Synthesis and Solid State Properties of a Poly(methyl methacrylate)-*block*-poly(2-(diethylamino)ethyl methacrylate)-*block*-poly(methyl methacrylate) Triblock Copolymer

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Introduction

It has been suggested that the future success of fully synthetic molecular machines will involve the use of soft, stimulus-responsive materials that can change shape/size according to their environment.[1] During such volume transitions, chemical energy is converted to mechanical energy in much the same way as molecular motors function in cell biology, and power is generated by contraction of the responsive material.[2] By creating synthetic analogues of naturally occurring materials, one can produce machines that will operate on the nanometer length scales of individual polymer chains. Devices that perform this energy conversion at the molecular level are known as "molecular motors".[3]

The ability of individual polymer chains to respond to changes in temperature or chemical environment with significant changes in size and conformation has been appreciated for many years. For example, a volume transition within a responsive gel represents a direct, macroscopic manifestation of the conformational response of the individual molecules making up the network.[4] Responsive gels have been enthusiastically greeted as candidates for a new generation of intelligent materials with sensor, processor and actuator functions. A wide range of stimulus-responsive gels have been developed for specific applications such as drug release and as actuators for an artificial muscle.[5] In short, the polymeric material is subjected to an environment that can switch from being a good solvent to a bad solvent for the polymer chains (or vice versa). This induces an expansion (or contraction) of the molecular "machine".

The chemical structure and molecular architecture of such a material plays a vital role in the design of molecular machines. For example, a linear responsive homopolymer would simply dissolve and reprecipitate, as the solvent power changes from good to bad. On the other hand, a chemically cross-linked responsive polymer network (or gel), prepared by standard free-radical methods, would expand and collapse while remaining intact. However, this expansion would not be isotropic due to the random distribution of cross-links, which generate localized stresses within the gel and ultimately lead to mechanical failure.[3,4] To overcome this problem, materials with uniform cross-linking can be used. For example, it is well-known that various ABA triblock copolymers, where "B" represents the responsive polymer and "A" represents a hydrophobic glassy polymer, similar to commercially successful thermoplastic elastomers.[6] Following microphase separation,[7−9] the hydrophobic "A" blocks aggregate into discrete domains to create evenly distributed *physical* cross-links between the responsive "B" polymer chains. By adjusting the relative volume fractions of the two blocks, one can create actuators that expand/collapse in either one (lamellae), two (rods) or three dimensions (spheres).

Herein we report the synthesis and characterization of an ABA triblock copolymer comprising high T_g poly(methyl methacrylate) [PMMA] end-blocks and a low T_g poly(2-(diethylamino)ethyl methacrylate) [PDEA] central block. Previous studies by Tsitsilianis et al.[10] show the effect of polymer concentration on self-organization in aqueous media in a similar system, where the midblock comprised of more hydrophilic poly(2-(dimethylamino)ethyl methacrylate) [PDMA]. We have chosen to use PDEA, rather than PDMA, as its volume is more responsive to changes in pH. While PDEA and PDMA have similar pK_a values, as determined by titration of the homopolymers,[11] the competing effects of slightly higher basicity and increased steric hindrance in PDEA mean that block copolymers and gels based on it exhibit a larger volume transition on ionization. For the PMMA-*b*-PDMA-*b*-PMMA triblock copolymers, end-to-end linear aggregates were formed at low concentrations, whereas at high concentrations an infinite hydrogel network was observed. The presence of an infinite network, made up by spherical "*anchor*" points, is essential to maintain the polymer's structural integrity during pH-induced size changes. To induce sphere formation following phase separation, the volume fraction of the minor component must be on the order of 0.20, with its exact value depending on both the copolymer molecular weight and the Flory−Huggins interaction parameter between the A and B blocks.[9,11] In the present study, a PMMA volume fraction of 0.17 was targeted. There have been numerous reports of the synthesis of PDEA-based AB diblock copolymers, and even ABC triblock copolymers.[12−15] We present here the synthesis, molecular characterization, and morphology determination of a PMMA-*b*-PDEA-*b*-PMMA triblock copolymer suitable for use as a pH-responsive molecular actuator. Indeed, pH-responsive elastomeric networks, or amphiphilic conetworks,[16,17] have been made by group transfer polymerization using similar monomers,[18−20] but these were chemically cross-linked (with the associated quenched structural anisotropy) and not physical gels which can be annealed to create structures approaching equilibrium. Compared to other weak polybases such as poly(2-vinylpyridine), PDEA is particularly interesting in this context since its pK_a is around neutral pH[14] and its T_g is below ambient temperature.[21] Atomic force microscopy (AFM) and small-angle X-ray scattering (SAXS) have been employed to characterize the morphology and the response to pH changes has also been demonstrated.

Experimental Section

Materials. 2-(Diethylamino)ethyl methacrylate (DEA, Aldrich, 99%) and methyl methacrylate (MMA, Aldrich, 99%) were dried over calcium hydride (ACROS, 93%) overnight and subsequently distilled using a high vacuum, short path distillation setup. Tetrahydrofuran (THF, Fisher) was dried over a sodium/potassium alloy using benzophenone (BDH, 99+%) as an indicator. *n*-Tetrabutylammonium bibenzoate (TBABB) was synthesized by the method described by Dicker et al.,[22] and bis(methoxytrimethylsi-

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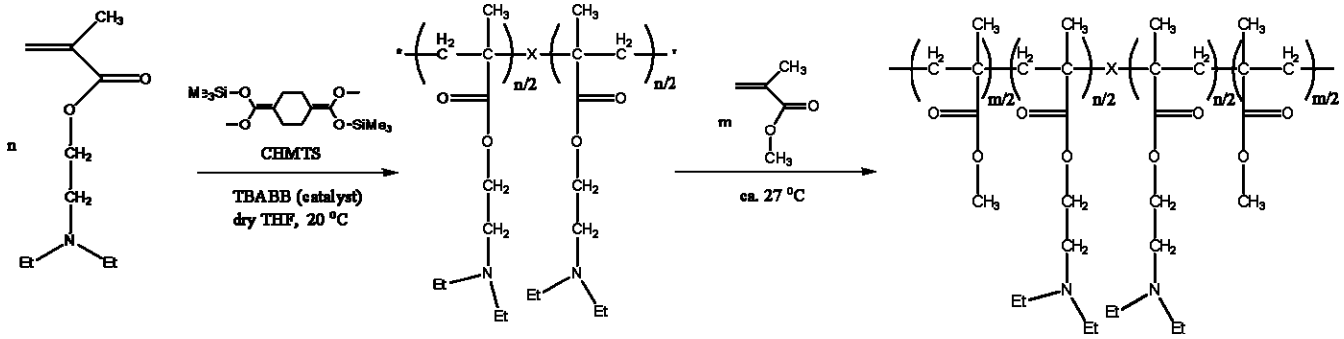
Scheme 1. Synthesis of the Near-Monodisperse PMMA-*b*-PDEA-*b*-PMMA Triblock Copolymer via Group Transfer Polymerization[a]



[a] The "X" featured at the center of the polymer chain represents the bifunctional initiator moiety.

loxymethylene) cyclohexane (CHMTS) was synthesized by the procedure outlined by Steinbrecht et al.[23] Deuterated chloroform (Aldrich, 99.8 atom % D) was used as received.

Synthesis. The PMMA-*b*-PDEA-*b*-PMMA triblock copolymer was prepared by sequential monomer addition via group transfer polymerization using the bifunctional CHMTS initiator**.** TBABB catalyst (75 mg, 0.15 mmol) was added to a clean, dry four-armed flask equipped with a magnetic flea. The vessel was evacuated on a vacuum line, and 150 mL of THF was distilled into the flask so as to dissolve the TBABB. CHMTS (500 mg, 1.5 mmol) was then added using a sidearm, which was prepurged with nitrogen. The reactant mixture was stirred for 15 min while the DEA monomer (38.0 mL, 0.19 mol) was added to another sidearm and subsequently purged with nitrogen. As the DEA was added to the initiator/catalyst solution, the reaction exotherm was followed, showing a steady increase in temperature of approximately 10 °C over 40 min. Once this exotherm had abated, the MMA monomer (5.0 mL, 47 mmol), prepurged with nitrogen, was added using a sidearm, and the second-stage polymerization was stirred for 16 h. This synthetic route is outlined in Scheme 1.

Polymer Characterization. Triple detector gel permeation chromatography (GPC) was employed for absolute molecular weight determination of the triblock copolymer. Measurements were performed using a Viscotek VE 1121 GPC solvent pump equilibrated at 35 °C with Polymer Laboratories PLgel 2 mixed-C columns, a dual refractometer/viscometer model 250 detector, and a RALS (right angle light scattering, $\lambda = 633$ nm) detector. The data were analyzed using *Multi offline* GPC software. For ^{1}H NMR analysis, the copolymer was dissolved in deuterated chloroform (4.0% w/w) for subsequent analysis using a 250 MHz Bruker spectrometer. The solid-state densities of linear PMMA and PDEA homopolymers were determined to be 1.185 and 1.035 g cm^{-3} respectively using an AccuPyc 1330 helium pycnometer (Micromeritics, U.K.).

Sample Preparation. The triblock copolymer was dissolved in THF (40% w/w solution) and a doctor blade was used to cast films of desired thickness onto PTFE sheets. The solvent-rich samples were then placed into a THF-rich atmosphere, where a small aperture allowed the slow release of THF vapor. This resulted in a very slow rate of solvent evaporation from the film over a period of 7 days, which allowed sufficient time for microphase separation of the copolymer. For AFM studies the triblock copolymer was dissolved in THF (5.0% w/w solution) and spin-coated onto a silicon wafer substrate (10 mm × 10 mm) at 2000 rpm, resulting in a film of approximately 1000 Å in thickness. This film was annealed for 72 h in a vacuum oven at approximately 10^{-3} Torr and 130 °C, prior to AFM studies.

Small-Angle X-ray Scattering (SAXS). SAXS measurements were carried out at room temperature using a Bruker AXS Nanostar laboratory instrument (with the primary X-ray flux collimated using cross-coupled Göbel mirrors and a three-pinhole collimator providing a Cu Kα radiation beam with a full width at half-maximum of about 0.4 mm at the sample position) equipped with a two-dimensional (2D) position sensitive gas detector (Hi-Star, Siemens AXS). Data acquisition was performed at a sample detector distance of 1.045 m (calibrated by a silver behenate standard) over the wave vector range: 0.01 Å^{-1} < q < 0.15 Å^{-1} ($q = 4\pi(\sin\theta)/\lambda$, where 2θ is the scattering angle and λ is the wavelength of radiation). 2D SAXS patterns were subjected to background correction and then reduced to a one-dimensional (1D) pattern by an area integration using software supplied by the instrument manufacturer. A computer program "mixture", developed by Svergun et al.,[24] was used to fit the reduced 1D SAXS patterns.

Atomic Force Microscopy (AFM). AFM images were recorded using a Nanoscope Multimode IIIa atomic force microscope (Veeco Instruments) operating in tapping mode. Olympus oxide sharpened tips with a resonant frequency of ∼300 kHz and a spring constant of approximately 40 N m^{-1} were used.

Results And Discussion

GPC analysis of the as-prepared triblock copolymer displayed a narrow unimodal peak (Figure 1, top trace) and subsequent analysis revealed that the copolymer had a number-average molecular weight (M_n) of 182 kg mol^{-1} and a polydispersity of 1.12. ^{1}H NMR analysis (Figure 1, bottom) was used to determine the mole fraction of PMMA. A detailed description of this calculation is provided as Supporting Information. The integrated signal due to the methoxy protons of the PMMA chains at 3.6 ppm was compared to that of the two oxyethylene protons of the PDEA chains at 4.0 ppm. This block composition, combined with the densities of the respective homopolymers, enabled a volume fraction (ϕ_{PMMA}) of 0.17 to be calculated for the PMMA blocks.

Tapping mode AFM was used to analyze the surface of the spin-cast triblock copolymer film. Figure 2 shows the AFM topographic image and the corresponding Fourier transform pattern of this image (inset). The topographical image revealed spherical-like domains, which protruded approximately 10 Å from the surface and corresponded to the harder PMMA blocks situated within the relatively soft PDEA matrix ($T_g \sim 16$ °C). Thus, this AFM image confirms that the copolymer morphology comprises spherical PMMA microdomains dispersed within a liquidlike pH-responsive PDEA matrix, as expected. The Fourier transform of the AFM topographic image clearly indicates that the distances between neighboring spheres is strongly correlated, with an average interdomain length scale (or d spacing) of around 300 Å. This distance is controlled by the number-average molecular weight, low polydispersity, and volume fraction of the mid-block. The theoretical maximum interdomain spacing is limited by the stretched chain length (as all the PMMA spheres are interconnected to one another by the PDEA chains) and the minimum spacing is limited by the interaction radius (referred to as the effective hard sphere radius, R_{eff}) of the glassy spherical PMMA domains. The R_{eff} value arises in such a material because there are matrix chains emanating from the spheres that create an inpenetrable coating, which prevents close

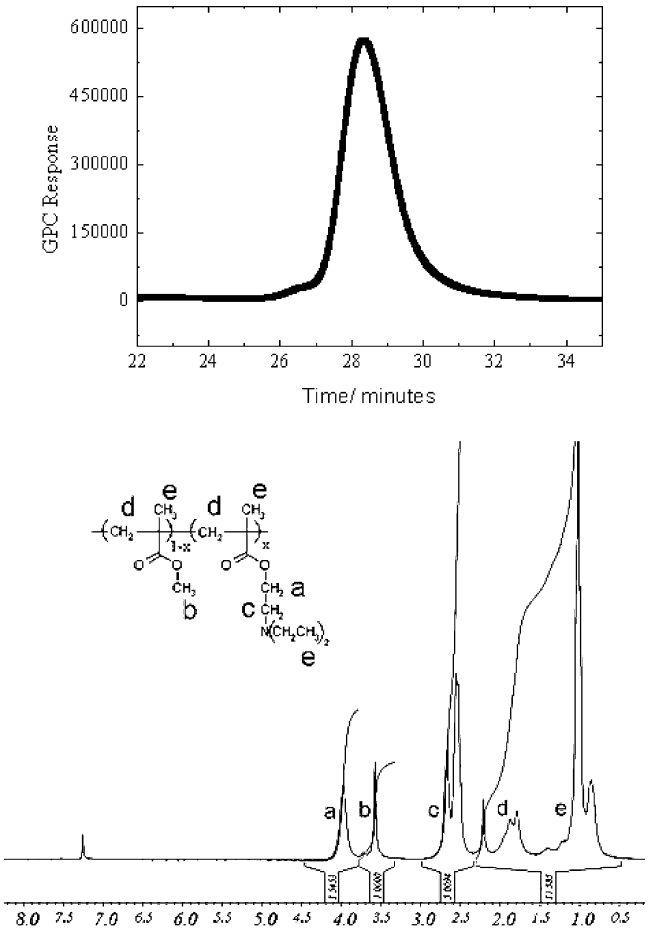


Figure 1. GPC trace (top) and ^{1}H NMR spectrum ($CDCl_3$) of the PMMA-*b*-PDEA-*b*-PMMA triblock copolymer.

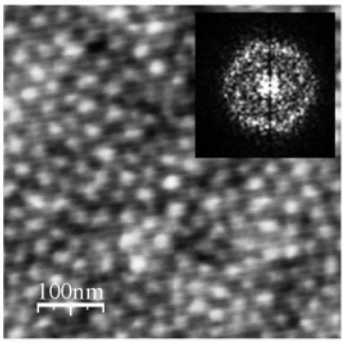


Figure 2. AFM topographic image and corresponding Fourier transform (inset) of the triblock copolymer film after annealing under vacuum for 72 h at 130 °C.

approach of the PMMA aggregates.[25] The thickness of this effective coating is directly dependent on the molecular weight of the central PDEA block. As this triblock copolymer has a relatively low polydispersity, there is a narrow distribution of length scales between the PMMA domains. This in turn controls the interdomain spacing, leading to the appearance of a distinct ring in the Fourier transform pattern. The AFM topographic image also reveals that the PMMA spheres have an approximate radius of 100 Å.

SAXS patterns of the as-prepared (raw) copolymer (see Figure 3, lower trace) showed a pronounced peak at 0.024 Å^{-1} and a shoulder at larger scattering values, with the latter feature becoming more pronounced as a broad peak after annealing the gel (see Figure 3, upper trace). Annealing allows equilibration and sharpens the boundaries of the microdomains across the

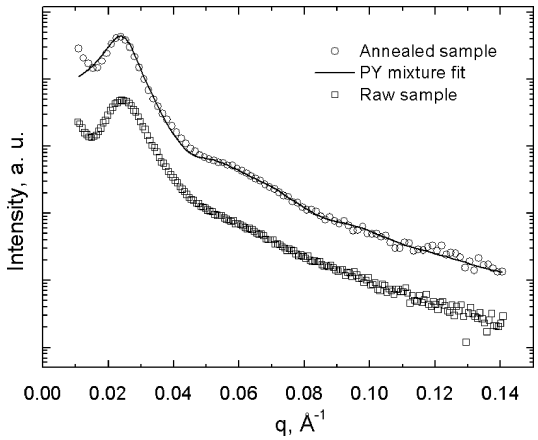


Figure 3. SAXS patterns of the copolymer in the solid state before (□) and after (○) annealing at 130 °C for 72 h. The solid line is a fit to the SAXS pattern using the computer program "mixture" developed by Svergun et al.[24] The SAXS profile of the annealed sample has been shifted vertically to avoid overlap.

polymer network. These patterns are similar to those observed for other ABA triblock copolymers, forming a structure of spherical microdomains distributed with short-range liquidlike order.[26,27] This is in good agreement with the surface morphology observed in the AFM studies, which revealed a "liquidlike" disordered array of spheres. The intense SAXS peak lies in the same q range as the Fourier transform of the AFM image (see Figure 2, inset), which indicates the correspondence to a structure peak generated by short-range ordering of the spherical microdomains, while the weaker broad feature corresponds to the first maximum of the form factor of the relatively monodisperse spheres. Thus, the scattering pattern can be fitted with the Percus−Yevick (PY) hard-sphere model,[25] whose structure factor is used to describe a liquidlike arrangement of spherical microdomains. The adjustable parameters of this model are the mean interaction radius of the spheres (R_{eff}), the radius of the spherical microdomains (R_{sd}) and the apparent volume fraction of the hard spheres (ν). Using the PY model, a reasonable fit to the SAXS patterns can be obtained with the following parameters: $R_{\text{eff}} \sim 127$ Å, $R_{\text{sd}} \sim 99$ Å, $\nu \sim 0.34$, and a sphere polydispersity of 15% (assuming a Shultz distribution). Given that $\phi_{\text{PMMA}} = (R_{\text{sd}}/R_{\text{eff}})^3 \times \nu$, these parameters lead to a volume fraction of 0.16 for the spherical microdomains, which corresponds well to the volume fraction of 0.17 calculated from the NMR spectrum and homopolymer densities. The SAXS patterns also revealed that this triblock copolymer has a mean interdomain spacing of around 254 Å (taken from $2 \times R_{\text{eff}}$), which is in reasonably good agreement with the AFM observations of approximately 300 Å. An average aggregation number per PMMA sphere was estimated to be 215. It should be noted that the model fitting lies below the experimental pattern for $q \sim 0.04$ Å^{-1}. This discrepancy may be caused by partial ordering of the spherical microdomains in a distorted cubic lattice (either a simple or body-centered cubic), which could produce a broad shoulder formed by overlapping second- and third-order peaks of the lattice (either 011 and 111 or 002 and 112, respectively). Following the work of Hashimoto and co-workers[26,27] it is suggested that there is a stable conformation of disordered PMMA spherical domains with some more ordered grains (in a cubic array) within the copolymer matrix. It has been shown that[26,27] above the order−disorder transition temperature (T_{ODT}) of a given triblock (volume fraction 0.20), just a single phase exists and only thermal concentration fluctuations are observed. When the temperature is lowered below the T_{ODT}, but is still above the lattice disordering/ordering transition temperature,

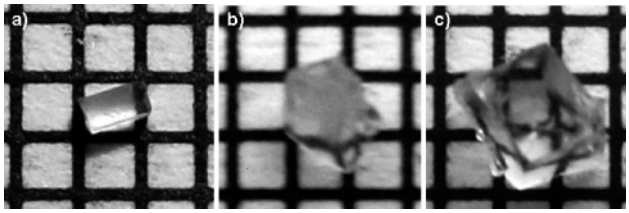


Figure 4. Photographic images of three samples of PMMA-*b*-PDEA-*b*-PMMA triblock copolymer gel after 1 h in (a) dry atmosphere, (b) distilled water at pH 7, and (c) dilute hydrochloric acid at pH 3. The respective masses were found to be (a) 1, (b) 1.9, and (c) 4.8 times the mass of the original dry state. The periodicity of the grid is 1 mm × 1 mm.

T_{LDOT}, a two-phase system of disordered spheres is observed. Below the T_{LDOT} the spherical domains are arranged in an ordered lattice. The ordering mechanism proceeds by a nucleation/growth process, as transient structures indicate the coexistence of spheres in both ordered and disordered regions.

The experimental evidence for spherical microdomains within this polymer network is very encouraging for their potential as actuators. The glassy PMMA domains provide physical cross-links for the pH-responsive PDEA chains, thus allowing them to expand and contract isotropically in all three dimensions. In contrast, other morphologies, such as lamellae or cylindrical rods, would restrict movement to one or two dimensions, respectively, and past experience shows that this leads to anisotropic internal stresses and ultimately failure by gel-fracture. The presence of a pronounced structural peak in the SAXS data should allow the size changes in the copolymer to be monitored at the molecular level when monolithic samples are immersed in aqueous solutions of varying pH, as previously demonstrated for PMMA-*b*-PMAA-*b*-PMMA triblock copolymers.[28] Triblock gels based on polyacids and polybases exhibit inverted pH response, and careful selection of monomers and block copolymer composition allows the response functions to be approximately equal and opposite. Three equal-mass samples of PMMA-*b*-PDEA-*b*-PMMA were subjected to three different environments; dry, pH 7 and pH 3 for 1 h to demonstrate the pH-responsive nature of this triblock copolymer gel (Figure 4). PDEA exhibits some swelling in water at neutral pH, but the chains are held close together because the hydrophobic substituents of the DEA repeat units favor a globule conformation to minimize unfavorable solvent−polymer interactions. Under sufficiently acidic conditions the tertiary amine groups along the PDEA chains become protonated, thus creating a cationic charge located on each nitrogen atom. This cationic charge density induces electrostatic repulsion between neighboring protonated amine groups and so the polymer expands. Work is currently being undertaken to identify the coil/globule transition pH and assess the effect of an autonomous pH-oscillating reaction on the inter-microdomain spacing of the triblock copolymer.

Conclusions

A near-monodisperse symmetric PMMA-*b*-PDEA-*b*-PMMA triblock copolymer with a number-average molecular weight (M_n) of 182 kg mol^{-1}, a polydispersity of 1.12 and a ϕ_{PMMA} of 0.17, has been successfully synthesized using GTP. AFM and SAXS studies confirmed that the solid-state structure of this copolymer is a "liquidlike" network of disordered PMMA spherical domains (perhaps containing some regions of more ordered cubic-like structures) with an approximate radius of 100 Å and an interdomain spacing of approximately 254 Å. These hard, hydrophobic PMMA spheres act as physical cross-links, with soft, pH-responsive PDEA polymer chains bridging between these domains. The presence of spherical domains allows isotropic three-dimensional expansion of the material when placed under acidic conditions.

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Supporting Information Available: Text giving the mathematical procedure to calculate the volume fraction of the triblock copolymer components as well as an NMR spectrum. This material is available free of charge via the Internet at http://pubs.acs.org.

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