Experimental report

16/01/2016

Proposal:	**9-10-1264**	**Council:**	4/2012

Title: Polymer shell structure of irreversibly stabilized superparamagnetic nanoparticles and their assembly into membranes

Research area: Materials

This proposal is a new proposal

Main proposer: **Erik REIMHULT**

Experimental team: Petrus VAN OOSTRUM
Erik REIMHULT
Ronald ZIRBS

Local contacts: Charles DEWHURST

Samples: Fe3O4 nanoparticles with nitrodopamine-poly(ethylene glycol) shell
Fe3O4-nitrodopamine-PEG-acrylate nanoparticle membranes formed around oleic acid emulsomes

Instrument	Requested days	Allocated days	From	To
D22	8	2	12/11/2012	14/11/2012

Abstract:

Superparamagnetic iron oxide nanoparticles (SPIONs) are intensively researched for biomedical imaging and drug delivery applications. Their functionality in such applications strongly depends on the density profile of the polymer shell grafted to the magnetic inorganic core. SPIONSs can also be used as building blocks for self-assembled superstructures, e.g. at liquid interfaces; likewise the shell distribution at the interface determines the structure and functionality of the assembly. We will use SANS to complement our current thorough characterization by determining the shell structure of individual state-of-the-art SPIONs as well as assembled in emulsome membranes.

Beamline: **D22**	**Experiment title: Polymer shell structure of irreversibly stabilized superparamagnetic nanoparticles and their assembly into membranes**	**Experiment number:** 55064
	Date of experiment: 12.11.2012/14.11.2012	**Shifts:** 48h
	Local contact(s): Charles Dewhurst	
Reporter: Erik Reimhult, University of Natural Resources and Life Sciences, Vienna, Department of Nanobiotechnology, Muthgasse 11, A-1190 Vienna, Austria		

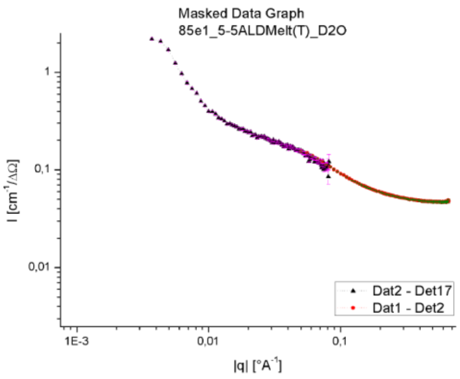
We performed SANS measurements on a set of Fe_3O_4 core nanoparticles with PEG shells of varied molecular weight while the grafting density was kept constant. The monodisperse cores were also varied in size. A rough set of the types of particles investigated by SANS can be found in the table below. Included in the samples were also multiple synthetic batches to check for possible sample preparation problems and also different grafting methods of the shell.[1] The majority of the nanoparticles were synthesized by a novel melt-grafting method that was recently published by us [1c], and which yields uniquely dense and uniform polymer brushes grafted to the monodisperse iron oxide cores.

PEG shell size	**∅5 nm core**	**∅6nm core**	**∅9 nm core**
2.5kD dendritic		x	
5kD linear	x		x
10kD linear	x		

The primary objective was to determine the polymer shell structures on these densely grafted and highly monodisperse core-shell particles. Secondary objectives were to do contrast variation to verify the signal from the core and brush respectively and to use spin-polarized neutrons to access a suggested difference in the magnetically scattering part of the single-crystalline core from the steric magnetite core size. The original proposal for 8-12 days also included suggested experiments on emulsomes with core-shell nanoparticles adsorbed to stabilize the interface of the droplets. Our experimental time was cut to a 2-days pilot study with a recommendation from the referees to focus our experiments significantly. In response to this, the emulsome experiments were completely removed and focus was exclusively put on determining the densely grafted shell structures. The original beamline contact for such work was not available for our experiment. Mr. Dewhurst kindly assisted us in our experiments, but also for him the kind of system was a new experience, and we therefore had limited possibilities analyze and directly trouble shoot during the measurements, which was our first experience at the ILL.

The experiments were successfully set up and data acquired for the core samples. Measurements were also performed at two detector distances for the samples, with partially overlapping q-ranges, to be sure to cover the relevant q-ranges for the shell and core structures we were to investigate. However, the signals that we recorded were unexpectedly weak and did not contain the expected features in addition to the core. Also the provided a low signal compared to our expectations based on measurement of core dimensions with SAXS.

Contrast variation created a noisier background, but did not reveal that any feature of the scattering curve related to shell (by perfect matching of the scattering length density to the PEG in the shell, nor any intermediate matching). The magnetite core could not be matched by any solvent mixture due to the scattering length density of Fe_3O_4.



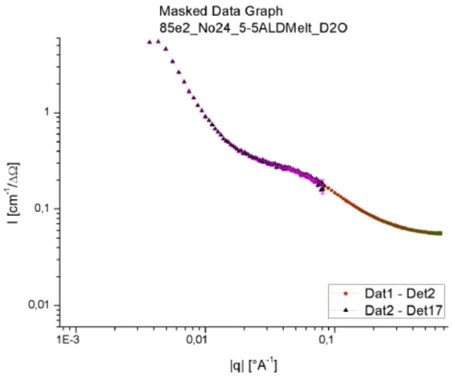


Fig. 1. Densely grafted nominally 5nm monodisperse Fe_3O_4 cores with 5kDa NDA-PEG grafted by the melt-method. Two different synthetic batches are shown. Measurement obtained in D_2O, normalized and background subtracted.

The whole range of nanoparticle cores and shell molecular weights were recorded, including of reserve batches for some samples, i.e. nominally identical core-shells structures, but different synthetic batches and approaches. The data was after discussion with our local contact treated through proper normalization and background subtraction. It was attempted to be modeled with a model under development for core-shell nanoparticles with very high grafting densities (see below). This model was based on the existing Daud-Cotton model for star polymer conformations and was later further developed by us for core-shell nanoparticles[2] and applied to the system under discussion here. This work was also redone in collaboration with a recently established SAXS group at our university. A short exemplifying summary of the type of results that were obtained is given below.

As can be seen in Fig.1 the scattering curves are relatively featureless. This was a recurrent problem despite adapting concentrations and data collection times together with our ILL contact. Generally, a spherical particle of the expected core size could be discerned, but there were no indications of a shells structure. We emphasize that the colloidal stability of these nanoparticles is excellent and we have other ways of demonstrating that the shell structure is there. We have published several papers on such core-shell nanoparticles, including on the type demonstrated in Fig. 1, which will also be exemplified below. Thus, the lack of signal seems to be related to how we performed the experiment and not to sample quality.

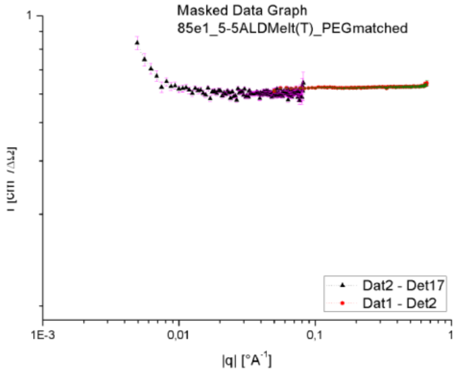


Fig. 2. One of the samples in Fig. 1 measured in H_2O/D_2O to match the PEG scattering length density. Data is normalized and background subtracted.

The result in Fig. 2 shows the result after data processing for a densely grafted sample measured in a H_2O/D_2O mixture set to match the PEG. The lack of feature is here not because the features shown in Fig. 1 were all due to PEG, but because of additionally high background noise that averages out the feature of the cores seen in Fig. 1.

As can be seen from the data in Fig. 3, which includes treated data from particles with both different sizes and different shell sizes as labeled, there are no major differences in features that could correspond to the shell. The differences that can be observed all relate to differences in concentration (total scattering intensity compared to background) and differences in core size from different samples. Attempts to fit different core-shell models yielded no significant deviation from this qualitative analysis, i.e. the presence of PEG shell features could not be obtained with confidence through fitting. Indeed, any fitting of a shell could as well be explained by e.g. core polydispersity within the bounds of the known polydispersity, SD 5-10% depending on sample as determined by SAXS and TEM.

The samples shown in Figs. 1 and 2 have very dense polymer shells close to the core that should translate into a star polymer-like density profile extending radially outwards from the core surface. However, even the cores that are monodisperse within an SD of 5% (as characterized by SAXS and TEM image analysis) yield only a weak and/or smeared signal. We contrast that to our experience with performing SAXS on the same particles where very distinct scattering profiles (many minima) could be obtained and a low polydispersity determined which agreed with image analysis of TEM data.

In summary, our conclusion from this pilot study was that we could not observe the expected shell features despite that SANS should be an ideal method to study such a system. We have continued our studies of the same type of core-shell nanoparticles with lab-SAXS; these results were published in Chemistry of Materials.[2] In these experiments we were able to not only resolve the cores, showing their monodispersity and low roughness also as modified core-shell nanoparticles in agreement with previous results,[1c] but additionally resolve parts of the shell for the very dense polymer brushes obtained by our synthetic approach. An example of these results is shown in Fig. 4. The data was analyzed with the theoretical model for the shell profile that was (supposed to be) used with the SANS data. The great difference in the scattering curves as well as the high confidence of the fit and the control measurements, e.g. actuation to change the hydration state of the brush, makes us incredulous to why our experiments at D22 failed. We therefore waited a long time to file this report in the hope of finding a plausible explanation to why our pilot study at D22 failed in this respect, but we have still failed to pinpoint any obvious error in the experiment of this magnitude, also in discussions with our ILL contact and other scattering experts.

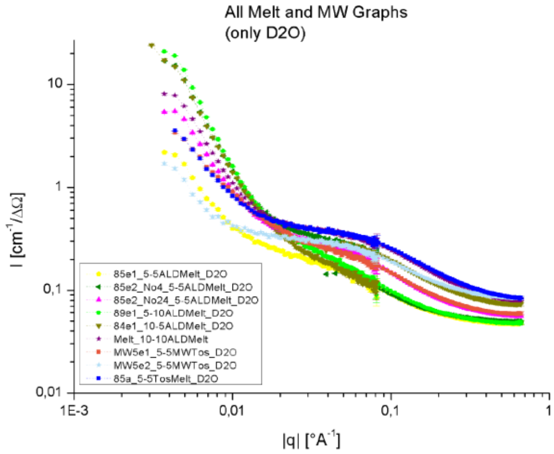


Fig. 3. The data shows a summary of different kinds of particles using different synthesis methods as well as shell sizes, but with varied shell properties. The shell properties were varied in terms of grafting density as well molecular weight, meaning different shell densities and thickness.

With SAXS it is only possible to resolve the inner part of the shell, where a shoulder in the scattering length density forms, due to the inherent low contrast of PEG to X-rays. We therefore still would like to and hope to perform further SANS measurements to capture dynamically changing polymer brushes synthesized with the same methods as those investigated here, as well as to extend the studies to novel shell structures with secondary structures and engineered non-monotonic polymer density profiles.

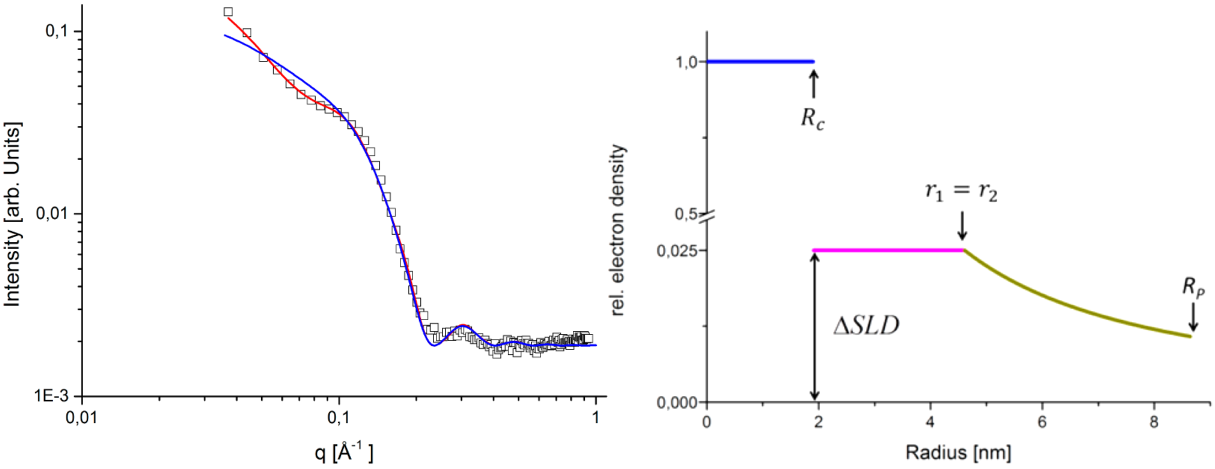


Fig. 4. Left, example of SAXS measurements (circles) and analysis of the same kind of core-shell nanoparticles as investigated in most of the SANS measurements, plus fitting using the model developed for the analysis of the SANS data.[2] These measurements showed strong features and demonstrated a unique segment density profile of the polymer shell that could have been further resolved by a successful measurement series during the preceding SANS experiments. The blue line shows the fit with a parabolic shell profile together with the spherical core in a conventional core-shell model. The red line shows a fit with the theoretically predicted star polymer-like segment density profile for the shell on a densely grafted core-shell nanoparticle shown to the right.

References

1. (a) Amstad, E.; Gillich, T.; Bilecka, I.; Textor, M.; Reimhult, E., Ultrastable Iron Oxide Nanoparticle Colloidal Suspensions Using Dispersants with Catechol-Derived Anchor Groups. *Nano Letters* **2009,** *9* (12), 4042-4048; (b) Isa, L.; Calzolari, D. C. E.; Pontoni, D.; Gillich, T.; Nelson, A.; Zirbs, R.; Sanchez-Ferrer, A.; Mezzenga, R.; Reimhult, E., Core-shell nanoparticle monolayers at planar liquid-liquid interfaces: effects of polymer architecture on the interface microstructure. *Soft Matter* **2013,** *9* (14), 3789-3797; (c) Zirbs, R.; Lassenberger, A.; Vonderhaid, I.; Kurzhals, S.; Reimhult, E., Melt-grafting for the synthesis of core-shell nanoparticles with ultra-high dispersant density. *Nanoscale* **2015,** *7* (25), 11216-11225; (d) Lassenberger, A.; Bixner, O.; Gruenewald, T.; Lichtenegger, H.; Zirbs, R.; Reimhult, E., Evaluation of high-yield purification methods on monodisperse PEG-grafted iron oxide nanoparticles. *Langmuir* **Submitted**.
2. Grünewald, T. A.; Lassenberger, A.; van Oostrum, P. D. J.; Rennhofer, H.; Zirbs, R.; Capone, B.; Vonderhaid, I.; Amenitsch, H.; Lichtenegger, H. C.; Reimhult, E., Core-shell structure of monodisperse PEG-grafted iron oxide nanoparticles studied by SAXS. *Chemistry of Materials* **2015**.