Phase-transfer of CdSe@ZnS quantum dots using amphiphilic hyperbranched polyethylenimine†

Thomas Nann

Received (in Cambridge, UK) 24th September 2004, Accepted 19th January 2005
First published as an Advance Article on the web 7th February 2005
DOI: 10.1039/b414807j

A new, straightforward method for the phase-transfer of CdSe@ZnS quantum dots from non-polar solvents into water and short-chained alcohols using amphiphilic hyperbranched polyethylenimine of different molar weights is suggested and the experimental procedure is discussed as well as the chemical properties of the resulting polymer-derivatised nanocrystals.

Following the discovery of a route to highly luminescent and monodisperse CdSe nanocrystals by Murray *et al.*[1] and the subsequent improvement with a ZnS-shell by Hines *et al.*,[2] there was tremendous interest in these kind of particles—especially as potential labels for bioanalytical purposes,[3] novel luminescent materials,[4] tunable light-emitting diodes,[5] quantum dot lasers,[6] and others.

Transfer of these nanoparticles (so called quantum dots or QDs) into water is a prerequisite for biological applications and several routes were published until now.[7] In the current communication we suggest a new, facile method for phase-transfer of QDs into water using amphiphilic hyperbranched polyethyleneimine. Besides its simplicity, the method has the advantage, that proteins can be directly coupled to the amine groups of the polymer by means of a peptide bond. Such a bond can be realised with commercially available coupling agents like 1-ethyl-3-(3-dimethylaminopropyl)-carbodiimide (EDC).[8]

CdSe@ZnS quantum dots were prepared similar to previously published procedures.[9] Hyperbranched polyethylenimine (PEI) was purchased from Aldrich in a low (800 D) and a high (25 kD) molecular weight modification.

Monodisperse QDs usually obtain a hydrophobic surface layer from the surfactants used in the synthesis (mostly trioctylphosphinoxide and/or hexadecylamine). Thus, they form sterically stabilised colloids in non-polar solvents and coagulate in polar solvents (a list is given in Table 1). Since aqueous colloids are mostly stabilised electrostatically, charges have to be added during the phase-transfer process. The proposed transfer protocol is based on the amphiphilic character of PEI.[10] PEI is soluble in many polar solvents and sufficiently soluble in chloroform and dichloromethane (*cf.* Table 1). Therefore, the first step of the phase-transfer includes the displacement of the original surface ligands of the QDs. The hydrophobic layer is exchanged with PEI in chloroform. QDs and PEI in chloroform build a very stable colloid, which cannot be centrifuged with a common laboratory centrifuge.

† Electronic supplementary information (ESI) available: experimental details and additional data. See http://www.rsc.org/suppdata/cc/b4/b414807j/

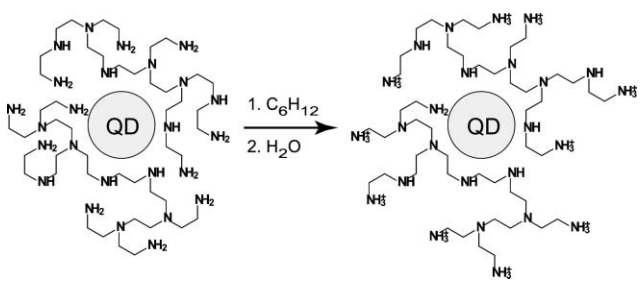
Table 1 Solubility of QDs and PEI in different solvents

Solvent	QDs	PEI (800 D)	PEI (25 kD)
Chloroform	Good	Good	Good
Dichloromethane	Good	Good	Fair
Cyclohexane	Good	Insoluble	Insoluble
Toluene	Good	Insoluble	Insoluble
Tetrahydrofuran	Fair	Partially	Insoluble
Methanol	Insoluble	Good	Good
Ethanol	Insoluble	Good	Fair
Water	Insoluble	Good	Good
Dimethylsulfoxide	Partially	Good	Fair
Dimethylformamide	Partially	Insoluble	Insoluble

The subsequent phase-transfer can be performed in two variations: First, direct extraction of the QDs from the chloroformic solution with water. Second, precipitation of the PEI-derivatised QDs with cyclohexane and subsequent redispersion in water (or any other protic solvent). The direct extraction occurs over several hours. In general, the precipitation method was preferred, because the water/chloroform boundary was not very clear and many QDs remained in this phase boundary zone.

After precipitation of the PEI-coated QDs with cyclohexane, the pellet was soluble in water, methanol, and ethanol and insoluble in *e.g.* chloroform and less polar solvents. At first, this was surprising, because the nanoparticles were precipitated *from* chloroform. This observation lead to the conclusion, that PEI facilitates steric stabilisation in chloroform and electrostatic stabilisation in protic solvents. Once 'switched' to the electrostatic conformation, the state seems to be irreversible. This mechanism is supported by the fact, that the pH-value is strongly basic in water and short-chained alcohols. Therefore, the solvents must have been deprotonated by the PEI, which is in consequence positively charged. Scheme 1 depicts the proposed mechanism of the amphiphilic phase-transfer.

The phase transfer was performed using two types of PEI: low molecular weight PEI (800 D) and high molecular weight PEI



Scheme 1 Switching of amphiphilic PEI from fairly lipophilic to hydrophilic.

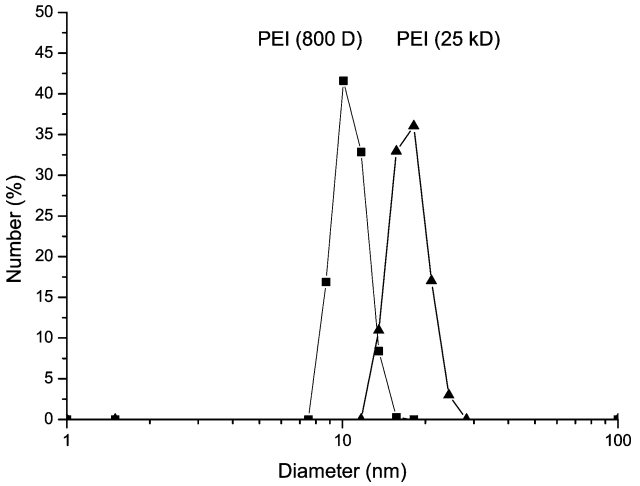


Fig. 1 Size distribution of PEI-derivatised QDs in water, measured by light back-scattering. Squares: 800 D PEI; triangles: 25 kD PEI.

(25 kD). Some minor differences were observed with these two polymers. In general, the 25 kD PEI was less soluble in less-polar solvents, but provided better stabilisation of the colloids in both, the steric and the electrostatic case. Much more cyclohexane or cyclohexane/chloroform was needed to precipitate the 25 kD PEI derivatised QDs from chloroform or methanol, respectively.

The hydrodynamic diameter of the water-soluble QDs was measured by means of a light back-scattering technique (Malvern Inc., Nanosizer ZS). Native QDs in non-polar solvents were not 'visible' in the Nanosizer. Results for low and high molecular weight PEI derivatised QDs are displayed in Fig. 1. As expected, the low MW PEI resulted in a smaller hydrodynamic diameter as the high MW PEI. The average diameter of the low MW PEI-QDs was 10.7 $\pm$ 1.4 nm, the high MW PEI-QDs 17.5 $\pm$ 2.5 nm, respectively. More than 99% of the QDs were found within these two peaks, indicating a very good electrostatic stabilisation in water.

A major advantage in using QDs instead of organic fluorophores for bioanalytical purposes is the increased photostability. QDs in chloroform or toluene do not show any photobleaching, rather photobrightening. In the presence of PEI, the QDs underwent fast photooxidation in both, chloroform and water. If the PEI-derivatised QDs were stored in the dark, they remained luminescent for months. Therefore, the PEI seems to enhance or even enables photooxidation of the QDs. It is assumed that the photooxidation process occurs at surface defects of the QDs. Therefore, it was tested if the photooxidation can be inhibited by saturation of the surface with mercaptoethanol (ME). It was found, that the luminescence intensity increases drastically—which is in agreement with the findings of Hohng *et al.*[11]—and the rate of photodegradation decreased. Thus, it is plausible to assume, that surface defects are the initial sites for this unusual effect.

In conclusion, a novel, straightforward method for phase-transfer of QDs by means of amphiphilic hyperbranched PEI is presented. It was found that the method is suitable especially for potential biological applications, as long as the QDs remain highly photoluminescent and provide functional groups for covalent binding of biomolecules.

Thomas Nann
Freiburg Materials Research Center (FMF), Stefan-Meier-Str. 21, D-79104 Freiburg, Germany. E-mail: thomas.nann@fmf.uni-freiburg.de; Fax: +49 761 203-4768; Tel: +49 761 203-4755

Notes and references

1 C. B. Murray, D. J. Norris and M. G. Bawendi, *J. Am. Chem. Soc.*, 1993, **115**, 8706.
2 M. A. Hines and P. Guyot-Sionnest, *J. Phys. Chem.*, 1996, **100**, 468.
3 *E.g.*: M. J. Bruchez, M. Moronne, P. Gin, S. Weiss and A. P. Alivisatos, *Science*, 1998, **281**, 2013; W. C. W. Chan and S. Nie, *Science*, 1998, **281**, 2016; J. Riegler, P. Nick, U. Kielmann and T. Nann, *J. Nanosci. Nanotech.*, 2003, **3**, 380.
4 S. T. Selvan, C. Bullen, M. Ashokkumar and P. Mulvaney, *Adv. Mater.*, 2001, **13**, 985.
5 *E.g.*: X. Peng, M. C. Schlamp, A. V. Kadavanich and A. P. Alivisatos, *J. Am. Chem. Soc.*, 1997, **119**, 7019; J. Lee, V. Sundar, J. R. Heine, M. G. Bawendi and K. F. Jensen, *Adv. Mater.*, 2000, **12**, 1102.
6 V. I. Klimov, A. A. Mikhailovsky, S. Xu, A. Malko, J. A. Hollingsworth, C. A. Leatherdale, H.-J. Eisler and M. G. Bawendi, *Science*, 2000, **290**, 314.
7 Review: J. Riegler and T. Nann, *Anal. Bioanal. Chem.*, 2004, **379**, 913.
8 *E.g.*: G. T. Hermanson, *Bioconjugate Techniques*, Academic Press, San Diego, 1996.
9 T. Nann and P. Mulvaney, *Angew. Chem. Int. Ed.*, 2004, **43**, 5393. The ESI† contain experimental details like the QD preparation and a typical protocol for phase-transfer.
10 C. Aymonier, U. Schlotterbeck, L. Antonietti, P. Zacharias, R. Thomann, J. C. Tiller and Stefan Mecking, *Chem. Commun.*, 2002, **24**, 3018.
11 S. Hohng and T. Ha, *J. Am. Chem. Soc.*, 2004, **126**, 13.

