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Monodisperse micelles composed of poly(ethylene glycol) attached surfactants: Platonic nature in a macromolecular aggregate

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Among the many studies on micelles, dating back more than 100 years, we first found a series of monodisperse micelles: spherical micelles made from calix[4]arene surfactants exhibited monodispersity in aggregation number (N_{agg}) with values of 4, 6, 8, 12, and 20. We named these Platonic micelles because these values coincided to the face numbers of the Platonic solids. The preferred N_{agg} values were explained in relation to the mathematical Tammes problem: how to obtain the best coverage of a sphere surface with multiple identical circles. In this paper, we synthesized Poly(ethylene glycol)-attached surfactants and carried out small-angle X-ray scattering (SAXS) and analytical ultracentrifugation (AUC) to determine the N_{agg} . We found that these polymeric surfactants also formed monodispersed micelles and N_{agg} discontinuously increased from 20 to 24, and then 32 with increasing the alkyl carbon numbers from 9 to 11 continuously. The determined N_{agg} was greater than 20 and the Platonic solid numbers. We assumed that the preferred N_{agg} values could be explained in relation to the Tammes problem as well.

Introduction

When surfactants disperse in water, most of them self-assemble to form spherical micelles¹⁻¹⁰. The micelles exhibit normal distributions in N_{agg} and size. In addition, the N_{agg} may adopt any value when the solvent conditions are changed; in other words, there is no preferential Nagg. However, we identified a system that may not follow these general rules. We recently reported on micelles composed of calix[4]arene-based lipids having a hydrophilic head group^{11, 12} and a hydrophobic alkyl chain tail^{13,14}. We found that these micelles have no distribution in terms of size and N_{agg} ; that is, these variables are monodisperse. We believe that when the N_{agg} becomes small enough, namely, less than 20, certain numbers are more preferable than others, and these numbers can provide a thermodynamically more stable configuration. These numbers are 4, 6, 8, 12, and 20, which interestingly match the numbers of the regular polyhedra Platonic solids; as such, these micelles were named "Platonic micelles." Here, we consider the "coverage density" of such micelles, which is how much the hydrophobic part is covered by the hydrophilic part when micelles are formed^{15,16}. Since the hydrophobic part preferentially avoids contact with water, when that part is more covered, the structure becomes more stable. Surfactants can usually be modeled as cones made from the hydrophilic upper and hydrophobic lower parts¹⁷. The interfacial area can be represented as a spherical cap. In this context, the following question arises: How can a spherical surface be efficiently covered with identical caps? In the case of a dodecamer, when the center of

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each cap is located at the vertex of the dodecahedron, it gives the best coverage of 89%. In contrast, when a micelle is composed of three cones, the best coverage is given when the center of the cone is located at the vertex of the regular triangle, which gives coverage of 75%¹⁵. In this case, there is a large uncovered domain, which explains why the relationship between the best coverage on a spherical surface and the number of cones should be considered. One may assume that the rather rigid building block of calixarene is needed to realize such a supramolecular structure. As we already reported¹³, a natural lipid, surfactin, also forms Platonic micelles. This confirms that calixarene is not necessary to construct Platonic micelles and we can create them using conventional surfactants. In other words, we have attempted to give an example in which the coverage theory of forming Platonic micelles is applied in a conventional micellar system. In this paper, we provide an introduction to Platonic micelles produced using conventional surfactants and explain why there are preferential N_{aggs} .

Results and discussion



Fig. 1. Scheme of the PEG surfactants.

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To verify the surfactant that the Platonic micelle theory applies not only to the calix[4]arene molecule but also to the conventional micellar system. For this reason, we designed these surfactants (Fig. 1). To obtain small N_{aggs} , it would be better to have a large hydrophilic volume. In the design of surfactants to construct Platonic micelles, we may not use an ionic headgroup of surfactants because the critical micelle concentration (CMC) would be high due to the solubility of the ions. Because of this, we employed a nonionic head, poly(ethylene glycol) (PEG). Fig. 1 shows the design of surfactants that include a hydrophilic PEG headgroup and a hydrophobic alkyl chain. To observe the effects of the alkyl chain length, we prepared the different alkyl chain lengths (C₉, C₁₀, and C₁₁) were prepared.

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Fig. 2. (A) SAXS profiles of C_m -PEG_{1k}, and C_m -PEG_{1k}-based micelles in water (gray points), and fitting lines calculated from the core-corona model. (B) I(q)/c as a function of q for different C_m -PEG_{1k} concentrations in water. The extrapolated values at an infinite dilution for each q are shown by the black markers.

Fig. 2A compares the SAXS profiles for the micelles made from the different alkyl chain lengths of of C₉, C₁₀, and C₁₁, with the molecular weight of PEG fixed at 1000 in water. The slope (α) was zero from the SAXS intensity in the low-*q* region, where the scattering intensity, *l*(*q*), is expressed as *l*(*q*) \propto *q*a. This indicates that these solutions contain isolated scattered objects without secondary aggregation; these objects are spherical micelles. These SAXS profiles were fitted well by a core-corona spherical model, except for the large q region where atomic scale ordering may be observed. The fitting parameters are shown in Table 1. All micelle shells are much longer

intercept values [I(0)] obtained by extrapolating the scattering intensity to zero angle. The fitting parameters and N_{agg} of the PEG micelles are provided in Table 1.



Fig. 3 Guinier plot [i.e., $\ln I(q)/c$ versus q^2] constructed from the extrapolated intensities: (A) C₉PEG_{1K} ,(B) C₁₀PEG_{1K}, and (C) C₁₁PEG_{1K}.

Fig. 3 shows the Guinier plot of C_m -PEG_{1K}. From the intercept, the micellar molar masses are determined. The gyration radius is calculated from the slope. As shown in fig. 3, the R_g value of C_{10} -PEG_{1K} was determined to be 3.87 nm [M_w = 3.24 x 10⁴g/mol, N_{agg} = 23±1.5].

le 1. SAXS Fitting Parameters for PEG Micelles with Different Alkyl Chain Lengths								
Sample	R _c	R _s	R-R s c/	ρ _c	ρ _s	$ ho_{_{ m sol}}$	R	
	[nm]	[nm]	[nm]	[e nm-3]	[e nm ⁻³]	[e nm-3]	[nm]	
C ₉ PEG _{1K}	0.83	3.40	2.57	270	345	334	3.81	
$C_{10}PEG_{1K}$	0.93	4.10	3.17	270	345	334	3.87	
C ₁₁ PEG _{1K}	0.98	4.35	3.37	270	345	334	3.89	

than the core due to the large molecular weight of PEG compared with that of alkyl chains.

We observed the core-shell micelle with the different concentrations and it was fitted by the core-corona model of eq.1¹⁸ in ESI. The scattering profiles of micelles extrapolated to zero concentration are shown in Fig. 2B, and the weight-averaged molar masses (M_w) of the micelles in water were determined from the

Fig. 3 showed the results when the molecular weight of PEG was fixed at 1K and the alkyl chain length was changed between C₉ and C₁₁. Upon decreasing the alkyl chain length from C₁₀ to C₉, the R_g value and N_{agg} became small at 3.81 nm and 20±1, respectively. On the other hand, increasing the alkyl chain length from C₁₀ to C₁₁ resulted in increases of the R_g value and N_{agg} to 3.89 nm and 32±1.5,

respectively. There is an experimental error inevitably involved, no matter how carefully measurements were carried out. We estimate the error range in the determination of the molar mass would be more or less 3-5 %. This error is not significant for the smaller N_{agg} values such as N_{agg} =6 or 8, but it becomes significant and thus causes ambiguity in the determination of N_{agg} . This is the reason that we had a some error range in N_{agg} such as 32 \pm 1.5. However, the presence of the error range does not necessarily mean distribution present in N_{agg} .



Fig. 4 The concentration dependence of M_w , App, and Q (= M_w , App/ M_z , App) (inserted figures) determined by analytical ultracentrifugation measurements for PEG micelles.

The SAXS profiles in Fig 2 showed a relatively sharp minimum in the intensity around $q = 1 \text{ nm}^{-1}$, suggesting that the distribution in shape and size are quite narrow. To directly measure the distribution in N_{agg} we carried out AUC. Fig. 4 shows the concentration dependence of the apparent weight-averaged molecular weight (M_w , App) and the ratio of M_w , App to M_z , App (Q), where M_z , App is the apparent zaveraged molecular weight. The values of the molar mass were 2.80 $x10^4$ g/mol for C₉-PEG_{1K}, 3.33 $x10^4$ g/mol for C₁₀-PEG_{1K}, and 4.48x 10^{4} g/mol for C₁₁-PEG_{1K}, which were consistent with those determined by SAXS measurements. The $N_{\rm agg}$ of each micelle may conclude to be "20" for C_9 -PEG_{1K}, "24" for C_{10} -PEG_{1K}, "32" for C_{11} - PEG_{1K} . The determined N_{aggs} showed quite good agreement with the SAXS data, and the micelles showed monodispersity. A summary of the N_{agg} determined by SAXS and AUC is shown in Table 2. The micellar N_{age} adopted values of 20, 24, and 32, exhibiting monodispersity.

Sample	<i>M</i> _w of sample [g/mol]	M _w (SAXS) [10⁴ g/mol]	N _{agg}	<i>M</i> _w (AUC) [10⁴g/mol]	N _{agg}
C ₉ PEG _{1K}	1358	2.73±0.13	20±1	2.80±0.11	20±1
$C_{10}PEG_{1K}$	1372	3.24±0.13	23±1.5	3.33±0.10	24±1
$C_{11}PEG_{1K}$	1386	4.47±0.13	32±1.5	4.48±0.12	32±1

Table 2. Molar Masses Determined with Different Methods and N_{agas}

The distinguishing feature of the Platonic micelles are both monodispersity and discreet aggregation numbers. The other interesting feature is that the observed aggregation numbers coincide to the local maximums of the plot (the Tammes plot) in which the best coverages D(N) of a sphere surface with multiple identical caps are plotted against the number of the caps N. It is

shown that N_{agg} increased discontinuously from 20 to 24, and then 32 with an increase of the alkyl chain number from 9 to 11. When we compared these N_{agg} values with the Tammes plot for the larger N (Fig. 5), the zigzag and the local maximum for the larger N becomes less obvious than that of the smaller N, we still have local maximum points at 20, 24, and 32. These numbers agree with the experimentally observed aggregation numbers in the present case, as observed in our previous works in which the aggregation number discretely increased with a continuous increase of the alkyl chain length. ^{13,14,20}



Fig. 5 The coverage D(N) of the Tammes problem plotted against the number of caps.

When we compare the obtained structural parameters listed in Table 1, it is seemed that the core sizes were relatively small and the shell sizes were large and the value of $R_S - R_C$ significantly increased with increasing the alkyl chain length. The core-shell model may be too simple to discuss such structural details comparing with the chemical structures. The fully stretched length of the alkyl chain in C₁₀-PEG_{1k} is around 1.25 nm and thus we can presume that the small core may be due to the interdigitation of the alkyl chains. The PEG chain density in the core-shell interface can be described.^{18,19}

$$\sigma = \frac{N_{\text{agg}} \pi R_{\text{g,PEG}}^2}{4\pi (R_{\text{c}} + R_{\text{g,PEG}})^2} \# (1)$$

When we calculated σ based on the obtained data to be 6.43, 6.97, and 8.85 for respectively C₉-PEG_{1K}, C₁₀-PEG_{1K}, and C₁₁-PEG_{1K}, respectively. These values suggest that the PEG chains are considerably elongated along the radial direction of the micelles. This feature is consistent with the large value of $R_S - R_C$. We suppose that the combination of the aromatic and alkyl chain moieties may provide strong coagulation, which makes the core small and the PEG chains extended.

Conclusions

In conclusion, we synthesized a novel surfactant with PEG as a hydrophilic group. C_m -PEG_{1K} formed monodispersed micelles. When we adjusted the alkyl chain length, we could change the

 N_{aggs} . The N_{aggs} of surfactants were determined to 20, 24 and 32 by SAXS and AUC. We provided a theoretical explanation for the aggregation behaviors by using the plot (the coverage D(N) of the Tammes problem plotted against the number of caps). We succeed to verify the surfactant that the Platonic micelle theory applies not only to the calix[4]arene molecule but also to the conventional micellar system.

Conflicts of interest

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There are no conflicts to declare.

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Graphical abstract

