Multi-Responsive Reversible Gels based on Charge-Driven Assembly

Marc Lemmers*, Joris Sprakel, Ilja K. Voets,
Jasper van der Gucht and Martien A. Cohen Stuart

*MSc. M. Lemmers, Dr. ir. J. van der Gucht, Prof. Dr. M.A. Cohen Stuart
Laboratory of Physical Chemistry and Colloid Science
Wageningen University
Dreijenplein 6, 6703 HB, Wageningen (The Netherlands)
Telephone: +31 317 483844
Fax: +31 317 483777
E-mail: Marc.Lemmers@wur.nl

Dr. ir. J. Sprakel
School of Engineering and Applied Sciences, Department of Physics
Harvard University
Cambridge, MA 02138 (USA)

Dr. ir. I.K. Voets
Adolphe Merkle Institute
University of Fribourg
Route de l'ancienne Papeterie, CP 209, CH-1723, Marly 1 (Switzerland)

MSc. M. Lemmers, Dr. ir. J. Sprakel
Dutch Polymer Institute
John F. Kennedylaan 2, 5612 AB, Eindhoven (The Netherlands)

November 11, 2009

Supporting information

Detailed synthetic protocol

Macro-initiator synthesis

A bifunctional macro-initiator was prepared by dissolving 150 g of poly(ethylene glycol)(PEG) with M_n 10.000 gmol^{-1} (Fluka) in 1.5 L toluene (Sigma Aldrich). After azeotropic distillation of 500 mL toluene, a ten-times molar excess with respect to the amount of PEG, of triethylamine (Sigma Aldrich) was added, which corresponds to 3 mL triethylamine. Subsequently, a ten-times molar excess, with respect to the amount of PEG, of 2-bromoisobutyryl bromide(Sigma Aldrich) was added dropwise, which corresponds to 2.74 mL of 2-bromoisobutyrylbromide. The reaction mixture was stirred for five days at 30°C.

Purification of the double macro-initiator was started by treatment of the reaction mixture with decolourising charcoal at 40°C for 30 min. Subsequently, the solids were removed by Büchner filtration. The solvent was partly removed by rotary evaporation before precipitation of the product in a ten-fold excess of petroleum ether. After filtration, the product was redissolved in 0.5 L THF before precipitation in a ten-fold excess of petroleum ether (twice). The product was obtained by filtration and dried under vacuum overnight. Yield was determined to be 88%. The degree of esterification was determined by ^{1}H NMR to be 100%.

Triblock copolymer synthesis

The triblock copolymer was prepared by degassing the solid mixture of 40 g of double macro-initiator and 56.3 g of 3-sulfopropylmethacrylate potassium salt (KSPMA) (Sigma Aldrich), which is a 59-fold excess of reactive monomer, aiming for an average degree of polymerization of 60. The solid mixture was dissolved in 80 mL of a degassed mixture of water/DMF (1:1) at 60°C. The reaction mixture was kept under argon flow until completion. An ATRP catalyst mixture was prepared by dissolving an equal molar amount, with respect to the amount of double macro-initiator, of Cu^{I}Cl (Sigma Aldrich), a double molar amount, with respect to the amount of double macro-initiator, of Cu^{II}Cl (Sigma Aldrich) and a 7.5-times molar excess, with respect to the amount of double macro-initiator, of 2,2-bipyridine (Sigma Aldrich) in 40 mL of a water/DMF mixture (1:1). The actual amounts used are 0.29 g Cu^{I}Cl, 0.77 g Cu^{II}Cl and 3.34 g 2,2-bipyridine. The ATRP catalyst mixture was added to the double macro-initiator/KSPMA solution to start the polymerization. The reaction was quenched after three hours by bubbling oxygen through the sample.

Purification of the product was achieved by diluting the polymer solution with water followed by dialysis against 1 M KCl solution at p$H \approx 3$. EDTA salts were added to the dialysis bath up to a concentration of 10 mM to bind the copper ions in the polymer solution. Next dialysis step was against 0.1 M KCl at p$H \approx 3$ and 10 mM of EDTA. Final purification step was extensive dialysis against pure water. The triblock copolymer was obtained by freeze-drying overnight. Yield was determined to be 16%, caused by an unfortunate massive loss of product during dialysis.

Structural analysis

The product was dissolved in D$_2$O to determine the structure by ^{1}H-NMR on a Bruker Avance III 400MHz NMR spectrometer. The triblock copolymer structure and its relation to the ^{1}H-NMR spectrum is indicated in figure 1. The degree of polymerization (DP) was determined using the ratio of the integrals of peak **e** to the peak of PEO. Taking into account the amount of protons in a PEO monomer and group **e** of the triblock copolymer, the DP was determined by DP $= \frac{4I_e}{2I_{PEO}} \cdot N_{PEO}$ with I_e the integral of peak **e**, I_{PEO} the integral of the PEO peak and $N_{PEO} = 230$ the amount of PEO groups in the starting PEO, based on SEC against PEO standards. From this it follows that the average degree of polymerization is 55.

Size exclusion chromatography (SEC) was performed to determine the relative molecular weight of the triblock copolymer, see figure 2. SEC was carried out in a NaNO$_3$ aqueous solution (0.1 M), with a Waters 600 liquid chromatograph equipped with a 2414 refractive index detector and four Waters Ultrahydrogel columns (Ultrahydrogel 1000, 500, 250 and 120). A flow rate of 0.8 mLmin^{-1} was used. Poly(ethylene oxide) standards were used for calibration.

Characterization techniques

Dynamic Light Scattering Titrations

Dynamic light scattering titrations were performed on an ALV light scattering instrument equipped with an ALV-5000/60X0 external digital correlator and a 300 mW solid state laser (Cobolt Samba-300 DPSS laser) operated at a wavelength of 532 nm. Angle of detection was always $90°$. A refractive index matching bath of filtered cis-decalin surrounded the cylindrical scattering cell, and the temperature was controlled at $20\pm0.1°$C using a Haake F8-C35 thermostat. Titration steps were automated using a Schott-Geräte TR 250 computer-controlled titration setup for sequential addition of titrant and cell stirring. After each DLS measurement, the pH was measured and the sample was stirred for one minute before addition of the titrant, followed by a period of stirring for eight minutes and a one minute rest period, before starting DLS measurements again.

Light scattering intensity was measured in 40 separate measurements of 12 s each after each titration step. Each separate measurement generates an average scattered light intensity over the measured 12 s. The values presented in the main text for the average light scattering intensity $\langle I \rangle$ are the averages over these 40 separate measurements.

The pH DLS titration data were obtained using a more sophisticated script, which evaluates the stability of the scattered light intensity during the measurement. The user can determine for how many DLS measurements the intensity should be within a certain range (depending on the intensity) to assume equilibrium. The duration of each measurement is automatically adjusted to the measured scattered light intensity. We decided that 15 runs stable is equilibrium, with a minimum duration of a measurement of 12 s.

The average scattered light intensity was normalized by the total polymer concentration ($\frac{\langle I \rangle}{C_p}$) in the measuring cell, assuming $I \propto C_p$, which was checked to be correct in the concentration regime investigated in this paper. The hydrodynamic radii (R_h) were determined by averaging the values of each separate DLS measurement, as given by the standard ALV software, which is based on the cumulants method.

Small-Angle X-ray Scattering

Small-angle X-rays scattering (SAXS) measurements were performed at the Adolphe Merkle Institute. The SAXSess lab system from Anton Paar (Graz, Austria) comprises an X-ray generator (PANalytical, PW 3830) operating at 40 kV and 50 mA with a sealed-tube Cu anode (Philips 2773/00 long fine focus). A Göbel mirror (AXO Dresden, C40-0641) and a Kratky block collimation system were used to convert the divergent polychromatic X-ray beam into a focused line-shaped beam of Cu K radiation ($\lambda = 0.1542$ nm). The samples were filled at room temperature into the sample holder (1 mm quartz capillary in a metal block, temperature controlled by a Peltier element, (0.1 K). The 2D scattering pattern was recorded by a CCD camera from Princeton Instruments (Trenton, NJ, USA). The 2D image was radially integrated to obtain $I(q)$ using SAXSQuant software (Anton Paar, Graz, Austria) in the range $0.08 < q < 2$ nm^{-1}.

The measured scattering curves were corrected for solvent scattering, put on absolute scale by measuring the scattering intensity of water, and desmeared using the SAXSQuant software. Interactions were modelled using a hard sphere structure factor, yielding an effective volume fraction and radius, as the micelles are not real hard spheres. Model fitting was done using the SASfit program (http://kur.web.psi.ch/sans1/SANSSoft/sasfit.html) employing a form factor for polydisperse (Gaussian distribution) homogeneous spheres. The data has also been analysed using generalized indirect Fourier transformation as described in detail elsewhere. (G)IFT analysis of SAXS data for samples between 2 and 160 g L^{-1} yielded p(r) functions with a very symmetrical shape, typical for spherical particles, with $R_g = 8.1 \pm 0.4$ nm.

Rheological measurements

Gels were prepared by mixing together two separate polyelectrolyte solutions containing either the triblock copolymer or the oppositely charged homopolymer. All gels were prepared at charge stoichiometric ratio: $f^+ = 0.5$. To determine and control the ionic strength of the samples, complete counter-ion release upon complexation was assumed. The values given for the viscosity in the main text were measured as

the low-frequency complex viscosity (η^*), or, assuming Newtonian behaviour for low shear rates, zero-shear viscosity (η_0). It was experimentally checked that these two viscosities coincide for the applied frequencies and shear rates.

Rheological measurements were performed on either an Anton Paar MCR 301 or Anton Paar MCR 501 rheometer, both in strain controlled mode. Cone-plate geometry was used for both oscillatory and rotational measurements. A cone with a diameter of 50 mm and a tilt angle of $1°$ was used for most experiments. Occasionally, a cone with a diameter of 25 mm and a tilt angle of $1°$ was used. The zero-shear viscosity (η_0) of low viscosity samples was measured separately using a Couette geometry with a diameter of 10 mm and a gap width of 0.841 mm. Temperature was controlled by a Peltier element in the plate or Couette measuring cell. Measurements started one hour after sample loading, to assure complete relaxation of the gel samples before starting measurements. A solvent trap was used to minimize the effect of evaporation. At least two different samples were measured for each concentration and ionic strength of the gels.

Frequency sweeps with an angular frequency (ω) between 0.01–628 rads^{-1}, were performed at a strain of 5%. It was checked that the applied strain of 5% corresponded to the linear visco-elastic regime for all applied frequencies, by performing amplitude sweeps at multiple frequencies. The complex viscosity (η^*) values used in the main text were determined by the plateau in the complex viscosity at low frequencies.

Rotational measurements were performed with shear rates ($\dot{\gamma}$) between 0.001–1 s^{-1}. Values for η_0 were obtained by the low shear rate viscosity plateau values, assuming Newtonian behaviour at shear rates approaching zero.

Movie

Two short movies are available to demonstrate i) the gel formation upon mixing the two separate polymer solutions and ii) the response of a gel to an increase in salt concentration.
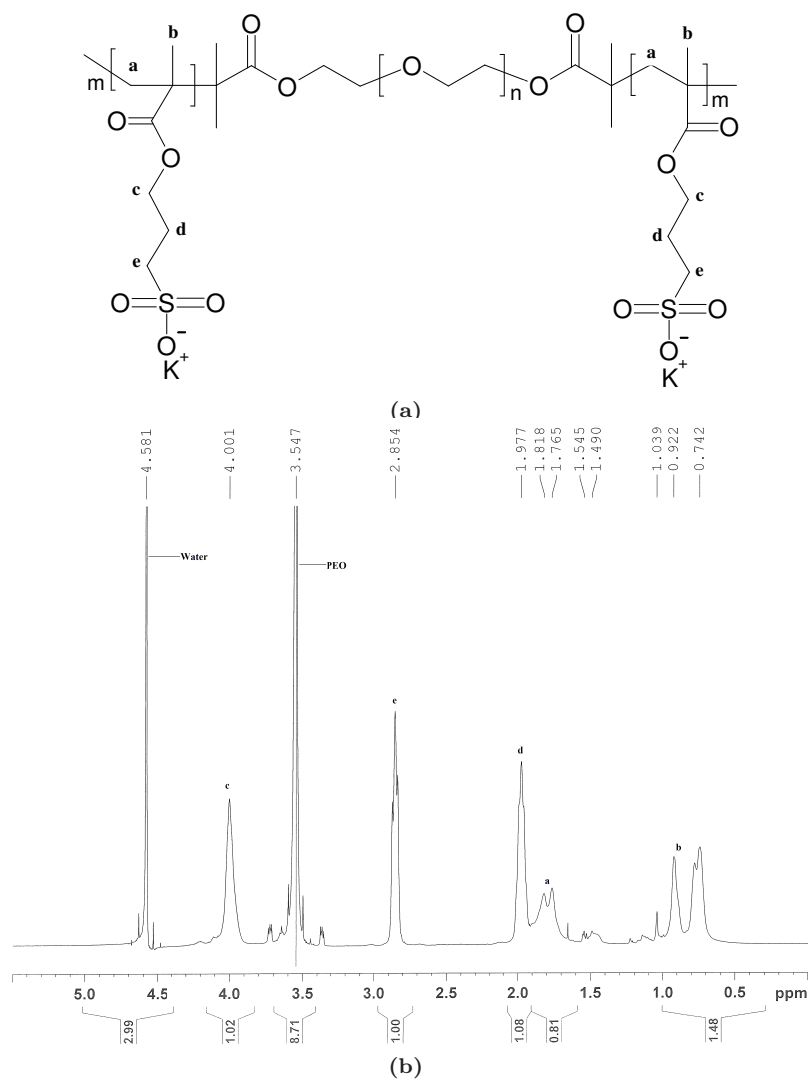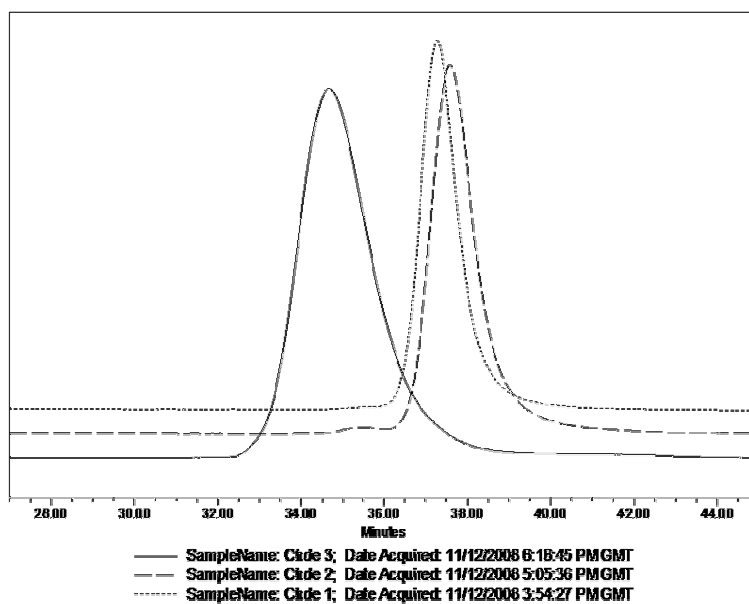
(a)

(b)

Figure 1: (a) Structure of PSPMA$_{28}$—PEO$_{230}$—PSPMA$_{28}$ with labeled groups. (b) NMR spectrum of PSPMA$_{28}$—PEO$_{230}$—PSPMA$_{28}$ with peaks corresponding to the labels.

GPC Sample Results

	Sample Name	RT (min)	Mn	Mw	MP	Mz	Poly-dispersity
1	Chde 1	37.269	10075	10479	10877	10833	1.040
2	Chde 2	37.584	8801	9424	9802	9983	1.071
3	Chde 3	34.671	22841	25592	26831	28187	1.120

Figure 2: Size exclusion chromatogram of PEG_{230} starting material (dotted line), double macro-initiator (dashed line) and triblock copolymer $PSPMA_{28}$—PEO_{230}—$PSPMA_{28}$ (full line).