Modulation of the solubility of luminescent semiconductor nanocrystals through facile surface functionalization

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Electronic Supplementary Information

Materials and methods

Reagents and solvents. Lipoic acid (LA, (±)-α-Lipoic acid, ≥98%), sodium borohydride ($NaBH_4$, ≥98%), anion exchange resin Cl^- loaded (Amberlite® IRA-400 chloride form), sodium hydroxide (NaOH, ≥98%), lithium hydroxide monohydrate (LiOH, >99.0%), potassium hydroxide (KOH, ≥98%), tetramethylammonium hydroxide (TMAOH, ~97%), tetraethylammonium perchlorate ($TEAClO_4$, 99%), tetraethylammonium nitrate ($TEANO_3$, >99%), tetra(*n*-octyl)ammonium hydroxide (TOAOH, 20% in methanol), cetyltrimethylammonium bromide (CTABr, ≥99.0%), and 5,5′-dithiol-bis(2-nitrobenzoic acid) (DTNB, ≥98%) were purchased from Sigma Aldrich and Fluka, and were used without further purification. Tetra(*n*-butyl)ammonium hydroxide (TBAOH, 25% in methanol) was purchased from J. T. Baker Chemical Co. Synthetic grade hexane, toluene, $CHCl_3$, acetone and methanol were purchased from Sigma-Aldrich. Spectroscopic grade tetrahydrofuran, acetonitrile and dimethyl sulfoxide were purchased from Merk-Uvasol. LA-PEG_{400} was synthesized following a published procedure.[1] A Milli-Q Millipore system was used for the purification of water (resistivity ≥ 18 MΩ·cm). Millipore Amicon Ultra-0.5 mL centrifugal filters (30000 Da cut off) were purchased from Sigma-Aldrich.

Microscopic and spectroscopic measurements. Transmission electron microscopy (TEM) experiments were carried out with a Philips CM100 transmission electron microscope operating at 80 kV. A drop of the nanocrystal solution diluted with hexane was deposited on a 400 mesh copper coated with formvar support grid (TAAB Ltd.), which was then dried up under vacuum to remove any solvent trace. Electronic absorption spectra were measured at room temperature on air-equilibrated solutions of the samples contained in quartz cuvettes (1-cm optical path length). The concentration of the solutions was typically 10^{-7} M. Absorption spectra in the 190-1100 nm range were recorded with a Perkin Elmer λ45 spectrophotometer. The precision on the wavelength values was ± 1 nm. Luminescence spectra in the 250-900 nm range were recorded with a Perkin Elmer LS50 spectrofluorimeter equipped with a Hamamatsu R928 photomultiplier. Luminescence spectra were recorded at room temperature (ca. 295 K) on solutions of samples contained in quartz cuvettes (1-cm optical path length). Luminescence quantum yields were determined with the optically dilute method using Rhodamine 6G ($\Phi = 0.94$ in EtOH) as a standard.[2]

Synthesis of the quantum dots. Hydrophobic core CdSe semiconductor nanocrystal quantum dots were prepared by reaction of organometallic precursors in organic solvents, following the published

procedures developed by Peng and coworkers[3] with minor modifications. Core-shell CdSe-ZnS QDs were prepared by overcoating a CdSe core with a ZnS shell using either SILAR[4] or one-time-precursors-injection[5] approaches. The core diameter and the QD concentration were estimated according to published methods.[6] The shell thickness was estimated as reported in each synthetic protocol.[4,5] The resulting nanocrystals were covered with TOPO (*tris*-[*n*-octylphosphine]oxide) and TOP (*tris*-[*n*-octyl]phosphine) as passivating surface ligands to prevent particle aggregation.

Preparation of the borohydride exchanged resin. The synthesis of the BH_4-resin was carried out following the procedure reported by Yoon and coworkers.[7] Briefly, 4 g of Amberlite® IRA-400 (chloride form) resin were placed in a 100 mL one-neck round-bottom flask equipped with a stirring bar. A water solution of $NaBH_4$ (920 mg in 40 mL) was added and the neck was sealed with a rubber seal. The mixture was gently stirred for at least 3 hours in order to allow the complete exchange of the chloride anions with borohydride. The resin was filtered and washed with water to remove the excess of sodium borohydride and sodium chloride released during the exchange reaction. The resin beads were then dried under reduced pressure. The amount of BH_4^- per g of resin was estimated via acid titration. The resin could be successfully re-used for at least three cap exchange reactions. Long-term storage of the borohydride-loaded resin under ambient conditions, however, was not possible, presumably because of the slow reaction of BH_4^- with water. Nevertheless, the resin beads can be re-loaded with borohydride after careful repeated washing with a HCl solution.

Ligand Reduction. In a 4-mL glass vial a solution of lipoic acid (2.66×10^{-5} mol in 500 μL of MeOH) was mixed with 19 mg of BH_4^- resin (2.5 mmol BH_4^- per g). The mixture was stirred at 400 rpm for at least 30 min. The decrease of the disulfide absorption band of lipoic acid at 330 nm indicates that the reduction has taken place (Fig. S1, a and b).[8] Also the DHLA absorption in the 220-260 nm region (which is initially out of scale) decreases, suggesting that DHLA is chemisorbed on the resin.

The methanol layer was removed and the beads were washed 3 times with 500 μL of methanol to remove unreacted lipoic acid and hydrolyzed borohydride products. Methanol (500 μL) and M^+X^- (from 1.2 to 4 eq with respect to the BH_4^- content) were then added to the beads. The mixture was stirred for at least 30 min in order to extract the reduced lipoic acid from the resin. In the case of hydroxide salts, 1.2 eq of M^+OH^- and 30 min of stirring were enough to extract the reduced ligand from the resin; perchlorate, nitrate and bromide salts required a larger amount (up to 4 eq) and a longer stirring time (up to 3 hours). The beads were washed two times with 200 μL of fresh

methanol to recover as much reduced ligand as possible. The methanol fractions were combined and the residual solid was discarded. In the case of ligands consisting of a lipoic acid moiety attached to a hydrophilic poly(ethylene glycol) chain (LA-PEG_{400}),[1] the reaction was slower than for parent LA, and no base was required to extract the reduced ligand from the resin.

The substantial absorption increase in the 220-260 nm region (Fig. S1, b and c) is consistent with the release of $DHLA^-$ from the resin, together with a minor amount of unreacted lipoic acid (slight absorption increase at 330 nm). The increase of the absorption intensity at 330 nm was used to estimate the amount of unreacted lipoic acid (Fig. S1, a and c), whereas the amount of $DHLA^-$ released in the solution was determined with Ellman's reagent (5,5′-dithiol-bis(2-nitrobenzoic acid), DTNB).[9] 10 μL of a MeOH solution containing a $DHLA^-M^+$/LA mixture after extraction from the resin (initial LA concentration, 1.6×10^{-2} M) were mixed with 2 mL of Ellman's reagent solution (2.1×10^{-4} M in 5 mM phosphate buffer at pH 7.5).[8] The formation of the reaction product, the 5-thio-2-nitrobenzoate (TNB^{2-}), was monitored recording the absorbance at 412 nm, and the concentration of the –SH groups was determined using a molar absorption coefficient of 14150 M^{-1} cm^{-1} for TNB^{2-} at 412 nm.[10] The DHLA concentration was calculated as [–SH]/2.

Under our experimental conditions (room temperature; 30 min stirring with the borohydride resin, addition of 2 equiv of NaOH and 30 min stirring), the $DHLA^-$ yield in the MeOH solution is 29%; 7% of unreacted LA was also extracted.

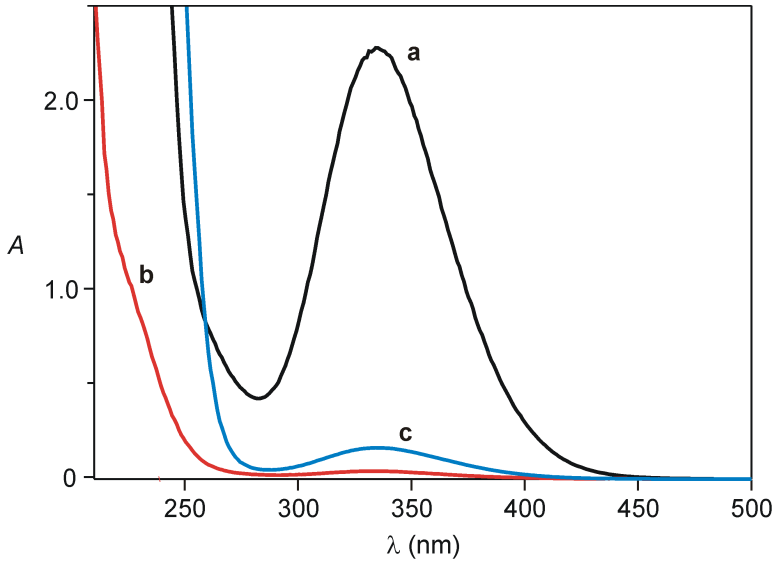

Fig. S1 Absorption spectrum of 1.6×10^{-2} M lipoic acid (LA) in MeOH before (a) and after the addition of the borohydride loaded resin (2 equiv of BH_4^- with respect to LA) and 30 min stirring (b). Curve c) is the spectrum obtained upon treating the mixture in b) with NaOH (2 equiv with respect to LA) and 30 min stirring.

QD Cap Exchange and Phase Transfer. The desired amount of QDs (from 1/20000 to 1/30000 QD/lipoic ligand ratio, depending on QD size) was dissolved in 1 mL of hexane. The solution was added to the vial containing the reduced ligand (see above) in methanol, thus forming a biphasic mixture. The transfer of QDs from the hexane to the methanol layer was immediately observed. To ensure a complete cap exchange, the biphasic system was stirred for 2-3 hours or, in the case of larger QDs, overnight. The methanol layer appeared clear or turbid, depending on the counter-cation employed in the previous step (see Table 1). The hexane layer (turned colorless) was removed and the methanol suspension was washed five times with hexane (2 mL) in order to remove unreacted nanocrystals and native hydrophobic ligands. The methanol was evaporated under reduced pressure and resulting dried QDs were dissolved in proper solvents for further studies. In the case of water solutions, the mixture was first passed through a syringe filter (0.46 μm pore size) to remove possible large aggregates and was successively purified with 3 cycles of dilution/concentration with a centrifugal filter (Amicon Ultra-0.5 mL, 30 kDa, 7000 rpm, 12 minutes) to eliminate the excess of free ligand. Alternatively, hydrophobic QDs were added as solid/paste to the solution of reduced ligand in methanol, thus obtaining a suspension. All the successive isolation and purification steps were performed as described above.

Table S1 Spectroscopic properties (H_2O, r.t.) of different $DHLA^-Na^+$ capped QDs obtained by ligand exchange and phase transfer.

	QD	d_{core} (nm)[a]	s_{shell} (nm)[b]	λ_{abs} [$\Delta\lambda_{abs}$] (nm)[c]	λ_{lum} [$\Delta\lambda_{lum}$] (nm)[d]	$\Phi_{em,n}$[f]	$\Phi_{em,w}$[g]
1	CdSe	2.6	—	528 [0]	*e*		
2	CdSe	3.8	—	583 [0]	*e*		
3	CdSe-5ZnS	2.7	1.6	545 [+3]	562 [+2]	0.14	0.044
4	CdSe-3ZnS	3.4	0.9	562 [0]	586 [–1]	0.34	0.18
5	CdSe-5ZnS	3.6	1.6	572 [0]	597 [0]	0.23	0.081
6	CdSe-4ZnS	3.7	1.2	576 [–2]	606 [–1]	0.18	0.06
7	CdSe-3ZnS	4.1	0.9	587 [–1]	605 [0]		

[a] Core diameter. [b] Shell thickness. [c] λ_{abs} = Wavelength of the lowest exciton absorption peak in H_2O; $\Delta\lambda_{abs} = \lambda_{abs}$ (H_2O) – λ_{abs} ($CHCl_3$). [d] λ_{lum} = Wavelength of the luminescence band maximum in H_2O; $\Delta\lambda_{lum} = \lambda_{lum}$ (H_2O) – λ_{lum} ($CHCl_3$). [e] Not luminescent. [f] Emission quantum yield of QDs with native ligands in $CHCl_3$ or hexane. [g] Luminescence quantum yield of QDs capped with $DHLA^-Na^+$ in water.

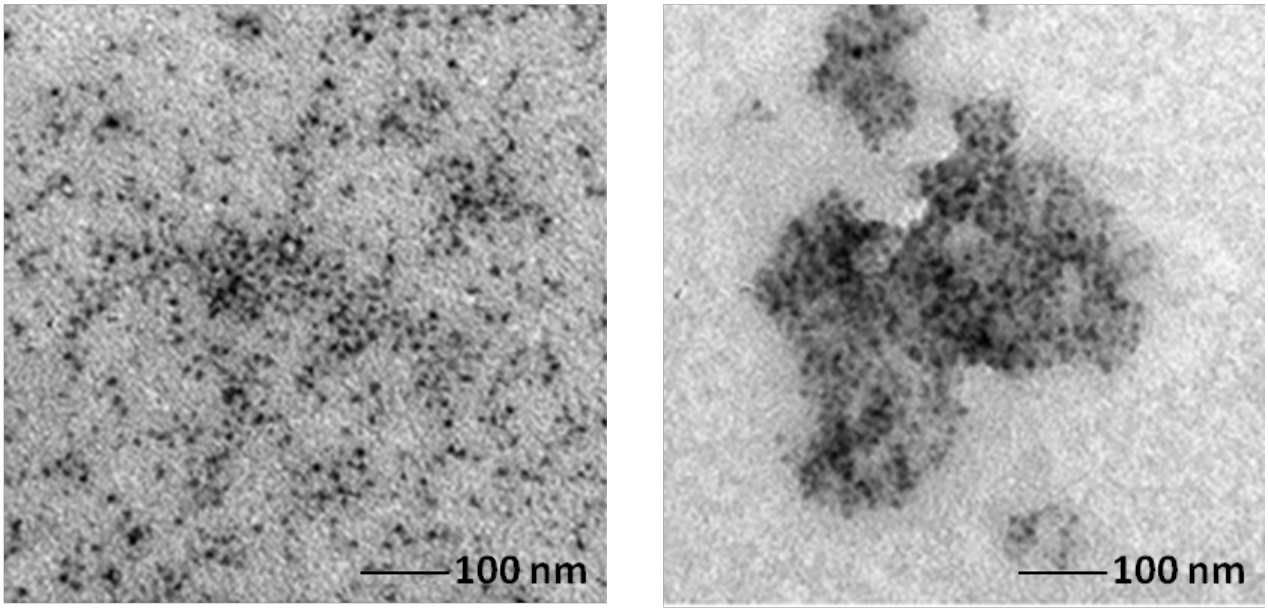

Fig. S2 TEM images of CdSe-3ZnS QDs (entry 4 in Table S1) before (left) and after (right) ligand exchange performed using the methodology described in the text. Left: TOP/TOPO-capped QDs; right: $DHLA^{-}Na^{+}$ capped QDs.

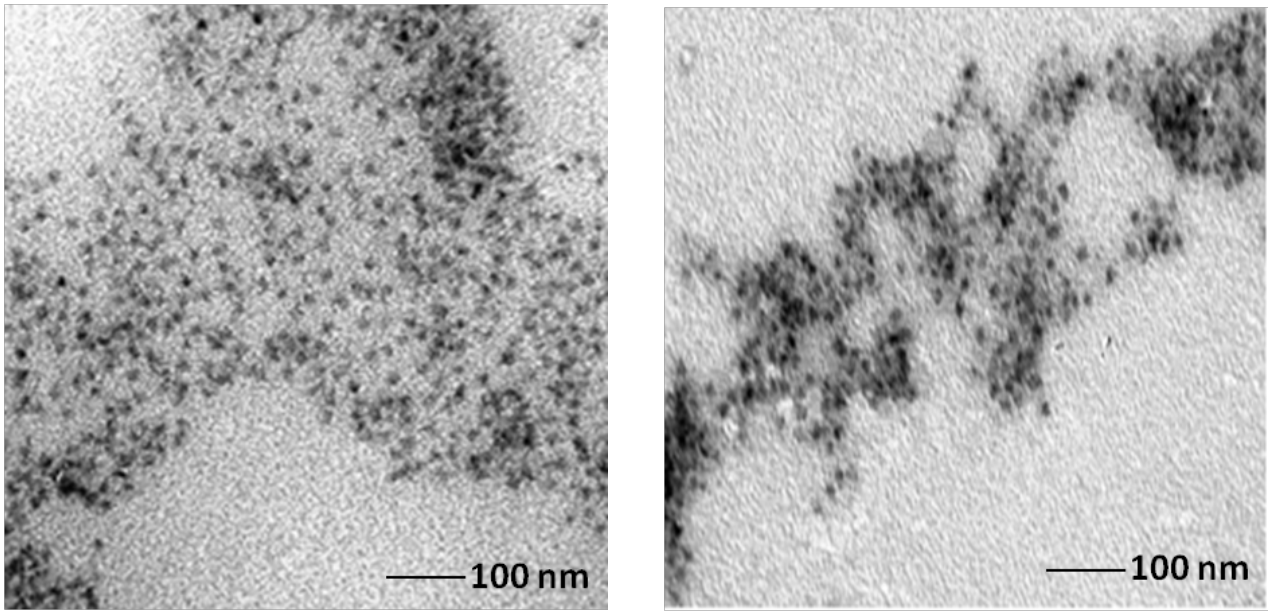

Fig. S3 TEM images of CdSe-4ZnS QDs (entry 6 in Table S1) before (left) and after (right) ligand exchange performed using the methodology described in the text. Left: TOP/TOPO-capped QDs; right: $DHLA^{-}Na^{+}$ capped QDs.

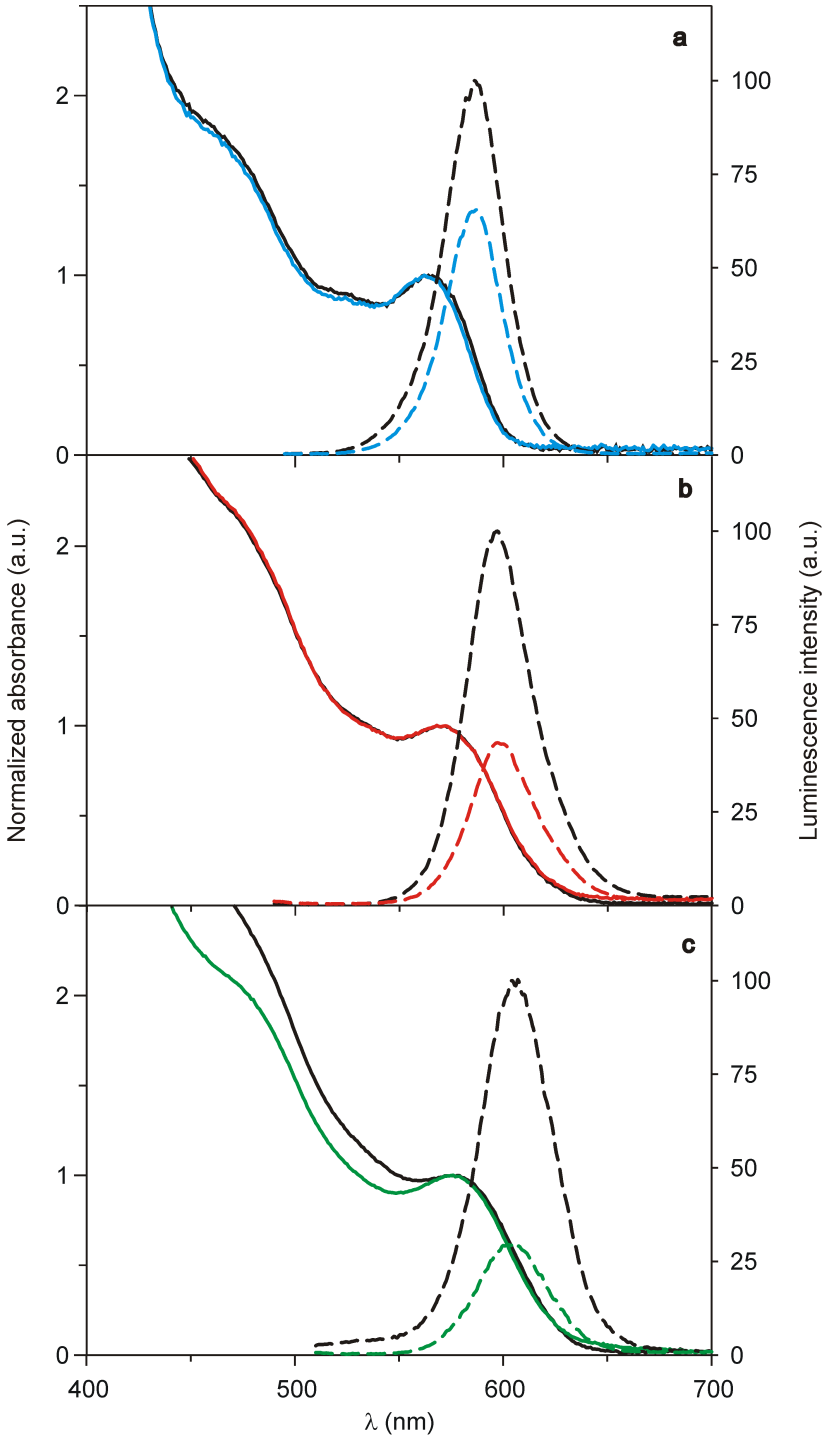

Fig. S4 a) Absorption (full line) and emission (λ_{exc} = 485 nm; dashed line) spectra of TOP/TOPO CdSe-3ZnS QDs (entry 4 in Table S1) in $CHCl_3$ (black) and $DHLA^-Na^+$ capped in H_2O (blue). This part of the figure is shown as Fig. 1 in the main text. b) Absorption (full line) and emission (λ_{exc} = 480 nm; dashed line) spectra of TOP/TOPO CdSe-5ZnS QDs (entry 5 in Table S1) in $CHCl_3$ (black) and $DHLA^-Na^+$ capped in H_2O (red). c) Absorption (full line) and emission (λ_{exc} = 450 nm; dashed line) spectra of TOP/TOPO CdSe-3ZnS QDs (entry 7 in Table S1) in $CHCl_3$ (black) and DHLA-PEG_{400} capped in H_2O (green).

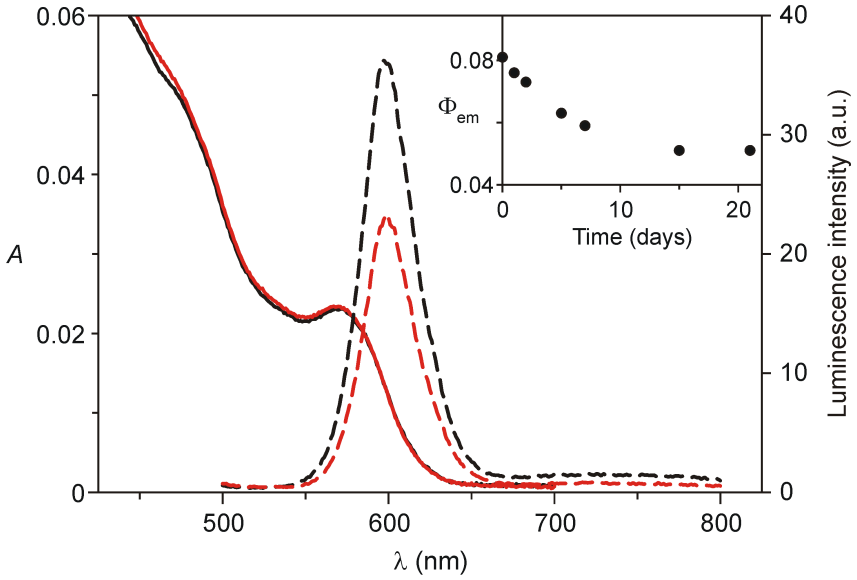

Fig. S5 Absorption (full lines) and emission (λ_{exc} = 480 nm; dashed lines) spectra of CdSe-5ZnS QDs (entry 5 in Table S1, 130 nM) capped with $DHLA^{-}Na^{+}$ in water, freshly prepared (black) and after 21 days of storage at 5 °C (red). No precipitation was observed. The inset shows the evolution of the luminescence quantum yield over time. The decrease of the emission quantum yield from 0.081 to 0.05 is consistent with literature reports for DHLA-capped QDs.[11] It is worthwhile to note, however, that such DHLA-capped QDs exhibit a substantial decrease in their luminescence efficiency in a few days, and undergo precipitation after one week, whereas suspensions of DHLA-capped QDs prepared with our protocol are stable for at least three months.

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