Experimental report

11/02/2019

Proposal:	**9-12-521**	**Council:**	4/2017
Title:	Topologically- and sequence-structured thermoresponsive polymer brushshells on core-shell superparamagnetic nanoparticles		
Research area:	Soft condensed matter		

This proposal is a new proposal

Main proposer:	**Erik REIMHULT**
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Local contacts:	Sylvain PREVOST

Samples: Superparamagnetic iron oxide nanoparticles with shells of Poly(2-ethyl-2-oxazoline) (PEOX), poly(2-isopropyl-2-oxazoline) (PIPOX), as well as p(EOX-ran-IPOX), p(EOX-b-IPOX) and p(IPOX-b-EOX)

Instrument	Requested days	Allocated days	From	To
D22	0	0		
D11	0	0		
D33	3	2	17/03/2018	19/03/2018

Abstract:

Superparamagnetic iron oxide nanoparticles (SPION) are intensively researched for biomedical imaging, drug delivery, therapeutics and separation applications. Their functionality in such applications strongly depends on the density profile of the polymer shell grafted to the magnetic inorganic core. We have developed methods to synthesize SPION that are extremely monodisperse (SD<5%) and to which uniquely dense and stable polymer brush shells are grafted. Recently, we have made the first such SPION with polyoxazoline copolymer and topologically varied brush shells. These provide a new level of control over shell structure and thermal responsiveness. We will use SANS to investigate and verify the internal shell structure of ultra-monodisperse SPION with densely grafted polymer shells of defined sequence and varied monomer solubility, as well as their restructured shells upon changing of shell solvation due to heating.

Beamline: **D33**	**Experiment title: Topologically- and sequence-structured thermoresponsive polymer brush shells on core-shell superparamagnetic nanoparticles**	**Experiment number:** **9-12-521**
	Local contact(s): Sylvain Prevost	
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We performed SANS measurements on a set of core-shell nanoparticles with the aim of elucidating differences in shell structure due to a variation in polymer brush structures due to change in core-shell particle dimensions. Our aim was to find the influence of changes in core and shell size as well as to perform a first study of the influence of the effect of polymer topology (cyclic vs. linear) on the shell structure. A secondary objective was to study the influence of thermally induced desolvation on the shell structure of colloidally stable core-shell nanoparticles as the thermal responsivity of the shell chemistry of the above-mentioned structures was changed. The core of the nanoparticles were highly monodisperse iron oxide nanoparticles synthesized by the thermal heat up method [1]. The data acquisition was highly successful, resulting in a large amount of distinct data sets to analyze in detail. The nanoparticles presented in this summary of the results are summarily listed in Table 1.

Table 1. Characterization data on the nanoparticles described in this summary. We additionally successfully measured nanoparticles grafted with random and comb copolymers of the same chemistries which are not presented in the report due to brevity reasons but are mentioned in the proposal.

	D_{core} [nm]	$Mn_{Polymer}$ [kg/mol]	DP	σ [molecules/nm²]	$D_{h,number}$ [nm]
Cyclic PEtOxA	9±0.7	11	110	2.2	19±5
Linear PEtOxA	9±0.7	10.5	106	1.2	26±5
PiPrOxA 5nm	5.0±0.5 (10.0%)	23.4	207	1.0	20.5±0.9
PiPrOxA 9nm	8.9±0.6 (6.3%)	23.4	207	1.1	25.2±1.5
PEtOxA 5nm	5±0.5 (10.0%)	22.9	231	1.1	20.9±0.4
PEtOxA 9nm	8.9±0.6 (6.3%)	22.9	231	0.7	27.6±2.3
PiPrOxA 6kDa	9.1±0.3 (3.1%)	6	51	1.0	18.7±2.0
PiPrOxA 14 kDa	9.1±0.3 (3.1%)	14	124	0.8	17.7±1.0
PiPrOxA 21kDa	9.1±0.3 (3.1%)	21	186	1.0	18.3±3.5
PiPrOxA 33kDa	9.1±0.3 (3.1%)	33	292	1.0	24.9±0.7

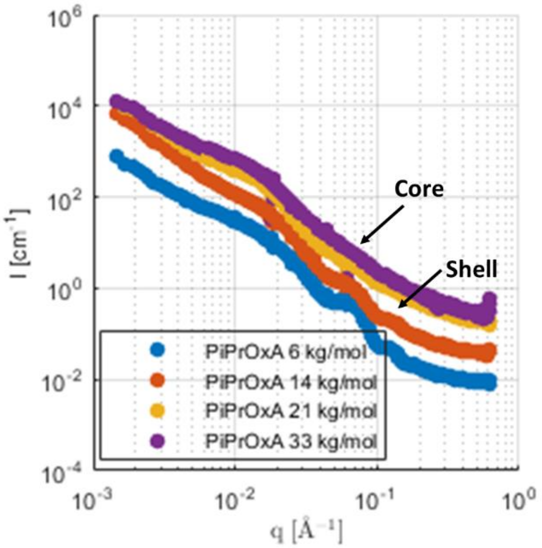

Figure 1. SANS scattering curves for 9 nm in diameter spherical iron oxide nanoparticles with ~1 chain/nm^2 of grafted poly(2-isopropyl-2-oxazoline) brush shells. A thinner shell leads to a more rapid transition from dense shell to the bulk and a more distinct shell signal.

We achieved a very good signal from core-shell nanoparticles that had a dense and well-characterized shell of linear thermoresponsive poly(2-isopropyl-2-oxazoline) (PiPrOxA) grafted to the surface of the iron oxide core using irreversible nitrodopamide anchor chemistry [2]. A representative example of the data collected is shown in Figure 1, where the scattering spectrum in water at room temperature for particles with the same core, but with different molecular weights of the expanded linear polymers grafted into a dense solvated shell. Some aggregation seemed to be evident at low q that we were not expecting based on other data such as dynamic light scattering. This is likely due to the extremely high concentrations (volume-% of hydrated core-shell nanoparticles) that were used for the SANS measurements. From preliminary fitting using a core-shell model, this does not seem to affect our ability to independently extract the shell structure and separate the (known) core size through their form factors, since these features are clearly distinguishable at much higher q. The structure factor can thus be taken into account and the form factor of the core-shell particle fitted.

However, the preliminary fits also showed that a standard core-shell model cannot be used for densely grafted polymer brushes on inorganic cores. This was expected and welcome news, because it enables us to indeed extract more information on how the brush structure is influenced by the polymer dispersant molecular weight and the core nanoparticle curvature. We are still working on appropriate ways to fit the data to extract the maximum amount of shell information comparable o theoretical models. A good approach seems to be to apply a Daoud-Cotton-like model to calculate the form factor for these shells, which takes into account the varying segment density within the shell in a theoretically sounder manner [3]. We have learned that original smearing of the signal of the shell and core signals that are often attributed to be due to polydispersity but that seemed excessive in our case, can better be taken care of by a more careful consideration of the instrumental resolution of the instrumentation at the beamline. We are currently at the stage of reapplying these insights into a comprehensive program to fit all the data, with the aim of getting a detailed fit for how the internal transitions in the brush vary with molecular weight and then further onto the other data presented below. This fitting implements the resolution functions and testing two different versions of Daoud-Cotton-inspired fitting model where the SAXS/TEM and chemical characterization data are considered.

The preliminary analysis shows that the shell feature observed at large q is likely related to the inner part of the shell. This part of the shell is dense and similar in its profile to a planar brush, before the polymer profile tapers off increasingly rapidly, as indicated in a previous preliminary study using X-rays on melt-grafted nanoparticles [3]. The signal due to this contrast difference appears less distinct in the scattering curves; this can be rationalized by the thicker shell essentially providing a smoother density transition to the bulk and thereby less sharp contrast. The more detailed fitting we are still working on is required to say this with more certainty, since the background and the instrumental resolution plays a greater role to fit the high polymer molecular weight core-shell nanoparticles.

Data obtained on varying the core size while keeping the molecular weight of the grafted polymer constant were in agreement with the above hypothesis for the origin of the observed shell features. Figure 2 shows the scattering data for 5 nm and 9 nm in diameter cores with 23 kg/mol PiPrOxA brush shells grafted. As we have recently published, calorimetry data can identify that the brush becomes more uniform as the curvature of the inorganic core goes down (diameter becomes larger): in essence, the dense part of the shell becomes thicker and the transition to lower density more abrupt (more like a planar brush). This can be seen in Figure 2 as a much more pronounced shell feature for the 9 nm cores than for the 5 nm cores.

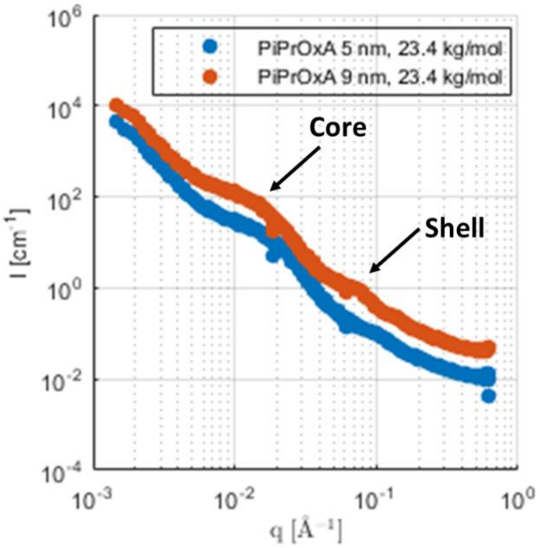

Figure 2. SANS scattering curves for 5 nm and 9 nm in diameter spherical iron oxide nanoparticles with ~1 chain/nm^2 of PiPrOxA 23 kg/mol brush shells. Lower curvature yields a more distinct transition from the dense part of the shell to the bulk, which is reflected in the signal from the shell.

Thermal cycling of the core-shell nanoparticle dispersions was performed for all different types of shells and with different types of temperature steps. Only two examples are shown for clarity in Figure 3, for poly(2-ethyl-2-oxazoline) (PEtOxA) 23 kg/mol shells grafted to 5 and 9 nm in diameter cores. It shows that the partial desolvation of the shell due to an increase in temperature to above the critical solution temperature of the polymer leads to partially reversible aggregation of the nanoparticles. That part of the sample remains aggregated after heating is expected due to the concentration and the length of time over which we had to keep the sample heated. The most interesting observation is that the 5 nm core sample that shows only a weak shell feature for an extended shell, shows a distinct shell feature similar to that of the lower curvature 9 nm core particles after being heated up. There seems to be additional changes to the thickness and density of the shell as expected upon heating and partial dehydration of the shell. We think that the fitting models we are currently exploring will be able to make that observation quantitative, since the monomer excluded volume per monomer can be used as a parameter in the model (either for fitting or for fixing using other data). Again, this fits with our hypothesis that densely grafted core-shell particles must be fitted with a star-polymer-like model for the shell.

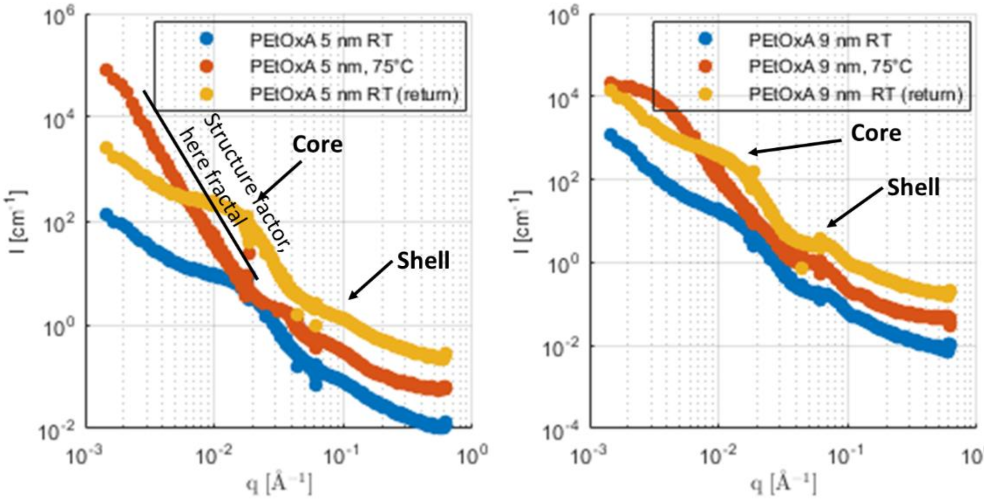

Figure 3. Thermal cycle of iron oxide cores of different diameter grafted by PEtOxA brush shells. Densification and formation of a thicker dense part of the spherical brush is observed above the PEtOxA critical solution temperature.

Unfortunately, the aim of observing equally distinct differences in the features of the cyclic vs linear brushes was not equally successful as the experiments to gain insights into the shell structure of densely grafted linear thermoresponsive brush core-shell nanoparticles. These samples should be compared to the particles above where PEtOxA was used (Fig. 3), which are potentially more strongly hydrated than the nanoparticles grafted with PiPrOxA. Despite that we expect to have a very high and homogeneous polymer concentration close to the core for the cyclic shell that should distinguish it from the linear shell, both tested particles showed only weak features. Since high particle concentrations were required for SANS, only one molecular weight and core size was possible to test due to limitations of the samples that could be prepared at the time of doing the experiments. The shells of linear PEtOxA and PiPrOxA grafted to 9 nm cores prepared especially for the scattering time showed much more distinct features than the ones from the previous work on cyclic and linear PEtOxA brought for analysis. This is likely to be an effect of that our synthesis methods have advanced (the later synthesized PiPrOxA particles also showed higher colloidal stability during the measurement, e.g. during T cycling) or that a higher concentration could be used. We believe it is the former and therefore suggest that new experiments are carried out with a variety of cyclic molecular weights, core sizes and PEtOxA as well as PiPrOxA to compare them also under thermal actuation.

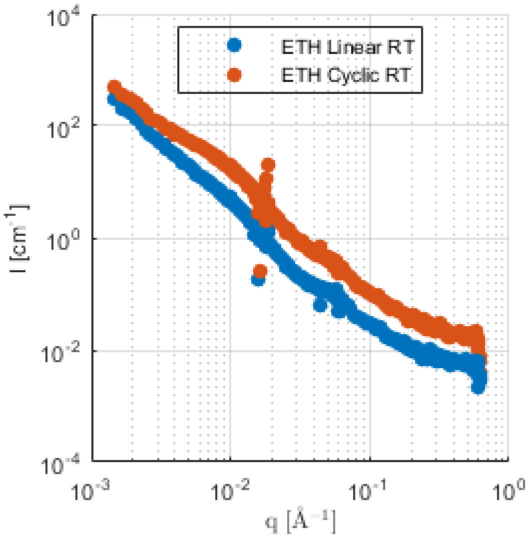

Figure 4. Comparison of the scattering curves of cyclic and linear brush shells for 9 nm cores and 11 kg/mol PEtOxA. Only small differences are observed between the two shells and the shell features are weaker than expected compared to the other obtained data.

The data obtained for the other samples, e.g. peptoid, block, random and comb copolymer brushes in different environments yielded data that can and are being similarly evaluated for the detailed structure of the shell of the core-shell nanoparticles.

1. Lassenberger A, Grünewald TA, Van Oostrum PDJ, et al. *Chem Mater*. 2017;29(10). doi:10.1021/acs.chemmater.7b01207

2. Schroffenegger M, Zirbs R, Kurzhals S, Reimhult E. *Polymers (Basel)*. 2018;10(4):451. doi:10.3390/polym10040451

3. Grünewald TA, Lassenberger A, van Oostrum PDJ, et al. *Chem Mater*. 2015;27(13):4763-4771. doi:10.1021/acs.chemmater.5b01488