements in water at 298 K. [c] Reference 44. [d] Reference 45. [e] Reference 46. [f] Reference 47. [g] Obtained in this work using V°_ϕ for Na^+ and COO^- shown above. [h] Reference 43.

Table 3 shows a compilation of van der Waals volume (V_W), molar volume (V_M), and the AMV at infinite dilution (V°_ϕ) in water for some molecular groups and ions obtained from the literature and in this study. The transfer volume at infinite dilution, ΔV°_S, of a surfactant from water to 0.013 *m* β-CD is defined by eq 4.

$$\Delta V^\circ_S(\text{W}\rightarrow\text{W+CD}) = V^\circ_{\phi,S}(\beta\text{-CD})_{aq} - V^\circ_{\phi,S}(H_2O) \quad (4)$$

An analogous relation can be defined for the transfer volume of β-CD, $\Delta V^\circ_{CD}(\text{W}\rightarrow\text{W+S})$. The transfer quantities can be interpreted in terms of the relative change in solvation that occurs upon complex formation. Positive values of ΔV°_S (Tables 1 and 2) are consistent with the fact that inclusion complexes are formed since the process involves the transfer of carbon chain segments from an aqueous to an apolar environment (cf. Table 3).[11] However, sodium propionate (SP) is an example of an inclusate that does not appear to form an inclusion complex with β-CD under these conditions since $\Delta V^\circ_S \approx 0$ (see Table 1).

The values of V°_ϕ in Tables 1 and 2 for hc and fc sodium carboxylate salts in water show an average incremental volume change at infinite dilution per CH_2 and CF_2 group of 15.7 and 23.9 $cm^3\ mol^{-1}$, respectively. Both values are in good agreement with literature data reported in Table 3. By comparison, the infinite dilution incremental volume values per CH_2 and CF_2 groups in 0.013 *m* β-CD are approximately 18.3 and 27.2 $cm^3\ mol^{-1}$, respectively. Therefore, the infinite dilution transfer volume for CH_2 and CF_2 from water to aqueous 0.013 *m* β-CD is 2.6 and 3.3 $cm^3\ mol^{-1}$, respectively. Using the values of V°_ϕ for COO^- and Na^+ in Table 3 and the AMV for CH_2 and CF_2 groups determined above, estimates of 27.1 and 45.7 $cm^3\ mol^{-1}$ were obtained for V°_ϕ of CH_3 and CF_3, respectively. The ratio of the CF_2/CH_2 volume data estimated above is very similar to the ratio of the volume changes of micellization, $\Delta V^{mic}(fc) \approx 1.5\Delta V^{mic}(hc)$,[31] and is consistent with the relative size and hydrophobicity of these groups.

Semiquantitative estimates of $\Delta V^\circ_S(\text{W}\rightarrow\text{W+CD})$ were calculated by utilizing the group contributions in Table 3 and comparing with the experimental transfer volumes shown in Tables 1 and 2. The method, based on the use of eq 5, utilizes V_W and V°_ϕ data from Table 3 and assumes the following: *y* methylene groups and a methyl group of the surfactant can be included in the CD interior, and *z* water molecules are expelled from the β-CD cavity during the inclusion process; the carbon chain within the cavity is unsolvated; and neither the COO^- nor Na^+ ions are included within the β-CD interior.

$$\Delta V^\circ_S(\text{W}\rightarrow\text{W+CD}) = [yV_W(CH_2) + V_W(CH_3) + zV(H_2O)] - [yV^\circ_\phi(CH_2) + V^\circ_\phi(CH_3)] \quad (5)$$

For example: $\Delta V^\circ_{SHex}(\text{W}\rightarrow\text{W+CD}) = [3(10.2) + 13.7 + 2(18.0)] - [3(15.7) + 27.1] = 6.1\ cm^3\ mol^{-1}$; ΔV°_{SDec} is 20.1 $cm^3\ mol^{-1}$ with $y = 7$ and $z = 4$; ΔV°_{SPFB} is 12.4 $cm^3\ mol^{-1}$ with $y = 2$ and $z = 3$; and ΔV°_{SPFH} is 22.2 $cm^3\ mol^{-1}$ with $y = 4$ and $z = 4.5$ (SHex = sodium hexanoate, SDec = sodium decanoate, SPFB = sodium perfluorobutyrate, SPFH = sodium perfluoroheptanoate). In each case reasonable agreement is obtained with the experimental transfer volume results listed in Tables 1 and 2, although the predicted number of expelled water molecules (*z*) seems low in view of available crystallographic data.[23] However, a closer examination of Figure 1 in ref 23 reveals that 4−5 water molecules reside within the hydrophobic core of β-CD and the remainder are located in the hydrophilic annular region and interstices of the crystal lattice. Therefore, it appears that the displacement of $z = 4-5$ water molecules from the hydrophobic interior may contribute to the observed transfer volumes due to the significant difference in environment that exists betweeen the bulk and CD interior. On the other hand, the interfacial hydration water does not seem to contribute a significant change in volume upon being displaced to the bulk solvent. Independent measurements of AMV were made for the host and guest species of the α-CD/SPFO (SPFO = sodium perfluorooctanoate) system to test this hypothesis. According to a previous ^{19}F NMR study,[24] α-CD/SPFO does not form an inclusion complex due to the small diameter of the α-CD macrocycle. Consequently, the interfacial complex that is formed occurs between the annular hydroxyl groups and the fc chain. The magnitude of ΔV° for α-CD/SPFO is small (ca. 2 $cm^3\ mol^{-1}$), which provides further support that it is the number of included water molecules that is important when applying the additivity scheme, eq 5.

The small differences that still exist between the experimental and calculated transfer volumes may be due to the inherent simplicity of the above additivity method. In applying eq 5, no provision was made for factors such as the inclusion mode, stoichiometry of the CD/S complex, and carbon chain coiling of the surfactant, all of which may affect hydration character-

TABLE 4: 1:1 and 2:1 Binding Constants (K_i) for β-CD/Surfactant Systems Obtained from the Simulation[a,b] of Apparent Molal Volume Data of the Surfactant in Ternary Aqueous Solutions[c] at 298 K

surfactant	$K_{1:1}$ (kg mol^{-1}) this work	$K_{1:1}$ (L mol^{-1}) literature[d]	$K_{2:1}$ (kg^2 mol^{-2}) this work
$C_3H_5O_2Na$	≈ 0	≈ 0	N/A[e]
$C_6H_{11}O_2Na$	$6.97 \pm 1.83 \times 10^1$	$5.5 \pm 0.7 \times 10^1$	N/A
$C_7H_{13}O_2Na$	$1.93 \pm 0.188 \times 10^2$	$2.2 \pm 0.3 \times 10^2$	N/A
$C_8H_{16}O_2Na$	$6.22 \pm 0.388 \times 10^2$	$6.6 \pm 0.8 \times 10^2$	N/A
$C_9H_{17}O_2Na$	$1.59 \pm 0.892 \times 10^3$	$2.2 \pm 0.3 \times 10^3$	N/A
$C_{10}H_{19}O_2Na$	$2.14 \pm 1.94 \times 10^3$	$5.1 \pm 0.6 \times 10^3$	N/A
$C_{12}H_{23}O_2Na$	$2.80 \pm 1.40 \times 10^4$	$1.6 \pm 0.2 \times 10^4$	$2.15 \pm 1.08 \times 10^2$
$C_{14}H_{27}O_2Na$	$3.50 \pm 1.75 \times 10^4$	$4.8 \pm 0.6 \times 10^4$	$3.00 \pm 1.50 \times 10^2$
$C_2F_3O_2Na$	$1.00 \pm 0.850 \times 10^2$		N/A
$C_4F_7O_2Na$	$1.70 \pm 0.384 \times 10^2$	$2.8 \pm 0.4 \times 10^2$	N/A
$C_5F_9O_2Na$	$1.64 \pm 0.260 \times 10^3$	$2.6 \pm 0.3 \times 10^3$	N/A
$C_7F_{13}O_2Na$	$8.75 \pm 6.60 \times 10^3$	$3.7 \pm 0.9 \times 10^4$	N/A
$C_8F_{15}O_2Na$	$1.00 \pm 0.500 \times 10^4$	$3.3 \pm 0.4 \times 10^5$	$1.20 \pm 0.600 \times 10^3$
$C_9F_{17}O_2Na$	$6.50 \pm 3.25 \times 10^4$	$9.4 \pm 1.2 \times 10^4$	$2.00 \pm 1.00 \times 10^3$
$C_{10}F_{19}O_2Na$	$7.00 \pm 3.50 \times 10^5$		$3.50 \pm 1.50 \times 10^3$

[a] Two-site model: $V_{\phi,S} = X_d V_{\phi,d} + X_{1:1} V_{\phi,1:1}$. [b] Three-site model: $V_{\phi,S} = X_d V_{\phi,d} + X_{1:1} V_{\phi,1:1} + X_{2:1} V_{\phi,2:1}$. [c] [$\beta$-CD] = 0.013 mol kg^{-1}. [d] Reference 26. [e] N/A indicates that 2:1 binding is not apparent under these experimental conditions.

istics arising from changes in polar/apolar vs apolar/apolar interactions of the surfactant. As well, volumetric contributions due to H-bond (solute−solvent and solvent−solvent) formation and the different nature of the hydrate water in the CD interior, bulk, and interfacial regions were not considered. Kharakoz[25] has estimated the volumetric contribution of H-bonding in water (cf. Table 2, ref 25) and its magnitude is such that it could make a contribution to the volume of complexation since the process involves extensive desolvation of the CD interior and the surfactant alkyl chain. Nevertheless, notwithstanding the simplistic nature of the scheme, the use of reasonable numbers for the alkyl groups and hydrate water molecules involved in the formation of the inclusion complex is seen to provide good estimates of the transfer volume.

Estimates of the binding constants (K_i) obtained from analysis of the volumetric data using the two- and three-site models are listed in Table 4 for all the hc and fc surfactant systems investigated in this study. Independent estimates of $K_{1:1}$ obtained from the spectral displacement technique[26] are included for comparison. Good agreement is observed despite differences in the nature and accuracy of each technique. For those surfactants which exhibit 2:1 binding, $K_{1:1} > K_{2:1}$, their values, typically, differ by 1−2 orders of magnitude. A similar difference in the magnitudes of $K_{1:1}$ and $K_{2:1}$ for CD/cationic and CD/anionic surfactants was determined from electromotive force (emf) studies.[27,28] The calculated values of $V_{\phi,i}$ are greater than $V_{\phi,d}$ and the former increase monotonically throughout the homologous series. The magnitudes of K_i and $V_{\phi,i}$ for the fc surfactant systems are systematically greater than those of the hc surfactants possessing similar alkyl chain length, and this can be attributed to their greater hydrophobicity.

Figure 1 illustrates a typical plot of $V_{\phi,S}$ and the mole fractions (X_i) of complexed (1:1) and dispersed surfactant vs $C_S^{1/2}$ for a short chain hc surfactant (SHex) bound to β-CD. In water, $V_{\phi,S}$ exhibits a slightly positive slope at low concentration, in agreement with the sign expected from the Debye Hückel limiting law for a 1:1 electrolyte. However, the amphiphilic nature of the salt should decrease the magnitude of the expected theoretical slope, and this is seen (Figure 1) to be the case. The concentration dependence of $V_{\phi,S}$ in ternary solutions follows a simple 2-S model (cf. eq 2). The magnitude of $V_{\phi,S}$ in the ternary system exceeds that in water, especially near infinite dilution, and decreases linearly with $C_S^{1/2}$ until the values at higher concentrations approach those obtained in water. This is due to the fact that the magnitude of the AMV of the 1:1 complex is greater than the dispersed surfactant and there is an increasing contribution from the unbound surfactant (X_d)

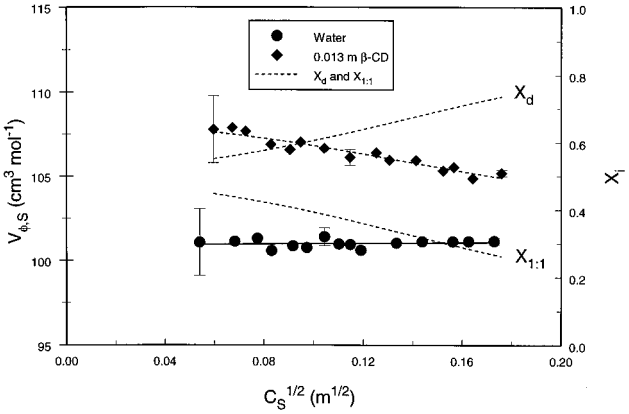


Figure 1. $V_{\phi,S}$ vs $C_S^{1/2}$ for sodium hexanoate (SHex) in water and 0.013 *m* β-CD at pH 10.5 and $T = 298$ K. X_d and $X_{1:1}$ vs $C_S^{1/2}$ are for SHex in 0.013 *m* β-CD.

component as the surfactant concentration increases. The dashed line through the data points in Figure 1 for SHex in 0.013 *m* β-CD corresponds to the best fit according to eq 2. The solid line through the data for SHex in water corresponds to the least-squares regression. The curves for $X_{1:1}$ and X_d in Figure 1 were derived using the value of $K_{1:1}$ listed in Table 4 and the same concentrations as for the ternary (W + S + CD) solution data. Figure 2 illustrates the sensitivity of the fitting process to values of the adjustable parameters ($K_{1:1}$ and $V_{\phi,1:1}$) for the ternary system shown in Figure 1. The solid line represents the best fit to the experimental data according to eq 2 when $K_{1:1} = 69.7$ kg mol^{-1} and $V_{\phi,1:1} = 115.8$ cm^3 mol^{-1}. The dashed lines (a−e) represent trial curves using various values of $K_{1:1}$ and $V_{\phi,1:1}$. Curves a−c represent changes in $K_{1:1}$ when $V_{\phi,1:1}$ is fixed at the best fit value whereas curves d and e represent changes in $V_{\phi,1:1}$ when $K_{1:1}$ is fixed at the best fit value. It is apparent that relatively small changes in either $K_{1:1}$ or $V_{\phi,1:1}$ dramatically alter the goodness of fit thereby illustrating the good sensitivity of the model.

Høiland et al. have successfully analyzed volumetric data of cation−crown ether complexes using a similar approach.[29] Unfortunately, in a previous study of CD/surfactant systems,[14] the analysis of volumetric data was complicated by the presence of micelle aggregates at the surfactant concentrations investigated. In the present work the surfactants have relatively high cmc values that allow data to be obtained over a sufficiently wide range of premicellar concentrations, and this avoids any complications arising from the presence of micelles.

Figures 3 and 4 are representative plots of $V_{\phi,S}$ vs $C_S^{1/2}$ for

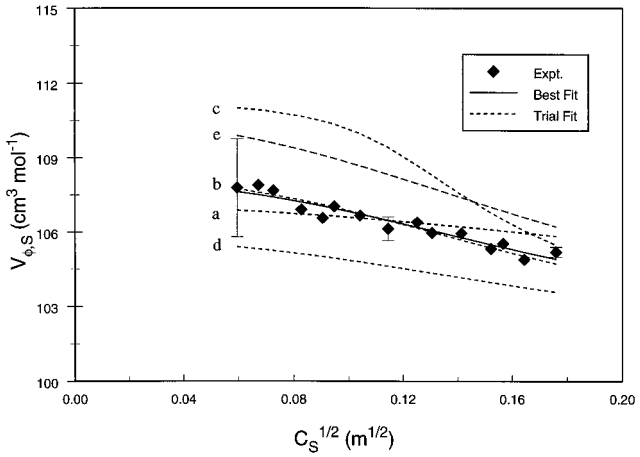


Figure 2. Experimental and simulated AMV data for sodium hexanoate (SHex) in 0.013 *m* β-CD at pH 10.5 and $T = 298$ K. Solid line represents the best fit ($K_{1:1} = 69.7$ kg mol^{-1} and $V_{\phi,1:1} = 115.8$ cm^3 mol^{-1}) according to the two-site model and the dashed curves (a−e) are trial fits using different estimates of $K_{1:1}$ and $V_{\phi,1:1}$: (a) $K_{1:1}$=10 kg mol^{-1}, (b) $K_{1:1} = 10^2$ kg mol^{-1}, (c) $K_{1:1} = 10^3$ kg mol^{-1}, (d) $V_{\phi,1:1} =$ 110.8 cm^3 mol^{-1}, and (e) $V_{\phi,1:1} = 120.8$ cm^3 mol^{-1}. The second parameter in curves a−e corresponds to the best fit values above.

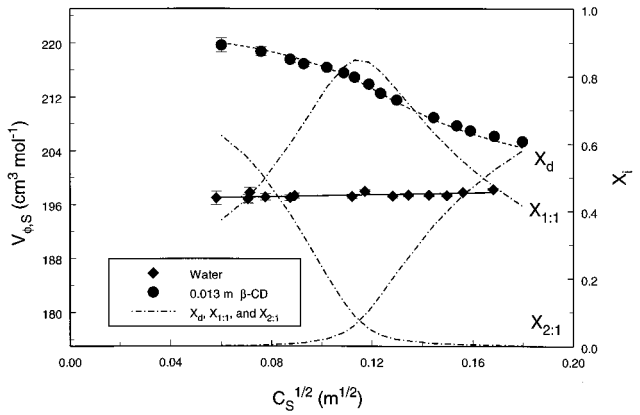


Figure 3. $V_{\phi,S}$ vs $C_S^{1/2}$ for sodium dodecanoate (SDodec) in water and 0.013 *m* β-CD at pH 10.5 and $T = 298$ K. X_d, $X_{1:1}$, and $X_{2:1}$ vs $C_S^{1/2}$ are for SDodec in 0.013 *m* β-CD.

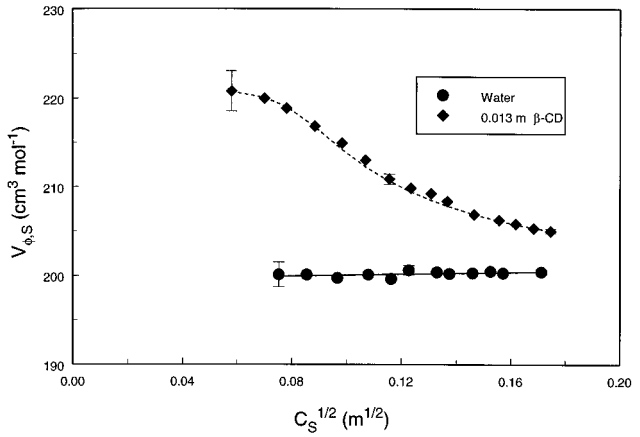


Figure 4. $V_{\phi,S}$ vs $C_S^{1/2}$ for sodium perfluorooctanoate (SPFO) in water and 0.013 *m* β-CD at pH 10.5 and $T = 298$ K.

longer chain hc (SDodec) and fc (SPFO) surfactants in water and 0.013 *m* β-CD, respectively. In Figure 3, the mole fractions (X_i) of the various species obtained from eq 3 are also plotted as a function of $C_S^{1/2}$. The qualitative features of these graphs are similar to those of Figure 1, however, the effect of increased carbon chain length is clearly evident as the magnitude of ΔV_S° is greater for the longer homologs compared to the shorter

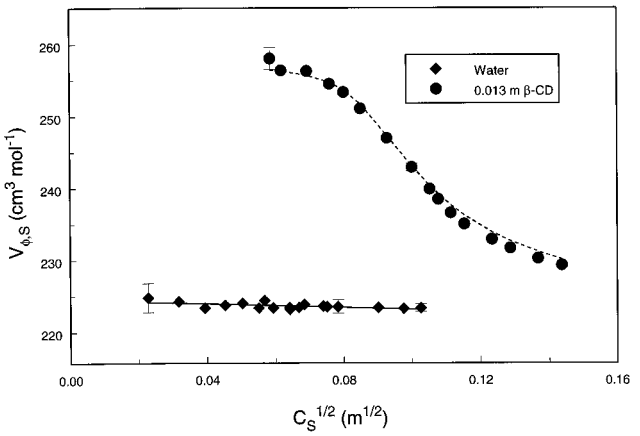


Figure 5. $V_{\phi,S}$ vs $C_S^{1/2}$ for sodium perfluorononanoate (SPFN) in water and 0.013 *m* β-CD at pH 10.5 and $T = 298$ K.

ones (cf. Tables 2 and 3). As well, the concentration dependence of $V_{\phi,S}$ vs $C_S^{1/2}$ becomes increasingly sigmoidal as n_x increases, consistent with an increase in K_i. The latter is more pronounced for fc surfactants than for hc surfactants and may be attributed to positive binding cooperativity between host and guest.[30,31] The dashed line through the data points for SPFO and SDodec (SDodec = sodium dodecanoate) in 0.013 *m* β-CD (Figures 3 and 4) corresponds to the best fit according to eq 3. Attempts to simulate the experimental data using eq 2 resulted in poorer fits. Therefore, the need to use eq 3 to fit the data in Figures 3 and 4 provides independent support for the existence of 2:1 CD/S complexes in some of these systems and corroborates the interpretations of previous NMR[24] and emf[28] studies. Generally, the magnitude of the AMV for complexes exhibiting 2:1 equilibria are greater than those where 1:1 equilibria dominate and the shape of the curves are more sigmoidal. This is consistent with the inclusion of methyl groups as well as methylene groups and more extensive desolvation of the alkyl chain as compared to 1:1 complexes.

Figure 5 shows a plot of $V_{\phi,S}$ vs $C_S^{1/2}$ for SPFN (SPFN = sodium perfluorononanoate) in water and 0.013 *m* β-CD. This represents a CD/S system which strongly favors the formation of 2:1 complexes in addition to 1:1 complexes. At infinite dilution, the AMV in the ternary solution is significantly greater than that in water. In contrast to Figures 3 and 4, the volumetric behavior for the β-CD/SPFN ternary system is markedly sigmoidal. SPFN and SPFO differ by one CF_2 group; however, this difference imparts additional hydrophobicity to promote 2:1 complex formation. Consequently, the best fit to the ternary solution data is obtained using the 3-S model (cf. eq 3). As well, the magnitudes of $K_{1:1}$ and $K_{2:1}$ for CD/SPFN are systematically greater than those for CD/SPFO (cf. Table 4). Higher order (2:1) complexation for CD/S complexes provides a means of increasing apolar/apolar interactions and reducing apolar/polar interactions. It is interesting to note that the apparent onset of 2:1 binding in fc and hc surfactants occurs for SPFO and SDodec, respectively. These surfactants possess similar AMVs at infinite dilution (cf. Tables 1 and 2) which indicates that their binding affinity toward β-CD can be correlated with their surface area and the group molecular volumes of their carbon chains. It has been argued from previous experimental[32] and theoretical[33] studies that the physicochemical properties of lipophilic compounds may be predicted from molecular sizes and surface areas of apolar alkyl groups.

The difference in the magnitude of the binding constants (K_i) of 1:1 and 2:1 complexes may reveal the relative importance of the surfactant alkyl chain and headgroup in the interactions

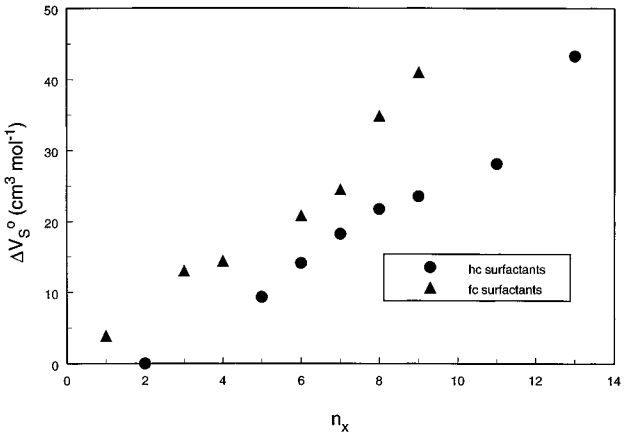
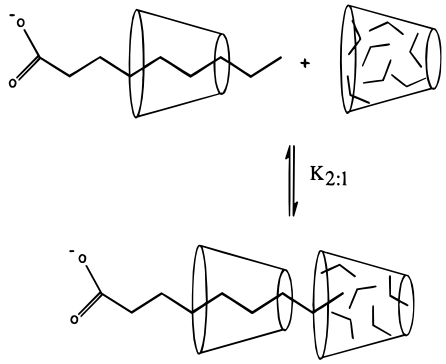


Figure 6. ΔV_S° vs alkyl chain length (n_x) for fluorocarbon (fc) and hydrocarbon (hc) surfactants at infinite dilution in 0.013 *m* β-CD at pH 10.5 and $T = 298$ K.

that lead to complex formation. Since $K_{1:1} > K_{2:1}$, it appears that dipole interactions between the surfactant head group and CD make an important contribution to the stability of the 1:1 complexes. Notwithstanding this, alkyl chain interactions with CD, governed by the hydrophobic effect, are also expected to play an important role in the host/guest binding affinity, and the latter is evident from the increase in $K_{2:1}$ as n_x increases. Despite the smaller magnitude of $K_{2:1}$ relative to $K_{1:1}$, 2:1 complexes contribute significantly to the AMV near infinite dilution since $[CD]_{total} > [S]_{total}$, as seen in Figures 3−5. The shape of the X_i vs $C_S^{1/2}$ curves in Figure 3 describes the dependence of stoichiometry on surfactant concentration. Below the 1:1 CD/S mixing ratio, 1:1 complexes are favored, while 2:1 complexes form thereafter. Thus 2:1 complexes are favored near infinite dilution for surfactants possessing a sufficiently long alkyl chain. The effect of an increase in 2:1 complexation due to increasing carbon chain length is evident in a plot of $V_{\phi,S}$ vs $C_S^{1/2}$ for the β-CD/SPFD system (not shown). This system shows a larger transfer volume and greater sigmoidal character compared to that of β-CD/SPFN. Thus, both K_i and $V_{\phi,i}$ increase with increasing n_x, which can be correlated to the hydrophobicity of the surfactant.

Figure 6 illustrates a plot of ΔV_S° vs alkyl chain length (n_x) for the hc and fc surfactants in aqueous 0.013 *m* β-CD. For the hc surfactants, ΔV_S° increases monotonically up to $n_x = 9$ and increases less rapidly up to $n_x = 11$, where a further sharp increase in transfer volume occurs for $n_x > 11$. For the fc surfactants, ΔV_S° increases monotonically with a sharp increase at $n_x > 6$. The initial increase as a function of n_x in each series can be attributed to the increase in $K_{1:1}$ (cf. Table 4). In a plot of $\Delta V_{1:1}^\circ$ vs n_x (not shown), the transfer volume levels off for hc ($n_x \geq 8$) and fc ($n_x \geq 4$) surfactants. If one neglects any inclusion of the carboxylate group, then the maximum number of alkyl groups that can be included within the β-CD core may be be inferred from these results, i.e., eight and four for hc and fc surfactants, respectively. The sharp increase in ΔV_S° for hc ($n_x > 11$) and fc ($n_x > 6$) surfactants corresponds to the onset of 2:1 complex formation due to the end capping of a second CD onto a 1:1 CD/S complex, as shown in Scheme 2. According to Tanford,[11] a fully extended alkyl chain consisting of four CH_2 groups can span the β-CD cavity, whereas Park and Song[34] indicate that eight CH_2 groups can be accommodated if allowance is made for carbon chain coiling due to the occurrence of gauche kinks. A fc chain assumes an extended conformation, compared to a hc of similar carbon number, because of its higher gauche/trans energy barrier.[35] The sudden increase in ΔV_S° that occurs at lower n_x for fc compared to hc

SCHEME 2: A Generalized Representation of the Formation of a 2:1 β-CD/Surfactant Complex



surfactants can be attributed to differences in the conformation of their alkyl chains; the onset of 2:1 complexation for fc and hc surfactants that occurs at ca. $n_x > 6$ and $n_x > 11$, respectively, is consistent with these facts. In a 1:1 inclusion complex it is reasonable to speculate that the carboxylate group is not included and that eight CH_2 groups reside within the CD cavity. For a hc surfactant such as ST ($n_x = 13$), five alkyl groups may remain unbound and project into the bulk solution, and this unbound segment of the surfactant carbon chain imparts additional hydrophobicity to promote the capping of a second CD onto the 1:1 CD/S complex (see Scheme 2). The greater hydrophobicity and preferred all-trans conformation of fc surfactants relative to hc surfactants strongly favors the formation of 2:1 complexes. Therefore, the onset of 2:1 complexation occurs at lower n_x, and the magnitude of ΔV_S° is systematically greater, as shown in Figure 6.

In previous work,[26] we have attributed sigmoidal-shaped curves as being the result of a positive cooperativity in the binding process. The molecular basis for this apparent cooperativity can be related to the rearrangement of H-bonds within the solvent (H_2O) network upon complex formation. In aqueous solution, H-bond cooperativity arises from enhancement of H-bond formation as more H-bonds are formed.[8,31] The "high-entropy" water within the β-CD interior can assume a more favorable H-bond arrangement when transferred to the bulk solvent. The hydration shell about the alkyl chain of the surfactant can also assume a more "relaxed" state in the bulk phase when the alkyl chain is included in β-CD. It follows that greater cooperativity will result when more high-entropy water is expelled to the bulk solvent, and this occurs more readily as the included segment of the surfactant alkyl chain increases.

The volumetric data presented above for hc and fc surfactants in ternary aqueous solutions that form CD/S complexes indicate that the AMV is dependent on several factors: (i) the magnitude of K_i, (ii) the mixing ratio of the host and guest, (iii) the nature of the host/guest stoichiometry, (iv) the alkyl chain length of the surfactant, and (v) the physicochemical properties of the surfactant. These factors can be directly related to the transfer volumes since it is a variable which is proportional to some aspect of complex formation. The arguments presented above can also be applied to rationalize the volumetric behavior of the host molecule in ternary aqueous solutions, as discussed below.

***β*-CD Volumes: $V_{\phi,CD}$.** Apparent molar volumes of β-CD ($V_{\phi,CD}$) were investigated in water and in binary (W + S) solutions of hc and fc surfactants. Figure 7 illustrates a comparison of $V_{\phi,CD}$ data in water obtained in this study and from the literature.[14,36] There is good agreement with the results of Milioto et al. However, poorer agreement was found with

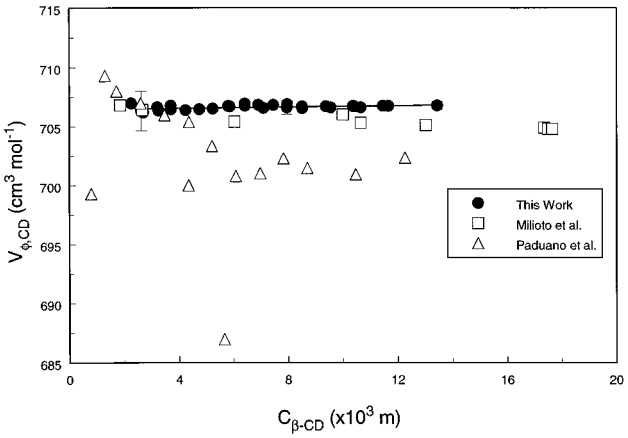


Figure 7. $V_{\phi,CD}$ vs concentration of β-CD (C_{CD}) in water at $T = 298$ K. Experimental data obtained at pH 10.5; pH of literature data not stated.

TABLE 5: Apparent Molar Volumes of β-CD in 5×10^{-3} *m* Aqueous Solutions of Sodium Alkyl Carboxylates at pH 10.5 and 298 K

surfactant	$V^\circ_{\phi,CD}$ (cm^3 mol^{-1})	ΔV°_{CD} (cm^3 mol^{-1})[a]
$C_6H_{11}O_2Na$	715.5	9.1
$C_8H_{15}O_2Na$	722.5	16.1
$C_{10}H_{19}O_2Na$	726.0	19.6
$C_{12}H_{23}O_2Na$	733.0	26.6
$C_{14}H_{27}O_2Na$	732.5	26.1

[a] $\Delta V^\circ_{CD} = V^\circ_{\phi,CD}$ (surfactant(aq)) $- V^\circ_{\phi,CD}$(water). $V^\circ_{\phi,CD}$(water) = 706.4 cm^3 mol^{-1}.

TABLE 6: Apparent Molar Volumes of β-CD in 5×10^{-3} *m* Aqueous Solutions of Perfluorinated Sodium Alkyl Carboxylates at pH 10.5 and 298 K

surfactant	$V^\circ_{\phi,CD}$ (cm^3 mol^{-1})	ΔV°_{CD} (cm^3 mol^{-1})[a]
$C_2F_3O_2Na$	711.9	5.5
$C_4F_7O_2Na$	717.8	11.4
$C_7F_{13}O_2Na$	718.0	11.6
$C_8F_{15}O_2Na$	718.1	11.7
$C_9F_{17}O_2Na$	717.0	10.6
$C_{10}F_{19}O_2Na$[b]	716.0	9.6

[a] $\Delta V^\circ_{CD} = V^\circ_{\phi,CD}$(surfactant(aq)) $- V^\circ_{\phi,CD}$(water). [b] The concentration of surfactant used was 2×10^{-3} *m*. $V^\circ_{\phi,CD}$(water) = 706.4 cm^3 mol^{-1}.

the data of Paduano et al., and this might be due to inaccuracies in their estimates of the water content of β-CD and/or their density data.

Values of $V^\circ_{\phi,CD}$ and ΔV°_{CD}(W→W+S) for β-CD in 0.005 *m* binary aqueous solutions of hc and fc surfactants are shown in Tables 5 and 6, respectively. For the hc surfactant series, the trend in ΔV°_{CD} (Table 5) shows a decreasing rate of increase with n_x up to $n_x = 9$, and then a further sharp increase occurs to a constant value for $n_x \geq 11$. Under the experimental conditions for which the data have been obtained, ΔV°_{CD} represents the increase in volume of β-CD upon transfer from water to the complexed form at infinite dilution when there is an excess of surfactant. The following factors are likely to affect these values: (i) the mode of inclusion of the guest in the host, (ii) the relative amounts of complexes of different stoichiometry, and (iii) the magnitude of the binding constants, K_i.

Analysis of the data from the perspective of the guest showed that the cavity interior of β-CD is filled and 1:1 binding prevails for $n_x \leq 8$ and $n_x \leq 4$ for the hc and the fc series, respectively. The more gradual increase in ΔV°_{CD} up to $n_x = 9$ in the hc series is consistent with the expectation that there is a larger amount of a more strongly bound 1:1 complex as n_x increases. The sharper increase beyond $n_x = 9$ supports the argument that the longer hydrocarbon guests form 2:1 complexes.

TABLE 7: Apparent Molar Volume Data of β-CD in Aqueous Fluorocarbon and Hydrocarbon Surfactant Solutions of Various Concentrations at pH 10.5 and 298 K

surfactant	[surfactant] ($\times 10^3$ *m*)	$V^\circ_{\phi,CD}$ (cm^3 mol^{-1})	ΔV°_{CD} (cm^3 mol^{-1})[a]
$C_6H_{11}O_2Na$	5, 120, 240	715.5, 726.0, 729.5	9.1, 19.6, 23.1
$C_8H_{15}O_2Na$	5, 15 120	722.5, 728.0, 733.5	16.1, 21.6, 27.1
$C_{10}H_{19}O_2Na$	5, 15, 60	727.0, 728.0, 731.0	20.6, 21.6, 24.6
$C_{12}H_{21}O_2Na$	5, 10, 20	732.5, 732.5, 732.5	26.1, 26.1, 26.1
$C_2F_3O_2Na$	5, 60, 240	712.0, 715.0 723.0	5.6, 8.6, 16.6
$C_4F_7O_2Na$	5, 60, 120	717.5, 724.1, 731.1	11.1, 17.7, 24.7
$C_7F_{13}O_2Na$	5, 30, 60	718.0, 721.0, 721.0	11.6, 14.6, 14.6
$C_8F_{15}O_2Na$	5, 30	718.1, 718.1	11.7, 11.7

[a] $\Delta V^\circ_{CD} = V^\circ_{\phi,CD}$(surfactant(aq)) $- V^\circ_{\phi,CD}$(water). $V^\circ_{\phi,CD}$(water) = 706.4 cm^3 mol^{-1}.

The corresponding dependence of ΔV°_{CD} on alkyl chain length in the fc series (Table 6) shows somewhat similar trends with two different features. First, the values of ΔV°_{CD} are smaller for all the fc homologs studied. Second, apart from an initial increase of ca. 6 cm^3 mol^{-1} between $n_x = 1$ and $n_x = 3$, ΔV°_{CD} remains constant at 11.6 cm^3 mol^{-1} up to $n_x = 7$ and then decreases slightly for $n_x > 7$. The latter appears to arise from the onset of the formation of 2:1 complexes (Table 4). It is interesting to note that the value of $\Delta(\Delta V^\circ_{CD}) = \Delta V^\circ_{CD}$(hc) $- \Delta V^\circ_{CD}$(fc) is approximately 8 cm^3 mol^{-1} for systems where 1:1 complexes are likely to dominate and the guest species completely fill the host cavity ($n_x > 4$ and $n_x > 8$ for fc and hc series, respectively). This value is close to the approximate difference in volume between transferring eight CH_2 groups or four CF_2 groups from the bulk phase to completely fill the CD cavity, e.g., (8 $CH_2 \times 2.6$ cm^3 mol^{-1}) $-$ (4 $CF_2 \times 3.3$ cm^3 mol^{-1}) $= 7.6$ cm^3 mol^{-1}. This simple calculation further corroborates the evidence adduced, above, that it is only the hc surfactant homologs that coil within the β-CD cavity. Independent evidence for the propensity of hc alkyl chains to coil at interfaces (solid/liquid) has been recently reported.[37]

Table 7 lists the values of $V^\circ_{\phi,CD}$ and ΔV°_{CD}(W→W+S) for β-CD in aqueous solutions containing different concentrations of hc and fc surfactants. The corresponding complementary data for the concentration dependence of $V^\circ_{\phi,S}$ and ΔV°_S(W→W+CD) for hc and fc surfactants in aqueous β-CD is not accessible due to the limited solubility of β-CD. The data in Table 7 illustrates the dependence of $V^\circ_{\phi,CD}$ and ΔV°_{CD} for selected conditions of low, medium, and high binary solvent (W + S) concentrations. In Table 7, the shorter carbon chain length surfactants give rise to a monotonic increase in $V^\circ_{\phi,CD}$ and $\Delta V^\circ_{\phi,CD}$ as the concentration of binary solvent (C_S) increases; however, the dependence of the magnitude of $V^\circ_{\phi,CD}$ and ΔV°_{CD} on C_S decreases as n_x increases in each homologous series. This behavior can be explained by consideration of eq 2. Surfactants exhibiting weak binding, such as shorter carbon chain length surfactants, will have a relatively small fraction bound ($X_{1:1}$) at infinite dilution. As C_S increases, the magnitude of $X_{1:1}$ increases as predicted by the expression for $K_{1:1}$. According to eq 2, $V_{\phi,CD}$ increases as $X_{1:1}$ increases since the volume of the complexed CD is greater than that of the dispersed host ($V_{\phi,1:1} > V_{\phi,d}$). Thus, the dependency of $V^\circ_{\phi,CD}$ and ΔV°_{CD} on C_S is more pronounced for weakly bound complexes due to the smaller fraction bound at infinite dilution, when C_S is low. Using the equilibrium expression for $K_{1:1}$, it can be shown that $V^\circ_{\phi,CD}$ reaches a limiting value since $X_{1:1}$ approaches unity at sufficiently high binary solvent concentrations. Strongly bound complexes (cf. Table 4) exhibit a weaker dependence on the magnitude of $V^\circ_{\phi,CD}$ and $\Delta V^\circ_{\phi,CD}$ as C_S increases since $X_{1:1}$ is relatively high even when C_S is low. As well, longer chain length surfactants which are strongly bound

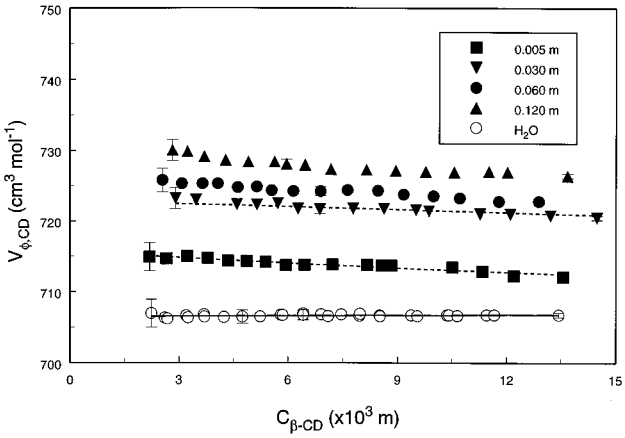


Figure 8. $V_{\phi,CD}$ vs C_{CD} for β-CD in water and 0.005, 0.030, 0.060, and 0.120 *m* SHex, respectively, at pH 10.5 and $T = 298$ K.

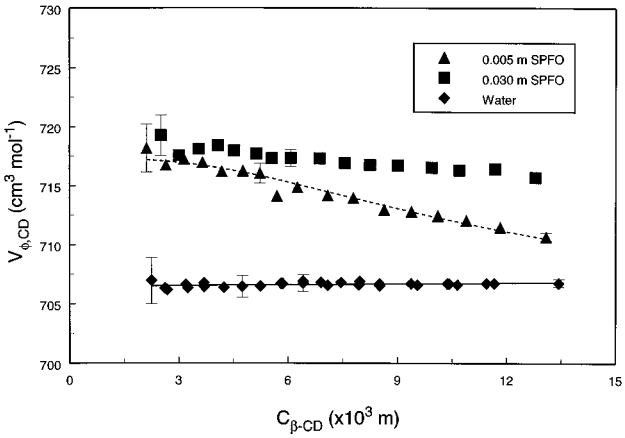


Figure 9. $V_{\phi,CD}$ vs C_{CD} for β-CD in water, 0.005 and 0.030 *m* SPFO, respectively, at pH 10.5 and $T = 298$ K.

tend to completely fill the CD cavity and expell all the hydration water from the CD interior.

Figure 8 is a typical plot of $V_{\phi,CD}$ vs C_{CD} for β-CD in water and aqueous solutions of SHex of different concentrations. $V_{\phi,CD}$ shows a negative linear dependence with increasing C_{CD} in each of the binary surfactant systems. As well, the magnitude of $V_{\phi,CD}$ increases as the concentration of the binary solvent (W + S) increases. The negative concentration dependence of $V_{\phi,CD}$ with C_{CD} is similar to that observed for $V_{\phi,S}$ vs $C_S^{1/2}$ in Figure 1 and is consistent with the concentration dependence of $X_{1:1}$ and X_d shown in Figure 1. It occurs because the mole fraction, $X_{1:1}$, increases as infinite dilution is approached and, also, because $V_{\phi,1:1} > V_{\phi,d}$. The best fit lines for $V_{\phi,CD}$ in 0.005 and 0.030 *m* SHex in Figure 8 were obtained using the 2-S model described by eq 2. The dependence of $V_{\phi,CD}$ and $V^\circ_{\phi,CD}$ on binary solvent concentration is due to the variation of $X_{1:1}$ with C_S as outlined above for the data in Table 7. β-CD/SHex is an example of a weakly bound complex (cf. Table 4) that exhibits a strong dependence on the binary solvent concentrations since $X_{1:1}$ is relatively small in dilute binary solvents. The best fit lines for $V_{\phi,CD}$ in 0.060 and 0.120 *m* SHex are not shown since the goodness of fit for these ternary solution data were relatively poor. The latter may be due to nonideal effects arising from the higher concentrations of surfactant employed and the assumption that $V_{\phi,d}$ in ternary solutions can be approximated as the AMV of β-CD at infinite dilution in water.

Figure 9 is a plot of $V_{\phi,CD}$ vs C_{CD} for β-CD in water, and 0.005 and 0.030 *m* aqueous solutions of SPFO. In the SPFO solutions, $V_{\phi,CD}$ at a given host concentration increases with increasing C_S; however, the values of $V^\circ_{\phi,CD}$ are similar for the

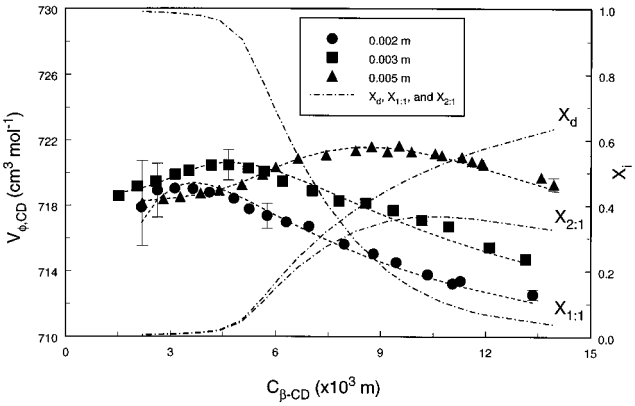


Figure 10. $V_{\phi,CD}$ vs C_{CD} for β-CD in 0.002, 0.003, and 0.005 *m* SPFN, respectively, at pH 10.5 and $T = 298$ K. X_d, $X_{1:1}$, and $X_{2:1}$ vs $C_{\beta\text{-CD}}$ for β-CD in 0.005 *m* SPFN.

two ternary solutions. These results are attributed to the magnitude of K_i (cf. Table 4) and the large fraction of complexed CD ($X_{1:1}$) in each binary solvent system near infinite dilution, as discussed above for the results presented in Table 7. In 0.005 *m* SPFO, the greater negative dependence of $V_{\phi,CD}$ vs C_{CD} is due to the greater contribution of X_d over the entire concentration range. The best fit curve for 0.005 *m* SPFO was obtained by using the 3-S model described by eq 3. The estimated value of $V_{\phi,2:1}$ is similar in magnitude to $V_{\phi,1:1}$ which indicates that the second CD that caps onto the 1:1 complex may not completely encapsulate the fc chain. Therefore, the behavior observed in 0.005 *m* SPFO near infinite dilution fortuitously resembles that expected for a typical 1:1 complex due to the similar magnitudes of $V_{\phi,1:1}$ and $V_{\phi,2:1}$ and, also, because $K_{1:1} \gg K_{2:1}$. In 0.030 *m* SPFO, a poorer fit was obtained and may be for the following reasons: the fitting process is less sensitive when attempting to fit data over an interval where the concentration of complexed species is relatively constant[27,38] and/or the system shows more nonideal behavior at higher surfactant concentrations. Conversely, in 0.005 *m* SPFO, the fraction bound of β-CD ranges from a high to low value over the fitting interval of interest, and there is a reasonably large change in AMV. Thus, in 0.005 *m* SPFO, the magnitude of SSR exhibits a rapid change at the point of convergence which results in good sensitivity in terms of the NLLS fitting procedure employed.

Figure 10 is a plot of $V_{\phi,CD}$ vs C_{CD} in aqueous solutions of SPFN at various concentrations. The mole fractions (X_i) of the various species (cf. eq 3) in 0.005 *m* aqueous SPFN were calculated with the expressions for $K_{1:1}$ and $K_{2:1}$ and the best fit values of K_i listed in Table 4. The values for X_i are plotted vs C_{CD} on the right-hand ordinate of Figure 10. The AMV for β-CD in each aqueous solution of SPFN displays a nonlinear dependence on C_{CD}. In each case, a maximum for $V_{\phi,CD}$ is observed near the 2:1 CD/S mole ratio, whereas a decrease beyond the maximum is due to the contribution of dispersed β-CD (X_d). The nonlinear behavior can be readily understood in terms of the concentration dependence of X_i and the fact that $V_{\phi,d} < V_{\phi,1:1} < V_{\phi,2:1}$. Since $[S]_{total} > [CD]_{total}$, 1:1 complexes predominate near infinite dilution. As C_{CD} increases, $X_{2:1}$ increases significantly beyond the 1:1 CD/S mole ratio since $K_{2:1} < K_{1:1}$ (cf. Table 4). Thus, the maxima in AMV observed in Figure 10 occur because of the contribution of 2:1 complexes. In contrast to Figure 9, the magnitude of $V_{\phi,2:1}$ is greater than that of $V_{\phi,1:1}$ for the β-CD/SPFN system. Since the fc chain of SPFN extends further into the second CD, this gives rise to a larger transfer volume. The best fit lines were obtained using the 3-S model described by eq 3. It is clear that 2:1

SCHEME 3: Coupling Pathways between Various Types of Host/Guest Stoichiometries with Mixing Ratios of Surfactant (S) and β-CD Employed in This Study

$$\beta\text{-CD} + S \underset{\text{excess S}}{\overset{K_{1:1}}{\rightleftharpoons}} \beta\text{-CD/S} \underset{\text{excess } \beta\text{-CD}}{\overset{K_{2:1}}{\rightleftharpoons}} \beta\text{-CD}_2\text{/S}$$

complexation becomes more apparent as the hydrophobicity (increase in n_x of surfactant) increases. This is amplified for the β-CD/SPFD system (not shown) by sharper and larger maxima in the AMV and is directly related to larger $K_{2:1}$ (cf. Table 4) and $V_{\phi,2:1}$ values for this system relative to those of the β-CD/SPFN system.

The self-consistency in the host and guest volumetric data is generally good. However, there are some important differences between the hc and fc series if one compares the magnitudes of $\Delta V°$. These differences can be attributed to two factors: (i) the effect of conformational chain coiling due to the presence of gauche kinks in the carbon chain and (ii) the type of stoichiometry. These two factors lead to changes in the number of polar/apolar and apolar/apolar interactions that result in changes in the magnitude of the AMV. Volumetric contributions due to conformational effects of the host can be disregarded due to the similarity in geometry of the free and complexed forms of β-CD as shown by molecular modeling and X-ray studies.[4,6] Chain coiling in the guest leads to pronounced changes in the transfer volume due to the reduction in polar/apolar interactions. These are less significant for fc surfactants because of their preferred all-trans conformation in the complexed form. Also, the formation of 1:1 vs 1:1 plus 2:1 complexes leads to marked differences in apolar/polar and apolar/apolar interactions due to the degree of inclusion of the guest alkyl chain. Scheme 3 summarizes the nature of the dependence of stoichiometry on binary solvent composition for surfactants capable of forming both 1:1 and 2:1 complexes.

Conclusion

The apparent molar volumes of a homologous series of hc ($C_xH_{2x+1}CO_2Na$, $x = 2$, 5−9, 11, 13) and fc ($C_xF_{2x+1}CO_2Na$, $x = 1$, 3, 4, 6−9) surfactants ($V_{\phi,S}$) in water and in ternary aqueous solutions of β-CD have been obtained. The complementary AMV of β-CD ($V_{\phi,CD}$) in water and in binary aqueous mixtures of hc and fc surfactants were also obtained. The magnitudes of $V°_{\phi,S}$ and $V°_{\phi,CD}$ in ternary solutions are greater than those in water in all cases where complexes are formed. Transfer volumes($\Delta V°$) generally increase as n_x increases and are dependent on the magnitude of K_i, the physicochemical properties of the surfactant, and the mole ratio of the host to guest.

At infinite dilution in binary aqueous hc and fc surfactant solutions, 1:1 CD/S complexes are formed for hc surfactants with $n_x < 11$. The fc surfactants tend to form 1:1 CD/S complexes for $n_x \leq 6$. As well, mole ratios of host to guest under these conditions favor the formation of 1:1 CD/S complexes according to mass balance. However, the longer chain length hc ($n_x \geq 11$) and fc ($n_x > 6$) surfactants tend to form both 1:1 and 2:1 complexes. At infinite dilution in binary aqueous CD solutions, 1:1 and 2:1 complexes are formed as discussed above for the binary aqueous hc and fc surfactant solutions. The mole ratio of host/guest under the condition $[CD]_{total} \gg [S]_{total}$ strongly favors the formation of 2:1 complexes for the longer carbon chain surfactant systems.

The use of two-site or three-site models for the simulation of the macroscopic volumetric behavior of 1:1 and 2:1 CD/S complexes in ternary aqueous solutions has been demonstrated. A semiquantitative additivity scheme was presented which provides additional insight into the solute−solute and solute−solvent interactions arising from complex formation. As well, estimates of $K_{1:1}$ and $K_{2:1}$ were obtained which are in good general agreement with values derived from a well-established spectroscopic method. The use of AMV measurements of host/guest complexes represents a useful and simple method for obtaining good estimates of binding constants. This is particularly true for apolar guest molecules that exhibit significant volume changes upon complex formation and do not possess a suitable chromophore for study by spectroscopic techniques. Additional volumetric studies are currently in progress which are designed to gain further insight into the relative roles of the hydrophobic effect vs interactions between the annular hydroxyl groups of β-CD and the surfactant head group in these complexes.

Acknowledgment. Financial assistance provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) is acknowledged. L.D.W. is grateful for the award of a Graduate Teaching Fellowship from the University of Saskatchewan.

References and Notes

(1) Brewster, M. E.; Loftsson, T. *J. Pharm. Sci.* **1996**, *85*, 1017 and references therein.
(2) Shieh, W. J.; Hedges, A. R. *Pure Appl. Chem.* **1996**, *A33*, 673 and references therein.
(3) Blokzijl, W.; Engberts, J. F. B. N. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1545.
(4) Lichtenthaler, F. W.; Immel, S. *Liebigs Ann.* **1996**, 27.
(5) Diederich, D.; Smithrud, B.; Sanford, E. M.; Wyman, T. B.; Fergus, S. B.; Carcanague, D. R.; Chao, I.; Houk, K. N. *Acta Chem. Scand.* **1992**, *46*, 205 and references therein.
(6) (a) Steiner, T.; Moreira da Silva, A. M.; Teixeira-Dias, J. J. C.; Saenger, W. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1452. (b) Claire Myles, A. M.; Barlow, D. J.; France, G.; Lawrence, M. J. *Biochim. Biophys. Acta* **1994**, *1199*, 27 and references therein.
(7) Israelachvili, J.; Wennerström, H. *Nature* **1996**, *379*, 219.
(8) (a) Lemieux, R. U.; Boullanger, P. H.; Bundle, D. R.; Baker, D. A.; Nagpurkar, A.; Venot, A. *Nouv. J. Chim.* **1978**, *2*, 321. (b) Lemieux, R. U. *Acc. Chem. Res.* **1996**, *29*, 373.
(9) Jobe, D. J.; Verrall, R. E.; Reinsborough, V. C. *Can. J. Chem.* **1990**, *68*, 2131.
(10) Marini, A.; Berbenni, V.; Bruni, G.; Massarotti, V.; Mustarelli, P.; Villa, M. *J. Chem. Phys.* **1995**, *103*, 7532.
(11) Tanford, C. *In The Hydrophobic Effect: Formation of Micelles and Biological Membranes*, 2nd ed.; Wiley: New York, 1980.
(12) Chalikian, T. V.; Plum, G. E.; Sarvazyan, A. P.; Breslauer, K. J. *Biochemistry* **1994**, *33*, 8629.
(13) Vikingstad, E. *In Aggregation Processes in Solution*; Wyn-Jones, E., Gormally, J., Eds.; Elsevier: New York, 1983; Vol. 26, Chapter 4.
(14) Milioto, S.; Bakshi, M. S.; Cristantino, R.; Delisi, R. *J. Solution Chem.* **1995**, *24*, 103.
(15) Høiland, H.; Harald, L. H.; Kvammen, O. J. *J. Solution Chem.* **1981**, *10*, 775.
(16) Ortona, O.; Paduano, L.; Constantino, L.; Vitigliano, V. *J. Mol. Liq.* **1995**, *63*, 291.
(17) Bakshi, M. S. *J. Solution Chem.* **1996**, *25*, 411.
(18) Bakshi, M. S. *Indian J. Chem. Sect. A.* **1996**, *35*, 499.
(19) Young, T. F.; Smith, M. B. *J. Phys. Chem.* **1954**, *58*, 716.
(20) Kell, G. S. *J. Chem. Eng. Data* **1967**, *12*, 66.
(21) *CRC Handbook of Chemistry and Physics*, 54th ed.; Weast, R. C., Ed.; CRC Press: Cleveland, OH, 1973.
(22) Funasaki, N.; Yodo, H.; Hada, S.; Neya, S. *Bull. Chem. Soc. Jpn.* **1992**, *65*, 323.
(23) Linder, K.; Saenger, W. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 694.
(24) Guo, W.; Fung, B. M.; Christian, S. D. *Langmuir* **1992**, *8*, 446.
(25) Kharakoz, D. P. *J. Solution Chem.* **1992**, *21*, 569.
(26) Wilson, L. D.; Siddall, S. R.; Verrall, R. E. *Can. J. Chem.* **1997**, *75*, 927.
(27) Mwakibété, H.; Cristiantino, R.; Bloor, D. M.; Wyn-Jones, E.; Holzwarth, J. F. *Langmuir* **1995**, *11*, 57.
(28) Wan Yunus, W. M. Z.; Taylor, J.; Bloor, D. M.; Hall, D. G.; Wyn-Jones, E. *J. Phys. Chem.* **1992**, *96*, 8979.
(29) Høiland, H.; Ringseth, J. A.; Vikingstad, E. *J. Solution Chem.* **1978**, *7*, 515.

(30) Connors, K. A. *In Binding Constants: The Measurement of Molecular Complex Stability;* Wiley: New York, 1987; Chapter 5.
(31) *In Water and Aqueous Solutions: Structure, Thermodynamics, and Transport Processes;* Horne, R. A., Ed.; Wiley: New York, 1972; Chapter 13, p 519.
(32) (a) Ravey, J. C.; Stébé, M. *Colloids Surf. A: Physicochem. Eng. Aspects* **1994**, *84*, 11 and references therein. (b) Mukerjee, P. *Colloids Surf. A: Physicochem. Eng. Aspects* **1994**, *84*, 1.
(33) Du, Q.; Arteca, G. A. *J. Comput.-Aided Mol. Des.* **1996**, *10*, 133.
(34) Park, J. W.; Song, H. J. *J. Phys. Chem.* **1989**, *93*, 6454.
(35) Tiddy, G. J. T. *In Modern Trends of Colloid Science in Chemistry and Biology;* Eicke, E., Ed.; Birkhauser Verlag: Basel, 1985; p 153.
(36) Paduano, L.; Sartorio, R.; Vitagliano, V.; Constantino, L. *J. Solution Chem*. **1990**, *19*, 31.
(37) Miranda, P. B.; Saijo, V.; Shen, Y. R. *Chem. Phys. Lett.* **1997**, *264*, 387.
(38) Junquera, E.; Peña, L.; Aicart, E. *Langmuir* **1995**, *11*, 4685.
(39) Vikingstad, E.; Skauge, A.; Høiland, H. *J. Colloid Interface Sci*. **1978**, *66*, 240.
(40) Milioto, S.; Cristantino, R.; De Lisi, R.; Inglese, A. *Langmuir* **1995**, *11*, 718.
(41) Tamaki, K.; Watanabe, S.; Daikoji, Y. *Bull. Chem. Soc. Jpn*. **1990**, *63*, 3681.
(42) Johnson, I.; Olofsson, G. *J. Chem. Soc., Faraday Trans. 1* **1988**, *84*, 551.
(43) Perron, G.; Desnoyers, J. E. *J. Chem. Eng. Data* **1997**, *42*, 172.
(44) Gianni, P.; Lepori, L. *J. Solution Chem*. **1996**, *25*, 1.
(45) Giulieri, F.; Krafft, M. *Colloids and Surfaces A: Physicochem. Eng. Aspects* **1994**, *84*, 121.
(46) Fisher, C. H. *J. Am. Oil Chem. Soc*. **1995**, *72*, 681.
(47) Huheey, J. E. *In Inorganic Chemistry: Principles of Structure and Reactivity*, 3rd ed.; Harper and Row: New York, 1983; p 258.