

Superparamagnetic and fluorescent thermo-responsive core-shell-corona hybrid nanogels with a protective silica shell

Thomas M. Ruhland¹, Paul M. Reichstein¹, Alexander P. Majewski¹, Andreas Walther² and Axel H. E. Müller¹

¹Department of Macromolecular Chemistry II, University Bayreuth, Bayreuth, Germany; thomas.ruhland@uni-bayreuth.de

²DWI at the RWTH Aachen, Aachen, Germany

INTRODUCTION

Colloidal hybrid nanostructures target multifunctional materials for future technologies, in which the most interesting functionalities of different material classes are combined in a single entity demonstrating unique and advanced size-dependent properties for an enormous number of possible applications ranging from drug delivery and biological sensing to materials engineering.¹⁻⁷

Herein, we are interested in combining optical and magnetic properties of inorganic NP's (semiconductor nanocrystals (quantum dots) and γ -Fe₂O₃) with the stimuli-responsive behavior of polymers (Poly(*N*-isopropylacrylamide, PNIPAAm) in hybrid inorganic/organic core-shell-corona nanogels. In more detail, multifunctional hybrids are realized by entrapping the magnetic or semiconductor NPs within the same silica spheres followed by an encapsulation with thermo-responsive polymer shells using a flexible and facile synthesis of well-defined PNIPAAm coronas. We chose the intermediate silica shell to provide the final hybrid particles with a beneficial barrier layer. The final particles consist of silica-coated maghemite and/or CdSe(ZnS) cores and thermo-responsive and lightly crosslinked PNIPAAm nanogel corona. Combining the soft-matter responsiveness with the advanced functionality, magnetism and fluorescence, can therefore result in very attractive multifunctional hybrids.

EXPERIMENTAL

Synthesis. The synthetic strategy towards monodisperse thermo-sensitive hybrid materials with core-shell-corona architecture is schematically illustrated in Scheme 1.

In a first step, we synthesized monodisperse and hydrophobically functionalized superparamagnetic (γ -Fe₂O₃) via thermal decomposition of Fe(CO)₅ using a procedure developed by Hyeon et al.⁸ Fluorescent (CdSe(ZnS)) NPs, which serve as functional cores for the final hybrid nanogels, were prepared using a modified literature procedure.⁹ This is followed by the encapsulation of single or multiples NPs with a silica layer by a dedicated microemulsion procedure, yielding monodisperse core-shell γ -Fe₂O₃/SiO₂, CdSe(ZnS)/SiO₂ particles. To attach the final thermo-responsive polymer corona, the surface of the core-shell NP is then activated by a silane-carrying methacrylate, 3-(methacryloyloxy)propyl trimethoxysilane (MPTS), which introduces double-bonds on the surface. In the end, a lightly crosslinked PNIPAAm shell is immobilized by a "grafting through/onto" polymerization of *N*-isopropylacrylamide (NIPAAm) in the presence of a bifunctional crosslinker, *N,N'*-methylene diacrylamide (BIS).

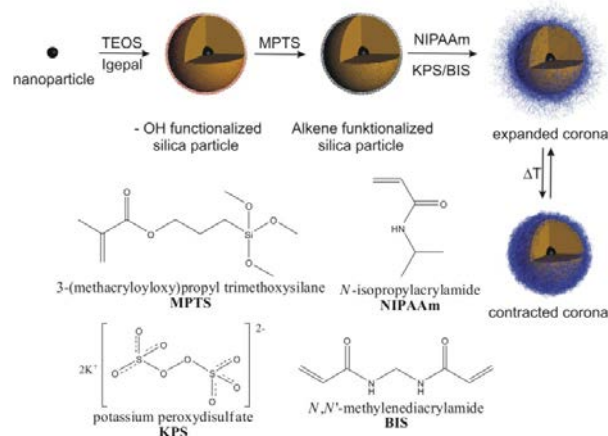
Dynamic Light Scattering (DLS) measurements were performed on an ALV DLS/SLS-SP 5022F compact goniometer system with an ALV 5000/E correlator and a He-Ne laser. CONTIN analysis of the autocorrelation functions was carried out.

(Cryo-)Transmission Electron Microscopy. TEM images were taken with a Zeiss CEM 902 or 922 OMEGA electron microscope operated at 80 kV or 200 kV, respectively. Both machines are equipped with an incolumn energy filter. For *cryo-TEM* studies, a drop of the sample dissolved in water was put on a lacey grid, where most

of the liquid was removed with blotting paper, leaving a thin film stretched over the lace. The specimens were instantly vitrified by rapid immersion into liquid ethane and cooled to approximately 90 K by liquid nitrogen in a temperature controlled freezing unit.

Vibrating Sample Magnetometer (VSM). The magnetic properties were investigated via quasi-static magnetization experiments.

UV-VIS excitation and fluorescence emission spectra were recorded on a Hitachi U-300 and a Shimadzu RF-5301 instrument, respectively.



Scheme 1 Synthesis of NP/SiO₂/PNIPAAm core-shell-corona hybrid nanogels.

RESULTS

We present an easy and reproducible method for the preparation of well-defined multifunctional thermo-responsive inorganic/organic hybrid particles via two consecutive encapsulation processes of superparamagnetic (γ -Fe₂O₃) or fluorescent semiconductor (CdSe(ZnS)) nanocrystals with a silica layer and a crosslinked and responsive poly(*N*-isopropylacrylamide) polymer shell.

The γ -Fe₂O₃ NPs as well as CdSe(ZnS) NPs (Figure 1 A,C) are monodisperse and of uniform shape. To achieve a thorough barrier layer as chemical protection, to gain wettability and biocompatibility and to enable a flexible surface chemistry, we coated these nanocrystals in a next step with a silica shell using a microemulsion process. Herein, we achieved a straight-forward modification of the silica-coated NPs (typical radius 25 nm) with double bonds using MPTS (Figure 1 B,D).

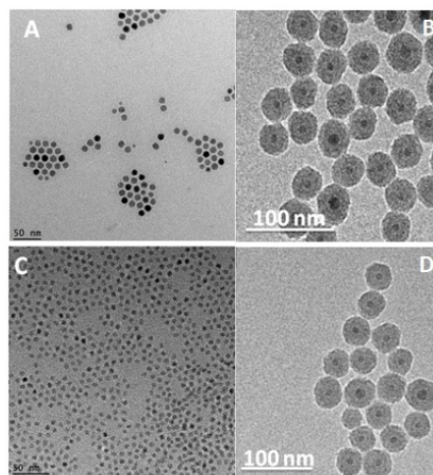


Figure 1 TEM images for (A) γ -Fe₂O₃, (B) γ -Fe₂O₃/SiO₂, (C) CdSe(ZnS) and (D) CdSe(ZnS)/SiO₂ NPs.

The immobilized, terminal double bonds serve as the linkage between the inorganic and the organic polymer part of the final hybrids. Subsequently, NIPAAm was polymerized with an additional bifunctional

crosslinking agent, BIS (10 w%). The MPTS-modified silica-coated core-shell particles act as seeds to immobilize the polymer layer in this precipitation polymerization. During the synthesis, the polymer chains collapse onto the silica surface due to the polymerization temperature of 70 °C, which is drastically above the LCST of PNIPAAm, leading to a self-limiting growth of the polymer shell. Minimization of the surface free energy forms regular spherical shapes. After purification, the highly water-soluble PNIPAAm corona enables a complete dissolution into core-shell-corona hybrid nanogel-type particles.

To confirm the structures of the hybrid nanogel particles, we show TEM and cryo-TEM images of the fluorescent CdSe(ZnS)/SiO₂/PNIPAAm hybrids in Figure 2. The lightly crosslinked PNIPAAm corona can be clearly seen in the TEM micrograph as a grayish homogeneous layer surrounding the central CdSe(ZnS)/SiO₂ core. Similar images can be obtained for the γ -Fe₂O₃ and containing particles. All resulting hybrids are very uniform in size and shape and exhibit a narrow size distribution. In some cases two silica-coated core-shell particles are encapsulated within one PNIPAAm corona, but there is no drastic influence on the size distributions observed in TEM or DLS. The cryo-TEM micrograph of CdSe(ZnS)/SiO₂/PNIPAAm display a fuzzy corona, highlighted by the encircled area. Due to the highly swollen PNIPAAm corona and the thereof originating low contrast, it is not possible to visualize the full extension of the corona with cryo-TEM. The imaging data however nicely confirm the successful formation of the hybrid core-shell-corona nanoparticles.

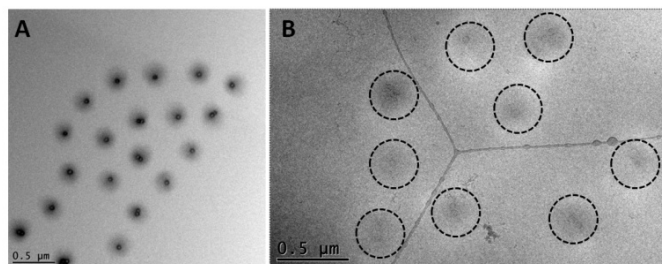


Figure 2 TEM image of CdSe(ZnS)/SiO₂/PNIPAAm (A) and cryo-TEM images of CdSe(ZnS)/SiO₂/PNIPAAm core-shell-corona hybrid nanogels (B). The circles correspond to the diameter obtained from DLS.

In a next step we investigated whether the functional properties of the nanocrystals were retained upon embedding them into a silica shell and polymer corona. The magnetic properties were investigated via quasi-static magnetization experiments using a Vibrating Sample Magnetometer (Figure 3A). After normalizing with the saturation magnetization, the three graphs of γ -Fe₂O₃, γ -Fe₂O₃/SiO₂ and γ -Fe₂O₃/SiO₂/PNIPAAm only show slight differences, proving that neither the incorporation into the core-shell nor core-shell-corona structure influences the superparamagnetic properties and the magnetic moment distribution. Fluorescence spectroscopy of the core-shell-corona CdSe(ZnS)/SiO₂/PNIPAAm particles demonstrates a preserved photoluminescence during the various encapsulation steps (Figure 3B).

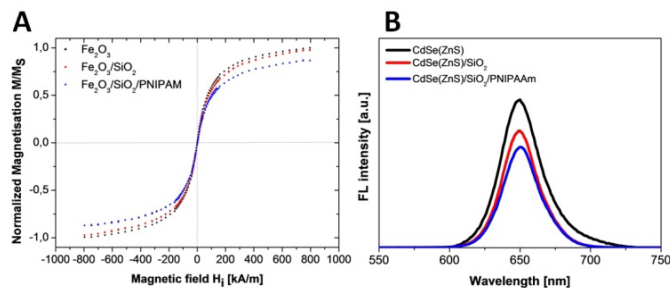


Figure 3 (A) Magnetic hysteresis curves of γ -Fe₂O₃ NPs, γ -Fe₂O₃/SiO₂ core shell particles and γ -Fe₂O₃/SiO₂/PNIPAAm hybrid material at RT. (B) Fluorescence spectra for CdSe(ZnS), CdSe(ZnS)/SiO₂ and CdSe(ZnS)/SiO₂/PNIPAAm.

Furthermore, the thermo-responsive character of the core-shell-corona PNIPAAm hybrid material was investigated by DLS. Figure 4 displays the dependence of the z-average hydrodynamic radius on temperature. The samples exhibit a temperature-induced volume phase-transition centered around 33 - 34 °C, originating from the smart PNIPAAm corona around the core-shell particles. The shrinking and swelling cycle of the CdSe(ZnS)/SiO₂/PNIPAAm particles is reproducible many times as depicted in the inset.

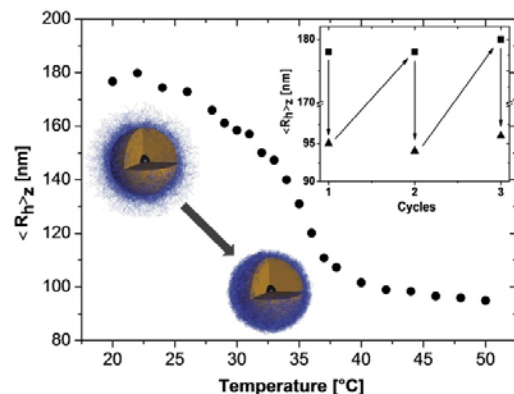


Figure 4 Dependence of the z-average hydrodynamic radius of CdSe(ZnS)/SiO₂/PNIPAAm nanogel particles on temperature. The inset depicts the changes in the z-average hydrodynamic radius for various temperature cycles.

Conclusion

We have developed an efficient and reproducible method for the synthesis of monodisperse core-shell-corona hybrid nanogels with a γ -Fe₂O₃/SiO₂, CdSe(ZnS)/SiO₂ and γ -Fe₂O₃/CdSe(ZnS)/SiO₂ core-shell structure and a thermo-sensitive PNIPAAm corona. The thickness of the SiO₂ shell can be controlled and the composition of the NPs within the silica particle can be manipulated according to the needs of a given application. The final particles retain full functionality of the superparamagnetic and fluorescent core materials and combine it with the barrier properties and ease of chemical functionalization of the silica shell. The responsive and interactive properties of the polymer corona, which can be easily attached, impart advanced functionality of soft matter materials, similar to the known property spectrum of microgels.

Acknowledgement

We thank André Gröschel for his help with the schemes, Alexander Majewski for providing the γ -Fe₂O₃ NPs, Thomas Lunkenbein for measuring the XRD spectra, Thomas Friedrich for performing the VSM measurements. This work was supported by the DFG within SFB 840 (TP A1). Thomas Ruhland thanks the Bavarian Graduate Support Program for a scholarship.

References

- Costi, R.; Saunders, A. E.; Banin, U. *Angew. Chem. Int. Ed.* **2010**, *49*, 4878.
- Kim, D. K.; Dobson, J. J. *Mater. Chem.* **2009**, *19*, 6294.
- Selvan, S. T.; Tan, T. T. Y.; Yi, D. K.; Jana, N. R. *Langmuir* **2009**, *26*, 1163.
- De, M.; Ghosh, P. S.; Rotello, V. M. *Adv. Mater.* **2008**, *20*, 4225.
- Mori, K.; Yamashita, H. *Phys. Chem. Chem. Phys.* **12** (2010) 14420.
- Kim, J.; Piao, Y.; Hyeon, T. *Chem. Soc. Rev.* **2009**, *38*, 372.
- Walther, A.; Matussek, K.; Müller, A. H. E. *ACS Nano* **2008**, *2*, 1167.
- Hyeon, T.; Lee, S. S.; Park, J.; Chung, Y.; Na, H. B. *J. Am. Chem. Soc.* **2001**, *123*, 12798.
- Zhelev, Z.; Ohba, H.; Bakalova, R. *J. Am. Chem. Soc.*, **2006**, *128*, 6324.