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Synthesis of Sterically-Stabilized Polystyrene Latexes Using Well-Defined Thermoresponsive Poly(*N*-isopropylacrylamide) Macromonomers

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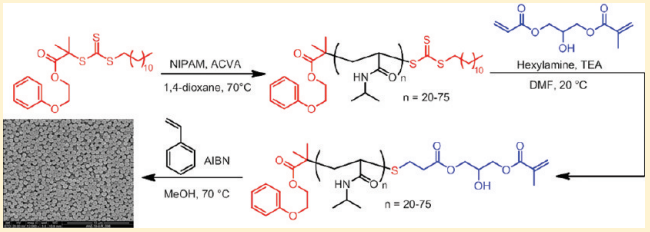
Supporting Information

ABSTRACT: A series of well-defined thermo-responsive poly(*N*-isopropylacrylamide) (PNIPAM) macromonomers was prepared by reversible addition−fragmentation chain transfer (RAFT) polymerization followed by aminolysis and nucleophilic Michael addition. 2-(Dodecylthiocarbonothioylthio)-2-methylpropanoic-2-phenoxyethyl ester (CTA) was used as the RAFT chain transfer agent to prepare six PNIPAM-CTA precursors with target degrees of polymerization of 20, 30, 40, 50, 60, and 75. These NIPAM polymerizations were conducted in 1,4-dioxane and proceeded with good control and low polydispersities (M_w/M_n < 1.10) up to more than 90% conversion. The PNIPAM trithiocarbonate end-groups were then converted to methacrylate end-groups by combining (i) aminolysis and (ii) nucleophilic Michael addition using the bifunctional reagent, 3-(acryloyloxy)-2-hydroxypropyl methacrylate (AHPMA), in a one-pot reaction. The resulting PNIPAM macromonomers were evaluated as reactive steric stabilizers for latex syntheses. Near-monodisperse submicrometer-sized latexes were obtained by alcoholic dispersion polymerization of styrene in methanol, as judged by scanning electron microscopy (SEM) and dynamic light scattering (DLS). In contrast, a latex synthesized in the presence of a PNIPAM-CTA had a bimodal size distribution, while thiol-capped PNIPAM chains produced ill-defined nonspherical particles and styrene polymerization conducted in the absence of any stabilizer led to macroscopic precipitation. These control experiments confirm that using the methacrylate-capped macromonomers is essential for successful latex syntheses. ^{1}H NMR analysis confirm the presence of PNIPAM chains in the latex particles and XPS measurements indicate that the stabilizer is located on the particle surface, as expected. The well-known thermo-responsive nature of the stabilizer was successfully transferred to these latexes, which exhibit reversible flocculation upon heating above the LCST of the PNIPAM chains.



INTRODUCTION

Macromonomers are polymer chains that contain one or more polymerizable groups. This broad definition encompasses a large number of possible architectures.[1] In practice, the term "macromonomer" is often used to designate macromolecules containing a single vinyl group located at one chain-end. Such macromonomers can be readily copolymerized using conventional free radical polymerization, which is one of the most industrially relevant polymerization methods. Macromonomers have been widely used to prepare sterically stabilized latexes,[2,3] graft copolymers,[4] dendritic polymers,[5] or so-called "bottle brush" polymers.[6] They can be prepared by two main methods: (i) polymerization from an initiator containing a vinyl group that does not participate in the polymerization process and (ii) postpolymerization modification of the chain-end functionality. In addition, catalytic chain transfer polymerization (CCTP) also provides a facile route to methacrylic macromonomers,[7,8] although this approach produces terminal vinyl groups that do not exhibit the same copolymerizability as more conventional methacrylates.[9] Both Lascelles et al.[10] and Nagasaki et al.[11] prepared a range of styrene-functionalized macromonomers via anionic polymerization using a 4-vinylbenzyl alkoxide initiator. Similarly, the preparation of poly(methyl vinyl ether) macromonomers by cationic polymerization using an acrylate initiator was recently reported.[12] Allyl-, vinyl acetate- and vinyl ether-based initiators have also been used to prepare well-defined macromonomers via atom transfer radical polymerization (ATRP).[13] Postpolymerization modification usually involves a two-step protocol and is therefore generally more time-consuming. Nevertheless, it is often much more versatile, since it allows the incorporation of vinyl functionalities which would otherwise participate in the chain-growth polymerization. This approach has been successfully employed in conjunction with free-radical polymerization, ATRP and anionic polymerization.[3,14] The well-known orthogonality of so-called "click" chemistry, in particular the copper(I)-catalyzed 1,3-dipolar cycloaddition of azides to alkynes, has been exploited to produce well-defined macromonomers.[15]

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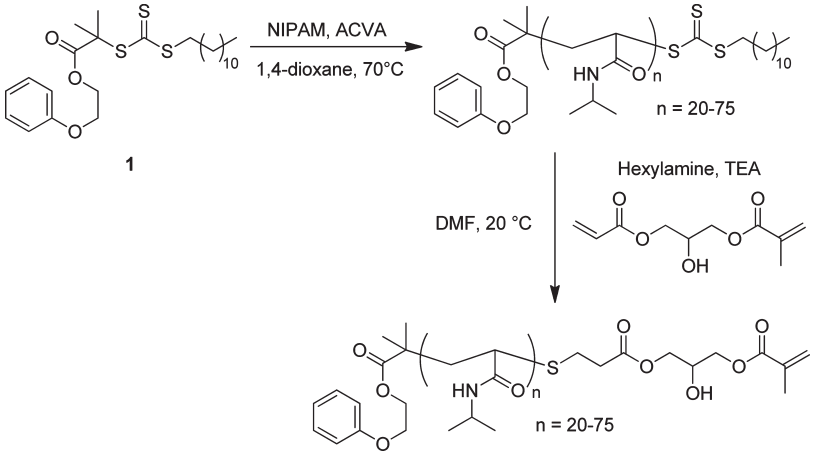
Scheme 1. RAFT Synthesis of the Well-Defined Methacrylate-Terminated PNIPAM Macromonomers Used in This Work



Homopolymer precursors obtained by ATRP can also be converted into macromonomers by substitution of the terminal halogen atom,[16] although this method may suffer from reduced efficiency due to premature loss of halide from the chain-ends toward the end of the polymerization. Recently, Boyer et al. combined reversible addition−fragmentation chain transfer (RAFT) polymerization[17] with thiol−ene chemistry to obtain model macromonomers by reacting polymeric thiols with diacrylates or dimethacrylates.[18]

Poly(*N*-isopropylacrylamide) (PNIPAM) is a nonionic hydrophilic polymer that is soluble in water below its lower critical solution temperature (LCST), but above this critical temperature the chains undergo a coil-to-globule transition and become insoluble.[19] The precise cloud point depends on the PNIPAM molecular weight, its chain-end groups[20,21] and its architecture,[22] but it is generally accepted to be around 31−32 °C for mean degrees of polymerization of 9 and above.[23] Controlled radical polymerization techniques have been used to prepare PNIPAM homopolymers and copolymers. Nitroxide-mediated polymerization was used to graft PNIPAM chains onto a polystyrene star polymer.[24] The ATRP of acrylamides is generally more challenging than that of methacrylates or acrylates due to a smaller ATRP equilibrium constant,[25] potential deactivation of the copper catalyst and *in situ* displacement of the terminal halogen atom, but this chemistry has also been utilized to prepare well-defined PNIPAM-based copolymers.[20b,26] For example, we recently reported a new class of thermo-responsive biochemically degradable gelators based on PNIPAM-containing ABA triblock copolymers [where A = PNIPAM and B = poly(2-(methacryloyloxy)ethyl phosphorylcholine)] prepared via ATRP.[27] However, according to the literature the most widely used technique for the synthesis of well-defined PNIPAM appears to be RAFT polymerization.[28]

The grafting of PNIPAM homopolymer (or copolymer) onto solid surfaces has been used in a range of applications, such as liquid chromatography,[29] permeation-controlled filters,[30] chemical sensors,[31] cell culture,[32] controlled bioadhesion,[33] protein adhesion,[34] and functional composite surfaces.[35] Thermo-responsive colloidal particles are of particular interest for biomolecule separation[29a,36] and cell culture scaffolds.[37] The preparation of thermo-responsive colloidal particles was pioneered by Pelton and Chibante,[38] who reported the synthesis of PNIPAM-based microgel particles via aqueous dispersion polymerization.[39] Subsequently, Kawaguchi and co-workers extended this work to include the aqueous emulsion copolymerization of styrene with various *N*-substituted acrylamides.[40] Pichot et al. used surfactant-free emulsion polymerization to prepare poly(styrene-*N*-isopropylacrylamide-2-aminoethyl methacrylate hydrochloride) latexes using a batch process or a 'shot-growth' strategy to ensure incorporation of the cationic comonomer at the surface of the latex particles.[41] Below 32 °C, these latexes were shown to be electrosterically stabilized by a combination of the thermo-responsive PNIPAM chains and the cationic surface charge conferred by the 2-aminoethyl methacrylate hydrochloride residues. In contrast, the latexes were mainly stabilized by electrostatic repulsion above 32 °C, since the PNIPAM chains collapse onto the latex particle surface above their LCST.[42] In addition, the covalent attachment of antibodies to the surface of such microgels was also studied.[43] Ballauff and co-workers studied the thermo-responsive properties of polystyrene−PNIPAM core−shell particles.[44] The high T_g cores were synthesized first via seeded emulsion polymerization, then NIPAM was copolymerized with a *N*,*N*′-methylenebis(acrylamide) to form a cross-linked shell. Tenhu and co-workers synthesized similar core−shell particles[45] and used a combination of DLS, ^{1}H NMR and differential scanning microcalorimetry to examine their thermo-responsive behavior in aqueous solution. The critical swelling temperature for the cross-linked PNIPAM shell was shifted to higher temperature and exhibited a broader phase transition compared to PNIPAM microgels. Moreover, this thermal transition is also affected by the shell thickness, although variable temperature DLS studies suggested only a relatively small change in the particle diameter.

In the present work, PNIPAM precursor chains were obtained by RAFT and readily converted into well-defined macromonomers via a convenient one-pot protocol that combines aminolysis and thia-Michael addition and utilizes a commercially available methacrylate-acrylate reagent. This approach produces well-defined PNIPAM macromonomers with somewhat higher atom efficiency than those synthesized by Boyer et al.[18] or the preparation of α, ω-hydroxy telechelic polymers described by Qiu and Winnik.[46] These methacrylate-capped macromonomers were then used as steric stabilizers for the dispersion polymerization of styrene in methanol to afford model thermo-responsive sterically stabilized polystyrene latexes.

EXPERIMENTAL DETAILS

Materials. The (2-(dodecylthiocarbonothioylthio)-2-methylpropanoic acid) precursor CTA was synthesized according to the method described by Skey and O'Reilly.[47] 2-Bromo-2-methyl-propionic acid, 3-(acryloyloxy)-2-hydroxypropyl methacrylate (AHPMA), 4-(dimethylamino) pyridine (DMAP), 4,4′-azobis(4-cyanovaleric acid) (ACVA), dimethylphenylphosphine, *n*-dodecanethiol, *n*-hexylamine, carbon disulfide (CS_2), K_3PO_4, NaH, *N*,*N*′-dicyclohexylcarbodiimide (DCC), 2-phenoxyethanol and triethylamine (TEA) were all purchased from Aldrich and used as received. Anhydrous $MgSO_4$ and Na_2SO_4 were purchased from Fisher and used as received. 2,2′-Azobis(isobutyronitrile) (AIBN) was purchased from BDH laboratories and used as received. ***N***-Isopropylacrylamide (NIPAM) was purchased from Aldrich (97%) and recrystallized from *n*-hexane and toluene (25:1). Styrene (Aldrich) was passed through a column of basic alumina to remove its inhibitor and stored at −20 °C prior to use. 1,4-Dioxane, dichloromethane (DCM), diethyl ether, ethyl acetate, methanol and petroleum ether were all purchased from Fisher as HPLC grade solvents and used as received. Deionized water was used in all experiments. Silica gel 60 (0.0632−0.2 mm) was obtained from Merck (Darmstadt, Germany). NMR solvents (D_2O, CD_3OD, DMSO-d_6 and $CDCl_3$) were purchased from Goss Scientific Instruments Ltd.

Synthesis of 2-(dodecylthiocarbonothioylthio)-2-methylpropanoic-2-phenoxyethyl Ester (DDMPEAT). DDMPEAT was synthesized by dissolving (2-(dodecylthiocarbonothioylthio)-2-methylpropanoic acid) (DDMAT) (3.0 g, 8.23 mmol) and 2-phenoxyethanol (1.137 g, 8.23 mmol) into 20 mL of anhydrous DCM at 0 °C. *N*,*N*′-dicyclohexylcarbodiimide (DCC) (2.04 g, 9.89 mmol) and 4-(dimethylamino)pyridine (DMAP) (100.65 mg, 0.823 mmol) were dissolved in 15 mL of anhydrous DCM and added dropwise into the reaction mixture, see Scheme 1. The reaction solution was stirred at 20 °C for 48 h under nitrogen and a white precipitate of (*N*,*N*′-dicyclohexylurea) (DCU) was formed. The crude product was further purified by first removing the DCU by filtration. Then the supernatant was evaporated under vacuum and the dark yellow crude product was dissolved in petroleum ether before being purified by flash chromatography (20:1 petroleum ether/ethyl acetate). The final yield of the purified DDMPEAT product (>99% purity as judged by ^{1}H NMR) was 75%.

^{1}H NMR (400.13 MHz, $CDCl_3$, 298 K), δ (ppm): 0.9 (3H, $-CH_3$); 1.3 (18H, $-CH_2-$); 1.6 (2H, CH_2-CH_2-S); 1.7 (6H, $-(CH_3)_2$); 3.2 (CH_2-S-); 4.2 (2H, $-CH_2-OPh$); 4.5 (2H, $COO-CH_2-$); 6.9 and 7.3 (5H, −Ar).

^{13}C NMR (100 MHz, $CDCl_3$, 298 K), δ (ppm): 14.2 (CH_3-CH_2-); 22.8, 27.9, 29.0, 29.2, 29.4, 29.5, 29.6, 29.7, 32.0 (10C, dodecyl chain); 25.4 ($C(CH_3)_2$)); 37.0 ($-CH_2-S$); 55.9 ($C(CH_3)_2$)); 64.2, 65.6 ($-O-CH_2-CH_2-O$); 114.7, 121.1, 129.5 (CH, Ar); 158.6 (($-CH)_2-C-O$); 173.0 (C═O); 221.4 (C═S).

Kinetics of Thia-Michael Addition. *n*-Dodecylthiol (18.89 mg; 93 μmol) and TEA (3.15 mg; 31 μmol) were dissolved in DMF-d_7 (0.90 mL) and this solution was placed in an NMR tube. Then AHPMA (20.0 mg; 93 μmol) was injected into the NMR tube and this was taken to be zero time. Spectra were recorded at 20 °C every 10 min for 2.5 h.

Kinetics of Aza-Michael Addition. *n*-Hexylamine (9.44 mg; 93 μmol) and TEA (3.15 mg; 31 μmol) were dissolved in DMF-d_7 (0.90 mL) and this solution was placed in an NMR tube. Then AHPMA (20.0 mg; 93 μmol) was injected into the NMR tube and this was taken to be zero time. Spectra were recorded at 20 °C every 10 min for 2.5 h.

Kinetics of Aminolysis. $PNIPAM_{65}$-CTA (100 mg; 12.8 μmol) was dissolved in DMF (2.0 mL) along with AHPMA (8.23 mg; 38.4 μmol) and the mixture was degassed for 20 min. In a separate vial, *n*-hexylamine (50.7 μL) and TEA (17.8 μL) were dissolved in DMF (5.0 mL) and this solution was also degassed for 10 min. *n*-Hexylamine (0.50 mL; 38.4 μmol) and TEA (12.8 μmol) of this stock solution were added to the $PNIPAM_{65}$-CTA solution and degassing was conducted for a further 10 min. Then, 150 μL aliquots were extracted at regular time intervals and immediately added to vials containing 200 μL of a DMF solution of acetic acid (1 mg mL^{-1}) and 750 μL DMF. Then, 100 μL of each of these solutions were then diluted further to 1.0 mL with DMF and their UV absorption spectra were recorded (λ_{max} at 313 nm) at 20 °C.

Homopolymerization of NIPAM via RAFT. NIPAM polymerizations were performed at 70 °C. The [NIPAM]/[CTA] molar ratio was adjusted so that an average DP of 20, 30, 40, 50, 60, or 75 was achieved when the monomer conversion reached 90−92%. Each polymerization was quenched by rapidly cooling using an ice bath. The reaction mixtures were dialyzed against methanol (cutoff: 1000 g mol^{-1}). After dialysis, methanol was removed under vacuum to yield a solid yellow product. The $PNIPAM_n$-CTA molecular weights were determined by ^{1}H NMR and the polydispersity was obtained via DMF GPC (using poly(methyl methacrylate) calibration standards). In a typical run, freshly recrystallized NIPAM (4.0 g; 35.35 mmol), DDMPEAT (317.00 mg; 0.65 mmol), and ACVA (18.35 mg; 0.065 mmol) were dissolved in 1,4-dioxane (10 mL) in a glass vial fitted with a rubber seal and the solution was degassed for 20 min using a dry nitrogen purge. The reaction mixture was then placed in an oil bath set at 70 °C and terminated after approximately 90 min.

Synthesis of Thiol-Capped PNIPAM ($PNIPAM_{50}$-SH). Thiol-ended PNIPAM ($PNIPAM_{50}$-SH) was synthesized by aminolysis in the presence of dimethylphenylphosphine (DMPP) as a reducing agent. A 3-fold excess of *n*-hexylamine and 0.1 equiv of DMPP was used with respect to $PNIPAM_{50}$-CTA. The reaction was conducted in THF and the product was isolated as a white powder after purification by precipitation (twice) into excess diethyl ether.

Macromonomer Synthesis. The aminolysis and subsequent Michael addition were conducted using a one-pot protocol. In a typical reaction, $PNIPAM_{50}$-CTA (2.00 g; 0.312 mmol) and 3-(acryloyloxy)-2-hydroxypropyl methacrylate (AHPMA) (200.00 mg; 0.938 mmol) were dissolved in DMF (49 mL). The yellow solution was degassed by nitrogen bubbling for 20 min, after which 1.0 mL of a degassed solution of *n*-hexylamine (126.00 mg; 1.25 mmol) and TEA (31.60 mg; 0.312 mmol) in DMF was injected. Nitrogen bubbling was continued for a further 10 min and the reaction solution was then stirred at 20 °C for 15 h, leading to the disappearance of its yellow coloration. The resulting $PNIPAM_{50}$-MA macromonomer was first dialyzed in methanol (cutoff: 1000 g mol^{-1}) to remove any water-insoluble impurities, then dialyzed in deionized water. The final purified macromonomer was isolated as a white powder after freeze-drying from water overnight. Optimization of the one-pot aminolysis Michael addition was performed on one-tenth of the scale, i.e., using 200 mg $PNIPAM_{50}$-CTA dissolved in 5.0 mL of DMF.

Alcoholic Dispersion Polymerization of Styrene. A typical polystyrene latex was synthesized by dissolving $PNIPAM_{50}$-MA macromonomer (50.0 mg) into methanol (4.50 g) along with styrene (500 mg) and AIBN (5.0 mg). Oxygen was removed by purging with dry nitrogen for 30 min. The polymerization was initiated by placing the vessel into an oil bath at 70 °C. After 1 h, the reaction mixture became slightly turbid, and 3 h later it became milky-white. The reaction was stirred at 70 °C for 24 h. The latexes were purified by five centrifugation/redispersion cycles, twice in methanol and then three times in deionized water. Precisely the same protocol was used for the control experiments using $PNIPAM_{50}$-SH and $PNIPAM_{50}$-CTA. The resulting sterically stabilized latexes were analyzed by ^{1}H NMR, dynamic light scattering, X-ray photoelectron spectroscopy and scanning electron microscopy (see below).

POLYMER CHARACTERIZATION

Dynamic Light Scattering (DLS). The intensity-average hydrodynamic diameter of each latex was recorded using a Malvern Nanosizer ZS instrument. Methanolic solutions of 0.1% w/v% latex were analyzed

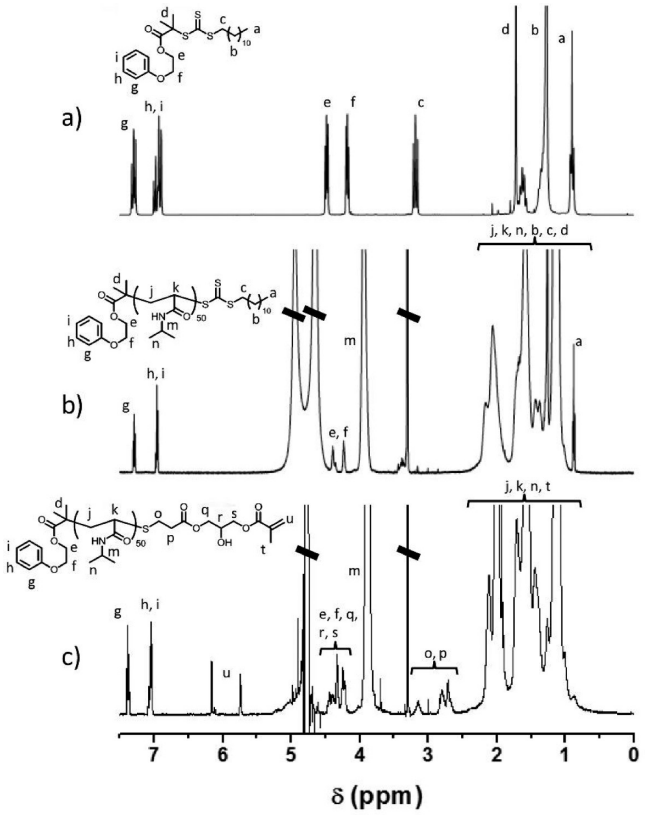


Figure 1. ^{1}H NMR spectra recorded for (a) DDMPEAT ($CDCl_3$), (b) $PNIPAM_{50}$-CTA homopolymer (CD_3OD:D_2O = 4:1 v/v), and (c) $PNIPAM_{50}$-MA macromonomer (D_2O:CD_3OD = 10:1 v/v). Note: the polymers are fully soluble in CD_3OD, D_2O helps to mask the amide protons of PNIPAM . $PNIPAM_{50}$-CTA gives a slightly turbid solution in pure D_2O at the concentration required to perform accurate end-group analysis due to its two hydrophobic chain-ends; thus, a mixture of D_2O/CD_3OD was used.

using disposable plastic cuvettes and data were averaged over three consecutive runs.

Gel Permeation Chromatography (GPC). The molecular weights and polydispersities of the various PNIPAM-MA macromonomers and their corresponding PNIPAM-CTA precursors were determined by DMF GPC at 60 °C. The GPC setup comprised two Polymer Laboratories PL gel 5 μm Mixed-C columns maintained at 60 °C in series with a Varian 390 LC refractive index detector. The flow rate was 1.0 mL min^{-1}, and the mobile phase contained 10 mmol LiBr. A total of 10 near-monodisperse PMMA standards (M_p = 625 to 618 000 g mol^{-1}) were used for calibration.

NMR Spectroscopy. All ^{1}H NMR and ^{13}C NMR spectra were recorded in either CD_3OD, $CDCl_3$, DMSO-d_6, DMF-d_7, or D_2O using either a 250 MHz Bruker Avance 250 or a 400 MHz Bruker Avance 400 spectrometer.

Scanning Electron Microscopy (SEM). SEM studies were performed using a FEI Sirion field emission scanning electron microscope at a beam current of 244 μA and an operating voltage of 5 kV. Samples were dried onto aluminum stubs and sputter-coated with a thin layer of gold prior to examination to prevent sample charging.

UV−Visible Spectroscopy. All spectra were recorded with a 1.0 cm quartz cuvette using a Perkin-Elmer Lambda 25 spectrometer operating at a scan speed of 480 nm min^{-1}.

X-ray Photoelectron Spectroscopy (XPS). X-ray photoelectron spectra (XPS) were acquired using a Kratos Axis Ultra DLD X-ray photoelectron spectrometer equipped with a monochromatic Al KR X-ray source ($h\nu$ = 1486.6 eV) and operating at a base pressure of 10^{-8} to 10^{-10} mbar. Latex particles were dried onto silicon wafers and evacuated to ultrahigh vacuum prior to XPS measurements.

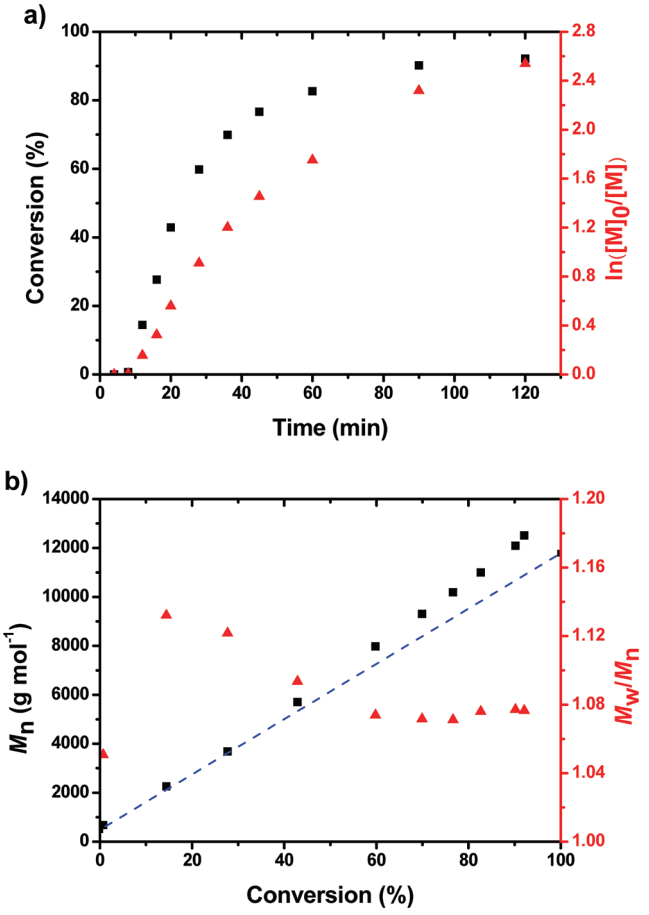


Figure 2. Kinetic data obtained for the RAFT homopolymerization of NIPAM using DDMPEAT CTA: (a) evolution of conversion and monomer consumption as a function of time; (b) evolution of molecular weight and polydispersity as a function of monomer conversion. Conditions: 4.00 g NIPAM in 10.0 mL of 1,4-dioxane at 70 °C; $[NIPAM]_0$:[DDMPEAT]:[ACVA] = 100:1:0.1.

RESULTS AND DISCUSSION

PNIPAM-MA Macromonomers. The CTA synthesis and the synthetic route adopted for PNIPAM-MA macromonomers are both outlined in Scheme 1. *S*-Dodecyl-*S*′-(α,α′-dimethyl-α″-acetic acid) trithiocarbonate, (DDMAT) was synthesized according to the method described by Skey and O'Reilly.[47] A phenoxyethyl moiety was introduced into DDMAT via esterification of the R group. This substituent provides a very convenient NMR label for the determination of number-average molecular weights via end-group analysis, as well as the extent of Michael addition. The ethyl proton signals due to the phenoxyethyl group at 3.8 and 4.0 ppm were shifted downfield to 4.2 and 4.8 ppm respectively due to ester formation. Esterification was stopped after 48 h at 77% conversion. After column chromatography, the purity of DDMPEAT was estimated to be more than 99% by ^{1}H NMR (see Figure 1).

The homopolymerization of NIPAM in 1,4-dioxane using 100:1:0.1 proportions for [NIPAM]:[DDMPEAT]:[ACVA] at 70 °C was well controlled. Polydispersities remained below 1.15 throughout the polymerization and the evolution of molecular weight with conversion was linear, see Figure 2. The slight deviation from the theoretical molecular weight line observed above 40% conversion arises from the use of PMMA standards for GPC calibration. After a short induction period of approximately 7 min the polymerization proceeded rapidly, with around 90% conversion being attained in 90 min. The rate of polymerization then slowed considerably, with no apparent adverse effect over the polydispersity.

A series of near-monodisperse PNIPAM homopolymer precursors (PNIPAM-CTA) with mean DPs ranging from 20 to 75 were synthesized in high yield and with good control. High end-group fidelity was maintained while minimizing monomer waste by using NIPAM/DDMPEAT molar ratios such that the desired DPs were attained at high conversion. More specifically, polymerizations were quenched at 88−94% conversion to minimize the possibility of termination by combination (see Table 2) and experimental DPs close to those targeted were obtained. Mean DPs were calculated using ^{1}H NMR (see Figure 1) by comparing the integrated aromatic protons due to the CTA end-group at 6.8−7.2 ppm to that of the pendent methine proton due to the NIPAM residues at 3.8 ppm. This analysis suggested a CTA efficiency of more than 90%. DMF GPC analysis confirmed excellent control over the RAFT polymerization of NIPAM. The M_n values obtained from GPC are in reasonably good agreement with the NMR analyses (see Supporting Information) and the final polydispersity of the PNIPAM chains remained below 1.10 (see Table 2).

The PNIPAM-CTA precursor is then converted into thiol-capped PNIPAM chains and nucleophilic Michael addition of the terminal thiol with the acrylate group on AHPMA affords the desired PNIPAM-MA macromonomer (see Scheme 1). In principle, these last two steps can be conducted separately or via a one-pot protocol. Conversion of the Z-groups of RAFT-synthesized polymers into thiols is well-documented and can be achieved by aminolysis,[18,48,49] hydrolysis[50] or the action of metal hydrides.[51] However, this transformation can be somewhat problematic. The formation of disulfide bonds by combination of two thiols via oxidative coupling can lead to bimodal molecular weight distributions and prevents subsequent reaction of the thiol. In addition, a recent study by Harrisson reported a radical-catalyzed side reaction between thiols and either trithiocarbonates or dithioesters which yields not only disulfides but also non-thiol-functionalized polymers.[52] Finally, Xu et al.[53] have reported that thiol-terminated poly(methyl methacrylate) chains obtained by aminolysis of the Z-group can irreversibly form thiolactones. This latter reaction proceeds via intramolecular backbiting of the thiol to the carbonyl carbon of the ester group on the penultimate monomer unit of the polymer chain. It is therefore only likely to occur with poly(meth)acrylates. This literature precedent suggests that it may be difficult to achieve quantitative conversion of Z-groups into free thiols. Thus, the best method to isolate thiol-terminated polymers is to conduct the aminolysis in the presence of a reducing agent such as sodium dithionite[54] or a phosphine.[39,55] In the present study dimethylphenyl phosphine was used to obtain thiol-capped PNIPAM. Nevertheless, the GPC trace shown in Figure 3 suggests the presence of a small amount of disulfide-containing species. When the thiol-capped polymer is not the desired final product but merely a reaction intermediate, it may be advantageous to conduct the reactions using a one-pot protocol without isolating the intermediate thiol species. Indeed, the Michael addition proceeds at such a high rate[56] that the known thiol side reactions may be suppressed. This approach has been investigated previously. Qiu and Winnik[46] reported the one-pot synthesis of thioethers starting from telechelic PNIPAM precursors prepared by RAFT polymerization. In this study, an efficient synthetic methodology was established and the order of reactivity for electron-deficient olefins in thia-Michael addition was confirmed as: acrylate ≫ methacrylate > acrylamide > methacrylamide. Boyer et al.[18] used a very similar approach to prepare a range of ω-functional polymers, including macromonomers from dimethacrylates and diacrylates. Herein we adapted this one-pot protocol for the synthesis of macromonomers in high yields with a significant reduction in the quantity of excess divinyl reagent required to produce well-defined macromonomers. 3-(Acryloyloxy)-2-hydroxypropyl methacrylate (AHPMA) is an asymmetric diene containing both an acrylate

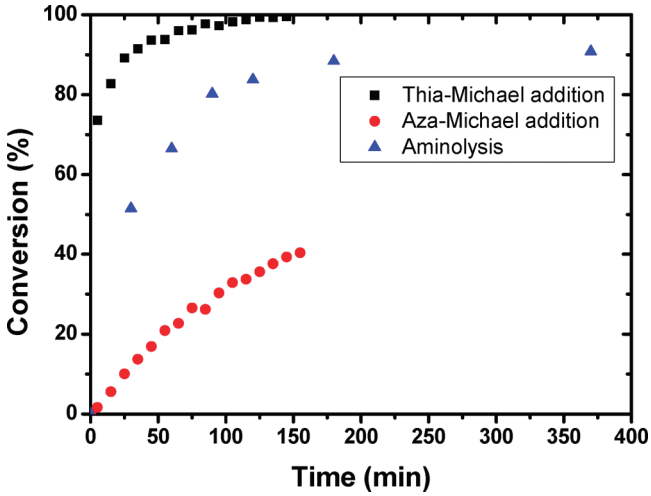


Figure 3. Kinetic plots for the aminolysis of PNIPAM$_{65}$-CTA, and the Michael additions of *n*-dodecylthiol and *n*-hexylamine to AHPMA in DMF at 20 °C.Reactions conditions: Aminolysis: [PNIPAM$_{65}$-CTA]:-[AHPMA]:[*n*-hexylamine]:[TEA] = 1:3:3:1, [PNIPAM$_{65}$-CTA]$_0$ = 5.12 mmol L^{-1} in DMF. Thia-Michael addition: [*n*-dodecylthiol]:-[AHPMA]:[TEA] = 3:3:1, [*n*-dodecylthiol]$_0$ = 0.1 mol L^{-1} in DMF-d_7. Aza-Michael addition: [*n*-hexylamine]:[AHPMA]:[TEA] = 3:3:1, [*n*-hexylamine]$_0$ = 0.1 mol L^{-1} in DMF-d_7.

Table 1. Summary of Data Obtained for One-Pot Aminolysis-Michael Addition of a PNIPAM$_{65}$-CTA Precursor (DP = 65, M_n = 7800 g/mol, M_w/M_n = 1.07) at 20 °C for 15 h[a]

entry no.	PNIPAM$_{65}$-CTA	AHPMA	amine	TEA	aminolysis/%	conversion/%
1	1.0	1.5	2.5	1.0	100	90
2	1.0	3.0	1.0	1.0	62	55
3	1.0	3.0	2.0	1.0	98	75
4	1.0	3.0	3.0	1.0	100	>95
5	1.0	3.0	4.0	1.0	100	>95
6	1.0	10.0	7.5	7.5	100	>95
7	1.0	3.0	2.0	0	97	73
8	1.0	3.0	3.0	0	100	84

[a] The PNIPAM$_{65}$-CTA, AHPMA, *n*-hexylamine, and TEA columns indicate the respective molar equivalents of these reagents relative to the PNIPAM$_{65}$-CTA precursor, the conversion and aminolysis columns refer to the yield of the thia-Michael addition product and the extent of the aminolysis respectively.

and a methacrylate moiety; this reagent was chosen to investigate the selectivity of the thia-Michael addition. *n*-Hexylamine was used rather than shorter, more volatile primary amines so as to minimize loss of reactant during nitrogen purging; this reagent is known to efficiently convert trithiocarbonates into thiols.[18] DMF was chosen as the reaction medium because thia-Michael addition proceeds faster in polar solvents that are able to stabilize thiolate anions. The catalytic role of triethylamine mentioned by Boyer et al. was also investigated.

Table 1 summarizes the experimental data obtained for our optimization of the macromonomer synthesis. All experiments were carried out using a near-monodisperse (M_w/M_n = 1.07) PNIPAM precursor of 7800 g mol^{-1} for a fixed reaction time of 15 h. Whether a large or small stoichiometric excess of AHPMA was used (see entries 1 and 8), no addition of thiol to methacrylate was observed. These results confirm those of both Winnik's group[46] and Prestwich et al.[57] and suggest a much faster rate of addition of thiols to acrylates than to methacrylates; according to Davis and co-workers, the reaction with methacrylates usually requires heating.[58] Under ideal conditions (i.e., in the absence of any side reactions), the theoretical molar ratios for aminolysis and the subsequent thia-Michael addition to acrylate should be [$PNIPAM_{65}$-CTA]:[AHPMA]:[*n*-hexylamine] = 1:1:2. Complete aminolysis of a polymer prepared using a trithiocarbonate-based CTA yields a thiourea and two thiol species (a small molecule thiol and a polymeric thiol). In the case of a one-pot synthesis, the possibility of aza-Michael addition must be considered in addition to the various side reactions discussed earlier. Indeed, the efficiency of this one-pot synthesis is very sensitive to the amount of *n*-hexylamine employed (see entries 1 to 5 in Table 1). When the *n*-hexylamine/trithiocarbonate molar ratio is below 3.0, the overall yield of the thia-Michael addition product is significantly reduced. This is presumably because aza-Michael addition competes with aminolysis of the trithiocarbonate end-groups. In order to assess the extent of influence of the aza-Michael addition, the kinetics of each of the three main reactions taking place during the macromonomer synthesis were investigated. Figure 3 shows the conversion vs time plots obtained for the aza- and thia-Michael additions and also for the aminolysis of the trithiocarbonate-capped PNIPAM chains. Aminolysis and thia Michael addition are both much faster than the addition of *n*-hexylamine to AHPMA. For example, addition of *n*-dodecylthiol to AHPMA reaches 90% conversion within 25 min and 80% of the trithiocarbonate is converted into thiol within 90 min at 20 °C. In contrast, addition of *n*-hexylamine to acrylate only proceeds to about 30% conversion after 90 min. Moreover, the thiol formed via aminolysis of the PNIPAM-CTA is likely to be even more reactive than *n*-dodecylthiol, since Lowe et al.[56] recently reported that *n*-alkanethiols were much less reactive toward acrylates than thioglycolates. Overall, our results suggest that the primary amine reacts preferentially with the trithiocarbonate moieties, rather than with the acrylate. Moreover, competition between the intermediate thiol and the remaining excess amine for Michael addition across the acrylic double bond strongly favors the thiol. Furthermore, Haddleton et al. recently demonstrated that primary amines can also behave as a nucleophilic catalyst for thia-Michael addition.[59] In summary, aza-Michael addition should only have minimal impact on the macromonomer synthesis under the stated synthetic conditions.

Despite insufficient AHPMA to react with the secondary macromolecular thiol and tertiary thiol formed by aminolysis of the trithiocarbonate, a yield of 90% is obtained for entry 1 in Table 1. This is due to the significantly higher reactivity of secondary thiols compared to tertiary thiols.[60] Triethylamine appears to be a mild catalyst for the thia-Michael addition. When two equivalents of *n*-hexylamine was used (see entries 3 and 7, Table 1) very similar yields were obtained. When using three equivalents of *n*-hexylamine, a modest increase in yield is observed in the presence of TEA (see entries 4 and 8, Table 1). These observations are consistent with a recent study by Lowe et al., which suggests that TEA has very little effect on the kinetics of thia-Michael addition.[56] In our case, the optimum reaction stoichiometry for the one-pot "aminolysis plus thia-Michael addition" synthesis appears to be [PNIPAM-CTA]:[AHPMA]:[*n*-hexylamine]:[TEA] = 1:3:4:1 (entry 5, Table 1). These conditions were used for all the macromonomers synthesized in this study. Compared to the previous one-pot route reported by Boyer et al.,[18] who synthesized closely related (meth)acrylate-functionalized PNIPAM-macromonomers using a ten-fold excess of either diacrylates or dimethacrylates, our method is rather more atom-efficient. This is because using an acrylate-methacrylate adduct (AHPMA) allows a significantly smaller excess of the unsaturated substrate, since coupling of two PNIPAM chains is strongly disfavored. Indeed, given the much higher reactivity of acrylates compared to methacrylates toward thia-Michael addition, such unwanted side-products were not observed even when using a relatively modest excess of AHPMA (see Figure 4).

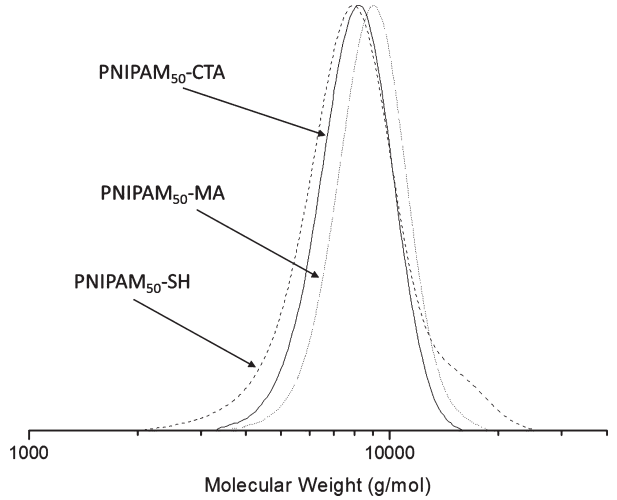


Figure 4. DMF GPC curves recorded for $PNIPAM_{50}$-MA macromonomer and the corresponding $PNIPAM_{50}$-CTA and $PNIPAM_{50}$-SH precursors. Note the weak shoulder observed at higher molecular weight in the $PNIPAM_{50}$-SH chromatogram, which is attributed to the formation of a disulfide species.

This one-pot "aminolysis plus thia-Michael addition" route was used to prepare a series of six well-defined PNIPAM-MA macromonomers (see Table 2). The mean degrees of polymerization and end-group fidelities were calculated by ^{1}H NMR spectroscopy (see Figure 1) in CD_3OD/D_2O mixtures and their molecular weight distributions were characterized by DMF GPC (see Figures 4 and 6). The degree of aminolysis was readily assessed (albeit qualitatively) by the disappearance of the characteristic yellow color originating from the trithiocarbonate end-groups. Complete loss of the characteristic maximum absorption due to trithiocarbonate end-groups at λ = 313 nm was observed by UV spectroscopy, which indicated that very high levels of aminolysis were achieved (Figure 5). ^{1}H NMR studies of the

Table 2. Summary of Monomer Conversions, Molecular Weights, Polydispersities, and Extents of Chain-End Functionalization for the Six PNIPAM-MA Macromonomers and Two Corresponding PNIPAM-Based Precursors Prepared in This Study

sample	target DP	DP[a]	conv. (%)[a]	initiator efficiency (%)	M_n (g/mol)[a]	M_w/M_n[b]	extent of Michael addition (%)
$PNIPAM_{50}$-CTA	54	51	93	99	6200	1.05	n.a.
$PNIPAM_{50}$-SH	54	51	93	99	6200	1.05	n.a.
$PNIPAM_{20}$-MA	23	21	91	99	2900	1.08	>95
$PNIPAM_{30}$-MA	33	33	93	93	4200	1.06	>95
$PNIPAM_{40}$-MA	44	38	90	96	5000	1.06	>95
$PNIPAM_{50}$-MA	54	51	93	99	6200	1.05	>90
$PNIPAM_{60}$-MA	65	63	88	91	7600	1.06	>90
$PNIPAM_{75}$-MA	75	75	94	94	9000	1.08	>90

[a] Calculated by ^{1}H NMR. [b] Measured by DMF GPC.

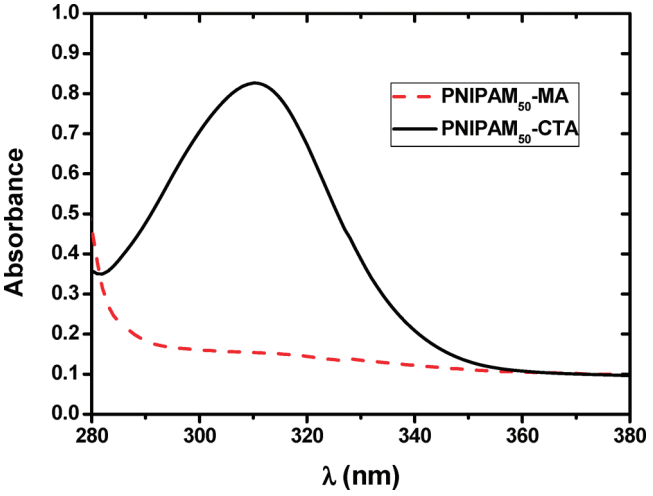


Figure 5. UV absorption spectra recorded in 1,4-dioxane for the $PNIPAM_{50}$-CTA precursor (0.33 g/L) and the corresponding $PNIPAM_{50}$-MA macromonomer (1.0 g/L).

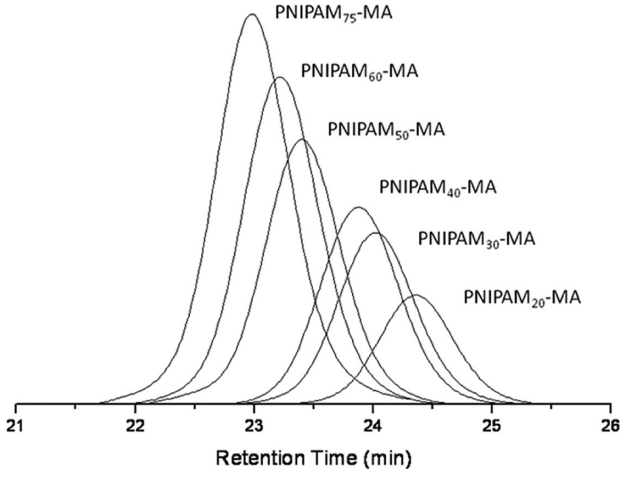


Figure 6. DMF GPC curves for the six PNIPAM-MA macromonomers (see Table 2) labeled according to their respective mean degree of polymerizations as determined by ^{1}H NMR spectroscopy.

purified macromonomers isolated after dialysis (see Figure 1) confirm the appearance of characteristic methacrylic vinyl peaks at 5.6 and 6.0 ppm, suggesting successful aminolysis and subsequent Michael addition of AHPMA. The extent of Michael addition was determined by comparing the integrated phenyl end-group signals at 6.9 and 7.3 ppm to that of the terminal methacrylate protons at 5.6 and 6.0 ppm (see Table 2).

PNIPAM-PS Latexes. Most previous studies dealt with the use of PNIPAM as a steric stabilizer to prepare aqueous latexes at close to ambient temperature, i.e., below its LCST. However, methanol was chosen as the polymerization medium in this study. Since PNIPAM does not exhibit LCST behavior in pure methanol, the dispersion polymerization of styrene can be conducted at 70 °C without compromising the latex stability. The PNIPAM-MA macromonomers were investigated as potential reactive steric stabilizers for the synthesis of model polystyrene latexes prepared by dispersion polymerization in methanol at 70 °C (see Table 3). One reviewer suggested that more well-defined particles might have been obtained by preparing latexes in water at a temperature below the LCST of PNIPAM. This may be true, but we are particularly interested in developing alcoholic dispersion polymerization formulations in our research group. Styrene does not dissolve in water, hence our choice of methanol to fulfill the criterion for a dispersion polymerization

Three control experiments were conducted to demonstrate that the presence of vinyl-functionalized macromonomer is essential for the formation of well-defined sterically stabilized latex. When the dispersion polymerization of styrene was conducted in the absence of any stabilizer (data not shown), only macroscopic precipitation occurred, as expected.[3a] In a second control experiment (see entry 1 in Table 3), the styrene polymerization was conducted using the $PNIPAM_{50}$-CTA precursor as a stabilizer. In this case, a colloidally stable latex was formed. However, SEM studies confirmed that this latex had a broad particle size distribution (see Figure 7a). In this case, AIBN initiator was utilized in a four-fold excess compared to the PNIPAM macro-CTA. Thus, it is reasonable to assume that the majority of the styrene was polymerized via conventional free radical polymerization under these conditions, rather than under RAFT control (since RAFT syntheses are normally conducted at CTA/initiator molar ratios of 5 to 10). Nevertheless, some background RAFT polymerization may partly account for the highly polydisperse particles observed by SEM. Moreover, growth of a polystyrene block from a polyacrylamide-based macro-CTA agent has been reported to be relatively inefficient, leading to incomplete chain extension and a bimodal molecular weight distribution.[61] Such a poor blocking efficiency may also explain the broad latex size distribution

Table 3. Summary of the Effect of Varying the DP and Concentration of the Macromonomer Stabilizer on the Mean Latex Particle Diameter, Polydispersity, Styrene Conversion, Stabilizer Grafting Density, Stabilizer Content, and Stabilizer Surface Coverage

no.	stabilizer	stabilizer (wt %)	d (PDI) (nm)[a]	d (nm)[b]	monomer conv. (%)[c]	Γ (chains/nm^2)[c]	Γ (mg/m^2)[c]	stabilizer content (wt %)[c]	stabilizer surface coverage (%)[d]
1	PNIPAM$_{50}$-CTA	10	70 (0.13)	bimodal[e]	93	-	-	-	-
2	PNIPAM$_{50}$-SH	10	410 (0.18)	[f]	93	-	-	-	43
3	PNIPAM$_{40}$-MA	10	340 (0.03)	480	88	0.04	0.34	4.0	46
4	PNIPAM$_{50}$-MA	10	680 (0.03)	570	93	0.03	0.31	3.1	40
5	PNIPAM$_{50}$-MA	20	510 (0.22)	390	82	0.03	0.33	4.8	62
6	PNIPAM$_{50}$-MA	30	320 (0.15)	290	86	0.03	0.27	5.3	75
7	PNIPAM$_{60}$-MA	10	780 (0.06)	730	87	0.04	0.55	4.3	66
8	PNIPAM$_{75}$-MA	10	830 (0.09)	780	91	0.02	0.37	2.7	67

[a] As determined by DLS. [b] As determined by SEM. [c] As determined by ^{1}H NMR. [d] As determined by XPS. [e] Mean diameter range: 500−1800 nm and 50−250 nm. [f] Mean diameter range: 250−1000 nm.

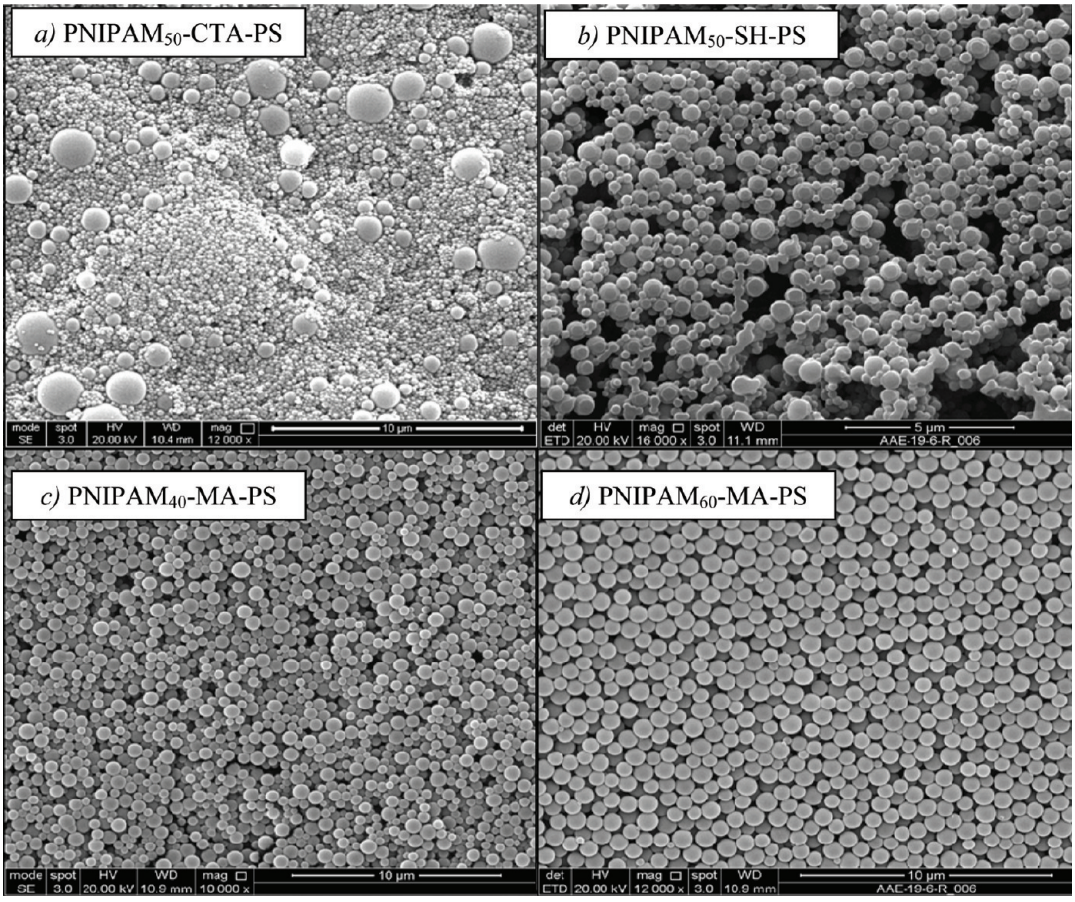


Figure 7. SEM images of sterically stabilized polystyrene latexes prepared by alcoholic dispersion polymerization in methanol at 70 °C with the following stabilizers: (a) PNIPAM$_{50}$-CTA precursor; (b) PNIPAM$_{50}$-SH intermediate; (c) PNIPAM$_{40}$-MA macromonomer; (d) PNIPAM$_{60}$-MA macromonomer. In each case, the stabilizer concentration was 10% based on styrene monomer.

observed in the present study. In a third control experiment, PNIPAM$_{50}$-SH was assessed as a potential steric stabilizer since thiols are well-known to be very effective chain transfer agents and thiol-terminated PEO has been successfully used to prepare polystyrene latex using an alcoholic dispersion polymerization formulation.[62] Latex particles were indeed obtained using the PNIPAM$_{50}$-SH stabilizer, but SEM studies again revealed a broad size distribution and also some evidence of interparticle fusion (see Figure 7b). In contrast, the PNIPAM-MA macromonomers proved to be much more effective steric stabilizers. In all cases, the styrene polymerization proceeded to very high conversion within 24 h at 70 °C without any observable formation of coagulum. Macromonomers with mean DPs ranging from 40 to 75 gave colloidally stable latex particles, as judged by both visual inspection and DLS. SEM studies confirmed a near-monodisperse spherical morphology, with mean number-average

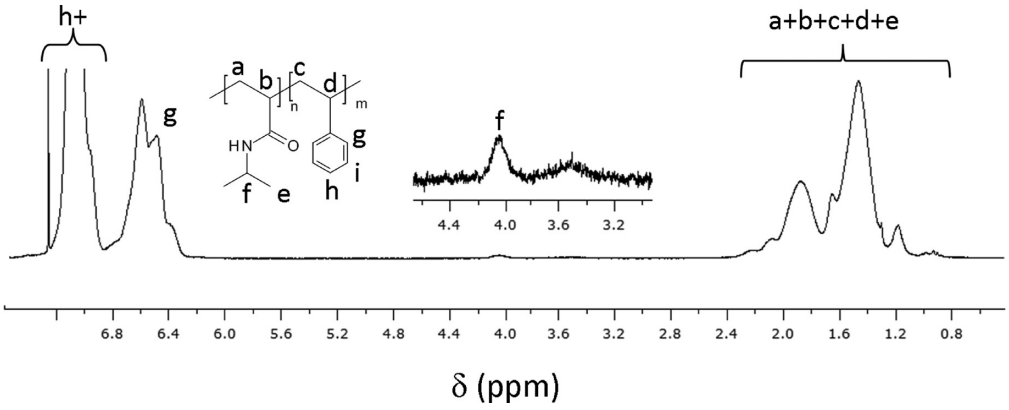


Figure 8. ^{1}H NMR spectrum recorded for a PNIPAM$_{60}$-MA-stabilized polystyrene latex dissolved in $CDCl_3$. Signal f at 4.1 ppm is assigned to the methine proton of the NIPAM residues in the stabilizer chains. Note: the weak signal at 3.5 ppm in this inset is due to CH_3OH.

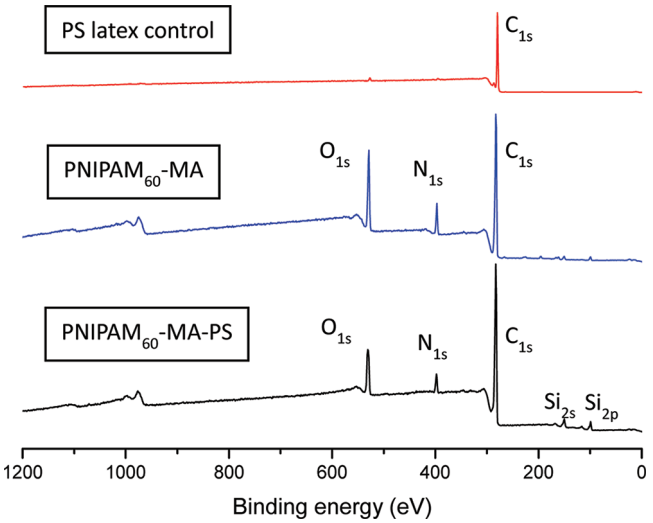


Figure 9. X-ray photoelectron spectra recorded for a PNIPAM$_{60}$-MA-stabilized polystyrene latex (see entry 7 in Table 3). The original PNIPAM$_{60}$-MA macromonomer and a charge-stabilized polystyrene latex were used as reference materials.

diameters ranging from 290 to 780 nm depending on the macromonomer chain length and concentration used in the formulation (see Figure 7, parts c and d). Because of polydispersity effects, DLS reported intensity-average diameters of 320 to 830 nm for the same latexes (see Table 3). The stabilizer content for each latex was calculated using ^{1}H NMR. Unfortunately the PNIPAM-MA signal due to the methine protons at 4.05 ppm was too weak for reliable quantitative analysis. Thus, the integrated signal for the two aromatic styrene protons at 6.25 to 6.90 ppm was compared to that corresponding to the two methylene protons in the polystyrene and PNIPAM backbone at 0.8 to 2.4 ppm and also that of the six methyl protons due to the pendent isopropyl group on the NIPAM residues (see Figure 8). These stabilizer contents were then used, together with the mean SEM diameters, to estimate the adsorbed amount of stabilizer (Γ, in mg m^{-2}) for each latex. These data are summarized in Table 3.

The mean latex diameter is reduced on increasing the macromonomer concentration, as expected (compare entries 4−6 in Table 3). Higher latex stabilizer contents are obtained on increasing the macromonomer concentration used in the formulation, while the adsorbed amount of PNIPAM chains remained approximately constant at around 0.3 mg m^{-2}. These observations are similar to previously reported findings for the alcoholic dispersion polymerization of styrene using hydrophilic macromonomer stabilizers. According to the literature, the higher stabilizer concentration allows a greater latex surface area to be accommodated, which accounts for the observed reduction in particle size.[10,62−64] It is noteworthy that PNIPAM macromonomers of DP = 20 or 30 (and, to a lesser extent, DP = 40) led to colloidally stable latex particles, but with relatively broad size distributions. For macromonomers of DP = 50 or higher, the particle size distribution becomes much narrower (see Figure 7). Increasing the DP of the macromonomer stabilizer at a fixed concentration of 10 wt % (based on styrene) tended to produce an increase in the mean latex diameter (compare entries 3, 4, 7 and 8, see Table 3). Presumably, this is due to the reduced number of stabilizer chains available for latex stabilization.

In order to further confirm that the PNIPAM chains are indeed located at the latex surface, we used X-ray photoelectron spectroscopy (XPS).[65] With a typical sampling depth of 2 to 10 nm, XPS is a powerful technique for the interrogation of surfaces. This technique has been previously used extensively by us,[3b,66] and also by others,[67] to investigate the surface of various colloidal particles, including latexes. A typical X-ray photoelectron survey spectrum obtained for polystyrene latex particles prepared using a PNIPAM$_{60}$-MA stabilizer is shown in Figure 9. Characteristic signals for N 1s, O 1s, C 1s, and Si 2s/Si 2p confirm the presence of these elements at the (near-)surface of the latex. The oxygen and nitrogen signals confirm the presence of PNIPAM stabilizer chains on the particle surface. The silicon signals suggest some small degree of contamination, possibly by silicone-based pump oil or from the underlying silicon wafer onto which the latex sample was deposited. This contamination could also explain why the N_{1s}/O_{1s} signal ratio is less than unity but stays constant at around 0.5 for all latexes (and also the PNIPAM$_{60}$-MA macromonomer). Comparing the relative intensities of the N_{1s} signal due to the macromonomer alone and the PNIPAM$_{60}$-MA-stabilized latex allows the surface coverage of the latex by the stabilizer chains to be estimated. This stabilizer surface coverage increases when higher macromonomer concentrations and molecular weights are utilized in the latex syntheses, as expected (see Table 3).

Finally, the thermo-responsive behavior of a 1.0% aqueous dispersion of a PNIPAM$_{50}$-MA-stabilized polystyrene latex

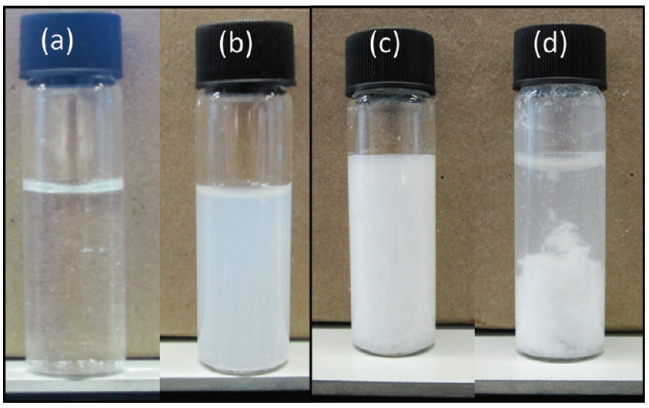


Figure 10. Visual appearance of (a) 1.0 wt % aqueous solution of $PNIPAM_{50}$-MA macromonomer at 20 °C and (b) the same solution heated up to 50 °C and a 1.0 wt % aqueous dispersion of $PNIPAM_{50}$-MA-stabilized polystyrene latex at (c) 20 and (d) 50 °C, respectively.

(see entry 7 in Table 3) and also a dilute aqueous solution of the corresponding $PNIPAM_{50}$-MA macromonomer was briefly investigated over the temperature range from 20 to 50 °C (see Figure 10). The macromonomer was water-soluble at 20 °C but precipitated at 50 °C, since the latter temperature is well above its characteristic LCST of 32 °C and hence leads to the well-known coil-to-globule transition.[17a] Similarly, the latex particles are colloidally stable at 20 °C, but become flocculated at 50 °C due to collapse of the chemically grafted PNIPAM chains on the latex surface. Visual inspection of a magnetically stirred aqueous latex dispersion gradually heated up with the aid of an oil bath confirmed that colloidal aggregation actually commences at around 35 °C, which is close to the LCST for linear PNIPAM chains. This thermally induced colloidal aggregation proved to be fully reversible, since the sedimented aggregates redispersed completely at 20 °C.

CONCLUSIONS

A series of well-defined near-monodisperse methacrylate-capped PNIPAM macromonomers were successfully synthesized using RAFT polymerization of NIPAM, followed by a combination of aminolysis and thia-Michael addition for the chain-end modification. A convenient one-pot protocol was established to optimize the macromonomer yield and minimize side reactions. The choice of 3-(acryloyloxy)-2-hydroxypropyl methacrylate (AHPMA) as an acrylate/methacrylate substrate for the thia-Michael addition allows a more atom-efficient route to well-defined methacrylate-capped macromonomers than previously reported synthetic routes. This approach relies on the well-known higher reactivity of acrylates toward thiols compared to methacrylates, as well as the relatively fast kinetics of trithiocarbonate aminolysis by primary amines compared to the rate of aza-Michael addition to acrylates (or methacrylates). Thus, highly selective chemistry was essential to the success of this efficient one-pot protocol for the synthesis of PNIPAM-based macromonomers. These macromonomers were then evaluated as reactive steric stabilizers in the alcoholic dispersion polymerization of styrene at 70 °C. Macromonomers with mean degrees of polymerization of 20 to 40 resulted in the formation of relatively polydisperse latex particles, but latexes were obtained with relatively narrow size distributions when using macromonomers with degrees of polymerization of 50, 60, or 75. XPS studies provided good evidence that the PNIPAM stabilizer chains were located at the latex surface, as expected. All latexes were colloidally stable as aqueous dispersions at 20 °C, with macroscopic aggregation being observed on heating above 35 °C. This transition proved to be reversible. Hence the well-known LCST behavior of the PNIPAM chains dictates the colloidal stability of these model thermo-responsive sterically stabilized latexes.

ASSOCIATED CONTENT

Supporting Information. Approximate linear relationship between the NMR-derived molecular weight and GPC molecular weight for various PNIPAM precursors. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Boutevin, B.; David, G.; Boyer, C. *Adv. Polym. Sci.* **2007**, *206*, 31–135.

(2) (a) Amalvy, J. I.; Wanless, E. J.; Li, Y.; Michailidou, V.; Armes, S. P.; Duccini, Y. *Langmuir* **2004**, *20*, 8992–8999. (b) Amalvy, J. I.; Unali, G. F.; Li, Y.; Granger-Bevan, S.; Armes, S. P.; Binks, B. P.; Rodrigues, J. A.; Whitby, C. P. *Langmuir* **2004**, *20*, 4345–4354. (c) Houillot, L.; Nicolas, J.; Save, M.; Charleux, B.; Li, Y. T.; Armes, S. P. *Langmuir* **2005**, *21*, 6726–6733.

(3) (a) Thompson, K. L.; Bannister, I.; Armes, S. P.; Lewis, A. L. *Langmuir* **2010**, *26*, 4693–4702. (b) Thompson, K. L.; Armes, S. P.; York, D. W.; Burdis, J. A. *Macromolecules* **2010**, *43*, 2169–2177.

(4) Cai, Y. L.; Hartenstein, M.; Müller, A. H. E. *Macromolecules* **2004**, *37*, 7484–7490.

(5) Chalari, I.; Hadjichristidis, N. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 1519–1527.

(6) (a) Ito, K.; Tomi, Y.; Kawaguchi, S. *Macromolecules* **1992**, *25*, 1534–1538. (b) Pantazis, D.; Chalari, I.; Hadjichristidis, N. *Macromolecules* **2003**, *36*, 3783–3785. (c) Koutalas, G.; Iatrou, H.; Lohse, D. J.; Hadjichristidis, N. J. *Macromolecules* **2005**, *38*, 4996–5001.

(7) Haddleton, D. M.; Depaquis, E.; Kelly, E. J.; Kukulj, D.; Morsley, S. R.; Bon, S. A. F.; Eason, M. D.; Steward, A. G. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 2378–2384.

(8) Soeriyadi, A. H.; Boyer, C.; Burns, J.; Becer, C. R.; Whittaker, M. R.; Haddleton, D. M.; Davis, T. P. *Chem. Commun.* **2010**, *46*, 6338–6340.

(9) Gridnev, A. A.; Ittel, S. D. *Chem. Rev.* **2001**, *101*, 3611–3659.

(10) Lascelles, S. F.; Malet, F.; Mayada, R.; Billingham, N. C.; Armes, S. P. *Macromolecules* **1999**, *32*, 2462–2472.

(11) Nagasaki, Y.; Sato, Y.; Kato, M. *Macromol. Rapid Commun.* **1997**, *18*, 827–835.

(12) Bernaerts, K. V.; Fustin, C.-A.; Bomal-D'Haese, C.; Gohy, J.-F.; Martins, J. C.; Du Prez, F. E. *Macromolecules* **2008**, *41*, 2593–2606.

(13) (a) Wang, X.-S.; Lascelles, S. F.; Jackson, R. A.; Armes, S. P. *Chem.Commun.* **1999**, 1817–1818. (b) Shen, Y. Q.; Zhu, S. P.; Zeng, F. Q.; Pelton, R. *Macromolecules* **2000**, *33*, 5399–5404. (c) Zeng, F.; Shen, Y. Q.; Zhu, S.; Pelton, R. *Macromolecules* **2000**, *33*, 1628–1635.

(d) Matyjaszewski, K.; Beers, K. L.; Kern, A.; Gaynor, S. G. *J. Polym. Sci., Part A: Polym. Chem.* **1998**, *36*, 823–830.
(14) (a) Schön, F.; Hartenstein, M.; Müller, A. H. E. *Macromolecules* **2001**, *34*, 5394–5397. (b) Ishizu, K.; Tahara, N. *Polymer* **1996**, *37*, 2853–2856. (c) Ishizu, K.; Yamashita, M.; Ichimura, A. *Polymer* **1997**, *38*, 5471–5474. (d) Ishizu, K.; Yamashita, M.; Ichimura, A. *Macromol. Rapid Commun.* **1997**, *18*, 639–642. (e) Uchida, T.; Furuzono, T.; Ishihara, K. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 3052–3058. (f) Bon, S. A. F.; Morsley, S. R.; Waterson, C.; Haddleton, D. M. *Macromolecules* **2000**, *33*, 5819–5824.
(15) (a) Vogt, A. P.; Sumerlin, B. S. *Macromolecules* **2006**, *39*, 5286–5292. (b) Topham, P. D.; Sandon, N.; Read, E. S.; Madsen, J.; Ryan, A. J.; Armes, S. P. *Macromolecules* **2008**, *41*, 9542–9547.
(16) (a) Muehlebach, A.; Rime, F. *J. Polym. Sci., Part A: Polym. Chem.* **2003**, *41*, 3425–3439. (b) Liu, Q.; Chen, Y. M. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 6103–6113. (c) Pioge, S.; Fontaine, L.; Soutif, J.-C.; Nicol, E.; Pascual, S. *J. Polym. Sci., Part A: Polym. Chem.* **2010**, *48*, 1526–1537.
(17) Boyer, C.; Stenzel, M. H.; Davis, T. P. *J. Polym. Sci., Part A: Polym. Chem.* **2011**, *49*, 551–595.
(18) Boyer, C.; Granville, A.; Davis, T. P.; Bulmus, V. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47*, 3773–3794.
(19) (a) Heskins, M.; Guillet, J. M. *Macromol. Sci. Chem.* **1968**, *A2*, 1441–1455. (b) Schild, H. G. *Prog. Polym. Sci.* **1992**, *17*, 163–249.
(20) (a) Xia, Y.; Burke, N. A. D.; Stöver, H. D. H. *Macromolecules* **2006**, *39*, 2275–2283. (b) Xia, Y.; Yin, X.; Burke, N. A. D.; Stöver, H. D. H. *Macromolecules* **2005**, *38*, 5937–5943.
(21) Boyer, C.; Bulmus, V.; Liu, J.; Davis, T. P.; Stenzel, M. H.; Barner-Kowollik, C. *J. Am. Chem. Soc.* **2007**, *129*, 7145–7154.
(22) Qiu, X.-P.; Winnik, F. M. *Macromol. Symp.* **2009**, *278*, 10–13.
(23) Li, Z.; Kim, Y.-H.; Min, H. S.; Han, C.-K.; Huh, K. M. *Macromol. Res.* **2010**, *18*, 618–621.
(24) Bosman, A. W.; Vestberg, R.; Heumann, A.; Fréchet, J. M. J.; Hawker, C. J. *J. Am. Chem. Soc.* **2003**, *125*, 715–728.
(25) (a) Teodorescu, M.; Matyjaszewski, K. *Macromolecules* **1999**, *32*, 4826–4831. (b) Rademacher, J. T.; Baum, M.; Pallack, M. E.; Brittain, W. J.; Simonsick, W. J. *Macromolecules* **2000**, *33*, 284–288.
(26) (a) Bontempo, D.; Maynard, H. D. *J. Am. Chem. Soc.* **2005**, *127*, 6508–6509. (b) Masci, G.; Giacomelli, L.; Crescenzi, V. *Macromol. Rapid Commun.* **2004**, *25*, 559–564.
(27) Li, C.; Madsen, J.; Armes, S.-P.; Lewis, A. *Angew. Chem., Int. Ed.* **2006**, *45*, 3510–3513.
(28) (a) Ganachaud, F.; Monteiro, M. J.; Gilbert, R. G.; Dourges, M.; Thang, S. H.; Rizzardo, E. *Macromolecules* **2000**, *33*, 6738–6745. (b) Schilli, C.; Lanzendörfer, M. G.; Müller, A. H. E. *Macromolecules* **2002**, *35*, 6819–6827. (c) Ray, B.; Isobe, Y.; Matsumoto, K.; Habaue, S.; Okamoto, Y.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2004**, *37*, 1702–1710. (d) Convertine, A. J.; Ayres, N.; Scales, C. W.; Lowe, A. B.; McCormick, C. L. *Biomacromolecules* **2004**, *5*, 1177–1180.
(29) (a) Kanazawa, H.; Yamamoto, K.; Matsushima, Y.; Kikuchi, A.; Sakurai, Y.; Okano, T. *Anal. Chem.* **1996**, *68*, 100–105. (b) Yakushiji, T.; Sakai, K.; Kikuchi, A.; Aoyagi, T.; Sakurai, Y.; Okano, T. *Anal. Chem.* **1999**, *71*, 1125–1130.
(30) Park, Y. S.; Ito, Y.; Imanishi, Y. *Langmuir* **1998**, *14*, 910–914.
(31) (a) Chen, J. H.; Yoshida, M.; Maekawa, Y.; Tsubokawa, N. *Polymer* **2001**, *42*, 9361–9365. (b) Yoshioka, H.; Mikami, M.; Nakai, T.; Mori, Y. *Polym. Adv. Technol.* **1995**, *6*, 418–420.
(32) (a) Yamato, M.; Konno, C.; Utsumi, M.; Kikuchi, A.; Okano, T. *Biomaterials* **2002**, *23*, 561–567. (b) Kim, D. J.; Heo, J.; Kim, K. S.; Choi, I. S. *Macromol. Rapid Commun.* **2003**, *24*, 517–521. (c) Akiyama, Y.; Kikuchi, A.; Yamato, M.; Okano, T. *Langmuir* **2004**, *20*, 5506–5511.
(33) Cunliffe, D.; Alarcon, C. D.; Peters, V.; Smith, J. R.; Alexander, C. *Langmuir* **2003**, *19*, 2888–2899.
(34) Duracher, D.; Elaissari, A.; Mallet, F.; Pichot, C. *Langmuir* **2000**, *16*, 9002–9008.
(35) Ionov, L.; Stamm, M.; Diez, S. *Nano Lett.* **2006**, *9*, 1982–1987.
(36) (a) Nagase, K.; Kobayashi, J.; Kikuchi, A.; Akiyama, Y.; Kanazawa, H.; Okano, T. *Biomacromolecules* **2008**, *9*, 1340–1347. (b) Nagase, K.; Kobayashi, J.; Kikuchi, A.; Akiyama, Y.; Kanazawa, H.; Annaka, M.; Okano, T. *Biomacromolecules* **2010**, *11*, 215–223.
(37) Gan, T.; Zhang, Y.; Guan, Y. *Biomacromolecules* **2009**, *10*, 1410–1415.
(38) Pelton, R. H.; Chibante, P. *Colloids Surf.* **1986**, *20*, 247–256.
(39) Pelton, R. H. *J. Polym. Sci., Part A: Polym. Chem.* **1988**, *26*, 9–18.
(40) (a) Hoshino, F.; Fujimoto, T.; Kawaguchi, H.; Ohtsuka, Y. *Polym. J.* **1987**, *19*, 241–247. (b) Hoshino, F.; Kawaguchi, H.; Ohtsuka, Y. *Polym. J.* **1987**, *19*, 1157–1164. (c) Kawaguchi, H.; Hoshino, F.; Ohtsuka, Y. *Makromol. Chem. Rapid. Commun.* **1986**, *7*, 109–114.
(41) (a) Duracher, D.; Sauzedde, F.; Elaissari, A.; Perrin, A.; Pichot, C. *Colloid Polym. Sci.* **1998**, *276*, 219–231. (b) Duracher, D.; Sauzedde, F.; Elaissari, A.; Perrin, A.; Pichot, C.; Nabzar, L. *Colloid Polym. Sci.* **1998**, *276*, 920–929.
(42) Nabzar, L.; Duracher, D.; Elaissari, A.; Perrin, A.; Chauveteau, G.; Pichot, C. *Langmuir* **1998**, *14*, 5062–5069.
(43) Taniguchi, T.; Duracher, D.; Delair, T.; Elaissari, A.; Pichot, C. *Colloids Surf. B: Biointerfaces* **2003**, *29*, 53–65.
(44) (a) Kim, J. H.; Ballauff, M. *Colloid Polym. Sci.* **1998**, *277*, 1210–1214. (b) Dingenouts, N.; Seelenmeyer, S.; Deike, I.; Rosenfeldt, S.; Ballauff, M.; Lindner, P.; Narayanan, T. *Phys. Chem. Chem. Phys.* **2001**, *3*, 1169–1174. (c) Seelenmeyer, S.; Deike, I.; Rosenfeldt, S.; Norhausen, C. H.; Dingenouts, N.; Ballauff, M.; Narayanan, T.; Lindner, P. *J. Chem. Phys.* **2001**, *114*, 10471–10478. (d) Senff, H.; Richtering, W.; Norhausen, C. H.; Weiss, A.; Ballauff, M. *Langmuir* **1999**, *15*, 102–106. (e) Dingenouts, N.; Norhausen, C. H.; Ballauff, M. *Macromolecules* **1998**, *31*, 8912–8917.
(45) Andersson, M.; Hietala, S.; Tenhu, H.; Maunu, S.-L. *Colloid Polym. Sci.* **2006**, *284*, 1255–1263.
(46) Qiu, X. P.; Winnik, F. M. *Macromol. Rapid Commun.* **2006**, *27*, 1648–1653.
(47) Skey, J.; O'Reilly, R. *Chem. Commun.* **2008**, *1*, 149–157.
(48) (a) Mayadunne, R. T. A.; Rizzardo, E.; Chiefari, J.; Krstina, J.; Moad, G.; Postma, A.; Thang, S. H. *Macromolecules* **2000**, *33*, 243–245. (b) Favier, A.; Ladaviere, C.; Charreyre, M.-T.; Pichot, C. *Macromolecules* **2004**, *37*, 2026–2034. (c) Wang, Z.; He, J.; Tao, Y.; Yang, L.; Jiang, H.; Yang, Y. *Macromolecules* **2003**, *36*, 7446–7452. (d) Mayadunne, R. T. A.; Jeffery, J.; Moad, G.; Rizzardo, E. *Macromolecules* **2003**, *36*, 1505–1513. (e) You, Y.-Z.; Zhou, Q.-H.; Manickam, D. S.; Wan, L.; Mao, G.-Z.; Oupický, D. *Macromolecules* **2007**, *40*, 8617–8624. (f) Lima, V.; Jiang, X. L.; Brokken-Zijp, J.; Schoenmakers, P. J.; Klumperman, B.; Van Der Linde, R. *J. Polym. Sci., Part A: Polym. Chem.* **2005**, *43*, 959–973. (g) Chan, J. W.; Yu, B.; Hoyle, C. E.; Lowe, A. B. *Chem. Commun.* **2008**, 4959–4961. (h) Segui, F.; Qiu, X.-P.; Winnik, F. M. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46*, 314–326.
(49) Li, M.; De, P.; Gondi, S. R.; Sumerlin, B. *J. Polym. Sci., Part A: Polym. Chem.* **2008**, *46*, 5093–5100.
(50) (a) Schilli, C.; Lanzendörfer, M. G.; Müller, A. H. E. *Macromolecules* **2002**, *35*, 6819–6827. (b) Stenzel, M. H.; Davis, T. P.; Barner-Kowollik, C. *Chem. Commun.* **2004**, 1546–1547. (c) Llauro, M.; Loiseau, J.; Boisson, F.; Delolme, F.; Ladavière, C.; Claverie, J. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 5439–5462. (d) Ladavière, C.; Dörr, N.; Claverie, J. P. *Macromolecules* **2001**, *34*, 5370–5372.
(51) (a) Lowe, A. B.; Sumerlin, B. S.; Donovan, M. S.; McCormick, C. L. *J. Am. Chem. Soc.* **2002**, *124*, 11562–11563. (b) Zhu, M. Q.; Wang, L. Q.; Exarhos, G. J.; Li, A. D. Q. *J. Am. Chem. Soc.* **2004**, *126*, 2656–2657. (c) Sumerlin, B. S.; Lowe, A. B.; Stroud, P. A.; Zhang, P.; Urban, M. W.; McCormick, C. L. *Langmuir* **2003**, *19*, 5559–5562. (d) Scales, C. W.; Convertine, A. J.; McCormick, C. L. *Biomacromolecules* **2006**, *7*, 1389–1392.
(52) Harrisson, S. *Macromolecules* **2009**, *42*, 897–898.
(53) Xu, J.; He, J.; Fan, D.; Wang, X.; Yang, Y. *Macromolecules* **2006**, *39*, 8616–8624.
(54) Patton, D. L.; Mullings, M.; Fulghum, T.; Advincula, R. C. *Macromolecules* **2005**, *38*, 8597–8602.
(55) Spruell, J. M.; Levy, B. A.; Sutherland, A.; Dichtel, W. R.; Cheng, J. Y.; Stoddart, F. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47*, 346–356.
(56) Chan, J. W.; Hoyle, C. E.; Lowe, A. B.; Bowman, M. *Macromolecules* **2010**, *43*, 6381–6388.

(57) Shu, X. Z.; Liu, Y. C.; Palumbo, F. S.; Luo, Y.; Prestwich, G. D. *Biomaterials* **2004**, *25*, 1339–1348.
(58) Soeriyadi, A. H.; Li, G.-Z.; Slavin, S.; Jones, M. W.; Amos, C. M.; Becer, C. R.; Whittaker, M. R.; Haddleton, D. M.; Boyer, C.; Davis, T. P. *Polym. Chem.* **2011**, *2*, 815–822.
(59) Li, G.-Z.; Randev, R. K.; Soeriyadi, A. H.; Rees, G.; Boyer, C.; Zhen, T.; Davis, T. P.; Becer, C. R.; Haddleton, D. M. *Polym. Chem.* **2010**, *1*, 1196–1204.
(60) York, A. W.; Scales, C. W.; Huang, F.; McCormick, C. L. *Biomacromolecules* **2007**, *8*, 2337–2341.
(61) (a) Wong, K. H.; Davis, T. P.; Barner-Kowollik, C.; Stenzel, M. H. *Polymer* **2007**, *48*, 4950–4965. (b) Bivigou-Koumba, A. M.; Kristen, J.; Laschewsky, A.; Müller-Buschbaum, P.; Papadakis, C. M. *Macromol. Chem. Phys.* **2009**, *210*, 565–578.
(62) Bourgeat-Lami, E.; Guyot, A. *Colloid Polym. Sci.* **1997**, *275*, 716–729.
(63) (a) Chen, M. Q.; Kishida, A.; Akashi, M. *J. Polym. Sci., Part A: Polym. Chem.* **1996**, *34*, 2213–2220. (b) Riza, M.; Tokura, S.; Iwasaki, M.; Yashima, E.; Kishida, A.; Akashi, M. *J. Polym. Sci., Part A: Polym. Chem.* **1995**, *3*, 1219–1225.
(64) Shay, J. S.; English, R. J.; Spontak, R. J.; Balik, C. M.; Khan, S. A. *Macromolecules* **2000**, *33*, 6664–6671.
(65) Watts, J. F. *An Introduction to Surface Analysis by Electron Spectroscopy*; Oxford University Press, Royal Microscopical Society: Oxford, U.K., 1990.
(66) (a) Deslandes, Y.; Mitchell, D. F.; Paine, A. J. *Langmuir* **1993**, *9*, 1468–1472. (b) Ali, A. M. I.; Pareek, P.; Sewell, L.; Schmid, A.; Fujii, S.; Armes, S. P.; Shirley, I. M. *Soft Matter* **2007**, *3*, 1003–1013. (c) Beadle, P. M.; Armes, S. P.; Greaves, S. J.; Watts, J. F. *Langmuir* **1996**, *12*, 1784–1788. (d) Perruchot, C.; Chehimi, M. M.; Delamar, M.; Lascelles, S. F.; Armes, S. P. *Langmuir* **1996**, *12*, 3245–3251. (e) Cairns, D. B.; Armes, S. P.; Chehimi, M. M.; Perruchot, C.; Delamar, M. *Langmuir* **1999**, *15*, 8059–8066. (f) Khan, M. A.; Armes, S. P.; Perruchot, C.; Ouamara, H.; Chehimi, M. M.; Greaves, S. J.; Watts, J. F. *Langmuir* **2000**, *16*, 4171–4179.
(67) (a) Kohut-Svelko, N.; Reynaud, S.; Dedryvère, R.; Martinez, H.; Gonbeau, D.; François, J. *Langmuir* **2005**, *21*, 1575–1583. (b) Chen, Y.; Ford, W. T.; Materer, N. F.; Teeters, D. *Chem. Mater.* **2001**, *13*, 2697–2704. (c) Fujii, S.; Suzaki, M.; Nakamura, Y.; Sakai, K.; Ishida, N.; Biggs, B. *Polymer* **2010**, *51*, 6240–6247. (d) Dahman, Y.; Puskas, J. E.; Margaritis, A.; Merali, Z.; Cunningham, M. *Macromolecules* **2003**, *36*, 2198–2205. (e) Liu, J.; Chew, C. H.; Gan, L. M.; Teo, W. K.; Gan, L. H. *Langmuir* **1997**, *13*, 4988–4994. (f) Thomas, R. R.; Lloyd, K. G.; Stika, K. M.; Stephans, L. E.; Magallanes, G. S.; Dimonie, V. L.; Sudol, E. D.; El-Aasser, M. S. *Macromolecules* **2000**, *33*, 8828–8841. (g) Davies, M. C.; Lynn, R. A. P.; Davis, S. S.; Hearn, J.; Watts, J. F.; Vickerman, J. C.; Paul, A. J. *Langmuir* **1993**, *9*, 1637–1645.