Experimental report

09/11/2018

Proposal:	**9-11-1852**	**Council:**	4/2017
Title:	Self-assembly of amphiphilic blockcopolymers under close-to-equilibrium conditions through controlled water dialysis.		
Research area:	Soft condensed matter		

This proposal is a new proposal

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Samples:
polydimethylsiloxane-b-poly(ethylene glycol)
poly(n-butyl acrylate)-b-(polyacrylic acid)
polystyrene-b-poly(acrylic acid)

Instrument	Requested days	Allocated days	From	To
D22	3	3	07/09/2018	10/09/2018

Abstract:

Block copolymer (BC) self-assembly in aqueous solution often occurs under non-equilibrium conditions leading to the formation of kinetically frozen aggregates. Under such conditions the outcome of the self-assembly is highly dependent on processing parameters like the final water content or the water addition rate. In order to study the BC self-assembly in close-to-equilibrium conditions, we propose to use a dialysis approach where the water slowly diffuses into the BC solution prepared in an appropriate organic solvent. A set of amphiphilic BCs varying in composition, structure and properties is proposed as model systems to study their mechanism of self-assembly. Specifically, we aim at identifying the various morphology changes undergone by BC aggregates when the water content is increased in a slow and continuous manner.

Is the formulation of colloids and macromolecules that easy? Can we fully control and predict out-of-equilibrium assemblies? A central question for academic laboratories and industries where formulation is a key step; and surprisingly scarcely investigated in the literature. We have started recently to tackle this issue and shown that the formulation pathway *or the ways the various components come into intimate contact* strongly influence the final morphology and properties of such complexes. Amphiphilic block copolymer (BCs) and oppositely charged polyelectrolytes (PEs) self/co-assembly in aqueous solution often occurs under non-equilibrium conditions leading to the formation of kinetically frozen aggregates/complexes. Under such conditions the outcome of the assembly is highly dependent on the formulation parameters like the final water content or the water addition rate for BCs or the mixing time, addition order and/or the initial concentration for the PEs. In order to minimize such inherent processing drawbacks due to out-of-equilibrium conditions, we have monitored by SANS the mechanism of BCs and PEs assembly through a dialysis approach where we assume that the assembly/complexation occurs under close-to-equilibrium conditions, that is, the system can relax completely toward equilibrium at each step of the assembly process. In such configuration we might identify the various morphological changes undergone either by the BC and PE aggregates/complexes when the interaction is resumed gradually.

This report summarizes the experiments performed at ILL on D22 from September 7 to 10 (proposal 9-11-1852). Two generic polymer systems were put under scrutiny and assembled under quasi-equilibrium conditions using the newly dialysis cell that we have developed in collaboration with the Large Scale Structures Group of D22 (Figure 1). Specifically, we aim at identifying the various morphology changes undergone by BC aggregates when the water content is increased in a slow and continuous manner. The first system is an amphiphilic block copolymer able to form vesicles and the second one is based on a polyelectrolyte pair capable to form a coacervate phase under defined conditions of pH and ionic strength.

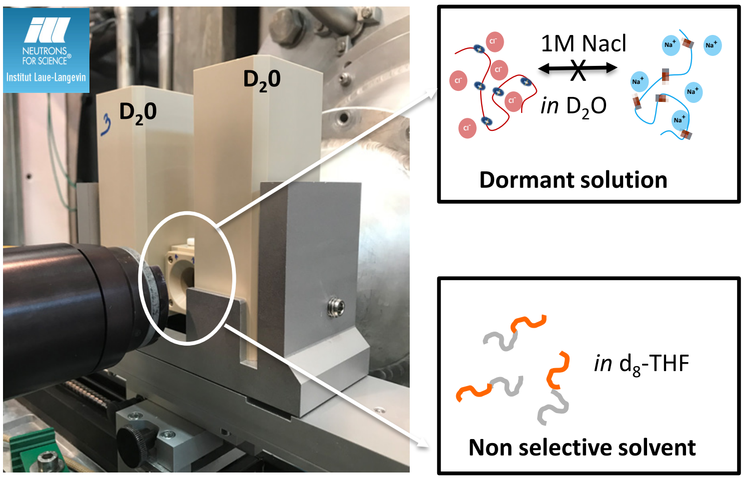

Figure 1. Dialysis cell used on D22 to monitor the formation of BC vesicles and PE coacervates. The 4ml cell containing the non-interacting BC or PE system is sandwiched between two D_2O reservoirs. Dialysis occurs through two thick regenerated cellulose filters (10 KDa cut-off). Both reservoirs and the cell have been customized with a stirrer to insure a good homogenisation of the solution. A conductivity meter is plugged into the cell to monitor either the ionic *strength* (PE) or the *water content* (BC) *vs. time.*

Block copolymer system

A series of PDMS-*block*-PEO and PCL-*block*-PEO copolymers varying in composition and molecular weight has been synthesized by M. Fauquignon at 'Laboratoire de Chimie des Polymères Organiques' in Bordeaux. Previous experiments performed by dynamic light scattering and cryoTEM have demonstrated the ability of these copolymers to form vesicles (polymersomes) through a solvent displacement approach which consists in dissolving the copolymer in a non-selective solvent, typically the THF, and then adding a certain amount of water (around 50% in volume) to trigger the hydrophobic effect which drives the self-assembly. As for many copolymer systems, the formation of vesicles under such conditions is highly dependent on the experimental conditions (polymer concentration, addition rate, stirring speed …) owing to the tendency of the copolymer to form metastable structures. Here, the purpose was to achieve the self-assembly through dialysis of the copolymer solution in THF against water to induce the formation of vesicles in the slowest manner as possible. All solvents are deuterated and the water contains 1mM of NaCl in order to follow the solvent exchange through conductimetry measurements. The conductivity probe is located in the polymer solution and a calibration curve of σ (µS/cm) as function of the NaCl concentration was established. Typical volumes used for an experiment are 4 mL of copolymer solution in d-THF, filtered on 0.1 µm PTFE membrane, and 2x100 mL of water containing 1mM NaCl. The dialysis membrane is made of regenerated cellulose with a molecular weight cut-off of 10 kDa. Results in Figures 2.A and 2.B show the scattering curves and the total counts of the self-assembly of the PDMS$_{23}$-b-PEO$_{13}$ as function of time. Various morphologies from small micelles at t=5h (coexisting with larger aggregates), to elongated rods (13h) and vesicles (22h) were observed confirming theoretical expectations. The final water content is 55% (v/v). Interestingly, the vesicles obtained by dialysis have a very low dispersity (Figure 2.C) which is usually the hallmark of vesicles that have been extruded through filter membranes of low porosity. Results with other block copolymer compositions are still under investigation and it seems that the pathway to vesicles based on PCL-PEO copolymer is different.

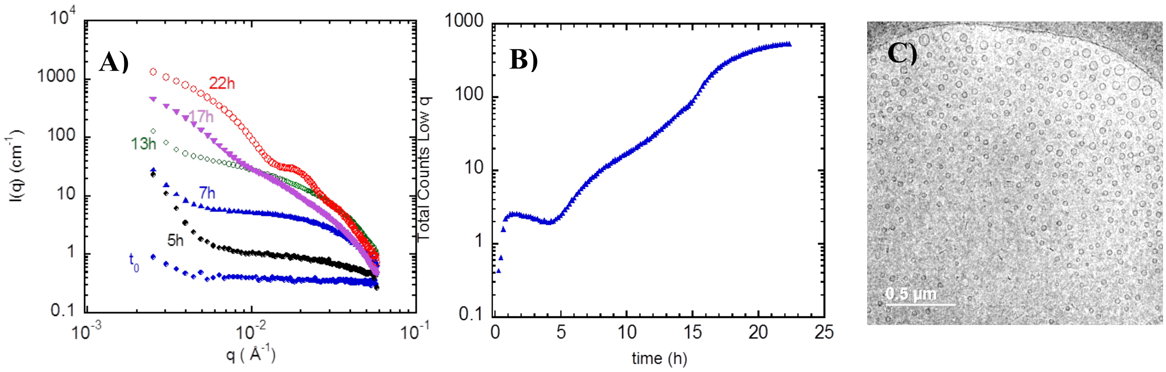

Figure 2. A) Scattering curves of PDMS$_{23}$-b-PEO$_{13}$ self-assembly through dialysis of the copolymer solution in d$_8$-THF against D$_2$O containing 1 mM NaCl. B) Total box counts at low q range. C) cryoTEM analysis of the final BC vesicle suspension at the end of the dialysis.

Oppositely charged polyelectrolytes

Depending on the strength of the interaction, at charge stoichiometry the complexation between oppositely charged PEs proceeds either through a liquid-solid or a liquid-liquid phase separation leading to the formation of a solid precipitate/aggregate or a liquid complex coacervate, respectively. We have put under scrutiny here the model PDADMAC (poly(diallyldimethylammonium chloride) PANa (sodium polyacrylate) pair known to generate a coacervate phase at stoichiometry (charge ratio z=1). Two molecular weight ratios and 3 concentrations were investigated. In the asymmetric case (PDADMAC of 45kDa/PANa of 2kDa, DP_{ratio}= 8) the presence of soluble complexes was recently evidenced at low charge ratio while in the symmetric case (PDADMAC 45kDa/PANa 45kDa) insoluble complexes are formed. Two so-called *dormant solutions* were prepared at sufficiently high ionic strength (0.45M and 0.7M NaCl respectively) and at pH=10 where the two PEs do not interact due to charge screening. Then, a slow and controlled decrease of the ionic strength through dialysis against water triggers the complexation of PEs featured through the sharp desalting-coacervation transition as seen at a larger scale by static and dynamic light scattering. The continuous decrease of the ionic strength was monitored through on-line conductivity measurements plugged into the cell in order to monitor in a continuous manner *the different intermediate structures throughout the liquid-liquid transition as a function of the ionic strength*. A calibration curve of the conductivity σ (µS/cm) as function of the NaCl concentration was established. The dialysis (dI/dt) kinetics (or desalting rate) depends on the initial ionic strength difference between the cell and the reservoirs (ΔI).

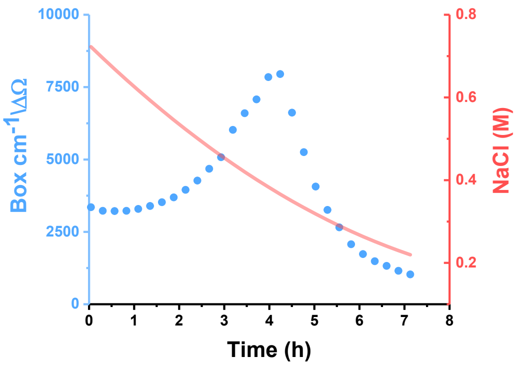

Figure 3. Overall neutron box count (L) and the ionic strength I_{Cell} (t) as a function of the dialysis time for the symmetric case ($PDADMAC_{45ka}$-$PANa_{45ka}$) with an initial ΔI =0.7M. The peak corresponds to the ionic strength at which the transition is seen by DLS.

As can be seen in Figure 3, the box count has a pronounced peak close to 0.28M where the desalting transition occurs. Before the peak, the electrostatic interaction is progressively *turned back* and triggers consequently the complexation of the PEs. At the desalting transition, full coacervation occurs (Z=1) generating µm size droplets that coarsen over a few hours and sediment down well in agreement with an overall count that slowly level-off. As can be seen in Fig. 4, the SANS curves monitored during the desalting experiment indicate the presence of Gaussian chains with increasing R_g before the transition. At T=0 in the dormant solution where both chains are flying around (0.7M), the measured R_g correspond likely to PDADMAC chains showing the highest contrast $\Delta\rho^2 = (6.33\text{-}0.48)^2\ 10^{-12}Å^{-4}$ (in agreement with individual PDADMAC chains at 0.7M). With time, the ionic strength decreases and we clearly see the presence of Gaussian chains with slowly increasing R_g up to very close to the transition. The coacervation burst cannot be captured by SANS as it is a very rapid phenomena (less than 1 s). On the other side of the transition we can see aggregated chains with smaller R_g tending at low ionic strength to form small spherical aggregate in line with the structures present in the poor-polymer phase (in equilibrium with the much denser coacervate phase) with no added salt. The asymmetric case and the other concentration are still under processing.

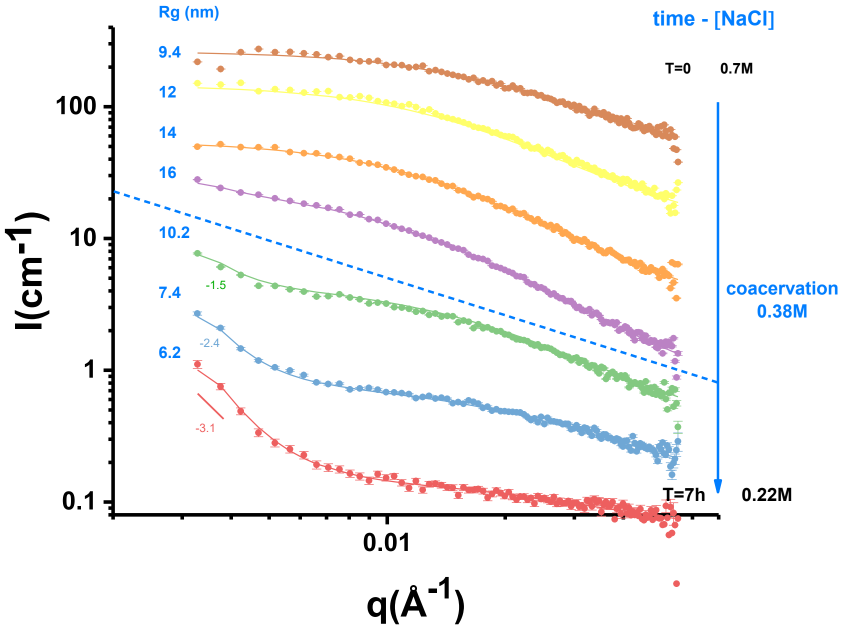

Figure 4. Neutron scattered intensity I(q) as function of the time/decreasing ionic strength during the dialysis performed at stoichiometry (z=1) for the symmetric system ($PDADMAC_{45k}$-$PANa_{45ka}$). The curves have been shifted vertically for clarity.