Predicting the size of salt-containing aqueous Na-AOT reverse micellar water-in-oil microemulsions with consideration for specific ion effects

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Abstract

Hypothesis: Reverse micellar solutions are thermodynamically stable systems in which surfactant molecules surround water droplets within a continuous organic phase. Among their many applications, they can be used for the synthesis of nanoparticles of controlled agglomeration. Here, we consider the role specific ion effects play in reverse micelle size reduction.

Experiments: Dynamic light scattering measurements and the Gouy-Chapman electrical double layer model were combined to study water/AOT/isooctane reverse micellar systems ($w_0 = 10$). Linear relationships between the solvodynamic diameter (*D*) of reverse micelles containing various concentrations of FeSO₄, Mg(NO₃)₂, CuCl₂, Al(NO₃)₃, Fe(NO₃)₃, Y(NO₃)₃, NaBH₄, ZrOCl₂, and NH₄OH, and their calculated Debye screening lengths, κ^{-1} , were observed with decreasing *D* and increasing salt concentration (*c*).

Findings: By comparing the linear fits for reverse micelle size as a function of $c^{-1/2}$, we determined the size can be described as a function of the Debye screening length, cation valency (z), and specific anion hydrated radius (r_{an}) , where $D = 3.1z \kappa^{-1} + b_i$, and b_i is linearly related to r_{an} . Our model accurately predicts reverse micelle sizes with the addition of monovalent, divalent, and trivalent salts for which the primary hydrolyzed cation species has a charge that is equal to the cation valency.

Keywords: Reverse micelle; Gouy-Chapman electrical double layer; dynamic light scattering; Debye screening length; microemulsion.

1. Introduction

Reverse micellar water-in-oil (*w*/o) microemulsions are thermodynamically stable systems in which surfactant molecules surround water droplets within a continuous organic phase [1-4]. Among their many applications, *w*/o microemulsions can be used for the synthesis of a variety of nanoparticles [5-20]; as protein, enzyme, and dye extraction systems for food science, fuel generation, and cosmetics production [21-23]; and as model systems for studying biological membranes and mimicking those biological processes for drug delivery [24, 25]. The addition of electrolytes, instead of pure water, is often involved in these applications, resulting in ion confinement within reverse micelles and ion exchange between micelles. Interactions between ions and surfactants have a significant impact on *w*/o microemulsion aggregate sizes and overall system stability [26-32]. Therefore, it is crucial to better understand the phenomenological effects that ions have on the reverse micelles to which they are added.

In many cases, electrolytes decrease microemulsion cloud point (*i.e.*, maximum allowable polar solvent concentration for the system to remain as a single phase) and shrink the single-phase reverse micelle region of the phase diagram [30-33]. Our previous work [26] showed, through dynamic light scattering (DLS) experiments [5,26] and molecular dynamics (MD) simulations [26-27, 34], that aqueous Na-AOT reverse micelles decrease in size with increased electrolyte concentration and/or valency, until the point of destabilization. In particular, we demonstrated that the average reverse micelle size in the water/AOT/isooctane system with additions of Al(NO₃)₃ and ZrOCl₂, is directly proportional to the Debye screening length (κ^{-1}):

Reverse micelle size
$$\propto \kappa^{-1} = \left(\frac{\epsilon_{\rm r}\epsilon_{\rm o}k_{\rm B}T}{1000q^2N_{\rm A}(z^2c)}\right)^{1/2}$$
 (1)

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where ε_r is the relative dielectric permittivity of the solvent (~78 for H₂O), ε_o is the electrical permittivity of vacuum (8.85 × 10⁻¹² C²/J•m), k_B is Boltzmann's constant (1.38 × 10⁻²³ J/K), *T* is temperature, *q* is the elementary charge (1.602 × 10⁻¹⁹ C), N_A is Avogadro's number (6.022 × 10²³ mol⁻¹), *z* is the valence of the electrolyte cation (*e.g.*, 3 for Al³⁺ or 4 for Zr⁴⁺), and *c* is the molar electrolyte concentration (*i.e.*, concentration of salt in water). A linear relationship between the average reverse micelle size and (*z*²*c*)^{-1/2} was determined, implying system behavior could be related to changes in electrical double layer (EDL) potential, as described by the Gouy-Chapman theory for ion distribution at a charged surface [4]. Applying this model to reverse micelles suggested that overlapping EDLs within the reverse micelle core would be compressed with increasing cation valence or concentration. We hypothesized that this compression would allow the negatively charged surfactant headgroups at the reverse micelle interface to move in closer proximity, thus causing reduction in the reverse micelle size.

Our previous description of reverse micelles, relating them to κ^{-1} , is an electrostatic model. That is, it only considers ion valence and concentration and is indifferent to the specific salt species that are added. Here, we consider the role specific ion effects—those not described completely by an electrostatic model, but instead influenced by ion species [35]—may play in the reduction of reverse micelle diameters. Thus, we investigate a more extensive set of electrolytes, FeSO₄, Mg(NO₃)₂, CuCl₂, Al(NO₃)₃, Fe(NO₃)₃, and Y(NO₃)₃, in addition to previously studied [5,26] NaBH₄, ZrOCl₂, and NH₄OH systems. We determine that two parameters are needed to predict the sizes of water/AOT/isooctane reverse micelles containing monovalent, divalent, and trivalent salts for which the primarily hydrolyzed cation species has a charge equal to the independent cation (*e.g.*, Al³⁺ primarily hydrolyzes as [Al(H₂O)₆]³⁺), namely cation valency and hydrated anion radius. Thus, specific ion effects cannot be ignored in the analysis of ion-containing reverse micelle systems.

2. Materials and methods

All water/AOT/isooctane reverse micelle solutions were prepared with a water-tosurfactant molar ratio (w_0) of 10 and characterized by the method we previously established [26]. First, 8.891 g of sodium bis(2-ethylhexyl) sulfosuccinate (AOT) [Sigma-Aldrich] were added to 100 mL of isooctane [2,2,4-trimethylpentane, 99+%, Sigma-Aldrich] and mixed for 30 minutes. Next, 3.6 mL of distilled water, containing either FeSO₄ [99+%, Sigma-Aldrich], Mg(NO₃)₂ [98%, Alfa Aesar], CuCl₂ [99+%, Alfa Aesar], Al(NO₃)₃ [99.99%, Alfa Aesar], Fe(NO₃)₃ [98+%, Alfa Aesar], or Y(NO₃)₃ [99.9%, Alfa Aesar] in concentrations from 0.1 to 0.6 M (in increments of 0.1 M) for the divalent salts and from 0.1 to 0.4 M (in increments of 0.1 M) for the trivalent salts, were added to the AOT/isooctane solution and stirred for an additional 30 minutes. Mass of each salt were 0.061 to 0.368 g for CuCl₂, 0.111 to 0.665 g for FeSO₄, 0.092 to 0.554 g for Mg(NO₃)₂, 0.118 to 0.471 g for Al(NO₃)₃, 0.145 to 0.582 g for Fe(NO₃)₃, and 0.138 to 0.552 g for $Y(NO_3)_3$. Three samples were prepared for each composition of each salt. The average solvodynamic size of the reverse micelles was measured by dynamic light scattering (DLS) using a Nanotrac Ultra instrument (Microtrac, Montgomeryville, PA). The average of five runs, each performed for 15 s, was considered one measurement. Five measurements were taken for each sample, the average of which are reported as the average reverse micelle size.

3. **Results and discussion**

3.1. Relationship between salt concentration and reverse micelle size

The average solvodynamic diameters for the reverse micelles relevant to this study are illustrated in Fig. 1 as a function of the electrolyte concentration and cation charge $(z^2c)^{-1/2}$. A linear dependence, predicted by equation (1), is observed for all six systems. The slope of the linear functions is dependent on the cation valency. The three divalent systems (Fig. 1a) have an average slope of 2.8 ± 0.1 nm•M^{-1/2} and the three trivalent systems (Fig. 1b) have an average slope of 3.7 ± 0.2 nm•M^{-1/2}. The constancy of the slope when changing between electrolytes with the same cation valency indicates that slope does not depend on the types of ions in the system. This is further confirmed by plotting reverse micelle sizes as a function of $c^{-1/2}$ instead of $(z^2c)^{-1/2}$, illustrated in Fig. 2. The slope for the linear relationship between average reverse micelle diameter and $c^{-1/2}$ is 1.3 ± 0.1 nm·M^{-1/2} for all systems regardless of electrolyte. Therefore, the slope only changes as a function of cation valency when plotting size with respect to $(z^2c)^{-1/2}$.

The other difference observed between the linear reverse micelle diameter *vs.* $(z^2c)^{-1/2}$ for divalent compared to trivalent electrolytes, is the shift of the *y*-intercept. In divalent systems (Fig. 1a), there is a vertical shift between lines when changing the electrolyte, whereas the trivalent systems (Fig. 1b), which have different cations but the same NO₃⁻ anion, do not show any significant vertical shift when changing salts. Thus, the vertical shift indicates that the reverse micelle sizes have a specific effect connected to the electrolyte anion. This is further confirmed by noting that the divalent electrolyte Mg(NO₃)₂ has the same average *y*-intercept of 4.0 ± 0.1 nm as the nitrate-containing trivalent electrolytes, and that the nitrate-containing electrolyte systems have a different *y*-intercept than the CuCl₂ system that also contains a monovalent anion.

The results in Fig. 1 show a linear dependence between average reverse micelle size and the charge concentration parameter $(z^2c)^{-1/2}$ that can be described by the equation:

$$D = [(z^2 c)^{-1/2}] \cdot m_z + b_i$$
⁽²⁾

where *D* is the average reverse micelle solvodynamic diameter, *z* is the electrolyte cation valency, *c* is the electrolyte concentration (mol/L), and m_z and b_i correspond to the slope and *y*-intercept. A list of m_z and b_i values are summarized in Table 1. A second equation for the average reverse micelle diameter as a function of $c^{-1/2}$, as graphed in Fig. 2, is given by:

$$D = [(c)^{-1/2}] \bullet m_0 + b_i$$
(3)

where $m_0 = m_z z^{-1} = (1.3 \pm 0.1) \times 10^{-9} \text{ m} \cdot \text{M}^{-1/2}$ for all salts. The *y*-intercept value, b_i , is the same for both equations (2) and (3). To explicitly relate the proportionality of reverse micelle size to the Debye screening length, κ^{-1} , another linear equation can be defined by:

$$D = g \kappa^{-1} + b_{\rm i} \tag{4}$$

where g is a proportionality constant determined by substituting equation (1) for the Debye screening length into equation (4), then equating equation (3) with (4), as follows:

$$g \bullet \kappa^{-1} + b_i = [(z^2 c)^{-1/2} \bullet m_z] + b_i$$
(5)

$$g \bullet \left(\frac{\varepsilon_{\rm r} \varepsilon_{\rm o} k_{\rm B} T}{1000 q^2 N_{\rm A} \left(z^2 c\right)}\right)^{1/2} = \left[\left(z^2 c\right)^{-1/2} \bullet m_z\right]$$
(6)

$$g \bullet \left(\frac{\varepsilon_{\rm r} \varepsilon_{\rm o} k_{\rm B} T}{1000 q^2 N_{\rm A}}\right)^{1/2} = m_z \tag{7}$$

Recall, from equation (3), $m_z = m_o \cdot z = [(1.3 \pm 0.1) \times 10^{-9} \text{ m} \cdot \text{M}^{-1/2}] \cdot z$ for all salts. Therefore, solving for *g* results in

$$g = \left(1.3 \times 10^{-9} \ M^{-1/2}\right) \cdot z \cdot \left(\frac{\varepsilon_{\rm r} \varepsilon_{\rm o} k_{\rm B} T}{1000 q^2 N_{\rm A}}\right)^{-1/2}$$
(8)

Thus, considering an aqueous $w_0 = 10$ reverse micelle system at room temperature (298 K) with added electrolytes, we find the predictive equation for reverse micelle solvodynamic diameter is:

$$D = 3.1 z \kappa^{-1} + b_i [\text{nm}]$$
(9)

As noted previously, the *y*-intercept for this linear equation is dependent on the specific anion of the system electrolyte. Since the units of equation (9) require that b_i have units of length, we now consider the possible physical relationship between anion size and reverse micelle size. A list of average hydrated anion radii, r_{an} , for the six electrolytes is found in Table 2 [36-37]. These radii are used to plot the *y*-intercepts, b_i , from the linear fits in Figs. 1 and 2 as a function of hydrated anion size (Fig. 3). A linear relationship is found between these values:

$$b_{\rm i} = 24.4 \, r_{\rm an} - 4.26 \, [\rm nm] \tag{10}$$

This equation can be used to generate b_i values for use in equation (9) to predict reverse micelle sizes as a function of added electrolyte concentration for the water/AOT/isooctane systems with $w_0 = 10$.

3.2. Model predictive capabilities

To test the validity and limits of this predictive equation, we apply equations (9) and (10) to $w_0 = 10$ water/AOT/isooctane reverse micelle systems with three different electrolytes for which we have previously collected DLS size measurement data, NaBH₄, ZrOCl₂ and NH₄OH [5,26]. The predictive parameters for each electrolyte—cation valency and hydrated anion radii [36-38]—along with their resulting linear equations for predicted reverse micelle size as a function of electrolyte concentration, $c^{-1/2}$, are listed in Table 3. Specific predicted sizes, measured sizes, and percent error between each are listed in Table 4.

The derived equation accurately predicts reverse micelle sizes for NaBH₄ with no more than 4.5% error in size between measured and predicted. The linear fit of the data differs from

the predictive equation by only 0.1 nm for the y-intercept, with a value of 4.1 nm obtained experimentally, to a value of 4.0 nm from the model (Fig. 4a). The predictive equation for ZrOCl₂ is close to fitting the measured reverse micelle size, but with notable differences in both slope and y-intercept (Fig. 4b). Recall, the slope predicted for all electrolyte systems as a function of concentration is $m_0 = m_z z^{-1} = (1.3 \pm 0.1) \times 10^{-9} \text{ m} \cdot \text{M}^{-1/2}$ [equation (3)]. The slope for the fit to measured data for the ZrOCl₂ system is $(1.1 \pm 0.1) \times 10^{-9}$ m•M^{-1/2}, a difference of 0.2 ± 0.1 from the predicted value. The y-intercepts between the experimental and theoretical equations also differ (5.0 \pm 0.1 from experimental and 3.4 \pm 0.7 from the model). The highest error range value for the theoretical b_i gives predicted reverse micelle sizes with smaller variances from the measured values (0.1-3.6%) than using the baseline predicted b_i (9.6-17.5%). The difference in slope, however, means that the predictive equation does not fit the ZrOCl₂ system. The DLS size data collected for reverse micelle systems with NH₄OH varies significantly from the predictive equation generated (Fig. 4c). The reverse micelle diameter predicted by equation (3) for the smallest concentration (0.05 M) of NH_4OH matches the measured reverse micelle size (data points on the right side of Fig. 4c), varying by only 1.79%. However, adding additional NH₄OH to the system produces negligible variations in reverse micelle size when increasing electrolyte concentration in contrast to the predicted decrease in size.

The difference in the predictive accuracy of equation (5) for each system points to some important limitations of our analysis. Recall, the proportionality factor, g = 3.1z, relating the reverse micelle diameter to the Debye screening length was derived by relating changes in size to the cation valency. Essentially, this means that using the Gouy-Chapman model to describe the reverse micelle interior relies on the assumption that the electrolyte cationic charge in solution

has a 1:1 relationship with ion valency. For the case of both $ZrOCl_2$ and NH₄OH this assumption is not valid. $ZrOCl_2$ has the ability to hydrolyze in several different species when dissolved in water, and not all of them have the same +4 charge as the individual zirconium metal ion [39]. NH₄OH is a weak base, and it is expected that only ~2% of the compound remains as ionized ammonium while the rest exists as ammonia when dissolved in water [40]. Therefore, ionic solutions of $ZrOCl_2$ and NH₄OH can have charge concentrations disproportionate to their respective cation valency.

In our prior work [21], we suggested that ZrOCl₂ in reverse micelles must hydrolyze primarily as a $[ZrO_2(H_2O)_{12}]^{4+}$ dimer on the basis of an observed linear relationship between cation valency and the critical electrolyte concentration for reverse micelle instability, c_{critical}, not fitting the commonly observed tetramer complex $[Zr_4(OH)_8(H_2O)_{16}]^{8+}$. However, we now find the previously observed linear relationship between critical electrolyte concentration and cation valency does not hold with other salts. Through visual inspection of each solution for cloud point, it was determined that the concentration for instability varies from 0.3 to 0.6 M for divalent salts and from 0.3 to 0.4 M for trivalent salts. As such, it is now reasonable to conclude that several hydrolyzed zirconium ion species can exist in the reverse micelle core just as in bulk water. This will result in a non 1:1 relationship between valency and charge concentration. Thus, a different derivation of the equation for Debye screening length (κ^{-1}) than that given in equation (1) would be necessary to determine an accurate relationship between reverse micelle size and the electrical double layer size for zirconyl salts and other electrolytes with cations that have several stable hydrolyzed species. That said, while the predictive equation for ZrOCl₂ derived in this analysis (Table 3) is imprecise, the predicted size values are accurate to 1.1 ± 0.2 nm (9.6 – 17.5% deviation) suggesting these differences in Debye screening length equations may be

negligible in predicting sizes within the stable concentration regime of ZrOCl₂ for certain applications.

Our previous study also noted the unique behavior of the reverse micelle system with NH4OH compared to those with other added electrolytes [21]. The negligible changes in reverse micelle size that occur with varying concentrations for this system were attributed to ammonium hydroxide in water existing primarily as NH₃ molecules dissolved in water and secondarily as NH4⁺ and OH⁻ ions [34]. This allows significant amounts of the NH4OH to dissolve in the oil phase as well as the reverse micelle water core and results in a non 1:1 relationship between cation valency and charge concentration within the reverse micelle core. Highlighting this behavior of NH4OH in a reverse micelle system is also important in the context of developing predictive equations for reverse micelle size because weak bases such as this electrolyte are commonly used as reducing agents in reverse micelle nanoparticle synthesis processes [5]. These results mean that when developing a new system for synthesis using a base to reduce a salt precursor, the concentration of reducing agent likely can be varied within the regime of reverse micelle stability as necessary without having to account for additional reductions in reverse micelle size.

In summary, we have shown that our model, which makes use of the Debye screening length to describe the reduction in diameter of reverse micelles with added electrolytes, accurately predicts reverse micelle sizes for several salts in the $w_0 = 10$ water/AOT/isooctane system. There is a linear relationship between κ^{-1} and *D* in which the slope depends on cation valency/concentration and the *y*-intercept depends on anion-hydrated radius. This confirms specific ion effects must be considered in applications of *w*/o microemulsions with added salts. Furthermore, by applying this model to systems with ZrOCl₂ and NH₄OH, we determine it is

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only valid in salt systems where the hydrated species of cations maintain the same charge as their independent cation, not generally for all electrolyte additions.

4. Conclusions

By applying the Gouy-Chapman model to water/AOT/isooctane systems with added electrolytes, we have developed a proportional relationship between Debye screening length and reverse micelle size for $w_0 = 10$ water/AOT/isooctane systems containing salts which takes specific ion effects into account. Linear fits to reverse micelle size as a function of salt concentration $(c^{-1/2})$ for systems with FeSO₄, Mg(NO₃)₂, CuCl₂, Al(NO₃)₃, Fe(NO₃)₃, and Y(NO₃)₃, were used to develop a predictive equation for reverse micelle size based on cation valency and hydrated anion radius. The efficacy of this predictive equation was demonstrated by calculating theoretical sizes for reverse micelles with the addition of NaBH₄, ZrOCl₂, and NH₄OH and comparing these sizes with our previously reported data for these systems [26]. We conclude that in systems containing salts for which the charge of the primary hydrolyzed cation species is equal to the cation valency, z, the reverse micelle size can be accurately predicted by the Debye screening length proportionality equation $D = 3.1 \ z\kappa^{-1} + b_i$ [nm], where D is the reverse micelle solvodynamic diameter and b_i is a size parameter that can be predicted by its linear relationship to the anion hydrated radius. The explicit relationship between Debye screening length and reverse micelle size is a noteworthy improvement to our previous observations [26] and highlights the importance of considering hydrolyzed ion species charges over valency in analyzing microemulsions with electrolytes. Our focus on specific ion effects complements studies that have investigated the impacts of w_0 , solvent properties, surfactant structures/types, and pH on microemulsion stability and in applications of reverse micelle

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systems containing inorganic salts [41-46]. Further investigation is needed to determine the cause of instability in these systems, but we have successfully demonstrated its use to accurately predict reverse micelle sizes when adding monovalent, divalent, and trivalent salts in low concentrations (up to ~0.4 M) for water/AOT/isooctane systems. The reliance of this new model on anion hydrated radius and on studies that have indicated specific ion hydration effects on microemulsion morphology [44] gives another avenue, besides electrical double layer theory, to begin deeply exploring the reverse micelle destabilization process as it occurs with added electrolytes.

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Fig. 1. Reverse micelle solvodynamic diameter measured by dynamic light scattering and plotted as a function of $(z^2c)^{-1/2}$ for (a) divalent and (b) trivalent cation electrolytes.



Fig. 2. Reverse micelle solvodynamic diameter measured by dynamic light scattering and plotted as a function of $c^{-1/2}$ for various salts.



Fig. 3. Values of the *y*-intercepts, b_i , from the linear fits of *D* with respect to $(z^2c)^{-1/2}$ (Fig. 1), as a function of hydrated anion radius for each salt. Note, b_i is the same value for a given salt when *D* is plotted as a function of $c^{-1/2}$.



Fig. 4. Theoretically predicted and experimental reverse micelle sizes plotted as a function of $c^{-1/2}$ for (a) NaBH₄, (b) ZrOCl₂, and (c) NH₄OH.

Cation Valence	Salt	$m_{\rm z} ({\rm nm} \cdot {\rm M}^{-1/2})$	$b_{\rm i}({\rm nm})$
Divalent	CuCl ₂	2.8 ± 0.1	3.4 ± 0.1
	FeSO ₄	2.8 ± 0.3	5.0 ± 0.3
	$Mg(NO_3)_2$	2.9 ± 0.2	4.0 ± 0.2
Trivalent	Al(NO ₃) ₃	3.7 ± 0.1	4.1 ± 0.1
	Fe(NO ₃) ₃	3.7 ± 0.4	4.0 ± 0.3
	$Y(NO_3)_3$	3.8 ± 0.3	3.7 ± 0.2

Table 1. List of slopes (m_z) and *y*-intercepts (b_i) for linear fits of reverse micelle size as a function of $(z^2c)^{-1/2}$.

Cation valence	Electrolyte	<i>r</i> _{an} (pm)
Divalent	Divalent CuCl ₂	
	FeSO ₄	382 ± 7
	$Mg(NO_3)_2$	330 ± 15
Trivalent	Al(NO ₃) ₃	330 ± 15
	Fe(NO ₃) ₃	330 ± 15
	$Y(NO_3)_3$	330 ± 15

Table 2. Hydrated anion sizes (r_{an}) for monovalent, divalent, and trivalent cationic salts. Radii values are from Ohtaki and Radnai [36] and Nightingale Jr. [37].

Table 3. Table of predictive parameters and resultant predictive size equations for NaBH₄, ZrOCl₂ and NH₄OH. Radii values are taken from Ohtaki and Radnai [36], Nightingale Jr. [37], and Zhou *et al.* [38].

Electrolyte	Cation	<i>r</i> _{an} (pm)	Predicted reverse micelle	Measured linear fit
	valency		size equation (nm)	(nm)
NaBH4	1	340 ± 3	$D = 1.3 \bullet c^{-1/2} + 4.0$	$D = 1.3 \bullet c^{-1/2} + 3.9$
ZrOCl ₂	4	314 ± 15	$D = 1.3 \bullet c^{-1/2} + 3.4$	$D = 1.1 \cdot c^{-1/2} + 5.0$
NH4OH	1	300 ± 9	$D = 1.3 \bullet c^{-1/2} + 3.1$	$D = 0.4 \bullet c^{-1/2} + 7.4$

NaBH ₄			
Concentration [M]	Calculated Size [nm]	Measured Size [nm]	% Error
0.1	8.3	8.16 ± 1.33	1.1
0.2	7.0	7.35 ± 0.70	4.5
0.3	6.5	6.45 ± 0.72	0.3
0.4	6.1	6.19 ± 0.64	0.7
0.5	5.9	5.89 ± 0.45	0.5

Table 4. Predicted and actual sizes of reverse micelles containing NaBH₄, ZrOCl₂, and NH₄OH.

ZrOCl ₂			
Concentration [M]	Calculated Size [nm]	Measured Size [nm]	% Error
0.1	7.6	8.41 ± 0.03	9.6
0.2	6.4	7.48 ± 0.20	14.8
0.3	5.8	6.99 ± 0.76	16.7
0.4	5.5	6.67 ± 0.60	17.5

NH4OH			
Concentration [M]	Calculated Size [nm]	Measured Size [nm]	% Error
0.05	9.0	9.20 ± 0.83	2.0
0.2	6.0	8.58 ± 0.82	29.7
0.4	5.2	8.05 ± 0.64	35.8
0.6	4.8	7.78 ± 0.59	38.6