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Complex Coacervate Core Micelles Containing Poly(vinyl alcohol) Inhibit Ice Recrystallization

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Complex coacervate core micelles (C3Ms) form upon co-assembly of oppositely charged polyelectrolytes. These co-assembled structures are widely investigated as promising building blocks for encapsulation, nanoparticle synthesis, multimodal imaging, and coating technology. Here, the impact on ice growth is investigated of C3Ms containing poly(vinyl alcohol), PVA, which is well known for its high ice recrystallization inhibition (IRI) activity. The PVA-based C3Ms are prepared upon co-assembly of poly(4-vinyl-N-methyl-pyrindinium iodide) and poly(vinyl alcohol)-block-poly(acrylic acid). Their formation conditions, size, and performance as ice recrystallization inhibitors are studied. It is found that the C3Ms exhibit IRI activity at PVA monomer concentrations as low as $1 \times 10^{-3}$ M. The IRI efficacy of PVA-C3Ms is similar to that of linear PVA and PVA graft polymers, underlining the influence of vinyl alcohol monomer concentration rather than polymer architecture.

1. Introduction

Complex coacervation is the electrostatically driven, liquid–liquid phase separation that occurs when two aqueous solutions of oppositely charged polyelectrolytes are mixed.\(^1\) Attaching a neutral hydrophilic polymer block to one or both of the polyelectrolytes leads to microphase separation and the formation of micelles, with a complex coacervate core, surrounded by a water-soluble neutral corona.\(^2\) Hence, complex coacervate core micelles (C3Ms) are structures co-assembled in aqueous solutions through electrostatic interactions. This makes them responsive to changes in their environment such as pH, ionic strength, and temperature. These properties render C3Ms applicable for use as multimodal imaging contrast agents,\(^3\) nanogels,\(^4\) nanoreactors,\(^5\) and encapsulation agents.\(^6\)

C3Ms have advantages when used to produce polymer films due to their ease of preparation, fast adsorption, and low description.\(^7\) Furthermore, they readily adsorb onto hydrophilic as well as hydrophobic surfaces by exposing their core to the surface while the corona chains extend out into solution.\(^7,8\) The surface chemistry of C3M-coated substrates can easily be tuned for specific applications, such as antifouling,\(^7b,9\) by changing the corona-forming block. In this work, we use poly(vinyl alcohol), PVA, a well-known ice recrystallization inhibitor,\(^10\) as our corona-forming block. Recently, it was shown that block copolymerization\(^11\) and chain architecture\(^12\) do not affect the ice recrystallization inhibition (IRI) activity of PVA. However, the IRI efficacy of self-assembled structures containing PVA remains a question. To address this challenge we study PVA-based C3Ms formed by poly(4-vinyl-N-methylpyridinium iodide), P4VMP, a cationic homopolymer, with poly(vinyl alcohol)-block-poly(acrylic acid), PVA-b-PAA, a neutral-anionic diblock copolymer, in aqueous solutions. We first determine the critical micelle concentration (CMC) and preferred micelle composition (PMC) at pH 10.5 in $10 \times 10^{-3}$ M NaNO$_3$ by light scattering. Next, we check whether PVA-based C3Ms exhibit ice recrystallization. A commonly used method to study IRI is the splat assay.\(^13\) Alternatively, to simultaneously view multiple samples, a practical capillary method can be adopted.\(^14\) Here, we determine ice growth rate constants ($k_d$) over a range of polymer concentrations in the more recently presented sucrose sandwich assay.\(^15\) This method warrants a constant, low ice volume fraction. We find that PVA-based C3Ms effectively inhibit ice recrystallization at vinyl alcohol monomer (VAM) concentrations as low as $1 \times 10^{-3}$ M. Their activity is comparable to linear chains and PVA bottlebrushes.\(^16\) This indicates that the IRI activity of PVA is dependent on the VAM concentration rather than the polymer architecture. These results unveil that PVA can be formulated into polymeric micelles without loss of IRI activity.
2. Experimental Section

2.1. Materials

Poly(vinyl alcohol)-b-poly(acrylic acid), PVAc173-b-PAA353 (Mn = 37 464 g mol⁻¹), was obtained through complete hydrolysis of poly(vinyl acetate)-b-poly(acrylonitrile), PVAc273-b-PAN353 (SEC (DMF): Mn = 130 700 g mol⁻¹, D = 1.22), which was synthesized by cobalt-mediated radical polymerization as described previously.[16] Poly(4-vinyl-N-methylpyridinium iodide), P4VM233 (SEC: Mn = 28 000 g mol⁻¹, D = 1.2, after quaternization), was purchased from Polymer Source Inc. (Montreal, Canada). The degree of quaternization is ≈5%.

Sodium nitrate >99% (Agros Organics) was purchased from Fischer Scientific. Sodium hydroxide >98% (Empore) and hydrogen peroxide (Emprove 35% H₂O₂) were purchased from Merck Millipore Chemicals. Sulfuric acid (Rectapur 95% H₂SO₄) was purchased from VWR. Sucrose ≥99.5% (BioUltra), silanization solution I ( ≥5% dimethyldichlorosilane in heptane, Selectophore), technical grade acetone and isopropanol, and GE Whatman syringe filters of 0.2 μm pore size with PVDF and PTFE membranes were purchased from Sigma Aldrich. All chemicals were used as received unless indicated otherwise.

2.2. Sample Preparation

All stock solutions were prepared in ultrapure water with 10 × 10⁻³ M NaNO₃. The pH was adjusted to 10.5 in all solutions using NaOH to ensure full deprotonation of PAA. The polymer stock solutions were prepared at 20 × 10⁻⁳ M chargeable monomer concentrations, so that after mixing

\[ c_{\text{mix}} = c_+ + c_- = c_{\text{PAA}} + c_{\text{PVAc}} \]

and dilutions were done with the 10 × 10⁻³ M NaNO₃ solution at pH 10.5. The polymer solutions were mixed at the desired mixing ratio which is expressed as the ratio of the molar concentration of positively charged monomers (c⁺) to the total concentration of chargeable monomers (c⁺ + c⁻).

\[ f_c = \frac{c_+}{c_+ + c_-} \]

No change in pH was observed after mixing the polymers to produce micellar solutions. All solvents and solutions, except the polymer solutions, were filtered through 0.2 μm syringe filters to remove trace quantities of dust for light scattering experiments. Experiments and sample storage were done at room temperature.

2.3. Methods

2.3.1. Static (SLS) and Dynamic Light Scattering (DLS)

Light scattering experiments were performed on an ALV/CGS-3 MD-4 goniometer system, equipped with a 50 mW Nd:YAG laser operating at 532 nm. The temperature was regulated at 20.0 ± 0.2 °C using a Lauda RM6-S refrigerated circulating bath. The light scattering intensity was recorded at various angles between 30° and 150°. Characteristic decay rates (Γ) were obtained from the CONTIN analysis and used to determine the translational diffusion coefficient (Dₜ) from the slope of Γ versus q². We determined the hydrodynamic radius (Rₜ) of the C3Ms using the Stokes-Einstein relation. The size distribution of the C3Ms was extracted from data measured at 90° using the CONTIN method.

2.3.2. Ice Recrystallization Inhibition Assay

A 2 μL droplet of sample was sandwiched between two cover slides and placed in a stage attached to a Nikon ECLIPSE Ci-Pol Optical Microscope where the temperature is controlled by a Linkam LTS 420. A thin polycrystalline ice layer was created by rapidly freezing (20 °C min⁻¹) to -40 °C. The temperature was then raised (10 °C min⁻¹) to -7 °C and kept constant for 1 h. Images were taken every 5 min and analyzed using ImageJ and an in-house written Matlab script to obtain the equivalent radius for each ice crystal (details in the Supporting Information). The ice crystal growth rate constants, kₕ, were obtained from the temporal increase in the number average radius cubed as described by LSW theory,[15] according to

\[ \langle R_i \rangle^3 = \langle R_0 \rangle^3 + \frac{8 \pi c_i \nu^2 D}{9RT} t = \langle R_0 \rangle^3 + k_d \cdot t \]

Finally, the inhibitory concentration cᵢ was obtained from kₕ(c) as a function of VAM concentration fit to

\[ k_d = k_{d0} \times \frac{1 + \exp\left(\frac{c_i - c}{s}\right)}{1 + \exp(1)} \]

where kₕ₀ is the growth rate constant at zero inhibitor concentration.[15]

2.3.3. Ice Nucleation Activity

We used a homemade setup consisting of a Peltier stage to cool an array of 24 droplets in a controlled environment (Figure S3, Supporting Information). Glass cover slides (32 × 32 mm) were etched with piranha solution (3:1 mixture of sulfuric acid and hydrogen peroxide). The slides were then rinsed with ultrapure water and acetone consecutively, followed by drying with N₂ flow. Then, a hydrophobic surface was obtained by exposing the slides to an 5% dimethyldichlorosilane solution for 30 min, which ensures reproducible contact area between the slide and droplets. The slides were rinsed with heptane and dried under nitrogen. Droplets of 1 μL were placed on a slide and cooled at 5 °C min⁻¹ until all were frozen, while recording video with a Lumenera Infinity 1. The freezing of individual droplets is signaled by the sudden increase of scattered light by the crystalline phase. Thus, the temperature at which the grayscale intensity suddenly rises is registered as the nucleation temperature (details in the Supporting Information). We performed at least three assays to obtain data for sufficient statistics on the distribution of nucleation temperatures.
3. Results and Discussion

The concentration above which micelles form is known as the critical micelle concentration, CMC. To determine the CMC, we perform SLS experiments at a fixed ionic strength, pH, and mixing ratio while varying $c_{\text{tot}}$ from $10 \times 10^{-3}$ to $20 \times 10^{-3}$ M. We prepare C3Ms at charge stoichiometry by mixing aqueous solutions of PVA$_{273}$-b-PAA$_{353}$ and P4VMP$_{233}$ at pH 10.5 in $10 \times 10^{-3}$ M NaNO$_3$ and record the SLS intensity at a fixed scattering angle of $90^\circ$. We find a gradual increase in SLS intensity with increasing chargeable monomer concentration until it exhibits a sudden jump in between concentrations of 1 and $2 \times 10^{-3}$ M (Figure 1A). We attribute this sudden increase in SLS intensity to the transition from small, charged, soluble complexes to C3Ms in solution. Thus, we consider a $1 \times 10^{-3}$ M chargeable monomer concentration as the CMC for this system.

Next, we prepare C3M solutions with $c_{\text{tot}} = 10 \times 10^{-3}$ M, well above the CMC, at various mixing ratios and a fixed pH = 10.5 and salt concentration of $10 \times 10^{-3}$ M NaNO$_3$. To confirm the presence of micelles and to determine the PMC, we again perform SLS experiments. Upon increasing the fraction of P4VMP$_{233}$ in solution, we observe an increase in SLS intensity which indicates the presence of complexes formed in solution due to electrostatic interactions (Figure 1B). The intensity reaches a maximum around charge stoichiometry where saturation of binding occurs. For this system, we obtain the maximum intensity corresponding to the PMC at $f_0 = 0.52$. Subsequently, we perform DLS experiments to determine the hydrodynamic radius ($R_H$) of the C3Ms. We obtain the area normalized size distribution by CONTIN analysis and find a unimodal distribution (Figure 1C). Using the cumulant method we obtain a hydrodynamic radius of $R_H = 47.8 \pm 1.1$ nm. The micelles are furthermore observed to maintain this size for a period of more than ten weeks (Figure S1, Supporting Information).

To reliably test whether PVA-containing C3Ms impact ice growth, we measure ice growth rates at low ice volume fractions in 30 wt% sucrose. This high sucrose concentration utilized in a so-called sucrose sandwich assay ensures that individual grains of ice are distinguishable during the entire assay. Therefore, we first check if sucrose addition influences the size distribution and the hydrodynamic radius of C3Ms by DLS. Figure 1C shows the micellar size distributions determined in both the presence and absence of 30 wt% sucrose at the PMC. We observe no significant changes in the micellar size distributions and the $R_H$ of the C3Ms upon addition of sucrose.

To quantify IRI activity, we perform IRI assays over a range of VAM concentrations from 0.2 to $7.5 \times 10^{-3}$ M. Ice growth rates are drastically decreased when VAM concentrations exceed $0.3 \times 10^{-3}$ M. Full inhibition of ice recrystallization occurs at concentrations above $1 \times 10^{-3}$ M (or 0.044 mg mL$^{-1}$ PVA), which corresponds to $c_{\text{tot}} = 2.7 \times 10^{-3}$ M chargeable monomer concentration (Figure 2A) (see the Supporting Information for representative images). This is in agreement with previously reported results from splat assays on linear PVA of comparable molecular weight: 0.10 mg mL$^{-1}$ for PVA$_{346}$ and 0.05 mg mL$^{-1}$ for PVA$_{351}$.[17] The IRI efficacy ($c_i$) is determined from the inflection point of the curve where the ice growth rate is decreased to half of its value at zero inhibitor concentration.[10c,15b] PVA-based C3Ms exhibit $c_i = 0.33 \times 10^{-3}$ M, which is similar to linear PVA ($c_i = 0.38 \times 10^{-3}$ M) and grafted bottlebrushes ($c_i = 0.31 \times 10^{-3}$ M)[12] and is slightly lower than PVA$_{273}$ b-PAA$_{353}$ ($c_i = 0.47 \times 10^{-3}$ M) (Figure 2B). These results imply that the VAM concentration is the defining factor for IRI activity instead of the architecture of the polymer chain and/or its association state. Note that the block copolymer itself exhibits a somewhat lower IRI activity, which might be due to repulsive interactions between anionic polymer chains.

Polymers that inhibit ice growth may also affect ice nucleation. PVA, among other macromolecules, has been reported to promote[10c,18] or reduce[19] ice nucleation, depending on the concentration and presence of other compounds like silica nanoparticles. To determine the effect of PVA-based C3Ms on the nucleation of ice crystals, we record the ice nucleation temperatures for aqueous solutions with $7 \times 10^{-3}$ M PVA-C3Ms. For comparison, we also assess $10 \times 10^{-3}$ M PVA$_{273}$ b-PAA$_{353}$ and P4VMP$_{233}$ solutions and a reference solution at pH = 10.5 and...
Using the recorded ice nucleation temperatures, we compute the fraction of frozen droplets as a function of temperature (Figure 3A). A comparison of the temperatures at which half of the droplets are frozen ($T_{50\%}$), does not reveal significant differences between the four solutions (Figure 3B). Statistical tests were performed to further quantify this finding (Table S1, Supporting Information). A Shapiro–Wilk test shows that the C3M and P4VMP data are not normally distributed, while the two other sets follow a normal distribution. Hence, we adopt a nonparametric test to compare all four distributions (Table S2, Supporting Information). This Mann–Whitney–Wilcoxon test confirms that there is no significant difference between the distributions from the solutions, except for the PVA$_{273}$-b-PAA$_{353}$ and P4VMP$_{233}$ solutions. Nevertheless, we can conclude that neither the block copolymer nor the C3Ms reduce or promote the nucleation of ice crystals in aqueous solutions under the investigated experimental conditions.

4. Conclusion

Poly(vinyl alcohol)-bearing C3Ms have been prepared upon electrostatically driven co-assembly of PVA$_{273}$-b-PAA$_{353}$ and P4VMP$_{233}$ in aqueous solutions at pH = 10.5 and $10 \times 10^{-3}$ M NaNO$_3$. Using the recorded ice nucleation temperatures, we compute the fraction of frozen droplets as a function of temperature (Figure 3A). A comparison of the temperatures at which half of the droplets are frozen ($T_{50\%}$), does not reveal significant differences between the four solutions (Figure 3B). Statistical tests were performed to further quantify this finding (Table S1, Supporting Information). A Shapiro–Wilk test shows that the C3M and P4VMP data are not normally distributed, while the two other sets follow a normal distribution. Hence, we adopt a nonparametric test to compare all four distributions (Table S2, Supporting Information). This Mann–Whitney–Wilcoxon test confirms that there is no significant difference between the distributions from the solutions, except for the PVA$_{273}$-b-PAA$_{353}$ and P4VMP$_{233}$ solutions. Nevertheless, we can conclude that neither the block copolymer nor the C3Ms reduce or promote the nucleation of ice crystals in aqueous solutions under the investigated experimental conditions.
NaNO₃. C3M characterization by light scattering yields a CMC of \( c_{\text{tot}} = 1.2 \times 10^{-3} \) m chargeable monomer concentration and a PMC of \( f_c = 0.52 \). A sucrose sandwich assay at \( f_c = 0.52 \) reveals that the PVA-based C3Ms effectively inhibit ice recrystallization even at low VA monomer concentrations of \( 1 \times 10^{-3} \) m. We find the inhibitory concentration of the PVA-C3Ms at \( c_1 = 0.33 \times 10^{-3} \) m, which is comparable to the \( c_i \) values for linear PVA and PVA bottlebrushes studied previously. This suggests that the VAM concentration is more influential for IRI activity than polymer architecture and association state. Furthermore, we observe that ice nucleation is neither promoted nor reduced by PVA-based C3Ms or by the PVA-b-PAA diblock copolymer. These results shed new light on the IRI activity of man-made materials and hold promise for the preparation of C3M-based coatings to control ice adhesion and growth on solid surfaces.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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bio-inspired functional materials, ice recrystallization inhibition, micelles, poly(vinyl alcohol), polyelectrolytes

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