Probing solvent-ligand interactions in colloidal nanocrystals by the NMR line broadening.

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Abstract

Although solvent-ligand interactions play a major role in nanocrystal synthesis, dispersion formulation and assembly, there is currently no direct method to study this. Here we examine the broadening of ^{1}H NMR resonances associated with bound ligands, and turn this poorly understood descriptor into a tool to assess solvent-ligand interactions. We show that the line broadening has both a homogeneous and a heterogeneous component. The former is nanocrystal-size dependent and the latter results from solvent-ligand interactions. Our model is supported by experimental and theoretical evidence that correlates broad NMR lines with poor ligand solvation. This correlation is found across a wide range of solvents, extending from water to hexane, for both hydrophobic and hydrophilic ligand types, and for a multitude of oxide, sulfide and selenide nanocrystals. Our findings thus put forward NMR line shape analysis as an indispensable tool to form, investigate and manipulate nanocolloids.

Introduction

Colloidal nanocrystals (NCs) are emerging synthetics with unique size-dependent properties.[1-6] In addition, colloidal NCs are excellent building blocks to create 1D, 2D and 3D assemblies[1, 2] or nanocomposites[7, 8] with enhanced functionality. Importantly, NCs are typically hybrid objects, consisting of an inorganic core capped with organic ligands (surfactants).[9, 10] Apart from electronically passivating the NC surface,[11] ligands determine the NC-solvent interaction. The latter is a unifying aspect of all NCs, be it oxide, selenide, sulfide, halide or metal NCs.[3-6] Ligands and ligand-solvent interactions govern the kinetics of NC nucleation and growth,[6] determine the stability of nanocolloids, enable NC coatings[12] or patterns[13] to be formed, and regulate oriented attachment or self-assembly in higher order architectures, such as composite particles, aerogels, and superlattices.[14-19] Despite its tremendous importance, no direct method exists to measure ligand-solvent interaction. Since this interaction determines

whether ligands are fully extended or bundled together, interparticle distances, measured via Transmission Electron Microscopy (TEM), have been used to infer the ligand shell thickness and have been correlated to superlattice formation dynamics.[20] Order in the ligand shell has also been probed by vibrational Sum Frequency Generation spectroscopy on solid state films,[21] and recently, the ligand shell morphology has been modelled in vacuum.[22] However, none of the current techniques is able to directly probe solvent-ligand interactions in solution.

Solution Nuclear Magnetic Resonance (NMR) spectroscopy has proven indispensable for the analysis of organic ligands on NC surfaces.[23, 24] Surface bound ligands feature broadened spectral lines (Figure 1) and are therefore easily distinguished from non-binding molecules with narrow NMR resonances. Generally, broadening is more severe the closer a proton is to the surface,[25] up to the point that small ligands can be undetectable by ^{1}H NMR.[26] Some studies found a narrower line width for the bound ligand in the case of smaller NCs or solvents with lower viscosity.[25, 27] Such observations support the interpretation that bound-ligand resonances suffer from homogeneous broadening, which implies that the line width $\Delta\nu$ is inversely proportional to the T_2 relaxation time constant ($\Delta\nu = \frac{1}{\pi T_2}$), itself governed by the rotational correlation time τ_c. The slow rotation of large molecules – or small ligands attached to a large NC – in solution thus leads to rapid transversal relaxation and broad, homogeneous resonances (see SI). On the other hand, hole burning studies suggested that bound ligand resonances are heterogeneously broadened, i.e., the NMR resonances are a superposition of signals with slightly different chemical shifts and line widths, each associated with a subpopulation of ligands (Figure 1A).[28] Most likely, both broadening mechanisms take place simultaneously but their relative weight is unknown. Most importantly, there is no handle available to manipulate the line width by design or to extract information from it. It is currently more a nuisance than a tool.

Here, we study the NMR line width of nanocrystal-bound ligands and quantify the relative contributions of homogeneous and heterogeneous broadening. We find that the solvation of the ligand shell is the main contributor to heterogeneous line broadening. Our conclusions are experimentally supported by diffusion filtered ^{1}H NMR spectra of NCs capped with the versatile ligand 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (MEEAA) in various solvents. The full-width-at-half-maximum (FWHM) of the methyl resonance of bound MEEAA is correlated with the hydrogen bonding Hanssen solubility parameter, and is lowest in water. Furthermore, the relation between the ligand shell solvation and the NMR line width is confirmed by classical molecular dynamics simulations. As such, the NMR line width is put forward as a descriptor for solvent-ligand interactions and is expected to become a major tool in nanomaterials research and development.

Results and discussion

We start our investigation by scrutinizing the ^{1}H NMR spectra of oleate capped CdSe, PbS and HfO_2 NCs, obtained after a judicious purification that removes unbound molecules. The ^{1}H NMR spectrum shows the familiar pattern of surface bound oleate ligands, showcased in Figure 1A for CdSe NCs (d = 3.3 nm, see Figure S1). Apart from the solvent (toluene-d_8), only broadened resonances are observed. The single exponential diffusion decay associated with these resonances in Pulsed Field Gradient ^{1}H NMR Spectroscopy confirms the successful purification and both the methyl and alkene resonances feature a diffusion coefficient of 91 μm²/s (Figure 1B, S2-3). From the diffusion coefficient, using the Stokes-Einstein relation, we calculate a solvodynamic diameter of 8 nm, which is in good agreement with the NC size, including the ligand shell.[5, 29]

Figure 1

Figure 1. (A) ^{1}H NMR spectrum of 3.3 nm oleate capped CdSe nanocrystals ([NC] = 261 µM, [oleate] = 39 mM) in toluene-d_8. Ligand density = 4.4 nm^{-2}. The resonance α belongs to the methyl of toluene. The inset is a cartoon illustrating the concept of heterogeneous broadening. (B) The diffusion coefficient (D), the full width at half maximum (FWHM), the T_2 relaxation time constant and the theoretical homogeneous line broadening for two selected resonances of the oleyl chain.

It is clear from Figure 1A that the alkene resonance **5** is broader than the methyl resonance **6**. Quantitatively, the experimental FWHM is about double for the alkene resonance (Figure 1B). This phenomenon could be attributed to a reduced local rotational mobility of the alkene protons due to their proximity to the NC surface. In support of this interpretation, the average T_2 relaxation time constant of the alkene protons is indeed 10 times shorter than of the methyl protons (Figure 2B, S4-5), which implies a much faster transversal relaxation. However, for both resonances, the corresponding homogeneous line width – $1/(\pi T_2)$ – is much smaller than the experimental FWHM (Figure 1B). To account for the triplet structure of the methyl resonance and the more complex fine structure of the alkene resonance, we simulated the homogeneous FWHM by applying a line broadening of 8.9 Hz to a spectrum of free oleic acid (Figure S6). This results in a loss of fine structure for all resonances and the homogeneous FWHM of resonance **5** was determined to be 18 Hz, still only 25 % of the total FWHM. We thus conclude that the total line width has only a relatively small homogeneous contribution linked to transversal relaxation. The heterogeneous nature of the resonances was further corroborated by hole burning experiments on both the alkene and the methyl resonance. Saturation of a band-width smaller than the observed line creates a dent in the resonance (Figure S7), rather than decreasing the overall resonance intensity as expected for a homogeneous line.

Indeed, a homogeneous line represents identical nuclei in a single chemical environment and saturation of those nuclei should affect the resonance as a whole. Since we observe a dent in the resonance, only part of the resonance is affected by the saturation and we conclude that resonances of NC bound ligands are a superposition of a set of more narrow peaks, all exhibiting slightly different chemical shifts (Figure 1A, inset; heterogeneous broadening). This is a general characteristic of NC bound ligands and similar ^{1}H NMR spectra are obtained for HfO_2 and PbS NCs (Figure S8-9).

To investigate the origin of the heterogeneous broadening, we sought to survey the impact of solvation on the line width. Being too hydrophobic to support colloidal stability in a wide variety of solvents, oleic acid is ill-suited as a ligand for such a study. Inspired by the versatility of polyethyleneglycol-based ligands,[30-33] we functionalized solvothermally synthesized HfO_2 NCs with 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (MEEAA), see Figure 2. After purification, these NCs could be dispersed in water, methanol, ethanol, acetone and toluene, and constitute thus an ideal model system. Interestingly, the ^{1}H NMR spectra of the dispersions in water, methanol and toluene look very different and it appears that the line broadening depends on the solvent (Figure 2C), with the narrowest lines in water and the broadest in toluene. Furthermore, solvent mixtures access all intermediate line widths. For example, when a dispersion of HfO_2 NCs in methanol is diluted with 20 v% D_2O, the resonances sharpen considerably, while addition of 60 v% of toluene broadens the resonances (Figure S10). However, even in pure D_2O, resonances **b**-**e** overlap and only the methyl resonance **f** yields a well-resolved resonance. Therefore, this latter resonance will serve as a probe in the remainder of the investigation.

Figure 2

Figure 2. (A) TEM image of HfO_2 nanocrystals, stabilized with 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (MEEAA), deposited from ethanol. (B) DLS size distribution in ethanol (C) The reference ^{1}H NMR spectrum of MEEAA in methanol and ^{1}H NMR spectra of HfO_2 nanocrystals stabilized with MEEAA in various solvents. The α and β resonance are assigned to the exchangeable protons (RCOOH, ROH, H_2O) and the methyl moiety of the solvent, methanol. D) DOSY fitting of the CH_3 resonance intensity of the NC dispersion in D_2O. The black data points were fitted to a bi-exponential and the sum of the two exponentials (blue and green) is the red line. The residuals are also depicted.

A complication of the HfO_2/MEEAA system is that resonance line widths cannot be directly compared. Analysis by Pulsed Field Gradient ^{1}H NMR spectroscopy of HfO_2/MEEAA dispersions in water reveals a bi-exponential diffusion decay, indicating that two species with a different diffusion coefficient contribute to the resonances (Figure 2D). The small diffusion coefficient (D_1 = 49.5 μm²/s) corresponds to a solvodynamic diameter of 9.8 nm and is associated with surface bound MEEAA. The larger diffusion coefficient (D_2 = 259.3 μm²/s) is attributed to free MEEAA. Similar results are found in methanol, ethanol, acetone and toluene (Figure S11-14). Since the resonances of tightly bound and free MEEAA overlap, the apparent line width of the overall resonance does not correspond to the true line width of the bound ligands. In addition, some solvent signals overlap with the resonances of MEEAA. To address this spectral crowding, we used diffusion filtered spectra. In such an experiment, the contribution of rapidly diffusing species is filtered out by applying a sufficiently large gradient strength (striped box in Figure 2D). Every data point of the decay curve corresponds to a 1D spectrum and we always selected the spectrum from the diffusion filter with the highest signal-

to-noise for our analysis. In this way, we obtained spectra of bound MEEAA ligands in water, methanol, ethanol, acetone and toluene.

As shown in Figure 3, the line width in these spectra continuously increases from water (20.7 Hz) to toluene (90.5 Hz). To further demonstrate the versatility of MEEAA and the generality of our conclusions, oleate ligands on CdSe NCs were exchanged for MEEAA ligands and the NCs were dispersed in methanol, ethanol, acetone and toluene. The same line broadening trend in the diffusion filtered spectra is observed (Figure S15 and Figure 3B).

Figure 3

Figure 3. (A) Diffusion filtered 1D ^{1}H NMR spectra of HfO_2 NCs stabilized with MEEAA in various solvents. (B) FWHM of the methyl group of MEEAA on HfO_2 and CdSe NCs in function of either the viscosity or the Hanssen hydrogen bonding parameter. FWHM was directly determined, except for acetone and toluene where the data was fitted to two gaussians (Figure S16).

In contrast to what would be expected for purely homogeneous broadening,[25] we find no correlation between the FWHM and the solvent's viscosity (Figure 3B). The line broadening is not related either to the line width of free MEEAA in the various solvents. Indeed, free MEEAA (measured without NCs) features the narrow resonances characteristic of small molecules in all studied solvents (Figure S17). In contrast, the line width trend is very well described by the Hanssen solubility parameters. Whereas the FWHM roughly scales with the Hanssen polarity parameter (Figure S18), we obtained the best correlation with the Hanssen hydrogen bonding parameter (Figure 3B).

Thinking in terms of ligand-solvent interactions, one expects water to deeply penetrate the ligand shell and interact with the polar MEEAA ligands through hydrogen bonding. Toluene, on the other hand, will be relatively more excluded from the ligand shell as it does not form hydrogen bonds with MEEAA. A better solvation by the solvent leads to a more uniform chemical environment of the ligands and thus a more narrow chemical shift distribution. Hence our conclusion that the experimental correlation between the line width of bound ligand resonances and, in the case of MEEAA, the Hanssen hydrogen bonding parameter reflects in essence a correlation between the line width and the solvation of bound ligands by the solvent. In a sense, the NMR line width is determined by the swelling of the ligand shell, not unlike the swelling of cross-linked polymers.[34, 35]

We verified our model of solvent exclusion via molecular dynamic simulations on a faceted ~2.8nm CdSe/MEEAA nanocrystal. The MEEAA ligands are bound through the carboxylate group to Cd atoms primarily on the Cd rich [100] facets (see Figure 4A for the initial configuration before relaxation).[36, 37] Simulations were performed with CdSe/MEEAA solvated at room temperature in methanol, acetone, and toluene. A snapshot of the NC solvated in methanol is shown in Figure 4B. It is clear that even in methanol, the MEEAA ligands are not fully stretched out, similar to oleate ligands on CdSe NCs,[37] but in contrast to the ordered packing of saturated alkyl thiols on Au NCs.[38] We calculate the average extension of the MEEAA ligands into the solvent as $\langle|r_L|\rangle = \langle|r_{OO}| - |r_{CH3}|\rangle$, where $|r_{OO}|$ and $|r_{CH3}|$ are the distance from the center of the NC to the carboxylate group and methyl carbon, respectively (see Figure 4C). The results in different solvents indicate a slight decrease of the ligand extension from methanol over acetone to toluene (Figure 4D). Figure 4E represents normalized radial plots of the solvent density. In all three cases, we found a stepwise increase in solvent density that reflects the different facets of the NCs. The (100) facets are located 14 Å from the center of the NC, while the (111) facets are 16 Å from the center. More importantly, we find

that the penetration of solvent in the ligand shell decreases from methanol over acetone to toluene. For example, at 17 Å from the NC center, the solvent density is 0 %, 18 % and 24 % for toluene, acetone and methanol respectively (see first dotted line in Figure 4E). This solvent exclusion points to increasingly unfavorable interactions with the ligand that comes, in line with the Gibbs adsorption isotherm, with solvent accumulation at the solvent-ligand interface (see shaded regions in Fig 4E). Clearly, these results correlate with the relation we deduced between ligand-solvent interaction (ligand solvation) and resonance line width in NMR.

Figure 4

Figure 4. (A) CdSe-MEEAA nanocrystal-ligand model before solvation. (B) CdSe-MEEAA nanocrystal-ligand model after solvation with methanol. (C) Calculation of ligand extension (D) Ligand extension in different solvents, (E) Normalized solvent density as a function of the distance from the nanocrystal center.

Having established poor ligand solvation as the primary cause for NMR line broadening, we return to the case of oleate ligands. Although the solvent choice is more restricted, the same behavior is observed. For CdSe and HfO_2 NCs, the alkene resonance is narrower in chloroform compared to toluene (Figure 5). In line with our hypothesis, this concurs with reports of a more favorable solvent-ligand interaction of oleate capped NCs in chloroform compared to toluene.[15, 16] Note that a spectrum of PbS NCs in $CDCl_3$ is not shown in Figure 5. In contrast to HfO_2,[29] and CdSe NCs (Figure S19), oleate ligands desorb from the PbS surface in chloroform, establishing a dynamic equilibrium.[39] In addition, whereas 3.3 nm CdSe NCs feature an alkene resonance FWHM of 70 Hz in pure toluene (Figure 5), the line width is drastically reduced to

36 Hz in 75/25 hexane/toluene (Figure S20). This is even smaller than the line width in chloroform (50 Hz) and identifies hexane as the best solvent for the solvation of the oleate ligand shell.

Figure 5

Figure 5. ^{1}H NMR spectrum (alkene region, resonance **5**) of oleate capped CdSe (3.3 nm), PbS (3.6 nm) and HfO_2 (4 nm) nanocrystals in toluene-d_8 (tol-d_8) and $CDCl_3$ and calibrated at 6.98 and 7.24 ppm respectively. The spectrum of free oleic acid is also displayed to highlight the difference in chemical shift between free and bound ligands.

Further support for our conclusions is found in the chemical shift difference between bound and free oleic acid in aromatic solvents (Figure 5). Solvation by an aromatic solvent leads to the well-described aromatic solvent-induced shift (ASIS).[40] When aromatic solvent is excluded from the ligand shell (poorer solvation), the alkene protons of bound oleates do not experience the same aromatic environment as fully solvated ligands. Hence the large difference in chemical shift for the alkene resonance (0.20 ± 0.02 ppm) between free and bound oleates on CdSe, PbS and HfO_2 nanocrystals in toluene (Figure 5) and other aromatic solvents (Figure S21). As expected, the difference between free and bound oleate is smaller for the methyl resonance (0.12 ± 0.01 ppm, Figure S21) since that moiety is more exposed to solvent. In chloroform, free and bound ligands are either only 0.06 ppm apart (alkene resonance, Figure 5) or have about the same chemical shift (methyl resonance, Figure S22). Absent any special solvent-induced shift in chloroform, the chemical shift difference between free and bound ligands are too small to systematically assess solvent penetration in the ligand shell. Hence the need for a more versatile descriptor of solvent-ligand interactions, such as the heterogeneous linewidth.

Finally, we systematically investigated the impact of nanocrystal core size on the line broadening. We choose PbS nanocrystals as model system since their size can be tuned over a wide range using thiourea precursors (Figure 6A).[41] Clearly, the line width of the alkene resonance (bound oleate) depends on the nanocrystal size (Figure 6B). The T_2 relaxation time constants are 53 ± 2 ms, 31 ± 1 ms, 14 ± 1 ms and 6.7 ± 1 ms for PbS nanocrystals with a diameter of 3.6, 5.4, 8.6 and 12.7 nm, respectively. Using the same procedure as described above, the homogeneous line widths were calculated (6, 10, 22 and 47.5 Hz) and the multiplet FWHM was determined by simulating the oleic acid spectrum (Figure S6). Together with the total FWHM, the heterogeneous broadening was determined (Figure 6C). Although initially both homogeneous and heterogeneous contributions increase with the nanocrystal size, heterogeneous broadening remains the main factor governing the line width. Interestingly, whereas the relative contribution of homogeneous broadening keeps increasing with the nanocrystal size, the heterogeneous broadening seems to saturate at large sizes. These observations are entirely consistent with our model. In general, the curvature of the nanocrystal surface decreases at larger sizes and the ligands are forced closer to each other,[42] excluding solvent and increasing heterogeneity. However, for large nanocrystals, the curvature is already small and further increasing the nanocrystal size does not decrease the curvature significantly. Hence the asymptotic behavior of the heterogeneous line width (Figure 6C). In contrast, ligands attached to larger nanocrystals will tumble slower in solution, such that homogeneous broadening will continue to increase as long as the core size increases (see Figure S23). The relation between the volume available for the ligand shell and the surface curvature[43] is also reflected in the ligand density as smaller nanocrystals can pack more alkyl chains per square nanometer of surface (Figure 6D). This observation can also be explained by the model of Choi *et al.* where the NCs transition from an octahedral shape to a cuboctahedron upon growth, thereby exposing poorly passivated (100) facets.[44]

Figure 6

Figure 6. (A) UV-VIS absorbance of different sized PbS nanocrystals. (B) ^{1}H NMR spectrum of the alkene resonance of oleate ligands bound to the different PbS nanocrystals. (C) The homogeneous and heterogeneous line broadening of the alkene resonance in function of nanocrystals core size. (D) The ligand density in function of the nanocrystal core size.

Conclusion

In conclusion, we found that the poor solvation of the ligand shell promotes the heterogeneous broadening of the ^{1}H NMR line width of nanocrystal bound ligands. More specifically, we correlated the resonance line width to the Hansen hydrogen bonding parameter by dispersing both HfO_2 and CdSe nanocrystals in multiple solvents using 2-[2-(2-methoxyethoxy)ethoxy]acetic acid as a ligand. Molecular dynamics simulations confirmed that the solvation of 2-[2-(2-methoxyethoxy)ethoxy]acetic acid decreased in nonpolar solvents. In line with this interpretation, we showed that upon increasing the nanocrystal size, the heterogeneous line broadening levels off, whereas homogeneous broadening keeps increasing. These results put forward the NMR line width as a sorely-needed descriptor for solvent-ligand interactions. Given the ubiquity of solvent-ligand effects, we thus expect the NMR line width to become a widely used, quantitative tool in nanocolloid research, with applications ranging from size-tuning during synthesis[45] and rational ligand exchange methods[46] to the formation of NC coatings[12] and NC superstructures.[20]

Experimental section

General considerations. 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (technical grade), Hafnium(IV) tert-butoxide (99.99 %), anhydrous benzyl alcohol (99.8 %), cadmium oxide (> 99.99%), oleic acid (90%), N,N'-diphenylthiourea (98%), hexyl isothiocyanate (95 %), phenyl isothiocyanate (99%), dodecylamine (98%), 1-octene (98%), diethylene glycol dimethyl ether ('diglyme', anhydrous, 99.5%) and methyl acetate (anhydrous, 99.5 %) were purchased from Sigma-Aldrich. Selenium (99.999%), lead(II) oxide (Puratronic, 99.999% (metals basis)) and 1-octadecene (tech.) were purchased from Alfa Aesar. n-dodecane (99% for synthesis) was purchased from Merck. Calcium hydride (ca. 93% extra pure) was purchased from Across Organics. Toluene (> 99.8%), methanol (> 99.85%) and 2-propanol (> 99.7%) were purchased from Fiers. 1-octene and n-dodecane were dried over CaH_2 and distilled.

Lead oleate, N-phenyl-N'-dodecylthiourea and N-n-hexyl-N'-dodecylthiourea were synthesized according to the procedure of Hendricks *et al.*[41] Hafnium oxide nanocrystals (5 nm) were synthesized according to De Roo et al.[5, 29] CdSe nanocrystals (3.3 nm) were synthesized according to Chen et al.[47]

Hafnium oxide nanocrystals (3.94 nm) were synthesized according to Lauria et. al.[48] Hafnium(IV) tert-butoxide (4.8 mmol, 2.26 g, 1.94 mL) and benzyl alcohol (40 mL) were heated for 96 hours at 220 °C in an autoclave. After synthesis, the nanocrystals were collected by adding diethyl ether (15 mL) to the reaction mixture and subsequent centrifugation. The precipitate was washed twice with diethyl ether (10 mL). The NCs were suspended in 15 mL toluene and 300 µL of 2-[2-(2-methoxyethoxy)ethoxy]acetic acid was added. The solution was shaken and stirred until clear (5 minutes). The nanocrystals were precipitated with hexane (30 mL) and redispersed in toluene (15 mL) twice to remove unbound ligands. Finally, the NCs are precipitated one more time with hexane and dispersed in 7.5 mL of either toluene, acetone or

ethanol. A dispersion in acetone (1 mL) is once more purified with hexane (5 mL) and dispersed in acetone. A solution in ethanol (1 mL) is also once more purified with hexane (12 mL) and dispersed in ethanol. The dispersion in ethanol can be dried and dispersed in methanol or water.

Cadmium selenide nanocrystals (4.0 nm) were synthesized according to the procedure of Flamée *et al*.[49] with some slight modifications in the quantity of materials used: 4 mmol CdO, 12 mmol oleic acid, 10 mL 1-octadecene and 1 mL of a heterogeneous ODE-Se precursor (10 mmol of Se powder to 5 mL of 1-octadecene). Five minutes after injection, the reaction is quenched by immersing the flask into a water bath. Once cooled to room temperature, 10 mL of both isopropanol and methanol are added, followed by centrifugation at 2000 RCF for 10 min. Three more precipitation cycles from toluene with methanol are performed to obtain purified nanocrystals. [NC] = 150 µM, [oleate] = 30 mM

Exchange for 2-[2-(2-methoxyethoxy)ethoxy]acetic acid on CdSe NCs. The CdSe stock solution (0.5 mL) was dried and ethanol (1 mL) and 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (140 µL) was added and subjected to ultrasound treatment for 30 min, resulting in a clear NC dispersion. Hexane (12 mL) was added to precipitate the NCs and after centrifugation, ethanol (1 mL) and 2-[2-(2-methoxyethoxy)ethoxy]acetic acid (40 µL) was added to the precipitate and subjected to ultrasound treatment for 10 min. Hexane (12 mL) was added to precipitate the NCs and after centrifugation, ethanol (0.5 mL) was added to redisperse the NCs. The NCs were then further purified three times by precipitation with 5 mL of hexane and redispersion in 0.5 mL ethanol. The nanocrystal dispersion could be dried and redispersed in methanol and ethanol. The same procedure was used for dispersion in acetone except ethanol was replaced with acetone. For measurements in toluene, 2-[2-(2-methoxyethoxy)ethoxy]acetic acid was added via an *in-situ* titration until no more bound oleate was found in the diffusion filtered spectra.

Lead sulfide nanocrystals were synthesized according to Hendricks et al.[41] For 3.6 nm PbS NCs, 1.5 mmol lead oleate, 20 mL 1-octene, 1 mmol N,N-diphenylthiourea and 1 mL diglyme are used. After reaction for 60 seconds at 95 °C, the reaction mixture is cooled with a water bath and transferred to a nitrogen-filled glove box. There, 45 mL of methyl acetate is added, followed by centrifugation at 2000 RCF for 10 min. The resulting clear, pale brown solution is discarded and the remaining nanocrystal precipitate is redispersed in toluene. Six more cycle of precipitation from toluene with methyl acetate are performed to reach a ligand coverage of 5.9 oleate ligands per square nanometer. For 5.4 nm PbS NCs, 3 mmol lead oleate, 20 mL 1-octene, 2 mmol N-phenyl-N'-dodecylthiourea and 1mL of diglyme are used, while the reaction is allowed to run for 10 min at 120 °C. A ligand coverage of 4.7 oleate ligands per square nanometer is obtained (7 purfication cycles from toluene/methyl acetate). For 8.6 nm PbS NCs, 1.2 mmol lead oleate, 20 mL n-dodecane, 1 mmol N-n-hexyl-N'-dodecylthiourea and 1 mL diglyme are used, while the reaction is allowed to run for 20 min at 150 °C. A ligand coverage of 4.3 oleate ligands per square nanometer is obtained (7 purfication cycles from toluene/methyl acetate). To grow even larger NCs of 12.7 nm, a double-injection synthesis is carried out. Here, 1.2 mmol lead oleate and 10 mL n-dodecane are used. 0.2 mmol N-n-hexyl-N'-dodecylthiourea in 0.25 mL diglyme is injected at 150 °C, followed by a second injection after 5 minutes of 0.6 mmol N-n-hexyl-N'-dodecylthiourea in 0.75 mL diglyme. The reaction is allowed to run for another 20 minutes at 150 °C. Five purifications cycles were performed from a 4:1 toluene:hexane mixture with methylacetate as non-solvent and three cycles from a 4:1 THF: hexane mixture, again with methylacetate as non-solvent. Intermediate ultra-sonication proved to be important to remove all the free species. A ligand coverage of 3.1 oleate ligands per square nanometer was obtained.

Simulations. The atomistic model for the CdSe NC was adapted from an earlier model.[37] A ~2.8nm CdSe/L NC with N_{Cd}=360 and N_{Se}=309, and with N_L=102 was used. L being the oleate

of MEEAA ligands bonded through the carboxylate group to Cd atoms primarily on the Cd rich facets. The MD simulations were performed at room temperature and pressure within the CP2K program suite utilizing the molecular mechanics (MM) module.[50] The atomic positions of the Cd, Se, and O's of the MEEAA carboxylic group were kept fixed throughout the simulations, with the ligand-Cd bonds taken from ref. 50. Non-bonded interactions for interactions of all atoms with Cd and Se ions were taken from Cosseddu et al.,[51] while the non-bonded and bonded interactions of the MEEAA ligands and solvent molecules were obtained from the SwissParam force field generation tool.[52] The cell size of the simulations were determined through an initial simulation run of 100 ps in the NPT ensemble with a variable cell volume. Starting cell sizes were $(10nm)^3$, with 10781/5537/3978 methanol/acetone/toluene molecules in the cell, arranged initially outside of the ligand shell. Upon equilibration of the cell volume, its average value ($(10.4nm)^3$/$(10.2nm)^3$/$(10.1nm)^3$ for methanol/aceton/toluene respectively)) was determined. The production runs were then performed in the NVT ensemble, using these optimized cell volumes. The systems were first solvated at 500K for 200ps, followed by 800ps of simulated dynamics at 300K. All results presented were averaged over the final 200ps of the simulation window. The solvent density is normalized to the density at 50 Å from the center of the cell.

Characterization. The optical band gap of the CdSe and PbS nanocrystals were determined by UV-VIS-NIR absorption spectroscopy (Perkin Elmer Lambda 900) and correlated to a nanocrystal diameter by aid of sizing curves that were recently re-evaluated by SAXS.[53] Transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) were performed on a FEI Talos F 200X operated at 200 kV. The samples were prepared by dropping 10 ul of ethanol dispersion of 2-[2-(2-methoxyethoxy)ethoxy]acetic acid functionalized HfO_2 NCs (1 mg/ml) on carbon coated Cu grids. Dynamic light scattering (DLS) measurements were recorded on diluted solutions (typical range 1−0.01 mg/mL) on a Zetasizer NS instrument (Malvern, U.K.) in backscattering mode (scattering angle 173°) at a

temperature of 25 °C. Nuclear Magnetic Resonance (NMR) measurements were recorded on a Bruker Avance III Spectrometer operating at a ^{1}H frequency of 500.13 MHz and featuring a BBI probe. The sample temperature was set to 298.15 K. For the quantitative 1D ^{1}H measurements, 64k data points were sampled with the spectral width set to 16 ppm and a relaxation delay of 30s. T_2 measurements were conducted with the CPMG pulse sequence. DOSY measurements were performed with a double stimulated echo and bipolar gradient pulses (dstebpgp2s). The gradient strength was varied quadratically from 2-95% of the probe's maximum value in 64 steps, with the gradient pulse duration and diffusion delay optimized to ensure a final attenuation of the signal in the final increment of less than 10% relative to the first increment. Spectral hole burning was performed by saturating a specific frequency by irradiation with a weak ($1\ 10^{-6}$ Watt) B1 rf field for 5 s prior to the 90 degree pulse and acquisition.

Acknowledgements

The authors acknowledge the FWO Vlaanderen, IWT Vlaanderen, the Belgian American Education Foundation (B.A.E.F.), Fulbright, Ghent University, ETH Zurich and the COMPASS project (H2020-MSCA-RISE-2015-691185) for financial support. The authors also thank Joep Peters for interesting discussions and suggestions. Brandon McMurtry is acknowledged for help with the TOC graphic.

Associated Content

Supporting information

Explanation on homogeneous broadening, UV-VIS spectrum of CdSe nanocrystals, DOSY decay fittings, T_2 relaxation time constant fittings, additional NMR spectra. This information is available free of charge via the internet at http://pubs.acs.org/

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