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Characteristic Differences in the Formation of Complex Coacervate Core Micelles from Neodymium and Zinc-Based Coordination Polymers

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In this paper we compare the formation of complex coacervate core micelles (C3Ms) from two different tricomponent mixtures, namely neodymium, the bisligand L_2EO_4 and the poly(cation)–block-poly(neutral) diblock copolymer $P2MVP_{41}$ – b – PEO_{205} , and zinc, L_2EO_4 and $P2MVP_{41}$ – b – PEO_{205} mixed systems. Three sets of titration experiments were carried out for each system: (i) titration of diblock copolymer $P2MVP_{41}$ – b – PEO_{205} with the stoichiometric mixture of metal ions and bisligands, (ii) titration of a mixture of diblock copolymer and bisligand with metal ions, and (iii) titration of a mixture of diblock copolymer and metal ions with bisligands. In all the above three cases, micelles are found to form either in a broad range of charge ratios or in a broad range of metal/bisligand ratios. Upon addition of Nd_2 –(L_2EO_4)₃ coordination polymer to $P2MVP_{41}$ – b – PEO_{205} solution, and upon addition of Nd^{3+} to a mixture of L_2EO_4 and $P2MVP_{41}$ – b – PEO_{205} , micelles are found to form immediately after the first addition, whereas micelles show up in the similar zinc system only after a certain threshold Zn –(L_2EO_4) or Zn^{2+} concentration. This difference can be traced to the different structures of the Nd_2 –(L_2EO_4)₃ and Zn –(L_2EO_4) coordination compounds. At very low concentrations, Zn –(L_2EO_4) are ring-like oligomers, but Nd_2 –(L_2EO_4)₃ are larger networks. The network structure favors the formation of coacervate micellar core with $P2MVP_{41}$ – b – PEO_{205} . Moreover, excess of Nd^{3+} ions will break up the C3Ms, while the same amount of Zn^{2+} has hardly any effect on the C3Ms. The breakdown of C3Ms by Nd^{3+} is due to the charge inversion of the coordination complex with increasing $[Nd^{3+}]/[L_2EO_4]$ ratio, which results in repulsive interaction between the coordination complex and the diblock copolymer, whereas no such interaction can occur in the zinc system.

Introduction

Complex coacervate core micelles (C3Ms), also called “polyion complex micelles (PIC micelles) or “block ionomer complexes” (BICs), are very promising self-assembled nanostructures in aqueous solution.^{1–3} In contrast to traditional micelles driven by hydrophobic interactions between amphiphilic molecules, this family of micelles is formed from a mixed system of oppositely charged water soluble polyelectrolytes.^{4,5} One of the prerequisites for the formation of this kind of micelles is that at least one of the polyelectrolytes must be a block copolymer with neutral water-soluble blocks to form a micellar corona and protect the micellar core from unbound growth into a macroscopic coacervate phase,^{6,7} as illustrated in Scheme 1.

In the past few years, the formation of C3Ms from different combinations of oppositely charged (diblock) polyelectrolytes have been systematically investigated,^{1–7} and it is well-known that certain lengths of the charged blocks are required to efficiently form C3Ms.⁸ Scheme 2 shows a typical diagram for the variation of the intensity of the scattered light upon variation of the negative charge fraction f^- . For a system with positive and negative chain

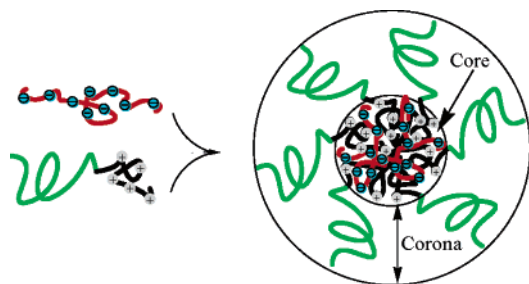
molecules, this is defined as

$$f^- = \frac{[-]}{[-] + [+]} \quad (1)$$

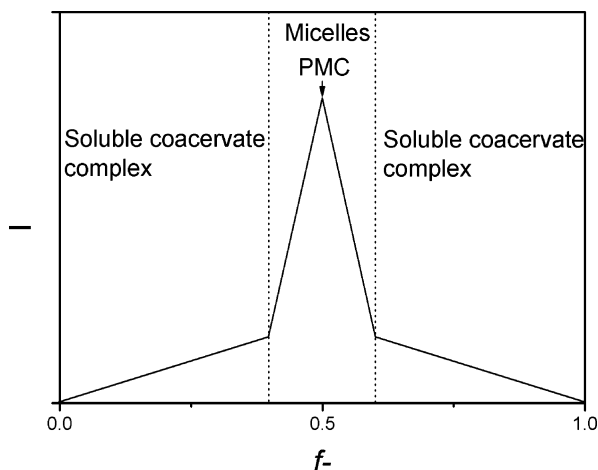
where $[-]$ and $[+]$ are the molar concentrations of charges for each of the chains. One can read from this scheme that with increasing the negative charge fraction f^- , a sharp peak of scattered intensity I is observed at $f^- \approx 0.5$, where $[-] \approx [+]$. At f^- far away from 0.5, the scattered light intensity is very weak. The appearance of a sharp peak in the I versus f^- diagram is an indication of micelle formation, and the f^- where the peak shows up (normally at $f^- = 0.5$) is denoted as the preferred micellar composition (PMC).⁴ Before and after micelle formation, soluble complexes with either excess positive or negative charges are formed which scatter only weakly.

The promising potential for C3Ms is that they can be used as nanocarriers for charged biomaterials, such as DNA and proteins.⁹ By choosing a diblock copolymer with one block carrying opposite charges to that of the target DNA or protein molecules, these molecules can be successfully suited in the micellar core of the C3Ms, which enables the C3Ms to be carriers of charged molecules.^{10,11} More surprisingly, we recently found that the C3Ms can also be formed using metal-containing reversible coordination polymers as the “homopolymers”, and thus can potentially be used as carriers for heavy metal ions. Generally, a coordination complex is formed by metal–ligand interaction;^{12,13} chain formation becomes possible when an

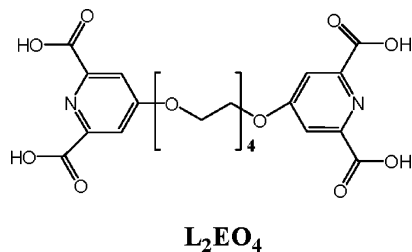
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SCHEME 1: Schematic Representation of Formation of Complex Coacervate Core Micelle^a

^a The core is formed by complexation of the anionic homopolymer and the cationic block of the diblock copolymer. The corona consists of the electroneutral hydrophilic blocks.

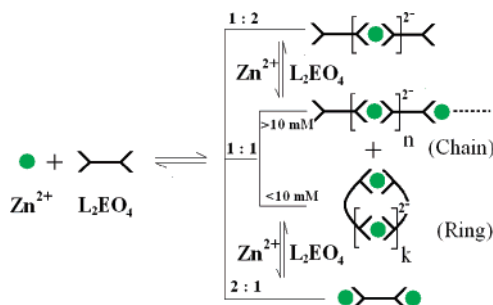
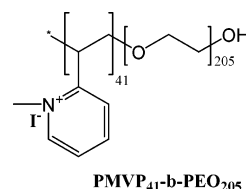
SCHEME 2: Light-Scattering Diagram of the C3Ms^a

^a The light-scattering intensity I is plotted against the molar fraction of the negative charge fraction f^- .

SCHEME 3: Structure of L_2EO_4 

organic molecule having two such ligands is mixed with multivalent metal ions.^{14–16} One of such metal–bisligand system developed by Vermonden et al. is water soluble,^{17–19} has high charge density, and responds quickly to changes in composition and concentration. It is based on terdentate ligand groups which are pyridine-2,6-dicarboxylic acid groups connected at the 4-position of the pyridine ring to a spacer of four ethylene oxide (EO) spacer. These bisligands are denoted by “ L_2EO_4 ” in the present study (rather than “ C_4 ” as in ref 17–19), as illustrated in Scheme 3. In acidic condition (pH < 6), the dissociation degree of the carboxylic groups in L_2EO_4 is very small, so that the charge of L_2EO_4 in pH 5.4 solutions is usually considered negligible in this work.

In aqueous solution, both “oligomers” with small rings and “polymers” with long chains are possible structures at 1:1 mixing of L_2EO_4 and zinc ions (Scheme 4), but the fractions of L_2EO_4 molecules in rings and chains and the average length of the

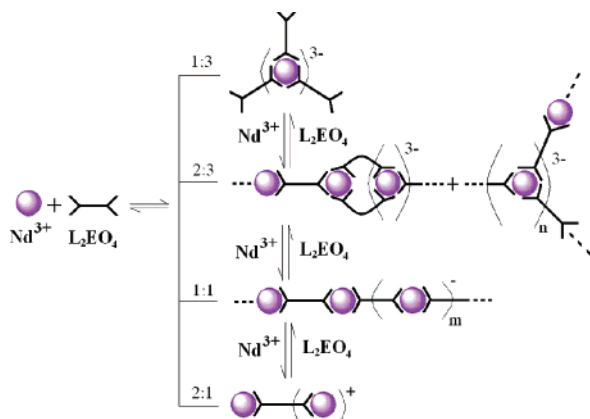
SCHEME 4: Schematic Illustration of the Dominant $Zn-L_2EO_4$ Coordination Complexes with Different $Zn:L_2EO_4$ Molar Ratios**SCHEME 5:** Structure of $P2MVP_{41}-b-PEO_{205}$ 

chains depend on the concentration. At L_2EO_4 concentrations less than 10 mM, most L_2EO_4 molecules exist in the form of small rings (oligomers), whereas linear chains (polymers) become more and more important at higher concentrations.¹⁷ Because each coordination center of the $Zn-(L_2EO_4)$ complex has overall two negative charges ($4COO^- + Zn^{2+}$), the $Zn-(L_2EO_4)$ coordination polymer can be considered as a negatively charged polyelectrolyte with a charge density of about 2 elementary charges per monomer. If Zn^{2+} and L_2EO_4 are mixed at a molar ratio other than 1:1, the average chain length will be decreased by the excess component. At $Zn^{2+}:L_2EO_4 = 1:2$, the predominant complex will be $[Zn-(L_2EO_4)_2]^{2-}$, and at $Zn^{2+}:L_2EO_4 = 2:1$ will be $Zn_2-(L_2EO_4)$, which is with zero charge, as illustrated in Scheme 4.

In a previous publication,²⁰ we reported the fascinating observation of hierarchical C3M formation in very dilute mixed systems of $Zn-(L_2EO_4)$ and $P2MVP_{41}-b-PEO_{205}$ diblock polyelectrolytes (Scheme 5). Additional experiments on the short coordination complex with 1:2 or 2:1 zinc to L_2EO_4 molar ratio proved that short oligomers cannot form C3Ms with $P2MVP_{41}-b-PEO_{205}$. The reason for the formation of micelles is thus attributed to the concentration responsiveness of the 1:1 coordination complex. Since each coordination center of the complex carries two elementary negative charges, they will interact with the positively charged polyelectrolytes, which results in the enhancement of the local concentration of the coordination polymer. The increase of the length of the coordination polymer is a consequence of the high local concentration inside the complex coacervate cores of the C3Ms, and is further promoted by the interactions with the oppositely charged P2MVP blocks, whereas simultaneously this increase of the length of the coordination polymer enables the formation of C3Ms.

In this contribution, we report on the characteristic differences between C3Ms where Zn^{2+} and Nd^{3+} are the metal ions, respectively. For the sake of convenience, we will call them $Zn-C3Ms$ and $Nd-C3Ms$, respectively. In contrast to bivalent zinc ions that can accommodate two (pyridine-2,6-dicarboxylic acid) groups with six chelating points, the trivalent neodymium ions (Nd^{3+}) with nine chelating points can accommodate at most three such groups, i.e., $[Nd^{3+}]:[L_2EO_4] = 2:3$, which therefore permit formation of branched clusters even at very low

SCHEME 6: Schematic Illustration of the Dominant Coordination Complexes between Nd^{3+} and L_2EO_4 with Different $\text{Nd}:\text{L}_2\text{EO}_4$ Molar Ratios in pH 5.4 Solutions



concentration.¹⁷ In this way, each fully coordinated neodymium ion carries three elementary negative charges ($6\text{COO}^- + \text{Nd}^{3+}$). However, linear chains can also be formed if the ratio between Nd^{3+} and L_2EO_4 is 1:1; the charge density becomes minus one (-1) per coordinated neodymium ion ($4\text{COO}^- + \text{Nd}^{3+}$) in this case. At ratios between 2:3 and 1:1, the average charge density is between -3 and -1 . At mixing ratios of $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] > 1$ or $< 2/3$, the excess component will form ends that stop the growth of the branches and the chains, as well as affects the charge density. Excess Nd^{3+} may even invert the sign of the charges carried by the coordination complexes. The various coordination complexes between Nd^{3+} and L_2EO_4 at different mixing ratios are illustrated in Scheme 6. It is clear that Nd^{3+} and L_2EO_4 at ratios of between 2:3 and 1:1 will form coordination “polymer”, other ratios give only short coordination complex.

One might expect the higher coordination capacity of Nd^{3+} as compared to Zn^{2+} to bring up new features to the C3M formation. It is the aim of the present work to investigate such new systems. For example, micelles may already be formed with a small amount of Nd^{3+} in the mixture of L_2EO_4 and P2MVP-*b*-PEO aqueous solution, or excess Nd^{3+} may have an effect on the C3Ms if positively charged complexes can form. For the convenience reason, the abbreviation of “PMC” (preferred micellar composition) is also used for the Zn-C3Ms and Nd-C3Ms in all the cases of optimum micelle formation in this work.

Experimental Section

Materials. The diblock copolymer used in this study is poly(2-vinyl-*N*-methyl pyridinium iodide)-*b*-poly(ethylene oxide) (P2MVP₄₁-*b*-PEO₂₀₅) (Scheme 5), which is quaternized from poly(2-vinylpyridine)-*b*-poly(ethylene oxide) (P2VP₄₁-*b*-PEO₂₀₅) (Polymer Source, $M_w/M_n = 1.03$, $M_w = 13.3$ K) following the procedure described elsewhere.²¹ The degree of quaternization is higher than 90%.²²

The coordination complex between zinc (II) or neodymium (III) and 1,11-bis(2,6-dicarboxypyridin-4-yloxy)-3,6,9-trioxaundecane bisligand molecules, were prepared according to literature.^{17,18} Piperazinebis(ethanesulfonic acid) (PIPES, 98%) was obtained from Aldrich. Sodium hydroxide (NaOH), neodymium nitrate ($\text{Nd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$), and zinc nitrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) were analytical grade. 20 mM PIPES-NaOH buffer with pH = 5.4 in bidistilled water was used as solvent throughout the experiments.

Methods. *Dynamic Light-Scattering Titration (DLS).* Light-scattering measurements were performed with an ALV light-scattering-apparatus, equipped with a 400mW argon ion laser operating at a wavelength of 514.5 nm. A refractive index matching bath of filtered cis-decalin surrounded the cylindrical scattering cell, and the temperature was controlled within ± 0.5 °C using a Haake F8-C35 thermostat. Titrations were carried out using a Schott-Geräte computer-controlled titration setup to control sequential addition of titrant and cell stirring. Typical concentrations of the titrated species are in the order of several micromoles per liter, expressed in terms of charge concentration. After every dosage, the laser light-scattering intensity (I) at 90° and the correlation function were recorded using DLS. The CUMULANT method was used to analyze the mean apparent hydrodynamic radius (R_h) and the polydispersity index (PDI). R_h is calculated from the inverse decay time Γ of the second order fitting and the width of the radial distribution as well as the PDI is calculated from the second moment μ_2 , according to the following formulas:

$$R_h = kT/6\pi\eta D \quad (2)$$

$$\text{PDI} = \mu_2/\Gamma^2 \quad (3)$$

where q is the scattering vector, k the Boltzman constant, T the absolute temperature, η the viscosity of the solvent, and D the diffusion coefficient of the particles. Variations in R_h and I are studied as a function of the mole fraction of negative charge ratios, f^- , or the ratio between the concentration of metal ions and bisligands, i.e., $[\text{M}]/[\text{L}_2\text{EO}_4]$. The scattering intensity I is corrected for volume charges for all experiments by calibration of the measured light intensity I_m in the following way:

$$I = I_m(V_d + V_t)/V_t \quad (4)$$

where V_d and V_t are the volumes of the dosed agent and of the titrated species, respectively. The CONTIN method is used to analyze the distribution of particle (C3M) radii. Unweighted data were recorded for all the experiments.

Results

Mixing of a negatively charged coordination polymer and a positively charged diblock copolymer results in the formation of complex coacervate core micelles (C3Ms).¹ We have performed light-scattering titrations in which C3Ms are obtained by titrating along different routes. This enables us to follow the micelle formation process as a function of stoichiometry. The three components in our system participating in self-assembly are block copolymers, ligands, and metal ions. The following titrations were carried out: (1) addition of coordination polymer (metal ions + ligands) to diblock copolymer; (2) addition of bisligands to a stoichiometric mixture of diblock copolymers and metal ions; (3) addition of metal ions to a stoichiometric mixture of block copolymer and bisligands; (4) addition of coordination complex (metal ions + ligands) at nonstoichiometric ratio to diblock copolymer

1. Titration of the Diblock Copolymer with Coordination Polymers. In Figure 1 we compare dynamic light-scattering titration results of Zn and Nd systems, respectively. Stoichiometric mixtures of metal ions and bisligands, i.e., mixtures of $[\text{Zn}^{2+}]:[\text{L}_2\text{EO}_4] = 1:1$, and of $[\text{Nd}^{3+}]:[\text{L}_2\text{EO}_4] = 2:3$, were added to the diblock copolymer P2MVP₄₁-*b*-PEO₂₀₅ solution. For both systems, the intensity of the scattered light shows a maximum at $f^- \approx 0.5$. However, before the PMC some characteristic differences between the Zn and Nd systems are observed. In

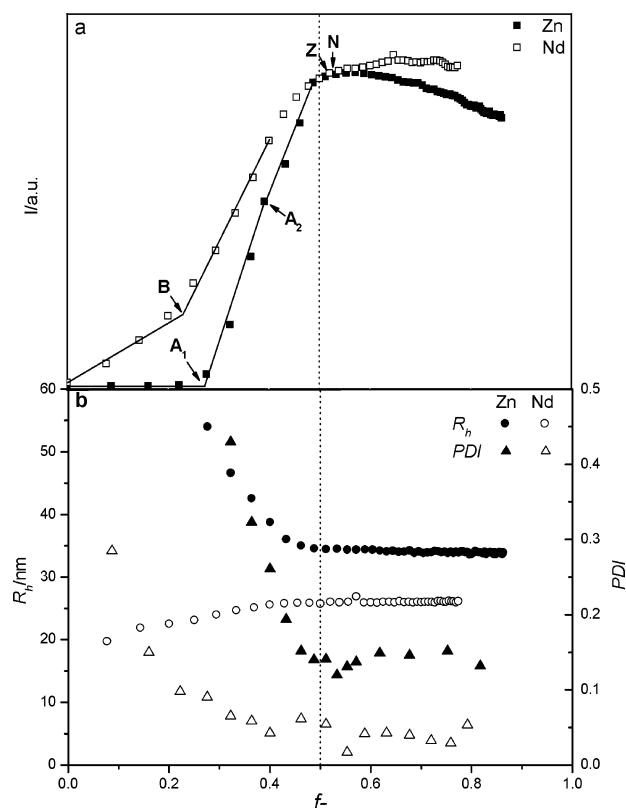


Figure 1. Light-scattering titration of P2MVP₄₁-b-PEO₂₀₅ solution with Zn-(L₂EO₄) and Nd₂-(L₂EO₄)₃ coordination polymers. f^- is the fraction of negative charge in the solution. Filled symbols, addition of 2.13 mM (Zn:L₂EO₄ = 1:1) to 0.87 mM P2MVP₄₁-b-PEO₂₀₅ solution; open symbols, addition of 1.65 mM (Nd:L₂EO₄ = 1:1.5) to 0.88 mM P2MVP₄₁-b-PEO₂₀₅ solution. Squares, volume normalized scattered light intensity (I); circles, hydrodynamic radius (R_h); and triangles, polydispersity index (PDI).

the Zn-(L₂EO₄)/P2MVP₄₁-b-PEO₂₀₅ system, the scattered light intensity starts to increase sharply only when the amount of Zn-(L₂EO₄) exceeds a certain threshold value, i.e., $f^- \approx 0.27$ (Arrow A1). Moreover, a second weaker kink was observed at $f^- \approx 0.40$ (arrow A2). In contrast, the increase of light intensity for the Nd system is observed immediately after the first addition of the Nd₂-(L₂EO₄)₃ complex to the P2MVP-b-PEO solution. At $f^- \approx 0.20$ (Arrow B) a kink occurs in the intensity I versus f^- curve, after which the intensity increases more steeply. These results indicate that in both systems, different self-organized structures were formed before and after the kink.

The difference between the particles formed before and after the kinks can also be seen from the variation of R_h (CUMULANT) versus f^- . In the zinc system, neither C3Ms nor any other clusters that cause significant scattering are formed at $f^- < 0.27$. Some loose clusters with bigger apparent average radii (40–50 nm) are formed upon further addition of Zn-(L₂EO₄). These clusters become "denser" with increasing amount of Zn-(L₂EO₄) and the average radii become constant (35 nm) at $f^- > 0.5$. In contrast, in the neodymium system, aggregates with radii of about 23 nm are obtained upon the very first addition of Nd₂-(L₂EO₄)₃ to the P2MVP₄₁-b-PEO₂₀₅ solution. These radii increase slightly with further addition of Nd₂-(L₂EO₄)₃ and reach a constant value of 25 nm after $f^- \approx 0.40$. The average CUMULANT radii of the Nd-C3Ms are significantly smaller than those for the zinc system. The difference between the micellar radii for the two systems probably is related to the polydispersity of the systems. As shown in Figure 1, the PDI

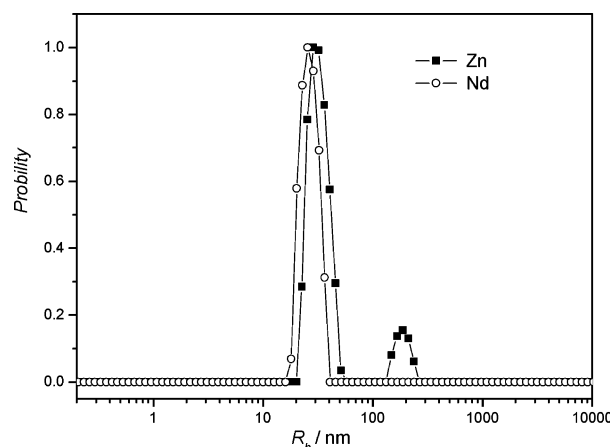


Figure 2. CONTIN analysis of the C3Ms formed in the Zn-(L₂EO₄)/P2MVP₄₁-b-PEO₂₀₅ system and Nd₂-(L₂EO₄)₃/P2MVP₄₁-b-PEO₂₀₅ system. Data are recorded from the titration DLS at $f^- = 0.5$.

for the zinc system is as high as ~26%, but that for the neodymium system is even lower than 5%.

The CONTIN analysis reflects two peaks for the zinc system, but only one narrow peak of C3Ms for the neodymium system. It is noticeable that the smaller radii for the zinc systems, ~25 nm, are almost the same as those of neodymium system. Of course one should realize that the number of bigger particles in the zinc system obtained by titration DLS is actually very small if we consider the R^6 relationship between the intensity and the radius for a given internal particle density and neglecting form factor effects. It seems that these bigger particles are produced in the titration process only: in case of direct mixing of the Zn-(L₂EO₄) and P2MVP₄₁-b-PEO₂₀₅ solution at $f^- = 0.5$, only one narrow CONTIN peak was obtained. It is interesting to note that, the relative populations of the two groups vary with f^- , a feature which we will address extensively in the context of sample history in a following article. Anyway, these results suggest a slow relaxation of the clusters formed at non-stoichiometric ratios.

Scheme 6 also clearly shows that at $[Nd^{3+}]:[L_2EO_4] = 1:1$, linear chains can be formed in the Nd-(L₂EO₄) complex system with a charge density of about minus one (−1) elementary charge per monomer. This information inspired us to investigate the light-scattering titration evolution upon adding the 1–1 coordination complex to the diblock copolymer system.

Shown in Figure 3 are the variations of scattered light intensity, mean hydrodynamic radius and PDI with the negative charge fractions. If compare Figure 3 and Figure 1, we find the following interesting results: (i) the scattered light intensity increases immediately upon the first addition of Nd-(L₂EO₄) coordination polymer, which is similar to addition of Nd₂-(L₂EO₄)₃ to the P2MVP₄₁-b-PEO₂₀₅ solution, but different from the addition of Zn-(L₂EO₄) coordination polymer; (ii) the CUMULANT radii (23–24 nm) and the PDI of the micelles are almost the same as those in the Nd-C3Ms in Figure 1, but obviously smaller than those of Zn-C3Ms. Accordingly, the CONTIN analysis (not shown) also gives only one narrow peak which is almost the same as that for Nd-C3Ms in Figure 1. These results indicate that the "linear" structure of Nd-(L₂EO₄) coordination polymer is different from that of Zn-(L₂EO₄); the immediate increase of the scattered light intensity upon the first addition of Nd-(L₂EO₄) is probably indicating that the linear structure is in fast equilibrium with networks.

2. Titration of a Mixture of Diblock Copolymer and Bisligand with Metal Ions. The formation of coordination polymers from bisligands and metal ions is reversible.¹⁷

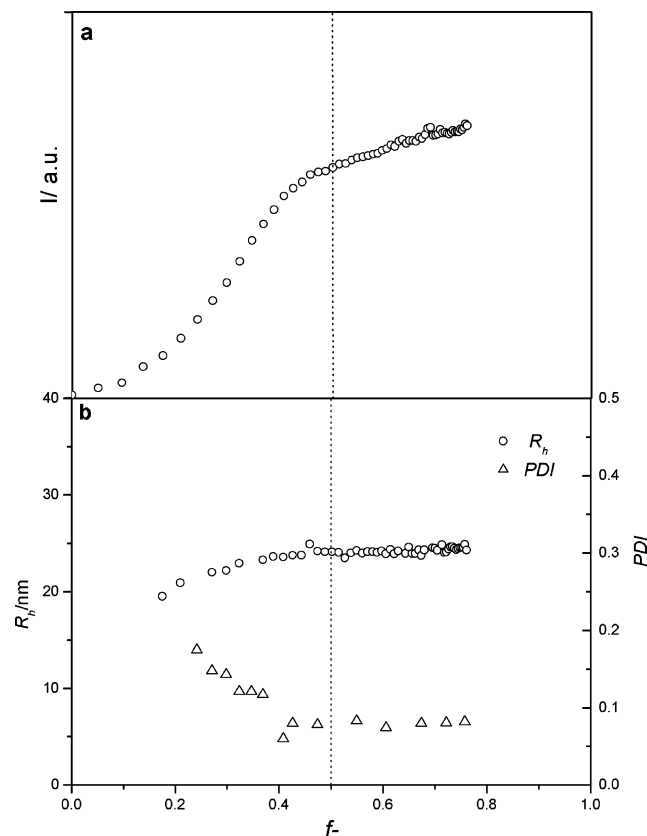


Figure 3. Light-scattering titration curves of $\text{Nd}:\text{L}_2\text{EO}_4 = 1:1$ complex (2.365 mM) to the $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ solution (0.863 mM). f^- is the fraction of negative charge in the whole system.

Therefore, we also expect formation of C3Ms upon addition of either metals to a mixture of (bisligand+diblock copolymer), or bisligand to a mixture of (metal ions + diblock copolymer). In Figure 4 results of addition of metal ions to a mixture of bisligand and diblock copolymer are chosen such that the balance of charges ($f^- = 0.5$) is reached when an amount of metal ions is added that corresponds to the stoichiometry of full coordination.

In both systems, the addition of metal ions leads to a maximum of the scattered light intensity at $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4] \approx 1.0$ and $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] \approx 0.67$, indicating the formation of C3Ms (Figure 4). Pronounced differences of the variation of the scattered light intensity (open and filled squares) upon varying $[\text{M}]/[\text{L}_2\text{EO}_4]$ between the two systems are also observed in this experiment: (i) Similar to the situation in Figure 1, the scattered light intensity increases immediately after the first addition of neodymium ions (Arrow D), but it does not increase upon addition of zinc ions until $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4] \approx 0.40$ (Arrow C). (ii) The scattered light intensity decreases slightly beyond $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4] \approx 1$ (Arrow Z), where the optimal stoichiometric ratio for full coordination of Zn^{2+} ions is reached. However, the scattered light intensity decreases almost linearly with neodymium after $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] \approx 0.67$ (Arrow N), which is the stoichiometric ratio for full coordination of neodymium ions. At $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] = 1.75$, the scattered light intensity falls to almost zero. This result shows that excess zinc ions have a weak effect on the C3Ms, but an excess of Nd^{3+} ions destroys the C3Ms. Apparently, free Nd^{3+} is able to extract ligands from the core of Nd -C3Ms. Upon increasing the $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4]$ ratio from 0.67, to 1.33, and then to 2, the charge density per monomer first decreases from -3 ($[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] = 0.67$) to 0 ($[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] = 1.33$), and finally inverts to $+1$ ($[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] = 2$). Therefore, the attractive electrostatic interaction

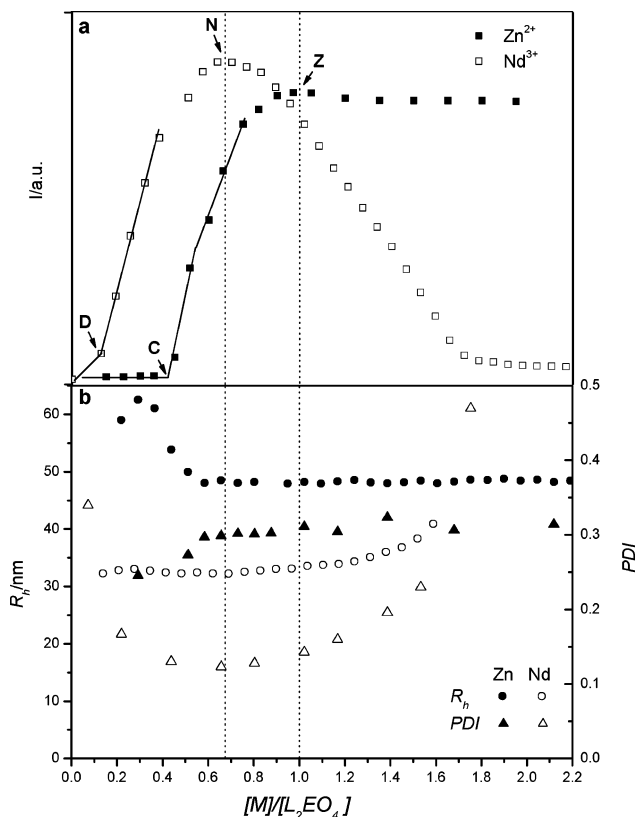


Figure 4. Titration of a mixture of bisligand and diblock copolymer at 1:2 molar ratio with metal ions. $[\text{M}]/[\text{L}_2\text{EO}_4]$ represents the molar ratio of metal ions over the bisligand L_2EO_4 . Filled symbols, addition of Zn^{2+} (4.35 mM) to $[\text{L}_2\text{EO}_4]$ (0.40 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution; open symbols, addition of Nd^{3+} (1.65 mM) to $[\text{L}_2\text{EO}_4]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution. Squares, volume normalized scattered light intensity (I); circles, hydrodynamic radius (R_h); and triangles, polydispersity index (PDI).

between the coordination complex and the diblock copolymer keeps decreasing with increasing concentration of metal ions, and gradually become repulsive for $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] > 1.33$. The repulsive force drives the C3Ms to fall apart. As we have seen experimentally in Figure 4b that the radii of the Nd -C3Ms is almost constant over the entire experimental composition range, the linear decrease of the scattered light intensity indicates that the number of the micelles decreases linearly with the amount of Nd^{3+} .

Just like in Figure 1, larger radii are found for the Zn -C3Ms ($R_h \approx 46$ nm) than for the Nd -C3Ms ($R_h \approx 32$ nm) in Figure 4. However, both radii of the Zn -C3Ms and of the Nd -C3Ms in Figure 4 are larger than those formed from the metal-bisligand coordination complex and the diblock copolymer in Figure 1. These large radii seem to be a consequence of polydispersity. This is further confirmed by the higher polydispersity index (PDI). We can read from Figure 4 that around PMC the PDI for the Zn system is about 30%, and for the Nd system 15%. Actually, the PDI passes through a maximum at $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] \approx 2/3$, whereas the PDI for the zinc system first increases with the $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4]$ ratio and stays constant within a wide range of the ratio.

CONTIN results (Figure 5) reveal a very broad single peak for the zinc system, which is obviously a combination of particles with R_h ranging from 10 nm to 300 nm; whereas two peaks are found for the neodymium system centered at 25 and 150 nm, respectively. Therefore, the larger mean hydrodynamic radii for Nd -C3Ms in Figure 4 as compared to Figure 1 are actually caused by the presence of a population of larger

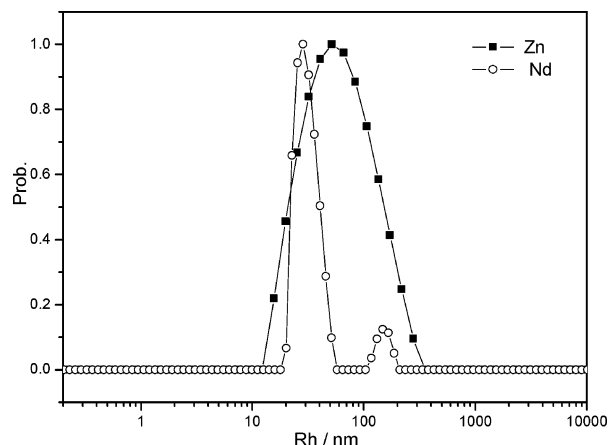


Figure 5. CONTIN analysis of the C3Ms formed in the addition of Zn^{2+} (4.35 mM) to $[\text{L}_2\text{EO}_4]$ (0.40 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution and addition of Nd^{3+} (1.65 mM) to $[\text{L}_2\text{EO}_4]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution. Data are recorded from the titration DLS at $f^- = 0.5$.

aggregates ($R_h \approx 150$ nm) next to the “normal” C3Ms with radii of about 25 nm.

3. Titration of the Mixture of Diblock Copolymer and Metal Ions with Bisligands. Before addition of bisligands, metal ions and diblock copolymer were mixed at a molar ratio of 1:2 for zinc and 1:3 for neodymium. Hence for both systems the optimum stoichiometric coordination is reached at $f^- = 0.5$. The common feature of the two systems (Figure 6) is that at the first beginning of addition of L_2EO_4 (coming from the right side of the diagram), the scattered light intensity did not increase at all, only after a certain L_2EO_4 amount is reached, i.e., $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4] = 2.4$ (Arrow E), and $[\text{Nd}^{3+}]/[\text{L}_2\text{EO}_4] = 1.35$ (Arrow F), the intensity rises sharply.

Meanwhile, similar to the results in Figure 1, loose clusters in the Zn system with larger radii are formed at the beginning of addition of bisligand solution to the zinc/polymer mixture. With increasing bisligand concentration to $[\text{Zn}^{2+}]/[\text{L}_2\text{EO}_4] < 1$, C3Ms with a constant mean radius of about 35 nm are eventually formed. In contrast, in the Nd system the clusters formed before the PMC have smaller radii than those at the PMC (23 nm). Comparing Figure 6 with the results obtained from Figure 1 and Figure 4, it is clear that both the radii and polydispersity index of the C3Ms in Figure 6 are similar to those in Figure 1. Again the CONTIN analysis (Figure 7) gives a broad peak for the zinc system but a narrow peak for the neodymium system, which also indicates the different polydispersity properties of the two systems.

4. Titration of the Diblock Copolymer with Nonstoichiometric Mixture of Metal Ions and Bisligands. In our previous work, it was found that the coordination complex of Zn^{2+} and bisligand at 2:1 or 1:2 molar ratio cannot form C3Ms with the diblock copolymer, because the system can only form short metal/ligand complexes (see Scheme 4). However, the situation is different when Nd^{3+} ions are applied.

Shown in Figure 8 are sharply contrasting light-scattering experiments of addition of coordination complex of $\text{Zn}:\text{L}_2\text{EO}_4 = 1:2$ and $\text{Nd}:\text{L}_2\text{EO}_4 = 1:3$, respectively, to a solution of $\text{P2MVP}_{41}\text{-b-PEO}_{205}$. One may suppose that short $\text{Zn-(L}_2\text{EO}_4)_2$ and star-like $\text{Nd-(L}_2\text{EO}_4)_3$ coordination complexes exist in these two solutions as illustrated in Scheme 4 and 6, respectively. It is clear from Figure 8 that the short $\text{Zn-(L}_2\text{EO}_4)_2$ complex has no detectable interaction with $\text{P2MVP}_{41}\text{-b-PEO}_{205}$, but a mixture of $\text{Nd-(L}_2\text{EO}_4)_3$ and $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ forms micelles immediately. The negative charges for the neodymium

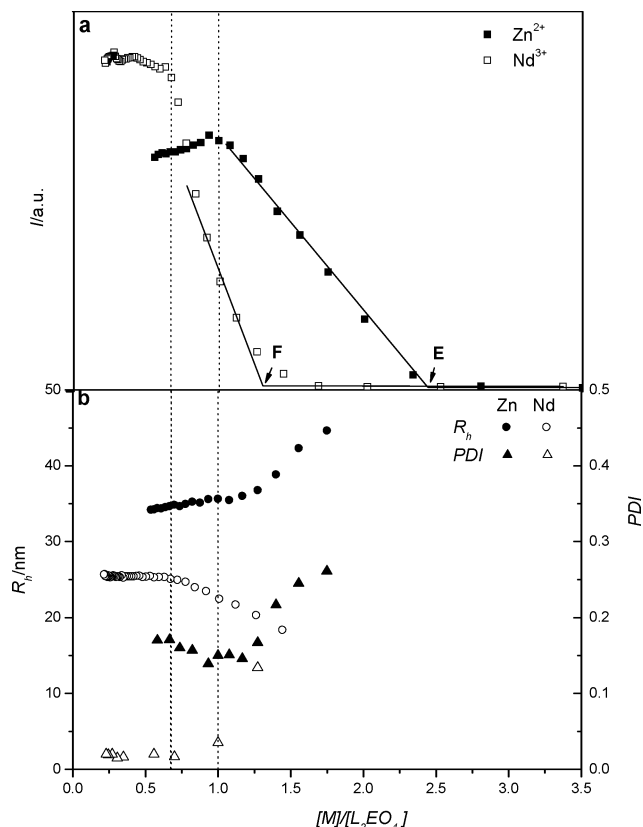


Figure 6. Light-scattering titration curves for addition of L_2EO_4 to mixtures of $\text{Zn}^{2+}/\text{P2MVP}_{41}\text{-b-PEO}_{205}$ and $\text{Nd}^{3+}/\text{P2MVP}_{41}\text{-b-PEO}_{205}$. $[\text{M}]/[\text{L}_2\text{EO}_4]$ represents the molar ratio of metal ions over the bisligand L_2EO_4 . Filled symbols, addition of L_2EO_4 (4.35 mM) to $[\text{Zn}^{2+}]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.82 mM) solution; open symbols, addition of L_2EO_4 (1.65 mM) to $[\text{Nd}^{3+}]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution. Squares, volume normalized scattered light intensity (I); circles, hydrodynamic radius (R_h); and triangles, polydispersity index (PDI).

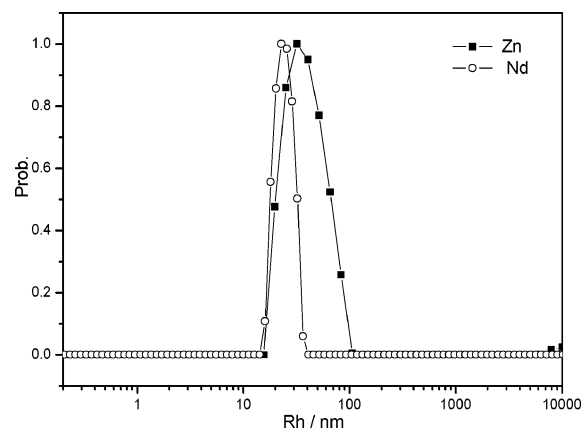


Figure 7. CONTIN analysis of the C3Ms formed in the addition of L_2EO_4 (4.35 mM) to $[\text{Zn}^{2+}]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.82 mM) solution and addition of L_2EO_4 (1.65 mM) to $[\text{Nd}^{3+}]$ (0.41 mM) + $\text{P2MVP}_{41}\text{-b-PEO}_{205}$ (0.80 mM) solution. Data are recorded from the titration DLS at $f^- = 0.5$.

system are calculated by assuming that each neodymium ion carries 3 negative charges after full coordination with L_2EO_4 . In this way we see again the plateau scattered light intensity at $f^- \approx 0.5$. This result indicates that most of the neodymium ions have been fully coordinated by the L_2EO_4 bisligands in a kind of network structure and that excess L_2EO_4 molecules are expelled. In other words, once the local concentration of $\text{Nd-(L}_2\text{EO}_4)_3$ has been enhanced by the P2MVP-b-PEO network

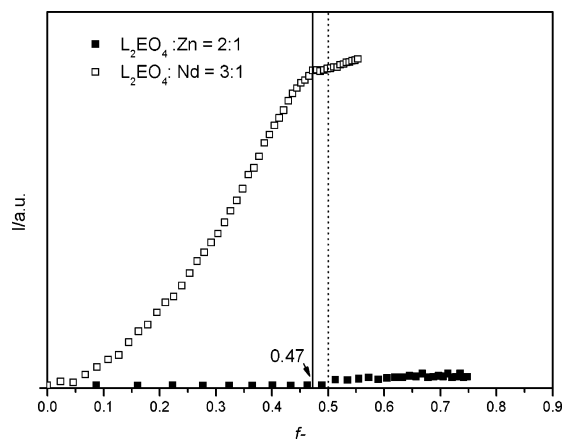


Figure 8. Comparison of the titration of P2MVP₄₁-b-PEO₂₀₅ aqueous solution with Zn-(L₂EO₄)₂ and Nd-(L₂EO₄)₃.

structures with a composition Nd₂-(L₂EO₄)₃ (may have less L₂EO₄) are formed, which in turn helps to the formation of C3Ms. However, it is not possible for the Zn-(L₂EO₄)₂ complex to rearrange in the presence of P2MVP₄₁-b-PEO₂₀₅ polycations into linear structure with a higher polymerization degree and less L₂EO₄, so that C3Ms cannot be formed in this system.

Discussion

As we have discussed in our previous work,²⁰ the formation of C3Ms in the mixed system of Zn-(L₂EO₄) and P2MVP₄₁-b-PEO₂₀₅ is attributed to the concentration responsiveness of the coordination polymer. The existence of P2MVP₄₁-b-PEO₂₀₅ enhances the local concentration of the ring-like coordination oligomers of Zn-(L₂EO₄), which then grow into polymers with higher polymerization degree. Simultaneously, the formation of linear Zn-(L₂EO₄) polymers helps to form C3Ms with the P2MVP₄₁-b-PEO₂₀₅ molecules. Therefore, only after the amount of rings of Zn-(L₂EO₄) oligomers is high enough, one can expect the formation of linear polymers and C3Ms. That is why we did not observe an increase of scattered light intensity for the zinc system at $f_- < 0.27$ in Figure 1. If the number of the linear chains is small, no well-defined spherical C3Ms can exist due to the overcharge of the electrostatic complexes with excess of P2MVP₄₁-b-PEO₂₀₅ molecules in the solution. That is why we observed “pre-C3Ms” with larger apparent average radii. With f_- exceeding 0.40, the net charges on the electrostatic complexes are greatly reduced and well-defined spherical C3Ms can be formed. As soon as all the P2MVP₄₁-b-PEO₂₀₅ molecules have been consumed at $f_- = 0.5$ by the formation of C3Ms, excess ring-like oligomers of Zn-(L₂EO₄) behave as free ions in the solution and have no influence on the already formed C3Ms. Hence a decrease of the scattered light intensity such as depicted in Scheme 2 which is usually observed with covalent polyelectrolytes, is not observed here. The constant radii and PDI at $f_- > 0.5$ in Figure 1 clearly indicate that the existence of well-defined C3Ms is not affected by excess Zn-(L₂EO₄). From Figure 1, 3, 4, and 6 it follows that for the zinc system, a minimum Zn²⁺ and L₂EO₄ concentration is always required. Below we will show that the product of the Zn²⁺ and the L₂EO₄ concentrations is the critical parameter.

The Nd system behaves rather differently. As we have discussed above, even at very low concentrations of Nd₂-(L₂EO₄)₃, the oligomers of Nd₂-(L₂EO₄)₃ have already three-dimensional network structures, although they do not have a significant effect on the viscosity. The ability for the Nd₂-(L₂EO₄)₃ to form network structures must be attributed to the

3-fold chelating points of the Nd³⁺ ion, instead of 2-fold as is the case for Zn²⁺ ion. This inhibits formation of small rings. It has been proven that the three binding constants for the monoligand molecules 2,6-pyridinedicarboxylic to one Nd³⁺ are $K_1 = 10^{8.78}$, $K_2 = 10^{6.72}$, $K_3 = 10^{5.06}$, respectively.²³ The binding of Nd³⁺ to the bisligand L₂EO₄ can be looked the same as the case of Nd³⁺ to monoligand (2,6-pyridinedicarboxylic acids).¹⁸ We can see that even the third binding constant is as high as 10^{5.06}! Therefore, the coordination bonds between the neodymium and L₂EO₄ behave almost as “covalent” bonds so that the network structure exists, no matter how dilute the solution is. It is probable that the critical Nd₂-(L₂EO₄)₃ concentration which leads to the formation of C3Ms is very low, so that in our experiments C3Ms start to form already after the first addition. Similar to the case of zinc system, excess of Nd₂-(L₂EO₄)₃ oligomers also has little influence on the already formed C3Ms.

The most pronounced difference between the Zn and Nd-C3M systems lies in the influence of excess metal ions on the formed C3Ms. We can read from Figure 4 that excess of zinc ions almost has no influence on the C3Ms, but an excess of neodymium ions destroys them (Figure 4). This difference is caused by the coordination ability of the two metals. A zinc ion can complex with two monoligands with binding constants $K_1 = 10^{6.4}$, and $K_2 = 10^{5.5}$, respectively.²⁴ After the PMC, additional zinc ions have the possibility to coordinate with L₂EO₄ in the core of C3Ms to form short Zn₂-(L₂EO₄) complexes. Since the Zn₂-(L₂EO₄) carries zero charge, it has no strong tendency to leave the micellar core. However, the case for neodymium is pronouncedly different. As analyzed in the results section, a positively charged neodymium complex will show up at $[Nd^{3+}]/[L_2EO_4] > 1.33$, so that the interaction between the coordination complex and the cationic polymer become repulsive, which results in more and more ligands leaving the micellar core; consequently, the C3Ms will disintegrate upon excess addition of neodymium ions.

In one aspect, the zinc and neodymium system are similar on addition of bisligand to the mixture of metal ions and diblock copolymer, no immediate increase of scattered light intensity was observed for the neodymium as well as for the zinc system. This can again be explained in terms of the charges on each coordination center (see the above discussion). When small amounts of bisligand molecules were added into the neodymium-rich mixture, the coordination complexes, which are capped with neodymium ions, have one positive charge per coordination center, so that they cannot form C3Ms with the diblock copolymer due to the repulsive interaction between them. Only when the charges on the coordination center become negative, formation of (pre-)C3Ms can be expected. Therefore, the scattered light intensity will increase after certain amount of bisligand is added.

As we have shown in the results section, C3Ms can be prepared along different routes, each of which has different features for the Zn and Nd systems. In order to rationalize the results, we tentatively introduce a quantity “coordination product” similar to the well-known “solubility product” as follows:

$$K_{c,Zn} = ([Zn][L_2EO_4])^{1/2} \quad (5)$$

$$K_{c,Nd} = ([Nd]^2[L_2EO_4]^3)^{1/5} \quad (6)$$

We can calculate characteristic K_c values for each of the points indicated by means of arrows in Figures 1, 4, and 6, referring to the three titration protocols. The values are

TABLE 1: The Coordination Products for C3Ms Achieved from Different Approaches^a

| | protocol | [M] (mM) | [L ₂ EO ₄] (mM) | <i>K_c</i> |
|---------|----------|-------------|---|----------------------|
| Zn–C3Ms | 1(Z) | 0.35 | 0.35 | 0.35 |
| | 2(C) | 0.13 | 0.57 | 0.27 |
| | 3(E) | 0.45 | 0.24 | 0.33 |
| Nd–C3Ms | 1(N) | 0.23 | 0.35 | 0.29 |
| | 2(D) | 0.036 | 0.54 | 0.18 |
| | 3(F) | 0.36 | 0.22 | 0.27 |

^a Numbers 1, 2, and 3 represent from Figures 1, 5, and 6, respectively. The capital letters in the parentheses are corresponding to the arrows in the above the figures. For each system, the concentrations in “protocol 1” are the same as those in Figure 1, and the compositions at optimum C3M formation is recorded for the two systems. Concentrations for protocols 2 and 3 are normalized to the total concentration of “protocol 1”.

summarized in Table 1. It is interesting to notice that the *K_c* values obtained from protocols 1 and 3 for each system are very close, but those obtained from approach 2 are always lower than the other two. It seems that for well-defined C3Ms formation, a certain *K_c* value should be achieved at given total concentrations of metal ions and bisligands. This *K_c* value is a threshold value for micelle formation. Systems with smaller *K_c* values will probably result in polydispersed clusters of less well-defined size and shape.

Conclusions

Characteristic differences in the formation of complex coacervate core micelles (C3Ms) from neodymium, L₂EO₄ and P2MVP₄₁–b-PEO₂₀₅ mixed system and from zinc, L₂EO₄ and P2MVP₄₁–b-PEO₂₀₅ mixed systems are reported. Micelles were prepared through 3 different protocols, i.e., (i) metal-coordination supramolecular complex was dosed to the aqueous solution of P2MVP–b-PEO; (ii) metal ions were dosed to the mixed system of L₂EO₄ and (P2MVP₄₁–b-PEO₂₀₅); (iii) addition of L₂EO₄ to the mixed system of metal ions and (P2MVP₄₁–b-PEO₂₀₅). Neodymium–L₂EO₄ coordination polymers are found to have a stronger ability to form C3Ms with the P2MVP₄₁–b-PEO₂₀₅ diblock copolymer. The stronger ability of Nd₂–(L₂EO₄)₃ to form C3Ms with P2MVP₄₁–b-PEO₂₀₅ is due to their ability to form network structures at very low concentrations, in contrast to the exclusively linear structure for the zinc system. Excess of neodymium is able to destroy the C3Ms due to formation of positively charged coordination complexes with the L₂EO₄ ligands which are extracted from the micellar core. Zinc ions and L₂EO₄ ligands have no influence on the C3Ms. The experimental process affects the polydispersity index of the C3Ms. Narrowly distributed micelle sizes were obtained in processes i and iii. Arithmetic rules in terms of a “coordination product” *K_c* may well govern the C3Ms formation. No matter what the protocol is, as long as the coordination product reaches

a specific threshold value, C3Ms start coming into formation. Systems with smaller *K_c* values will result in poorly defined polydisperse clusters.

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Supporting Information Available: Figure showing TEM results of C3Ms. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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