

Reversible Phase Transfer of (CdSe/ZnS) Quantum Dots between Organic and Aqueous Solutions

Denis Dorokhin,^{†,*} Nikodem Tomczak,^{†,§} Mingyong Han,^{§,-,‡} David N. Reinhoudt,[‡] Aldrik H. Velders,[‡] and G. Julius Vancso^{†,*}

[†]Materials Science and Technology of Polymers and, [‡]Supramolecular Chemistry and Technology, Faculty of Science and Technology and MESA⁺ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands, [§]Institute of Materials Research and Engineering, ^{A*}STAR (Agency for Science, Technology and Research), 3 Research Link, Singapore 117602, and ⁻Division of Bioengineering, National University of Singapore, Singapore 117576

Hybrid organic–inorganic composite materials find numerous applications in optoelectronics,^{1,2} nanocomposites,³ biotechnology,⁴ and biodiagnostics.⁵ For luminescence applications, semiconductor nanocrystals (quantum dots, QDs) are materials with unique optical properties, most notably due to the QD's size- and composition-tunable luminescence emission, broad absorption and narrow emission lines, and low photobleaching rates.⁶ Because of these attractive properties QDs are currently applied in fields of optoelectronics,^{7–10} biolabeling,^{11–15} and sensing.^{16–18} For application of QDs in biological sensing, or biolabeling, the nanoparticles must be dispersible in aqueous solution and in relevant biological buffers.¹⁹ Ligand exchange reactions have been widely used to modify the surface of quantum dots to tune the QD solubility^{11,20} as well as to provide functionality for further coupling to biomacromolecules.²¹ Phase transfer of QDs between solvents with markedly different polarity can be also achieved by coating the QDs with amphiphilic molecules *via* electrostatic²² hydrophobic/hydrophobic,^{23,24} or host–guest interactions.^{25–28} For some applications it is desirable to transfer the nanoparticles from the sensing medium and perform analysis in a new medium free from the interfering background molecules. Therefore there is a need to develop QD materials, which would undergo reversible phase transfer between solvents of markedly different polarity. This might be realized by employing stimulus responsive ligands, which upon external *stimuli* (temperature, pH, electric field) change their chemistry, and therefore the physicochemi-

ABSTRACT Trioctylphosphine oxide (TOPO) stabilized CdSe/ZnS quantum dots (QD) were modified with 6-ferrocenyl-1-hexanethiol (FcHT) or 11-ferrocenyl-1-undecanethiol (FcUT) *via* ligand exchange. The presence of ferrocenyl thiol ligands on the surface of the QDs was proven by diffusion ordered NMR spectroscopy. Upon replacement of the initial TOPO ligand with ferrocene derivatives the emission of the QDs decreased. Phase transfer of ferrocene-modified QDs from organic solvents into water was achieved by complexation reactions with β -cyclodextrin (β -CD). The QDs coated with ferrocene thiols are soluble in nonpolar solvents and are transferred into the aqueous phase upon formation of host–guest complexes between the ferrocene units and the cavity of β -CD. The reversibility of the phase transfer was probed by the addition of naphthalene and adamantane derivatives to the aqueous phase containing QD-[Fc-CD] adduct.

KEYWORDS: quantum dots · CdSe/ZnS · ferrocene · cyclodextrin · host–guest complexes · solution phase transfer · luminescence quenching

cal properties of the QD surface, or by using ligands able to form supramolecular complexes with other molecules.

Nanoscale materials with multiple ferrocene units have attracted attention owing to possible applications of such materials in sensing,^{17,29–31} catalysis,^{32,33} or in optoelectronic devices.³⁴ Ferrocene-coated metal^{32,35} and silica nanoparticles,^{30,33} dendrimers functionalized at the periphery,^{31,36,37} and metal-selenide nanoclusters passivated with ferrocenyl ligands^{38–40} have been reported. However, to the best of our knowledge there are no reports describing the direct attachment of ferrocene-thiol ligands to the surface of QD.

In this article we describe the synthesis of ferrocene-coated CdSe/ZnS quantum dots for reversible phase transfer *via* host–guest interactions. TOPO-coated CdSe/ZnS QDs were functionalized with ferrocenyl thiols of various alkyl chain lengths (6 and 11 CH₂ units) *via* the ligand exchange reaction. NMR spectroscopy proved the exchange of ligands at the QD surface. The

*Address correspondence to g.j.vancso@utwente.nl.

Received for review October 3, 2008 and accepted February 06, 2009.

Published online February 20, 2009. 10.1021/nn8006515 CCC: \$40.75

© 2009 American Chemical Society

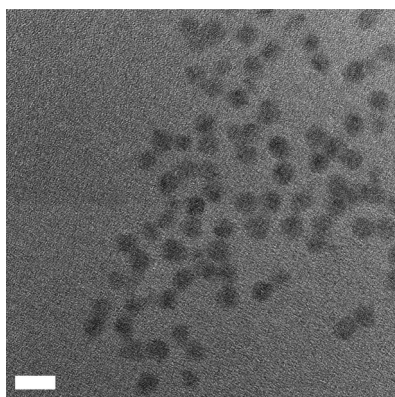


Figure 1. Transmission electron microscope image of individual TOPO-coated CdSe/ZnS nanocrystals. The size of the nanocrystals is ~ 5.2 nm. The scale bar is 10 nm.

presence of ferrocene causes a decrease of the luminescence quantum yields (QY) of QDs. Ferrocene-coated QDs are shown to undergo reversible phase transfer from chloroform to water (and *vice-versa*) upon formation/release of inclusion complexes of β -cyclodextrin with the ferrocene units on the surface of the QDs.

RESULTS AND DISCUSSION

The initial TOPO-coated QDs were purified by centrifugation to remove excess TOPO from the storage solution. The solution of purified QDs was clear and transparent indicating that no aggregation of the QDs occurred after the purification procedure. The CdSe/ZnS QDs were characterized by transmission electron microscopy (TEM), UV-vis, and spectrofluorometry. In Figure 1 individual TOPO-stabilized CdSe/ZnS nanocrystals are shown. The average diameter value of the QDs was estimated from the images to be 5.2 ± 0.3 nm. Absorption and emission spectra of CdSe/ZnS QDs (QD625) are shown in Figure 2. The maximum of the first absorption peak is located at 618 nm. The concentration of the nanocrystals was estimated by following the procedure of Peng *et al.*⁴¹ The emission spectrum has a maximum located at 625 nm, and the full width at half-maximum (fwhm) value of the emission peak is equal to 32 nm. The calculated QY of TOPO-coated QDs is equal to 27.8%.

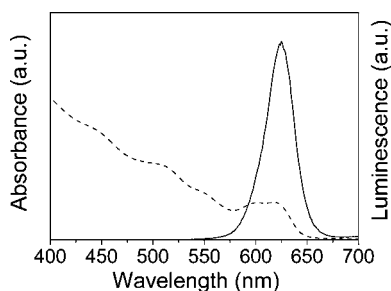


Figure 2. UV-vis spectrum (dash) and photoluminescence spectrum (solid) of CdSe/ZnS in toluene. The emission maximum is at 625 nm; the full width at half-maximum is equal to 32 nm.

The initial QDs are coated with TOPO to stabilize them in an organic solvent. Ligand exchange reaction with an appropriate thiol is a convenient and rapid method to modify the surface of TOPO-coated QDs.⁴² To perform the ligand exchange reaction TOPO-coated QDs were mixed with a large excess of the ferrocene derivatives. The molar ratio between the ferrocenyl thiols and QDs was 1:130, and it was chosen by taking into account the geometrical size of the nanoparticles and the surface coverage of a ferrocene sulfide monolayer on gold.⁴³ To prevent possible oxidation of the QDs as well as that of the thiol group, the reaction is performed under nitrogen atmosphere. The solution was stirred vigorously to facilitate the replacement of TOPO molecules from the surface of the QDs. Although it seems that the reaction is fast and is close to completion within a few hours, in order to reach high surface coverage a longer reaction time of 6 days was used. After the reaction ultracentrifugation was applied to remove the untreated ferrocene derivative and TOPO from the solution.

We employed NMR spectroscopy to prove that the ligand exchange reaction takes place, and that the new ligand binds to the surface of the quantum dots. Solution-state ^1H NMR spectroscopy is a powerful tool for the characterization and investigation of nanoparticles, including semiconducting nanocrystals.^{44–47} In particular, pulsed field gradient (PFG) spectroscopy is a most valuable tool for the investigation of these relatively large systems that show relatively broad signals. PFG experiments allow the discrimination of small and larger molecules, using the different self-diffusion coefficients of the molecules. Discrimination of differently sized molecules can be obtained by performing diffusion-ordered spectroscopy (DOSY) experiments, pseudo-2D experiments where NMR signals from a mixture of compounds in solution are spread along a diffusion-coefficient axis.⁴⁸ Another, faster, easy-to-perform method is using the 1D sequence of a bipolar, stimulated echo experiment with a fixed gradient strength and fixed diffusion time, which acts like a filter. Signals of small solvent molecules, like toluene or water, and small organic molecules like TOPO or FcHT, can so readily be filtered out, leaving a clear spectrum of the functionalized QDs.

In Figure 3 the diffusion-filtered ^1H spectra of QDs are shown. The pulse sequence used emphasizes the signals of relatively large molecules, suppressing those of small molecules, like residual protonated toluene, water, impurities, uncapped TOPO, *etc.* In fact, the intense signals at high field in a normal experiment, almost completely vanish in the diffusion-weighted experiment. In Figure 3 the diffusion-filtered ^1H NMR spectra of FcHT and FcUT-modified QDs are compared to the native TOPO-capped QDs. The TOPO-capped nanocrystals exhibit characteristic peaks of the alkyl chains with chemical shifts in the range of 1–2 ppm,

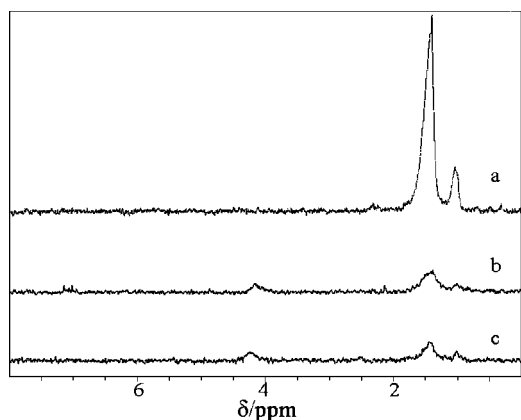


Figure 3. ^1H NMR spectrum of (a) CdSe/ZnS–TOPO, (b) CdSe/ZnS–FcHT and (c) CdSe/ZnS–FcUT QDs in toluene-*d*. Chemical shifts in the range of 1–2 ppm are attributed to alkyl chains of TOPO and ferrocene derivatives. Peaks in the range of 4–5 ppm are attributed to the ferrocene protons of the FcHT or FcUT ligands linked to the CdSe/ZnS QDs.

but do not show peaks in the range of 4–5 ppm. The spectra of the FcHT and FcUT modified QDs on the other hand show a broad peak in the range of 4–5 ppm, which can be attributed to the ferrocene protons of the FcHT or FcUT ligands linked to the CdSe/ZnS QDs. The broad peaks around 1.5 ppm are related to the alkyl protons of the remaining TOPO, still present on the surface, and from the alkyl protons of the FcHT or FcUT chains. Also for the QDs used in the phase transfer studies, the ferrocene-functionalization and ligand-exchange reactions have been followed by 1D-filtered diffusion-ordered spectroscopy.

The ^1H NMR data of TOPO-capped QDs and the ferrocene-derivatized QDs unambiguously prove that ligand exchange reaction between TOPO and ferrocene thiols indeed has occurred. The lines of the ^1H NMR for the ferrocene region, were however too broad to obtain reliable results for the molar ratios between the TOPO and Fc ligands present on the QD surface. Previous NMR studies have shown that during the ligand exchange reactions with thiols the TOPO ligands are replaced between 85 and 95%.⁴² The ligand length and the bulkiness of the end-group can also be a factor. Longer ligands may exclude ligands with shorter chains from the QD surface.³² Thus the displacement of TOPO should in principle be more efficient for the FcUT molecules than for FcHT. However, steric hindrance of the bulky Fc groups may prevent full displacement of the TOPO ligands on the QD surface.

Spectrofluorometry and UV–vis absorption were applied to characterize the optical properties of ferrocenyl-coated QDs after the purification from the excess of ferrocene thiols. For both FcHT and FcUT the luminescence of modified QDs significantly decreased after the reaction (Figure 4b). Absence of

changes in the absorption spectra between modified and unmodified QDs (Figure 4a) shows that the decrease in luminescence is due to the presence of ferrocene rather than to changes in QD composition or size due to long reaction times or high reaction temperature. No significant changes in the absorption profile were found either directly after ligand exchange reaction or after the purification of the materials obtained in comparison to the original TOPO-coated QDs.

A relatively weak emission of the ferrocene-coated QDs was detected when exciting the QDs at 510 nm (Figure 4b). The QY of the modified QDs was 0.89% and 1.66% for FcHT- and FcUT-coated QDs, respectively. Ferrocene and ferrocenyl derivatives are known quenchers of excited states.⁴⁹ In previous studies ferrocenes were also shown to affect the emission of QDs.^{34,50} The exact mechanism of the quenching is currently under investigation, but electron transfer reactions involving ferrocene units and QDs are most likely to be responsible for the decrease of the luminescence. It should be noted that the QY of the ferrocene-coated QDs depends on the reaction time. Shorter reaction times lead to lower degrees of quenching. Surface coverage, therefore, might influence the QY of the materials.

Ferrocene is known to form complexes with β -cyclodextrin with a complexation constant $K = 1230 \text{ M}^{-1}$.³⁷ The chemical structure of β -CD forms a hydrophilic ring with hydrophobic cavity, which can interact with a suitable hydrophobic molecule that fits to the cavity. Therefore, transfer of ferrocene-coated QDs in and out of the aqueous phase upon complexation and decomplexation with β -CD can be achieved. The simulated lengths of FcHT, FcUT, and TOPO ligands are equal to 12, 19, and 13 Å, respectively. FcHT ligands are therefore slightly buried in the remaining TOPO. In the complexation reactions with β -CD the access of the β -CD to the guest molecule is important. Additionally, the orientation of the guest in the β -CD cavity can affect the complexation behavior. The location of Fc moieties above the TOPO layer should in principle facilitate the complexation reaction. Thus, to demonstrate the complexation of ferrocene-coated QDs by β -CD we chose QDs coated with the FcUT ligands. Two series of experiments were performed using QD605 and QD595. We

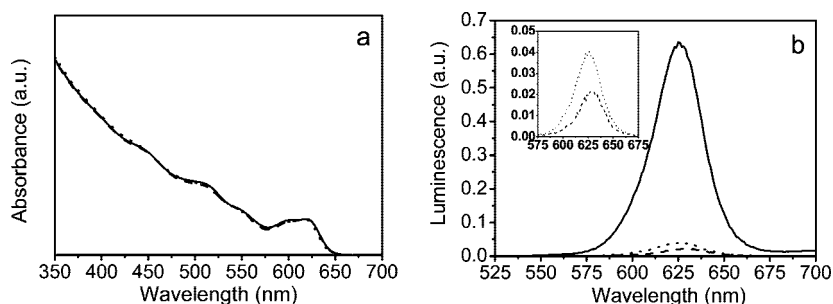


Figure 4. (a) Absorption and (b) emission spectra of QD-TOPO (solid), QD-FcHT (dotted), and QD-FcUT (dashed) in toluene. The inset in panel b shows the rescaled emission spectra for QD-FcHT (dotted) and QD-FcUT (dashed).

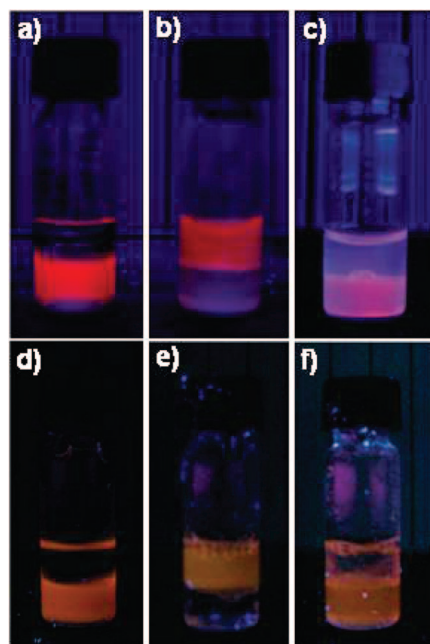


Figure 5. Photographs of the phase transfer experiments using QD605 (a,b,c) and QD595 (d,e,f) quantum dots. The QD-Fc-UT in the chloroform phase (a,d) are transferred to water (b,e) upon complexation of the ferrocene units with β -CD. Upon addition of sodium 2-naphthalene sulfonate (c) and AdCOOH (f) the QDs migrate back to the chloroform phase.

have kept the ligand exchange reaction times short in order to avoid steric hindrance of the ferrocene units during complexation with β -CD. The QY for unmodified and modified QDs was calculated to be 37.6% and

25.8%, and 39.3% and 17.9% for QD605 and QD595, respectively, indicating low surface coverage of ferrocene thiols for both QD samples. The related absorption, emission, and NMR spectra of these compounds are shown in the Supporting Information. In Figure 5 we show two series of photographs of vials containing water and chloroform. Initially the QDs are present in the chloroform phase (Figure 5a,d). Upon addition of cyclodextrin, complexation of the ferrocene units on the surface of QD occurs, and the nanocrystals migrate to the water phase (Figure 5b,e). This is accompanied by a noticeable emission from the water phase. In Figure 6 we show the corresponding absorption and emission spectra of the chloroform phase before adding β -CD and of the water phase after adding β -CD.

The position of the first absorption peak for the organic and aqueous phases does not change noticeably for both QDs. There are, however, some minor changes in the profile of the absorption curve, which could be related to some aggregation of the nanoparticles in the aqueous medium. Dispersability of the QDs in water indicates that the complexation of the ferrocene units on the QD surface by β -CD was not prevented by steric hindrance. Because of short ligand exchange reaction times, the remaining TOPO ligands on the QD surface may serve as spacers between ferrocenyl thiol molecules. Additionally, we have deliberately chosen to use the FcUT ligands, which are longer than the TOPO molecules. Therefore we created an easy access for the β -CD molecules to the Fc units.

Based on the absorption spectrum we may estimate

the efficiency of the β -CD driven phase transfer to be equal to $\sim 80\%$ for both QDs. The emission spectra (Figure 6 b,d) clearly confirm the presence of QDs in the aqueous phases. Although the overall emission intensity decreased, no noticeable changes in the emission peak position are present. The reason for the luminescence decrease is unclear at present, but it is likely related to the presence of cyclodextrin and different media. Feng *et al.* reported cyclodextrin-induced phase transfer performed for TOPO-derivatized CdSe/ZnS QDs.²⁶ In their work a 15 nm red shift after transfer of QDs to water was observed, and it was related to the coordination of β -CD to the surface of the QDs. In this study we do not observe any shift in the emission and direct attachment of β -CD to the ZnS surface is rather unlikely.

The formation of host–guest complex between β -CD and ferrocene is usually reversible upon addition of molecules having a higher binding constant to the cavity of the β -CD.⁵¹ To show that

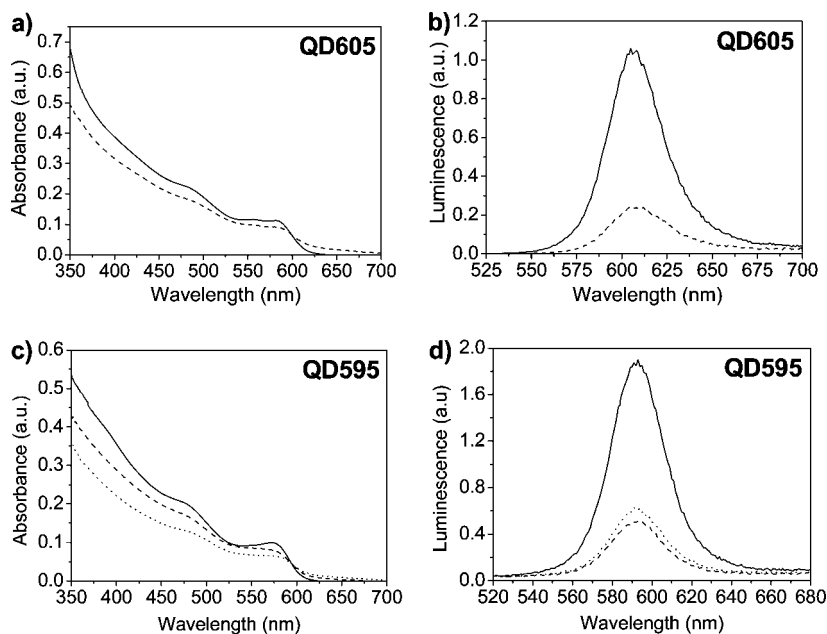


Figure 6. (a) Absorption spectra of QD-FcUT (QD605) in chloroform solution (solid) and QD-[FcUT-CD] complex in water (dashed), (b) emission spectra of QD-FcUT (QD605) in chloroform (solid) and QD-[FcUT-CD] (dashed) in water, (c) absorption spectra of QD-FcUT (QD595) in chloroform solution (solid), QD-[FcUT-CD] complex in water (dashed), and chloroform after addition of AdCOOH (dotted), (d) emission spectra of QD-FcUT (QD595) in chloroform (solid), QD-[FcUT-CD] in water (dashed), and QD-FcUT in chloroform after addition of AdCOOH (dotted).

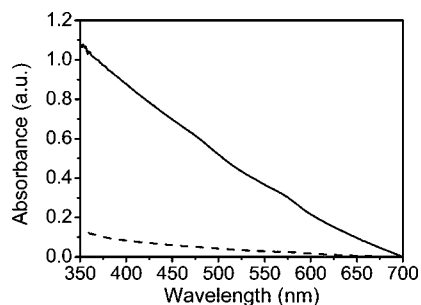


Figure 7. Absorption spectra of QD-FcUT (QD605) in chloroform (solid) and aqueous phase (dashed) after addition of sodium 2-naphthalene sulfonate.

the phase transfer is reversible, sodium 2-naphthalene sulfonate (NAS) and adamantane carboxylate (AdCOOH), which are known to be effective in replacing ferrocene from the ring of β -CD, were added to the water phase.^{37,51} To displace ferrocene from the β -CD cavity an excess of 10 times of NAS and 100 times of AdCOOH with respect to β -CD was added to the water phase.

Upon addition of the naphthalene salt and vigorous shaking the organic phase becomes luminescent under the UV lamp illumination (Figure 5c). UV-vis spectroscopy of the aqueous and chloroform phases upon addition of the naphthalene salt is shown in Figure 7. Although the majority of the QDs transfer back to the chloroform phase, the changes in the absorption profiles indicate that some aggregation of the QD occurred and the solution turned slightly opaque. Probably not all β -CD molecules have been displaced before the QDs transferred into the chloroform phase. Aggregation of the QDs in the chloroform phase can be largely avoided when an adamantane derivative is used in the experiments. Similarly to naphthalene the majority of the QDs transfer back to the chloroform phase upon addition of a large excess of AdCOOH. However, unlike in the experiments with naphthalene, upon addition of AdCOOH the chloroform QD phase is clear and transparent. Substantially diminished aggregation of the QDs is also visible on the absorption spectra of the

chloroform phase after the addition of AdCOOH (Figure 6c). Adamantane therefore is a more efficient complexing agent for β -CD on the surface of the QDs. Transfer of the QDs from water to chloroform is accompanied by a rise in fluorescence intensity. This observation complements to our initial statement that the cyclodextrin is largely responsible for the quenching of the emission of the QDs in the water phase. The release of β -CD from the QD surface leads to the formation of new host-guest complexes between respective complexing agents (naphthalene and adamantane) and β -CD molecules. In the case of naphthalene a weak blue emission from the water phase originating from the NAS- β -CD complex is clearly visible under UV-illumination. These data demonstrate that reversible phase transfer due to replacement of ferrocene by naphthalene or AdCOOH from the β -CD cavity does indeed occur. The choice of the competing complexing molecules seems however critical.

CONCLUSION

We have coated CdSe/ZnS QD with ferrocenyl thiol ligands of various alkane chain lengths *via* ligand exchange reaction. The photoluminescence of the ferrocene-coated QDs decreased, probably due to electron transfer processes between the QD and the ferrocene unit. Reversible phase transfer to and from the aqueous phase was demonstrated using the complexation reaction of ferrocene on the surface of QDs with β -cyclodextrin and subsequent decomplexation *via* competitive reaction of β -cyclodextrin with naphthalene and adamantane derivatives. The emission of QDs in the water phase is quenched due to the presence of the cyclodextrin. The use of adamantane as the decomplexing agent results in clear and transparent solutions of QDs in the chloroform phase unlike for the case of naphthalene where aggregation of the QDs is observed. The choice of the decomplexing agent is therefore crucial to establish a reversible phase transfer of QDs from the aqueous to the organic phase.

EXPERIMENTAL SECTION

Materials. Core-shell CdSe/ZnS nanocrystals were synthesized as described by Janczewski *et al.*⁵² Three differently sized nanoparticles emitting at 625 nm (QD625), 605 nm (QD605) and 595 nm (QD 595) were chosen for this work. Ferrocenyl-thiols 6-ferrocenyl-1-hexanethiol (FcHT) and 11-ferrocenyl-1-udecanethiol (FcUT) were obtained from Dojindo (Dojindo Europe, Amsterdam, The Netherlands) and used as received. Toluene, chloroform, and deuterated toluene, chloroform were obtained from Aldrich (analytical grade). Phosphate buffer ($\text{Na}_2\text{HPO}_4/\text{NaOH}$, pH 11.6) was used to prepare solutions of β -cyclodextrin (CD, Aldrich). Sodium 2-naphthalene sulfonate (Fluka) and 1-adamantane carboxylic acid (Aldrich) were used as received.

Methods. Transmission electron microscopy (TEM) images were obtained with a Philips CM300ST-FEG. For imaging, a drop of quantum dot solution in toluene was placed directly onto a

copper grid and subsequently dried in air. At least 100 QDs were imaged to obtain statistically relevant results. The absorption spectra of quantum dot solutions in toluene and water were measured using a Varian model Cary 300 UV-vis spectrophotometer. The photoluminescence spectra were recorded on an Edinburgh XE-900 spectrofluorometer. The QY for the substrates and products was estimated by comparing the integrated luminescence intensities to the $[\text{Ru}(\text{bpy})_3]^{2+}$ complex standard (QY = 0.028).^{53,54} Nuclear magnetic resonance spectra were recorded on a Bruker Avance II 600 MHz NMR spectrometer at room temperature, using an SEI 2.5 mm probe head equipped with z-axis gradient system. Appropriate 2.5 mm tubes were used to limit convection during the pulsed field gradient (PFG) experiments. Pseudo-2D DOSY experiments and 1D diffusion-filtered ^1H experiments were performed using the bipolar stimulated echo sequence with typically a diffusion time (d) of 100 ms and gradients between 5 and 95% of maximum 35 Gauss.⁵⁵

Synthesis of QD-Fc Nanoparticles. The nanocrystals were stored in chloroform, or toluene, and purified before use by precipitation with methanol and subsequent ultracentrifugation. After centrifugation, the transparent solution was discarded and the remaining solid was dispersed again in toluene or chloroform. Nanocrystals coated with the initial TOPO ligands (4 mL, 4×10^{-6} M) were added to a toluene solution containing FcHT or FcUT (650 μ L, 3.3×10^{-3} M) in a three-necked flask equipped with a condenser. The flask was immersed into a heating bath and the reaction was allowed to proceed for 6 days at 40 °C under nitrogen environment. After the reaction, the ferrocenyl-coated nanoparticles were purified by ultracentrifugation in toluene (22000 rpm, 3 h), and the ultracentrifugation was repeated twice.

Complexation of Fc-QDs with β -Cyclodextrin. Purified ferrocene-modified QDs were dispersed in 1 mL of chloroform (5.4×10^{-7} M) and mixed with 1 mL of phosphate buffer solution containing β -CD (1.1×10^{-4} M). The molar ratio between the QD-Fc and β -CD was therefore equal to 1:200. The solution was stirred for 10 h at room temperature, until the water phase became luminescent under UV irradiation. For reversible phase transfer, 145 μ L of phosphate buffer solutions containing sodium 2-naphthalene sulfonate (7.6×10^{-3} M), or 100 μ L phosphate buffer solutions containing 1-adamantanecarboxylic acid (1.3×10^{-2} M) have been added to the QD-[Fc- β -CD] solution to replace ferrocene from the inclusion complex with β -CD. The mixture was intensively shaken overnight. Samples from the organic and aqueous phases were taken for further analysis.

Acknowledgment. Financial support given by the Strategic Research Orientation "Nanofabrication" of the MESA⁺ Institute for Nanotechnology is highly appreciated. We also thank NanoNed, a nanotechnology program of the Dutch Ministry of Economic Affairs, for financial support.

Supporting Information Available: Absorption and emission of QD595 and QD 605 and NMR spectra of Fc-modified QD. This material is available free of charge via the Internet at <http://pubs.acs.org>.

REFERENCES AND NOTES

- Beecroft, L. L.; Ober, C. K. Nanocomposite Materials for Optical Applications. *Chem. Mater.* **1997**, *9*, 1302–1317.
- Huynh, W. U.; Dittmer, J. J.; Alivisatos, A. P. Hybrid Nanorod-Polymer Solar Cells. *Science* **2002**, *295*, 2425–2427.
- Rajeshwar, K.; Tacconi, N. R.; Chenthamarakshan, C. R. Semiconductor-Based Composite Materials: Preparation, Properties, and Performance. *Chem. Mater.* **2001**, *13*, 2765–2782.
- Niemeyer, C. M. Nanoparticles, Proteins, and Nucleic Acids: Biotechnology Meets Materials Science. *Angew. Chem., Int. Ed.* **2001**, *40*, 4128–4158.
- Rosi, N. L.; Mirkin, C. A. Nanostructures in Biodiagnostics. *Chem. Rev.* **2005**, *105*, 1547–1562.
- Trindade, T.; O'Brien, P.; Pickett, N. L. Nanocrystalline Semiconductors: Synthesis, Properties, and Perspectives. *Chem. Mater.* **2001**, *13*, 3843–3858.
- Colvin, V. L.; Schlamp, M. C.; Alivisatos, A. P. Light-Emitting Diodes Made from Cadmium Selenide Nanocrystals and a Semiconducting Polymer. *Nature* **1994**, *370*, 354–357.
- Klein, D. L.; Roth, R.; Lim, A. K. L.; Alivisatos, A. P.; McEuen, P. L. A Single-Electron Transistor Made from a Cadmium Selenide Nanocrystal. *Nature* **1997**, *389*, 699–701.
- Coe, S.; Woo, W.-K.; Bawendi, M.; Bulovic, V. Electroluminescence from Single Monolayers of Nanocrystals in Molecular Organic Devices. *Nature* **2002**, *420*, 800–803.
- McDonald, S. A.; Konstantatos, G.; Zhang, S.; Cyr, P. W.; Klem, E. J. D.; Levina, L.; Sargent, E. H. Solution-Processed PbS Quantum Dot Infrared Photodetectors and Photovoltaics. *Nat. Mater.* **2005**, *4*, 149–152.
- Chan, W. C. W.; Nie, S. Quantum Dot Bioconjugates for Ultrasensitive Nonisotopic Detection. *Science* **1998**, *281*, 2016–2018.
- Bruchez, M., Jr.; Moronne, M.; Gin, P.; Weiss, S.; Alivisatos, A. P. Semiconductor Nanocrystals as Fluorescent Biological Labels. *Science* **1998**, *281*, 2013–2016.
- Dubretre, t B.; Skourides, P.; Norris, D. J.; Noireaux, V.; Brivanlou, A. H.; Libchaber, A. *In Vivo* Imaging of Quantum Dots Encapsulated in Phospholipid Micelles. *Science* **2002**, *298*, 1759–1760.
- Gao, X.; Cui, Y.; Levenson, R. M.; Chung, L. W. K.; Nie, S. *In Vivo* Cancer Targeting and Imaging with Semiconductor Quantum Dots. *Nat. Biotechnol.* **2004**, *22*, 969–976.
- Michalet, X.; Pinaud, F. F.; Bentolila, L. A.; Tsay, J. M.; Doose, S.; Li, J. J.; Sundaresan, G.; Wu, A. M.; Gambhir, S. S.; Weiss, S. Quantum Dots for Live Cells, *In Vivo* Imaging, and Diagnostics. *Science* **2005**, *307*, 538–544.
- Medintz, I. L.; Clapp, A. R.; Mattoussi, H.; Goldman, E. R.; Fisher, B.; Mauro, J. M. Self-Assembled Nanoscale Biosensors Based on Quantum Dot FRET Donors. *Nat. Mater.* **2003**, *2*, 630–638.
- Katz, E.; Willner, I.; Wang, J. Electroanalytical and Bioelectroanalytical Systems Based on Metal and Semiconductor Nanoparticles. *Electroanalysis* **2004**, *16*, 19–44.
- Anikeeva, N.; Lebedeva, T.; Clapp, A. R.; Goldman, E. R.; Dustin, M. L.; Mattoussi, H.; Sykulev, Y. Quantum Dot/Peptide-MHC Biosensors Reveal Strong CD8-Dependent Cooperation between Self and Viral Antigens That Augment the T Cell Response. *Proc. Nat. Acad. Sci. U.S.A.* **2006**, *103*, 16846–16851.
- Boldt, K.; Bruns, O. T.; Gaponik, N.; Eychmuller, A. Comparative Examination of the Stability of Semiconductor Quantum Dots in Various Biochemical Buffers. *J. Phys. Chem. B* **2006**, *110*, 1959–1963.
- Pathak, S.; Choi, S.; Arnheim, N.; Thompson, M. E. Hydroxylated Quantum Dots as Luminescent Probes for *In Situ* Hybridization. *J. Am. Chem. Soc.* **2001**, *123*, 4103–4104.
- Jaiswal, J. K.; Mattoussi, H.; Mauro, J. M.; Simon, S. M. Long-Term Multiple Color Imaging of Live Cells Using Quantum Dot Bioconjugates. *Nat. Biotechnol.* **2003**, *21*, 47–51.
- Jiang, H.; Jia, J. Complete Reversible Phase Transfer of Luminescent CdTe Nanocrystals Mediated by Hexadecylamine. *J. Mater. Chem.* **2008**, *18*, 344–349.
- Pellegrino, T.; Manna, L.; Kudera, S.; Liedl, T.; Koktysh, D.; Rogach, A. L.; Keller, S.; Radler, J.; Natile, G.; Parak, W. J. Hydrophobic Nanocrystals Coated with an Amphiphilic Polymer Shell: A General Route to Water Soluble Nanocrystals. *Nano Lett.* **2004**, *4*, 703–707.
- Yu, W. W.; Chang, E.; Falkner, J. C.; Zhang, J. Y.; Al-Somali, A. M.; Sayes, C. M.; Johns, J.; Drezek, R.; Colvin, V. L. Forming Biocompatible and Nonaggregated Nanocrystals in Water Using Amphiphilic Polymers. *J. Am. Chem. Soc.* **2007**, *129*, 2871–2879.
- Wang, Y.; Wong, J. F.; Teng, X.; Lin, X. Z.; Yang, H. "Pulling" Nanoparticles into Water: Phase Transfer of Oleic Acid Stabilized Monodisperse Nanoparticles into Aqueous Solutions of α -Cyclodextrin. *Nano Lett.* **2003**, *3*, 1555–1559.
- Feng, J.; Ding, S.-Y.; Tucker, M. P.; Himmel, M. E.; Kim, Y. H.; Zhang, S. B.; Keyes, B. M.; Rumbles, G. Cyclodextrin Driven Hydrophobic/Hydrophilic Transformation of Semiconductor Nanoparticles. *Appl. Phys. Lett.* **2005**, *86*, 033108.
- Depalo, N.; Comparelli, R.; Striccoli, M.; Curri, M. L.; Fini, P. α -Cyclodextrin Functionalized CdS Nanocrystals for Fabrication of 2/3D Assemblies. *J. Phys. Chem. B* **2006**, *110*, 17388–17399.
- Wu, H.; Zhu, H.; Zhuang, J.; Yang, S.; Liu, C.; Cao, Y. C. Water-Soluble Nanocrystals Through Dual-Interaction Ligands. *Angew. Chem., Int. Ed.* **2008**, *47*, 3730–3734.
- Labande, J. R.; Ruiz, J.; Astruc, D. Supramolecular Gold Nanoparticles for the Redox Recognition of Oxoanions: Syntheses, Titrations, Stereoelectronic Effects, and Selectivity. *J. Am. Chem. Soc.* **2002**, *124*, 1782–1789.
- Qiu, J.-D.; Guo, J.; Liang, R.-P.; Xiong, M. A Nanocomposite Chitosan Based on Ferrocene-Modified Silica

- Nanoparticles and Carbon Nanotubes for Biosensor Application. *Electroanalysis* **2007**, *19*, 2335–2341.
31. Kaifer, A. E. Electron Transfer and Molecular Recognition in Metallocene-Containing Dendrimers. *Eur. J. Inorg. Chem.* **2007**, 5015–5027.
 32. Ingram, R. S.; Hostetler, M. J.; Murray, R. W. Poly-Hetero- ω -Functionalized Alkanethiolate-Stabilized Gold Cluster Compounds. *J. Am. Chem. Soc.* **1997**, *119*, 9175–9178.
 33. Budny, A.; Novak, F.; Plumere, N.; Schetter, B.; Speiser, B.; Straub, D.; Mayer, H. A.; Reginek, M. Redox-Active Silica Nanoparticles. Part 1. Electrochemistry and Catalytic Activity of Spherical, Nonporous Silica Particles with Nanometric Diameters and Covalently Bound Redox-Active Modifications. *Langmuir* **2006**, *22*, 10605–10611.
 34. Cyr, P. W.; Tzolov, M.; Hines, M. A.; Manners, I.; Sargent, E. H.; Scholes, G. D. Quantum Dots in a Metallopolymer Host: Studies of Composites of Polyferrocenes and CdSe Nanocrystals. *J. Mater. Chem.* **2003**, *13*, 2213–2219.
 35. Wolfe, R. L.; Balasubramanian, R.; Tracy, J. B.; Murray, R. W. Fully Ferrocenated Hexanethiolate Monolayer-Protected Gold Clusters. *Langmuir* **2007**, *23*, 2247–2254.
 36. Takada, K.; Diaz, D. J.; Abruna, H. D.; Cuadrado, I.; Casado, C.; Alonso, B.; Moran, M.; Losada, J. Redox-Active Ferrocenyl Dendrimers: Thermodynamics and Kinetics of Adsorption. *In-Situ Electrochemical Quartz Crystal Microbalance Study of the Redox Process and Tapping Mode AFM Imaging*. *J. Am. Chem. Soc.* **1997**, *119*, 10763–10793.
 37. Castro, R.; Cuadrado, I.; Alonso, B.; Casado, C. M.; Moran, M.; Kaifer, A. E. Multisite Inclusion Complexation of Redox Active Dendrimer Guests. *J. Am. Chem. Soc.* **1997**, *119*, 5760–5761.
 38. Wallbank, A. I.; Borecki, A.; Taylor, N. J.; Corrigan, J. F. Ferrocenyl-Passivated Nanoclusters: Synthesis of $(\text{Cu}_{20}\text{Se}_6(\text{Se}_2\text{fc})_4(\text{PR}_2\text{R}')_{10})$ and $(\text{Cu}_{40}\text{Se}_{12}(\text{Se}_2\text{fc})_8(\text{PPh}_3)_9)$. *Oganometallics* **2005**, *24*, 788–790.
 39. Nitschke, C.; Fenske, D.; Corrigan, J. F. Ferrocenyldiselenolate-Stabilized Copper-Selenium Clusters. *Inorg. Chem.* **2006**, *45*, 9394–9401.
 40. Nitschke, C.; Wallbank, A. I.; Fenske, D.; Corrigan, J. F. Ferrocenyl Functionalized Copper-Selenium Clusters. *J. Cluster Sci.* **2006**, *18*, 131–140.
 41. Yu, W. W.; Qu, L.; Guo, W.; Peng, X. Experimental Determination of the Extinction Coefficient of CdTe, CdSe, and CdS Nanocrystals. *Chem. Mater.* **2003**, *15*, 2854–2860.
 42. Querner, C.; Reiss, P.; Bleuse, J.; Pron, A. Chelating Ligands for Nanocrystals' Surface Functionalization. *J. Am. Chem. Soc.* **2004**, *126*, 11574–11582.
 43. Beulen, M. W. J.; Veggel, F. C. J. M.; Reinhoudt, D. N. Coupling of Acid–Base and Redox Functions in Mixed Sulfide Monolayers on Gold. *Chem. Commun.* **1999**, *6*, 503–505.
 44. Hens, Z.; Moreels, I.; Martins, J. C. *In Situ* ^1H NMR Study on the Trioctylphosphine Oxide Capping of Colloidal InP Nanocrystals. *Chem. Phys. Chem.* **2005**, *6*, 2578–2584.
 45. Sachleben, J. R.; Wooten, E. W.; Emsley, L.; Pines, A.; Colvin, V. L.; Alivisatos, A. P. NMR Studies of the Surface Structure and Dynamics of Semiconductor Nanocrystals. *Chem. Phys. Lett.* **1992**, *198*, 431–433.
 46. Majetich, S. A.; Carter, A. C.; Belot, J.; McCullough, R. D. ^1H NMR Characterization of the CdSe Nanocrystallite Surface. *J. Phys. Chem.* **1994**, *98*, 13705–13710.
 47. Berrettini, M. G.; Braun, G.; Hu, J. G.; Strouse, G. F. NMR Analysis of Surfaces and Interfaces in 2 nm CdSe. *J. Am. Chem. Soc.* **2004**, *126*, 7063–7070.
 48. Voets, I. K.; De Keizer, A.; De Waard, P.; Frederik, P. M.; Bomans, P. H. H.; Schmalz, H.; Walthers, A.; King, S. M.; Leermakers, F. A. M.; Cohen Stuart, M. A. Double-Faced Micelles from Water-Soluble Polymers. *Angew. Chem., Int. Ed.* **2006**, *45*, 6673–6676.
 49. Fery-Forgues, S.; Delavaux-Nicot, B. Ferrocene and Ferrocenyl Derivatives in Luminescent Systems. *J. Photochem. Photobiol. A* **2000**, *132*, 137–159.
 50. Chandler, R. R.; Coffey, L. J.; Atherton, S. J.; Snowden, P. T. Addition of Ferrocene Derivatives to the Surface of Quantum-Confined Cadmium Sulfide Clusters: Steady-State and Time Resolved Photophysical Effects. *J. Phys. Chem.* **1992**, *96*, 2712–2717.
 51. Rekharsky, M. V.; Inoue, Y. Complexation Thermodynamics of Cyclodextrins. *Chem. Rev.* **1998**, *98*, 1875–1917.
 52. Janczewski, D.; Tomczak, N.; Khin, Y. W.; Han, M. Y.; Vancso, G. J. Designer Multi-Functional Comb-Polymers for Surface Engineering of Quantum Dots on the Nanoscale. *Eur. Pol. J.* **2009**, *45*, 3–9.
 53. Montalti, M.; Credi, A.; Prodi, L.; Gandolfi, M. T. *Handbook of Photochemistry*, 3rd. ed.; CRC Press: Boca Raton, FL, 2006; pp 572–576.
 54. Lakowicz, J. R. *Principles of Fluorescent Spectroscopy*, 2nd ed.; Kluwer Academic/Plenum Press: 1999; pp 10–12.
 55. Gomez, M. V.; Guerra, J.; Velders, A. H.; Crooks, R. M. NMR Characterization of Fourth-Generation PAMAM Dendrimers in the Presence and Absence of Palladium Dendrimer-Encapsulated Nanoparticles. *J. Am. Chem. Soc.* **2009**, *131*, 341–350.