FEATURE ARTICLE

Polymer Micelles: An Example of Self-Assembling Polymers

S. E. Webber

Department of Chemistry and Biochemistry and Center for Polymer Research, The University of Texas at Austin, Austin, Texas 78712

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Diblock and graft copolymers for which the blocks are sufficiently different in their solvation properties often self-assemble into micelle structures. In this feature article we emphasize only diblock polymers. We discuss various aspects of this field including the synthesis of diblock polymers containing fluorescent probes placed at precise points in the polymer chain and the preparation and characterization of polymer micelles. These chromophores may undergo photoredox chemistry or be utilized as probes of the local micelle environment. We also discuss our studies of the rate of release of absorbed small molecules (e.g., phenanthrene, pyrene) using fluorescence techniques. Last we describe our approach to the modification of surfaces by either adsorption or chemical attachment of polymer micelles.

Introduction

It is hard to imagine a turn of phrase more prevalent in chemistry over the past few years than "self-assembled nanostructures" or its many synonyms.[1] It is easy to understand the attraction of this area because it combines the skills of synthetic and physical chemists who strive to understand the principles of self-assembly for various classes of molecules, controlled small clusters of metals and/or semiconductors, and, the subject of this article, synthetic polymers. In the case of polymers one feels obliged to point to the exquisitely complex self-assembly that occurs with biological macromolecules, often by a combination of interactions and effects that are poorly understood in detail. While one might hope to use nature's tricks to advantage to design synthetic polymers or use the principles learned from relatively simple synthetic polymers to understand polymers of biological significance, it is our opinion that these two fields will remain on parallel courses for quite some time with only occasional cross-fertilization.

Many physical chemists with an interest in materials may not be aware of the very large effort in polymer science applied to structures that spontaneously form in block copolymers as a consequence of phase separation between the blocks. Chemically similar small molecules that are totally miscible (e.g., benzene and pyridine) are incompatible as the polymers polystyrene or polyvinylpyridine. This is the result of the very small entropy of mixing for polymers. A small endothermicity of mixing, which would be of no consequence to the ΔG_{mix} of small molecules, can dominate the thermodynamics of polymer miscibility. If chemically distinct groups are combined on a single polymer, then phase separation in the solid state can lead to a domain structure. This is especially true for "block polymers", which are composed of sequences of a single type of monomer (e.g., A_n-B_m or $A_n-B_m-A_n$ where n and m represent the number of repeating units of type A and B). This polymer architecture leads to a variety of solid-state mesophase structures (domains that are spherical, cylindrical, gyroid, bicontinuous double diamond, lamellar) that depend on the overall molecular weight and composition of the polymers.[2] Similar considerations apply to block copolymers in the presence of a solvent or solvent mixture which is "selective" (e.g., good or marginal for one block, poor for the other).[3−6]

Generally the rich array of structures that can exist in the solid phase are not available to self-assembling polymers in the presence of a large excess of solvent. An unfortunate choice of solvent combination and/or processing conditions can lead to a precipitate or an uncontrolled array of large structures that will eventually aggregate and fall out of solution. The most common "good outcome" of a particular choice of solvent, processing condition, and polymer is a stable micelle solution in which the micelles are spherical and the distribution of sizes is clustered around the average with a half-width on the order of ±15%. Such a distribution is usually referred to as "monodisperse", by analogy to monodisperse polymers produced by "living polymerization".[7] Other morphologies have been produced in the solution phase (2D micelles, wormlike micelles, etc.[8]) but most studies, including our own, concern spherical micelles. Our work has emphasized the use of aqueous solutions, and therefore our polymers are composed of a hydrophobic and hydrophilic block. The latter is often a polyelectrolyte, leading to interesting complexities in the distribution of charge or the extent of ionization within the micelle "corona" (see Scheme 1 for the definition of some terms). Amphiphilic graft polymers can also be used to prepare polymer micelles,[9] but we will concentrate on linear diblock polymers in this article.

Polymer micelles may eventually prove to have important technological applications because various materials can be solubilized in them. Their size is typical of a virus (thereby avoiding renal filtration and reticuloendothelia system uptake) and can circulate in the blood for long periods of time, eventually passing through capillaries that are disrupted near tumor growth.[10] Antonietti et al. have used polymer micelles

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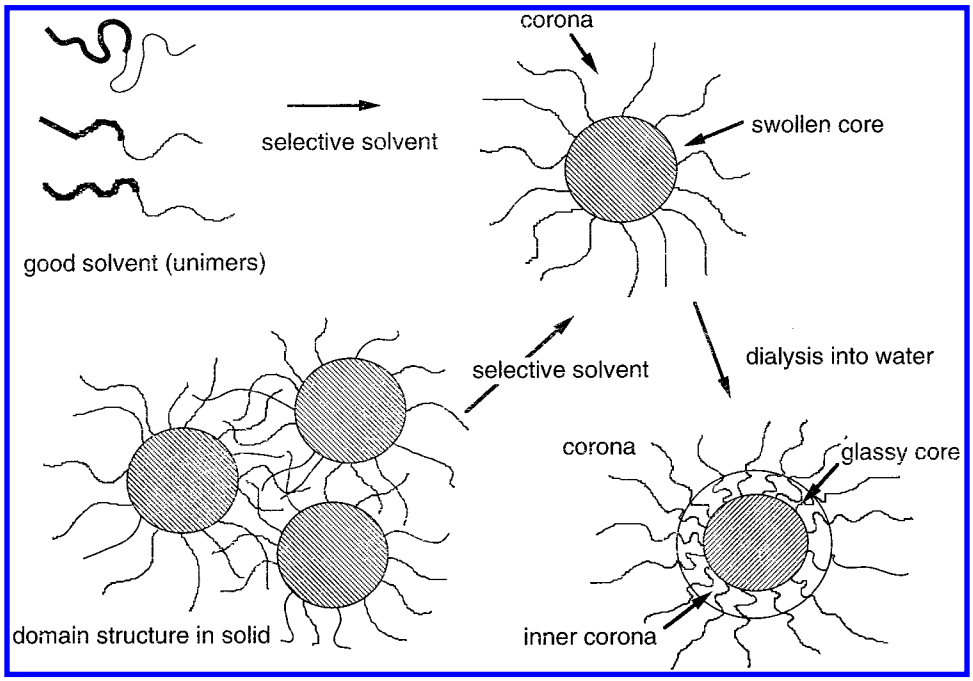

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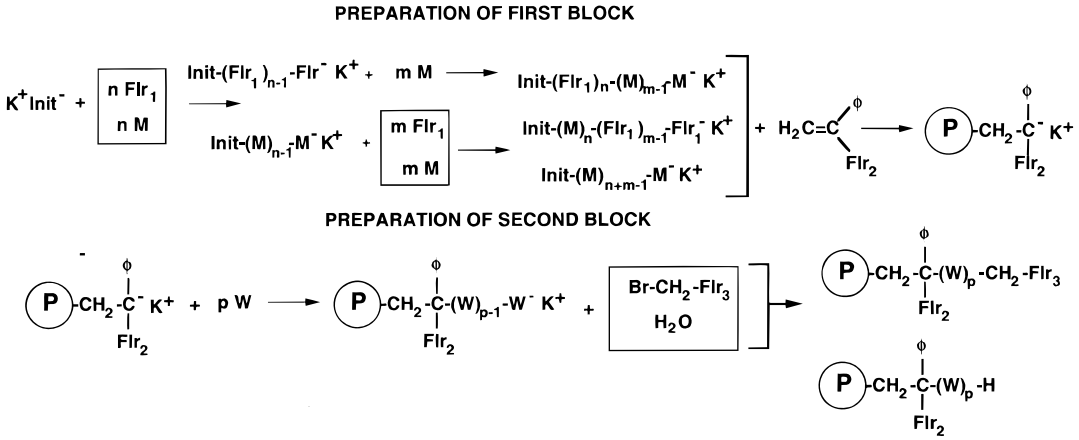


as "nanoreactors" to produce highly dispersed metal or semiconductor particles.[4,11] Eisenberg et al. have used films of neutral polymers that contain a small fraction of charged groups ("ionomers") to accomplish similar aims.[12] We have employed photophysical methods to characterize fluorescently tagged polymer micelles but have also explored the use of such micelles for excited-state electron-transfer reactions, as will be discussed later. Even within the "spherical motif" relatively complex structures can be produced, which may turn out to have useful solubilization properties. pH-dependent micellization and/or micelle properties suggests applications as sensors or pH-driven chemical- or drug-delivery systems. We have also explored covalently binding or adsorbing polymer micelles to surfaces, which in our view opens up some unique avenues for surface modification. Such surfaces are the synthetic polymer analogue of semiconductor or metallic "quantum dots".

In this feature article we will describe our particular approach and contributions to the field of polymer micelles and illustrate some of the general principles. Essentially all the work described herein has been part of a collaboration with my colleague at the University of Texas, Prof. P. Munk, and frequent collaborations with our Prague colleagues, in particular Dr. Zdenek Tuzar of the Institute of Macromolecular Chemistry (whose long-standing interest in this area truly has been infectious) and Prof. Karel Procházka, Charles University.

Chemical Background and Properties of Polymer Micelles

A. Synthesis of Diblock Polymers. Anionic ("living") polymerization has been very influential in polymer science because this method can produce diblock and triblock polymers with well-defined block lengths ($M_w/M_n < 1.10$ for each block in most cases).[13] Anionic polymerization requires some experience before it becomes routine because of the necessity for rigorous exclusion of water (or other protic species) and oxygen. One can employ a number of schemes for the introduction of chromophores at specific points in the polymer.[14] These are illustrated in Scheme 2, which is by no means exhaustive. In recent years other forms of "living polymerization" have been developed (e.g., ROMP,[15] group transfer,[16] cationic,[17] and free radical[18]) which may be applied to produce polymers suitable for micelle formation.

Certain aspects of the anionic polymerization will be described briefly without any attempt to review this very large subject in detail. First, the order the addition of monomers is

not arbitrary, so the polystyrene anion can initiate methacrylate but not vice-versa. Some desired combinations may not be easily accomplished (e.g., 4-vinylpyridine and methacrylate) because the polymers do not remain soluble in the same solvent under reaction conditions (typically −78 °C for reactions in THF). It is very important to remove a sample of the first polymer block for molecular weight analysis before the second monomer is added. Gel permeation chromatography (GPC, also known as size exclusion chromatography, SEC) is used extensively to evaluate the molecular weight distribution of the initial block and the final di- or triblock. It is especially important to verify that none of the initial block contaminates the final diblock polymer as a homopolymer. This might be the case if there is an adventitious addition of a terminator upon introduction of the second monomer. If the homopolymer impurity is hydrophobic, it can "bridge" micelles and cause aggregates to form during micelle preparation. This is one mechanism that can lead to so-called "anomalous micellization".[5,19] However the micelle can accommodate a small weight fraction of the hydrophobic homopolymer, and this property can be used in principle to modify the micelle properties.[20] NMR analysis of the final polymer is required to verify the mole fraction of each type of monomer, and classical methods such as light scattering or osmometry are used to establish the absolute molecular weight of the final block copolymer. For polymers with fluorescent tags it is necessary to use UV or fluorescence detection of the GPC elutant to verify that the tag is attached uniformly over the entire molecular weight distribution.

For most of our studies the corona has been composed of a polyacid. During the polymerization the acid must be protected, and we have used *tert*-butylmethacrylate for this purpose. After the polymerization is completed, the *tert*-butyl group can be removed by reaction with acid. It is essential to verify the completeness of this deprotection reaction by NMR because residual *tert*-butyl groups in the micelle corona can greatly compromise the quality of the final micelles.

B. Micelle Preparation and Characterization. In Scheme 1 we illustrate the preparation of micelles by the addition of a precipitating solvent for one block or direct dissolution of the dry polymer into an appropriate mixed solvent. The term "addition of a precipitating solvent" can be taken as a process more general than literally adding a second component. For example, temperature changes, changing ionic strength, or changing the pH can all result in selective solvent condition. An example of the latter is the formation of a micelle from poly(2-vinylpyridine)-*b*-poly(ethylene oxide) (PVP-*b*-PEO) in aqueous solution by titration from pH 1 to pH 10.[21] An example of direct dissolution is provided by polystyrene-*b*-poly(methacrylic acid) (PS-*b*-PMA) added directly to 80:20 vol:vol dioxane:H_2O (followed by stepwise dialysis to pure aqueous buffer).[22] In general the conditions to effect micellization have to be discovered by trial and error, guided by the solubility properties of the individual blocks. Not only is the choice of mixed solvents important, but all aspects of the protocol are important (e.g., direct addition of precipitating solvent, solvent exchange by dialysis or evaporation, heating the solution, etc.). For a given polymer sample the size of the final micelle may depend on the preparation protocol. In our experience the micelle properties are very stable once the micelle resides in a solvent that is a strong nonsolvent for the core.[23] For a micelle with a glassy core the structure that forms is undoubtedly "kinetically frozen" and may not represent the thermodynamic equilibrium.

As micelles are formed, it is very convenient to monitor the solution with quasi-elastic light scattering (QELS). The size

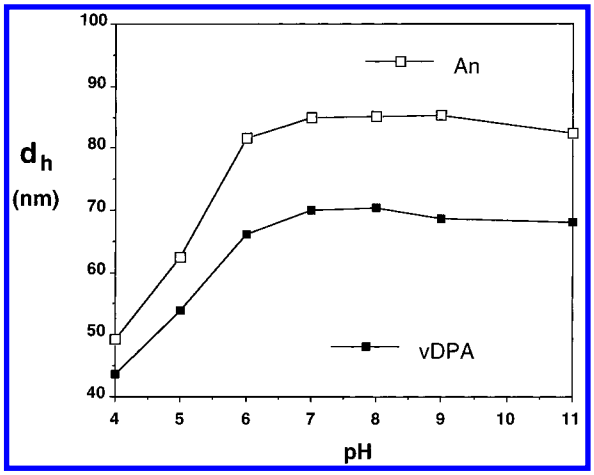


Figure 1. Hydrodynamic diameter of PS-*b*-PMA micelles as a function of pH. The notation An and vDPA relates to the type of chromophore covalently bound at the PS and PMA interface (taken from ref 26).

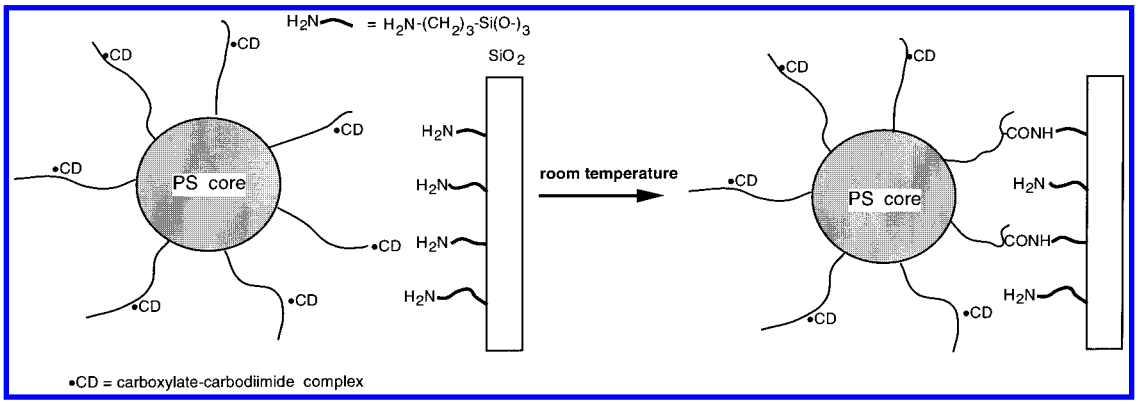
distribution that is obtained from this analysis immediately reflects the presence of polydisperse aggregates, in which case the micellization protocol can be said to have failed. It is very rare for aggregates to be redispersed into monodisperse micelles. The typical micelle solution is prepared in the concentration range 1−5 mg/mL and has a characteristic blue color from light scattering that is immediately recognized as the sign of a successful preparation, as opposed to the milky color that accompanies aggregation. In our experience it is important to maintain a fairly low concentration during the preparation of micelles, but once 100% aqueous solution has been achieved, the micelles can be concentrated or even freeze-dried and redispersed if the core is composed of a glassy polymer.

Once a successful micelle preparation protocol has been developed, the procedure is usually found to be reliable and reproducible. Characterization of the micelle is completed by carrying out classical light scattering and using a Zimm analysis to obtain the weight-average molecular weight, radius of gyration (R_G), and second virial coefficient (A_2). As can be imagined, the molecular weights obtained are very high, and given the known molecular weight of the constituent polymers, the aggregation number can be obtained. An aggregation number on the order of 200 polymers of molecular weight 50 000 is typical ($MW_{micelle} = 10^7$ g/mol). The aggregation number is a very strong function of the polymer block length, especially the core block.[24]

The *Z*-average hydrodynamic radius (R_H) is obtained from the QELS measurement. For a simple spherical object the ratio of R_G/R_H should be 0.775 although we find lower values of this ratio for our micelles, presumably because our corona is more diffuse than the core.[24a] In the case of a polyacid corona, R_H is a very strong function of pH and/or ionic strength (Figure 1), becoming much larger as the polyacid is deprotonated. Both theory[25] and some of our experiments[26] suggest that deprotonation near the micelle core is repressed, as will be discussed in section A of Representative Experimental Results.

We have also found it useful to chemically attach micelles to surfaces so that SEM or AFM can be used to characterize size distributions. These micelles will have a collapsed corona, so the absolute size of the micelle will be smaller than in the solution phase. Nevertheless the corrected size distribution agrees very well with that obtained from QELS, and we have concluded that the chemical attachment procedure does not greatly perturb the micelle.[27] We will discuss this in more detail

SCHEME 3



in the next section. We consider covalent attachment of micelles to surfaces to be an especially interesting direction for future research.

C. Chemical Attachment of Micelles to Surfaces. Covalent attachment or adsorption of polymers to surfaces has been heavily investigated for a variety of systems and for a variety of reasons. So far as we know, we are the only group that has reported covalent bonding of a polymer micelle to a surface. In the case of micelles with a polyacid corona the chemistry is very simple, although many details of these process are not yet investigated. The acid groups of the micelle corona can be activated by a carbodiimide, and the activated micelle is exposed to a surface with primary amines, thereby coupling by formation of amide bonds. As will be discussed later, a large number of carbodiimide−carboxylate adducts remain available for subsequent reaction. The fraction of adducts that react to form amide bonds to the surfaces is a topic of current interest and effort. This chemical process is represented in Scheme 3.

We have also be able to "fix" PS-*b*-PMA micelles to polystyrene surfaces by simple adsorption from a dioxane:H_2O solvent.[28] In this case the proposed mechanism is interpenetration of the core polystyrene chains with those on the suface. The use of a dioxane:H_2O solution that is relatively rich in dioxane is essential to this process in order to swell the polystyrene, permitting sufficient chain mobility for interpenetration to occur.

Representative Experimental Results

A. Photophysical and Excited-State Electron-Transfer Studies.[26] As indicated in Scheme 2, it is possible to insert one or more chromphores at the junction between the hydrophobic and hydrophilic blocks of a diblock polymer. The polymers used had an anthracene chromophore inserted between the polystyrene and poly(methacrylic acid) blocks. In the next section we will describe how such tags can provide information about local segmental mobility. In the study we review here, one of the objectives was to examine the fluorescence quenching by a simple monovalent ion (Tl^+) in order to gain insight into the accessibility of the anthryl group to the aqueous phase.

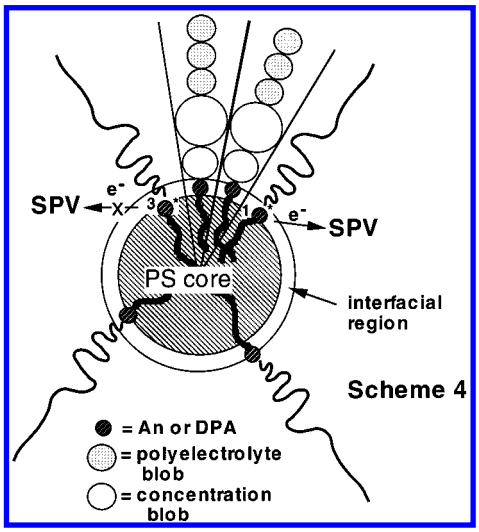
In separate studies we have attached anthracene moieties to poly(methacrylic acid) (PMA) and studied the effect of pH on the quenching efficiency.[29] In general one observes that at pH < 5 the polyacid is only weakly deprotonated and the PMA actually protects the chromophore, presumably by some local micellization or "hypercoiling". At higher pH the polyacid is deprotonated and the polyanion assumes an extended configuration. Under these circumstances the quenching by ions such as Tl^+ becomes very effective because of the high local concentration (the apparent second-order rate constant is on the order of 10^{12} M^{-1} s^{-1}).[30] This effect is very sensitive to the total ionic strength of the solution as quenching and nonquenching ions compete for the region near the polyelectrolyte.

For the anthracene moieties at the micelle interface between the polystyrene and polymethacrylic blocks the fluorescence quenching by Tl^+ was not very effective and almost independent of pH. Furthermore the Stern−Volmer quenching curve exhibited downward curvature, indicative of hindered access to the chromophore (the accessible fraction was estimated to be 0.44[31]). There exist theoretical predictions that deprotonation will be suppressed near the curved hydrophobic interface because of the very high charge density that would result.[25] Our quenching result is consistent with this idea. One could also imagine that the anthracene moieties are partially protected by the polystyrene phase and therefore are unquenchable by any aqueous phase species. However this is not borne out by studies with the zwitterion viologen, 4,4′-bipyridyl-1,1′-bis(propanesulfonate) which we refer to as SPV. We have also used SPV as a fluorescence quencher for tagged linear polyacids, and the pH dependence of quenching is similar to simple ions, e.g., very inefficient at low pH and extraordinarily efficient at high pH.[29] For the interfacially tagged micelle the SPV is a fairly efficient singlet-state quencher with no hint of hindered access. A rough estimate of k_q based on the quencher concentration required for 50% quenching is ca. $3 \times 10^9 - 8 \times 10^9$ M^{-1} s^{-1}, at pH 4 and 9, respectively. Because the anthracene is immobilized, this rate should be multiplied by 2 in order to be compared to homogeneous solution ($k_{diff}^{H_2O} = 7.0 \times 10^9$ M^{-1} s^{-1} at 25 °C[32]). Thus we believe the surfactant-like character of SPV permits it to approach the PS−PMA interface and quench the chromophore, while the "inner corona" acts as a barrier to Tl^+.

Space does not permit a more detailed discussion of this particular system. Long-time charge separation with a quantum yield of 0.3−0.7 per quenching event was observed from either singlet- or triplet-state quenching by SPV. However, unlike simple polyelectrolyte systems we have studied in the past, the anthracene cation radical was removed by some unidentified adventitious "sacrificial reagent", producing a buildup of the SPV radical anion.

The most general conclusion of this work is that it is possible to generate interesting spatial arrangements of chromophores by taking advantage of the self-organizing properties of amphiphilic diblock polymers.[33] This concept applied to this particular case is represented in Scheme 4 (adapted from ref 26). The terminology "concentration blob" and "polyelectrolyte blob" is taken from Shusharina et al.[34] These terms describe the characteristics of the uncharged portion of the chain (which

SCHEME 4



acts like a normal "random coil") and the charged portion (which behaves more or less like a stretched polyelectrolyte).

B. Use of Fluorescence To Characterize Segmental Mobility within a Micelle Core.[14] The ability of a polymer micelle to incorporate small fluorophores has been exploited to detect micelle formation or aid in micelle characterization.[35] Similarly one may use a fluorescently tagged polymer to monitor micelle properties, and this method has the advantage that the tag is essentially permanently associated with the micelle, especially if the core is glassy.[36] There are two approaches we have used: (1) A short sequence of chromophores (e.g., 2-vinylnaphthalene) is inserted into the hydrophobic block. If there is sufficient sequential motion, intracoil excimer fluorescence is observed. (2) A single chromophore is inserted into the hydrophobic block. In this case the fluorescence depolarization is a strong function of segmental mobility.[37] In both cases it may be necessary to dilute the tagged chains with untagged chains (choosing similar block lengths for each component) to eliminate interchain excimer formation or depolarization by energy transfer.

The excimer-to-monomer fluorescence intensity changes systematically upon micelle formation and/or swelling the core with an appropriate solvent. The interpretation of these changes is necessarily qualitative. In principle the time-dependent depolarization can be connected to a dynamical model, but in practice this is not straightforward and the details of the "liberated motion" that yields excimer fluorescence are not known. We have used the "residual polarization (r_8) as a measure of segmental mobility. The empirical equation used to fit data is

$$r(t) = \frac{I_{||}(t) - I_{\perp}(t)}{I_{||}(t) + 2I_{\perp}(t)} = (r_0 - r_\infty)\sum_{i=1}^{N} a_i e^{-t/\tau_i} + r_\infty \qquad (1)$$

where a_i sums to unity. We have found the excimer/monomer fluorescence ratio and r_8 to correlate with each other very well, which is particularly satisfying because different tagged polymers are used for these experiments.[38]

The types of experiments represent our earliest work in the polymer micelle area, and we used only 2-vinylnaphthalene as a probe. If one were to use probes with different fluorescence lifetimes, the sensitivity to changes in the local mobility would be modified. The use of fluorescence permits a very convenient and sensitive method for monitoring properties of self-organized polymers in general, so long as one is convinced that the presence of the probe does not disturb the local environment so grievously that any conclusion about the untagged polymer is suspect. Our attitude is that fluorescence methods should be combined with as many other techniques as possible (e.g., NMR line shapes of the core polymer combined with fluorescence probes in order to characterize segmental mobility[5a,39]).

C. Kinetics of Release of Small Molecules from Polymer Micelles. One of the attributes of polymer micelles is their ability to solubilize small molecules, and in our work this has usually meant hydrophobic species (phenanthrene, pyrene) solubilized in water. The partition coefficient (K_P) of such species between micelles such as PS-*b*-PMA and water is very favorable (ca. 10^5 and 10^4 for pyrene and phenanthrene, respectively), but chemical specificity is also possible. For example a poly(2-vinylpyridine) core solubilizes pyrene much less efficiently than polystyrene (cf. 10^4 and 10^5). Large partition coefficients can be misleading because the concentration of polymer micelles is often rather low (ca. 1−5 mg/mL) so that a nonnegligible fraction of the probe may reside in the aqueous phase. Thus it is useful to consider the distribution coefficient (K_D), which is related to K_P by

$$K_D = K_P \frac{V_{micelle}}{V_{solvent}} = \frac{m_{micelle}}{m_{solvent}} \qquad (2)$$

where V refers to the volume of the micelle or solvent phase and m refers to moles or mass of the probe in the two phases. For a highly hydrophobic solute such as pyrene K_D may be well over 100 even for a 1 mg/mL micelle concentration.

Given the ability of a polymer micelle to solubilize small molecules, how rapidly can the solubilizate diffuse out of the micelle? Because we have used fluorescent probes extensively, it is natural for us to have developed a fluorescence method for this characterization. The concept is simple: A small amount (typically 10 μL) of a "loaded micelle" solution is added to excess water or buffer (3 mL). The probe immediately begins to diffuse out of the micelle in order to reestablish equilibrium. The difference in the fluorescence intensity with time of two solutions, one without a quencher and one with an aqueous phase quencher (Tl^+), can be analyzed to yield the fraction of probe that remains inside the micelle as a function of time.[40] The underlying assumption is that the Tl^+ quencher cannot penetrate the hydrophobic region of the micelle, which has been verified by studying the quenching of polymer-bound fluorophores. The relevant equations are

$$I_U(t) = I_{exc}\phi_{fl}^{core}[x(t)_{core} + b(1 - x(t)_{core}] \qquad (3)$$

$$I_Q(t) = I_{exc}\phi_{fl}^{core}[x(t)_{core} + qb(1 - x(t)_{core}] \qquad (4)$$

where $I_U(t)$ and $I_Q(t)$ refer to the unquenched and quenched solutions, respectively, and $x(t)_{core}$ is the fraction of probe that is within the micelle core. ϕ_{fl}^{core} refers to the fluorescence quantum yield of the probe within the micelle core, and b is the ratio of the fluorescence quantum yield in the solvent to ϕ_{fl}^{core}. The quantity q is the fractional quenching of the probe in the quenched solution and in the case of simple Stern−Volmer quenching is given by

$$q = \frac{I_Q}{I_0} = \frac{1}{1 + K_{SV}[Q]} \qquad (5)$$

where I_0 is the fluorescence intensity of the probe in the bulk

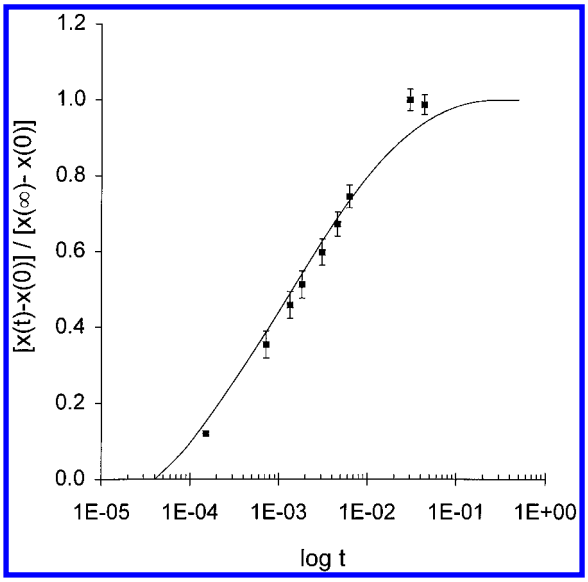


Figure 2. Release curve of pyrene from PS-*b*-PMA micelles, obtained from the fluorescence method. The smooth curve is the best fit to the theoretical release from a homogeneous spherical object.

solution in the absence of quencher. q is determined by an independent experiment, and b is obtained from the slope of

$$I_U(t) - I_Q(t) = I_{exc}\phi_{fl}^{core} b(1-q) - b[I_U(t) - qI_Q(t)] \quad (6)$$

By rearrangement of eqs 3 and 4, $x(t)_{core}$ is obtained:

$$x(t)_{core} = \frac{I_u(t) - qbI_q(t)}{I_{exc}\phi_{fl}^{core}(1-qb)} \quad (7)$$

We have analyzed the $x(t)_{core}$ curves using the model of diffusion out of a sphere into a finite volume. In the case of more complex multilayer micelles[41] it has been our experience that it is not possible to distinguish a simple sphere model from a concentric sphere model unless the diffusion constant of the probe in the outer layer is orders of magnitude smaller than in the inner region, in which case one effectively has a zero-order release curve. The analytical solution for diffusion out of a simple sphere into a finite volume is given by[42]

$$\frac{x(t) - x_0}{x_\infty - x_0} = 1 - \sum_{n=1}^{\infty}\left[\frac{6\alpha(\alpha+1)}{9 + 9\alpha + q_n^2\alpha^2}\right]\exp(-q_n^2 Dt/r_c^2) \quad (8)$$

where α corresponds to $(K_D^\infty)^{-1}$, the distribution coefficient at equilibrium for the diluted solution. Because of the way eq 8 is constructed, $x(t)$ can correspond to the mole fraction of the diffusing species either inside or outside the sphere, if K_D^∞ is defined appropriately. The q_n values depend on α. The fraction remaining in the core at infinite time is given by

$$\frac{x_\infty}{x_0} = \frac{K_D^\infty}{1 + K_D^\infty} \quad (9)$$

where K_D^∞ is given by eq 2 and we ignore the fraction of probe in the bulk solution in the initially injected sample because typically this represents no more than a few percent of the total.

When experimental data and the theoretical curve[43] are both plotted on a log(t) axis, the best fit provides a time-shift factor that corresponds to $\log(D/r_c^2)$ (see Figure 2[44]). r_c^2 can be estimated from the aggregation number of the micelle and the density of the core polymer or appropriate SANS scattering data, if available. On the basis of these assumptions D for pyrene and phenanthrene diffusing out of a PS core has been estimated as 10^{-17} and 10^{-16} cm^2 s^{-1}, respectively. Values approximately 10× higher have been obtained for a core composed of poly(*tert*-butyl acrylate), which has a much lower T_g (cf. 100 and 40−43 °C[45]).

There is at least one flaw in the above model, which probably does not affect the values of D/r_c^2 significantly but which does influence the kinetics of release. Our recent studies have made it clear that the "inner corona" can solubilize a significant fraction of the probe.[40b] Probe molecules in this region of the micelle are expected to diffuse relatively rapidly and contribute to the observed value of x_0 (see eq 8), the fraction of probe that is nominally in the bulk solution at time zero. While the diffusion of the probe in the "inner corona" region may be substantially slower than in bulk solution, so long as it is significantly faster than from the glassy core, the value of D/r_c^2 will reflect the core. The very small values of D we measure are reasonable given the size of the probes and other measurements of diffusion in glassy polymers.[46] This method provides some insight as to the suitability of polymer micelles as "delivery vehicles" for chemicals or drugs in addition to obtaining estimates of very small diffusion constants.

D. Surface Modification by Polymer Micelles: Adsorption or Covalent Attachment. The potential number of functional groups in the polyacid corona is very large, e.g., 10^5 per micelle for an aggregation number of 200 and a degree of polymerization for the polyacid of 500. Of course one would not anticipate all groups to be accessible for chemical reaction because of steric effects, but nevertheless a very high degree of functionality is expected. Additionally the corona is usually hydrophilic, so that one may expect to modify the wetability of a surface upon attachment of a polymer micelle.

We have employed two methods to accomplish this end: (1) adsorption onto a surface that is miscible with the core polymer;[28] (2) chemical attachment of the corona to a suitable surfaces.[27]

Adsorption from Mixed Solvents. This method is very simple. A 60:40 vol:vol dioxane:H_2O solution of PS-*b*-PMA was placed in contact with a spin-cast film of polystyrene for 15−20 min at room temperature, and then excess solvent was removed. Extensive washing with water is then used to remove those micelles that do not adhere strongly to the PS surface. SEM images of the surface demonstrate that intact micelles have adsorbed without loss of the spherical structures (the SEM pictures are practically identical to those discussed in the next subsection). It is presumed that this process involves the contact of the highly swollen PS micelle core with the swollen PS film and that the PS chains can interpenetrate, so that a "hemimicelle" is formed. While long-time annealing was not studied, it is reasonable to imagine that eventually a polymer brush would be formed. The density of the micelles on the surface for equal reaction time varied systematically with the concentration of micelles in the solution in a manner reminiscent of the Langmuir isotherm (Figure 3a). The contact angle of water decreases systematically with coverage (Figure 3b) down to a low of 36° for maximum coverage. If the PMA chains uniformly covered the PS surface, we would expect the value of Θ_{H_2O} to be close to zero. The analysis of the data supposed that "patches" of the underlying PS film remained exposed because the corona serves to maintain some separation between the cores during the adsorption of the micelles. In the adsorbed dry state the corona is expected to collapse around the core and even in the

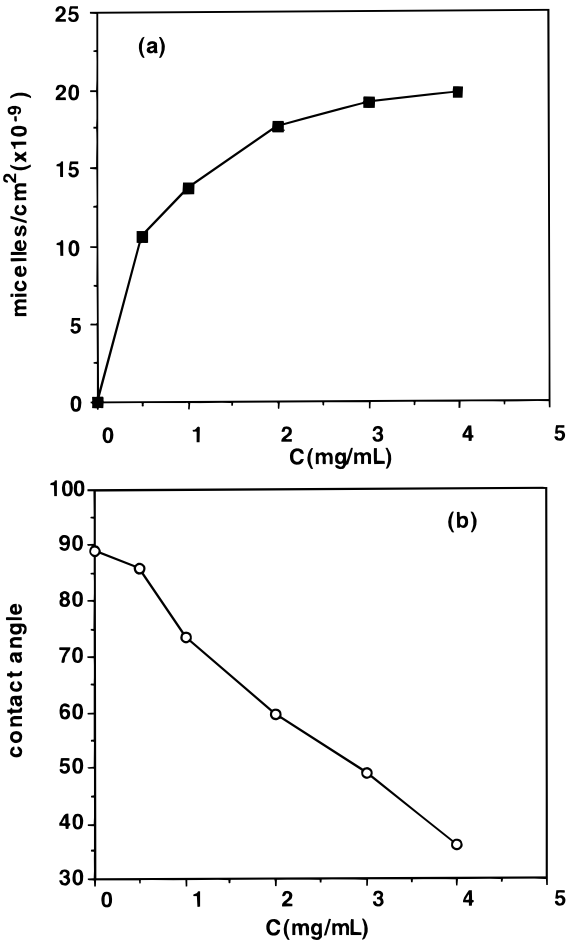


Figure 3. Comparison of (a) the number of micelles per square centimeter from SEM and (b) the H_2O contact angle, both as a function of the micelle concentration in the bulk solution (taken from ref 28).

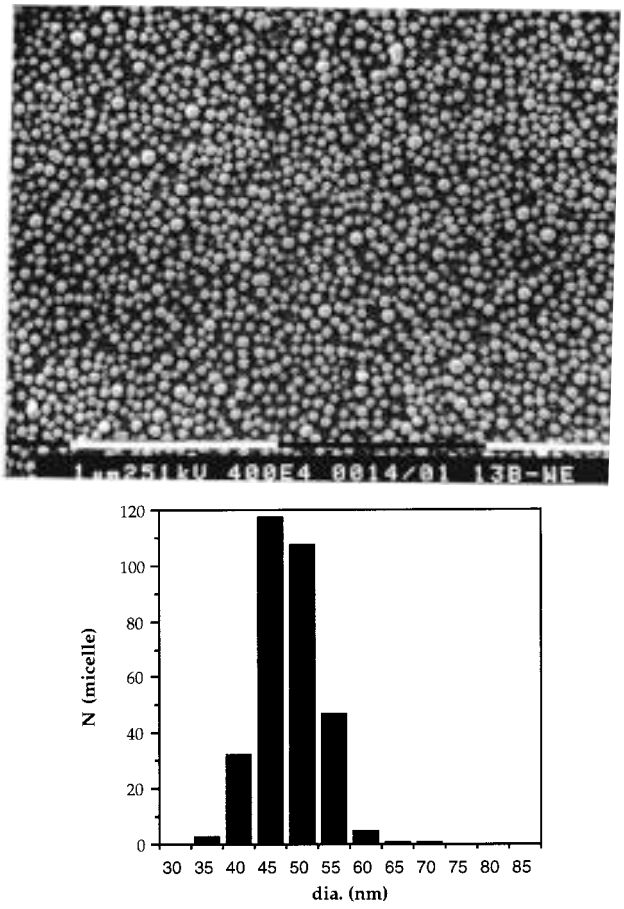


Figure 4. SEM of micelle coverage on a quartz disk and the distribution of micelle diameters (from ref 27b). Average diameter = 45.7 ± 5.4 nm.

presence of H_2O may not be able to expand to cover the total area available. This simple model was able to account for the observations self-consistently. There has been some recent work on adsorption of polystyrene-*b*-poly(2-vinylpyridine) onto mica surfaces this is very similar to the observations described above.[47]

Covalent Attachment of Si_3N_4 or SiO_2. In this case the surface was first activated by attaching amino groups. For Si_3N_4 this involved successive reactions with 1-bromo-3-chloropropane followed by ethylenediamine. This was presumed to produce a short chain with a terminal $-NH_2$ group, but the nature of this reactive surface was not fully characterized.[27a] A more traditional method was applied to SiO_2 disks.[27b] After vigorous cleaning of the quartz disk, the disk was exposed to (3-aminopropyl)trimethoxysilane in the vapor phase under anhydrous conditions. In a separate reaction the PS-*b*-PMA is reacted with 1-((3-dimethylamino)propyl)-3-ethylcarbodiimide in 80:20 dioxane:H_2O. Much lower dioxane contents could be used, but this solvent mixture produced the most reliable results. When the treated SiO_2 disk is placed in contact with the micelle solution, a fairly uniform micelle coverage is observed by either SEM (Figure 4) or AFM. The density of attached particles could be controlled by the concentration of the micelles in solution, similar to the adsorption method. This procedure produced much more uniform densities than the method used for Si_3N_4. We presume this is the result of a more uniform coverage of the surface by amino groups.

For the covalent attachment the value of Θ_{H_2O} after attachment was relatively high (ca. 90°). We presume that this is because there remains an excess of carbodiimide−carboxylate adducts on the exterior of the micelle surface and that these are hydrophobic. The excess activated carboxylates can be used for subsequent reaction. For example, we carried out the attachment of fluoresceinamine (isomer 1) (**2**)) to these surfaces. The fluorescence from the surface was easily observed, but when the modified disk was in contact with water, there was essentially no effect of pH on the fluorescence, unlike aminofluorescein dissolved in aqueous solution. We presume this is the result of the covalently bound aminofluorescein being sequestered in the hydrophobic corona where it is essentially protected from the aqueous phase. The use of micelles for surface modification presents a rich opportunity for producing unique structures. This topic continues to be actively pursued in our laboratory.[48]

Summary

In this article we have tried to illustrate how the self-assembling properties of amphiphilic polymers to form polymer micelles can be exploited for (1) photoredox reactions, (2) solubilization and controlled release of hydrophobic molecules, and (3) surface modification by adsorption and/or covalent attachment to surfaces. We have also described how photophysics can be used to characterize segmental mobility within the micelle or the accessibility of different regions to ions or small hydrophobic molecules. Obviously these different examples can be linked (e.g., hydrophobic release from a modified surface, sensitized photoredox reactions with the transport of small molecular products in to or out of the micelle). We have

not emphasized aspects of this area that are often the purview of "polymer physics", e.g., the dependence of the thermodynamically stable morphologies on polymer properties, solvent quality or density of charge, etc.

Polymer micelles have a relatively long history (>20 years), but in our opinion there remains much to do as more sophisticated polymer synthetic methods are developed and more complex structures can be formed. We feel very lucky to have been introduced to this field by our Czech colleagues and to have established what we hope remains a strong Czech−Austin axis of polymer research.

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