

Stabilization of Inorganic Nanocrystals by Organic Dendrons

Y. Andrew Wang,^{†,‡} J. Jack Li,[†] Haiyan Chen,[‡] and Xiaogang Peng^{*,†}

Contribution from the Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, and Nanomaterials and Nanofabrication Laboratories, Fayetteville, Arkansas 72701

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Abstract: A series of hydrophilic organic dendron ligands was designed and synthesized for stabilizing high-quality semiconductor and noble metal nanocrystals. The focal point of the dendron ligands is chosen to be a thiol group which is a universal coordinating site for compound semiconductor and noble metal nanocrystals. The methods for binding these dendron ligands onto the surface of the nanocrystals are simple and straightforward. The thin, about 1–2 nm, but closely packed and tangled ligand shell provides sufficient stability for the “dendron-protected nanocrystals” to withstand the rigors of the coupling chemistry and the standard separation/purification techniques. The chemistry presented can be immediately applied for the development of a new generation of biomedical labeling reagents based on high-quality semiconductor nanocrystals. It also provides an alternative path to apply noble metal nanocrystals for developing sensitive detection schemes for chemical and biochemical purposes. The concept may further provide an optimal solution for many other problems encountered in nanocrystal-related research and development, for which the stability of the nanocrystals is a critical issue. Furthermore, the experimental results confirmed that the photochemical stability of colloidal semiconductor and noble metal nanocrystals is the key for developing reliable and reproducible processing chemistry for these nanocrystals.

Introduction

Synthesis and processing are two key issues in the field of nanomaterials. For semiconductor nanocrystals, the synthetic chemistry for high-quality cadmium chalcogenides nanocrystals has been recently advanced to a reproducible, affordable, and practical level through alternative routes,^{1–3} which are developed on the basis of the traditional organometallic approach.^{4–8} If desired processing chemistry for these nanocrystals was available, their interesting size-dependent properties could be fully exploited for fundamental research and technical development.^{9,10} For other types of colloidal nanocrystals, there is also a need for developing reliable processing chemistry, although the synthesis of those nanocrystals may not be as advanced as that of those cadmium chalcogenides nanocrystals.

Highly luminescent semiconductor nanocrystals are being developed as a new generation of biomedical labeling re-

agents.^{11–13} This specific application along with many others requires reliable, general, and practical methods to conjugate nanocrystals with other chemical or biochemical species, which are difficult to accomplish with the nanocrystal/ligand complexes available at present. This is mainly because these nanocrystal/ligand complexes cannot survive the coupling environment and/or the following purification procedures.¹⁴ On the aspect of fundamental research, the stability of colloidal semiconductor nanocrystals has also caused some major problems. For example, the synthesis of “nanocrystal molecules” of colloidal semiconductor nanocrystals has been limited to the homodimers because the nanocrystals coated by conventional ligands cannot withstand the desired coupling and separation processes.¹⁵

A similar situation occurs for other types of colloidal nanocrystals. For example, colloidal gold nanocrystals modified with single-stranded DNA have been used for developing sensitive detection schemes of the complementary single-stranded DNA,^{16,17} and for assembling these nanocrystals into nanocrystal molecules.^{18–20} For both cases, single-strand DNA

* To whom correspondence should be addressed. Phone: 479-575-4612. Fax: 479-575-4049. E-mail: xpeng@uark.edu.

[†] University of Arkansas.

[‡] Nanomaterials and Nanofabrication Laboratories.

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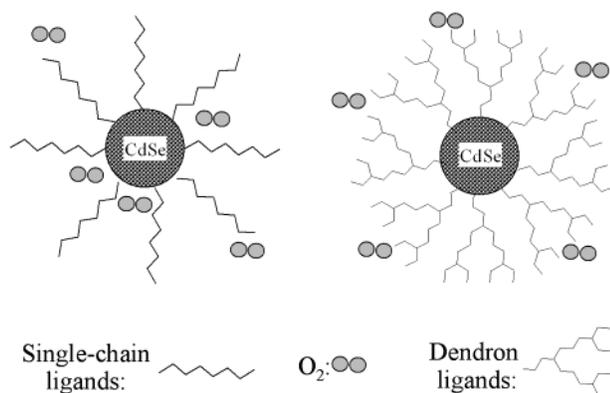


Figure 1. Schematic comparison of the diffusion of O₂ molecules into the interface between a nanocrystal and its ligand shell. Left: A nanocrystal coated by ligands with a single hydrocarbon chain. Right: A dendron-nanocrystal coated with generation-2 (G2) dendron ligands. For clarity, the chain tangling is not shown.

was attached onto the surface of gold nanocrystals directly, and traditional coupling reactions were again found too vigorous for the nanocrystals.¹⁹ It should be pointed out that, for small-sized gold nanoclusters, the regular coupling reactions were found possible.^{20–22} This is somewhat better than that for semiconductor nanocrystals, which may be a result of the significantly better stability of the gold nanocrystal cores.

The mechanisms of the photochemical instability of the CdSe and Au nanocrystals coated by hydrophilic thiols were recently studied systematically.¹⁴ The diffusion of active oxygen species into the interface between a colloidal nanocrystal and its ligand monolayer was proven as the initial and key step for the entire process. Overall, the CdSe and Au nanocrystals coated by conventional thiol ligands were found very active to photooxidation, which may be the intrinsic reason for the tough processing chemistry of these nanocrystals.

The above mechanisms of the photochemical instability of the thiol-coated nanocrystals imply that a thick and densely packed ligand layer should be a solution for this critical problem, because the diffusion of small molecules into the ligand shell is the key step. However, a thick ligand shell is not desirable for many applications. For example, the size of the nanocrystal/ligand complex will determine their physical penetration into a biological structure. This consideration motivated us to design a new family of ligands, organic dendron ligands.

Organic dendron ligands are regularly hyperbranched organic molecules (examples in Figures 1 and 2) with a central focal point which will be used as the binding site for the cationic/metallic elements on the surface of nanocrystals. The number of the branching points along one chain from the focal point to the outer terminal group is the generation number of the dendrons.²³ There are two reasons to choose organic dendron ligands. First, their steric crowding characteristics may provide a closely packed but thin ligand shell which may be as efficient as a shell formed by the ligands with a long and floppy single chain. Importantly, the steric crowding of a dendron is very ideal for filling the spherical ligand layer because the dendron ligands can naturally pack in a cone shape on the surface of

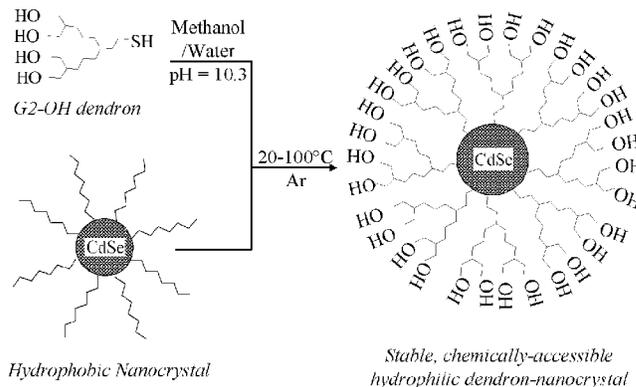


Figure 2. Schematic process for converting hydrophobic semiconductor nanocrystals into hydrophilic and chemically processable dendron-nanocrystals.

nanocrystals. Second, the inter- and intramolecular chain tangling of the dendrons with relatively flexible branches may further slow the diffusion of small molecules or ions from the bulk solution into the interface between a nanocrystal and its ligands. Figure 1 shows a schematic comparison for the diffusion of O₂ from the bulk solution into the inner interface between a nanocrystal and its ligand shell in the cases of simple ligands and dendron ligands. A similar mechanism was actually proposed to explain the improved photoluminescence efficiency of organic dyes encapsulated inside dendrimers.²³

Experimental results to be presented below reveal that the resulting CdSe and Au “dendron-protected nanocrystals” (dendron-nanocrystals) are a class of stable nanocrystal/ligand complexes, and traditional coupling reactions for chemical and biochemical macromolecules and the standard chemical/biochemical purification/separation techniques can be readily applied to the resulting dendron-nanocrystals. These results revealed that the processing chemistry of semiconductor and noble metal nanocrystals is indeed dependent on the photochemical stability of the nanocrystal/ligand complexes. We expect that dendron-nanocrystals may be proven as an optimal solution for stabilizing colloidal nanocrystals for many different purposes although the current work focuses on hydrophilic thiols which are a class of universal ligands for stabilizing compound semiconductor nanocrystals and noble metal nanocrystals. Since processing chemistry of noble metal nanocrystals is more advanced than that of semiconductor nanocrystals, at least for small-sized nanoclusters,^{20–22} this paper will mostly deal with semiconductor dendron-nanocrystals.

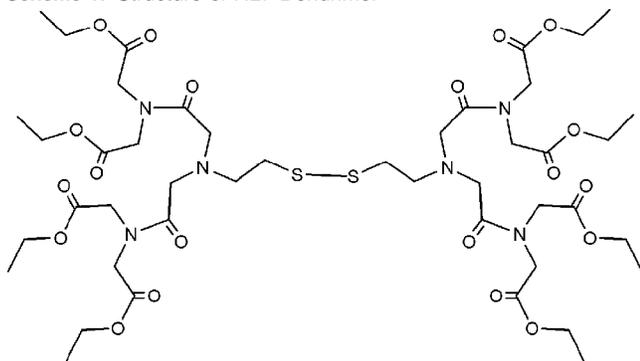
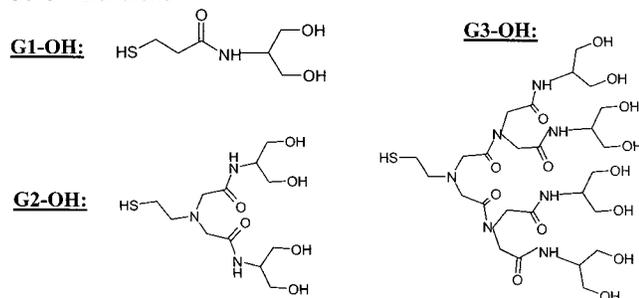
Experimental Section

Chemicals. Cystamine dihydrochloride, 2-bromomethylacrylic acid, iodine, glutaric anhydride, triethylamine, chloroacetyl chloride, bromoacetic bromide, serinol, triphenylmethanol, trifluoroacetic acid (TFA), triethylsilane, diethyl iminodiacetate, technical grade (90%) trioctylphosphine oxide (TOPO), cadmium acetate hydrate (99.99+%), selenium powder (–100 mesh, 99.999%), anhydrous toluene (99.8%), mercaptoacetic acid (MAA, 97+%), mercaptoundecanoic acid (MUA), sodium citrate dihydrate (99%), glycine hydrochloride (98%), 1-[3-(dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride (EDC, 98+%), and dithiothreitol (DTT) were purchased from Aldrich. Chloroauric acid was purchased from Strem Chemicals. Anhydrous ethyl ether, toluene, chloroform, *N,N*-dimethylformamide (DMF), acetone, K₂CO₃, Na₂SO₄, ethyl acetate, and methanol were purchased from EM Science.

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Scheme 1. Structure of NL7 Dendrimer**Scheme 2.** Molecular Structures of the G1-OH, G2-OH, and G3-OH Dendrons

Synthesis of Nanocrystals. The synthesis of CdSe nanocrystals followed the large-scale scheme described previously.¹⁴ Gold nanocrystals, 12 nm in diameter, were synthesized through a modified procedure reported in reference 17. Briefly, 250 mL of deionized water (18 M Ω -cm) mixed with 2.5 mL of chloroauric acid (1%) was brought to boiling, and sodium citrate aqueous solution (7.7 mL, 1%) was injected into the boiling solution. The reaction was kept heating and stirring for another 20 min. The burgundy color solution was allowed to cool to room temperature and was then stored in the dark for later use.

Synthesis of Dendron Ligands. The dendron ligands were synthesized and stored in the form of either their parent disulfide dendrimers (Scheme 1) or the (triphenyl)methylthiol-protected dendrons (Scheme 2), because of the synthetic strategies and also the instability of thiols. From the structural point of view, a dendrimer is a compound with 2–4 dendrons attached to a center core. Different from dendrons, dendrimers do not have a focal point (see the structure of NL7 as an example).

Scheme 1. Synthesis of Dendron Ligands through Their Parent Dithiol Dendrimers. NL7 Dendrimer, The Parent Dendrimer of NL7 (G2-COOC₂H₅) Dendrion. Step I. Chloroacetyl chloride (9 mL, 0.11 mol) was added dropwise into a cold solution of diethyl iminodiacetate (10 g, 0.052 mol) in 40 mL of ethyl acetate under stirring. The reaction was then carried out at refluxing temperature for 30 min. The solvent and excess of chloroacetyl chloride were removed under reduced pressure. The chloroform was added to the residue and then washed with aqueous 5% NaHCO₃ and brine. The organic portion was dried with NaSO₄ and evaporated to remove the solvent. A liquid product, *N,N*-diethylacetatochloroacetamide (CIDIA), was obtained. ESI-MS (m/z): 267 ($M + H^+$). ¹H NMR (270 MHz, CDCl₃): δ 1.24 (m, 6H, CH₃), 4.17 (m, 10H, CH₂). *N,N*-Diethylacetatobromoacetamide (BrDIA) was synthesized using the same procedure but with bromoacetyl bromide as the starting material instead of chloroacetyl chloride.

Step II. Cystamine dihydrochloride (4 g, 0.0174 mol) in 10 mL of H₂O was mixed with 20 g (0.075 mol) of CIDIA in 150 mL of DMF. K₂CO₃ (7.4 g) was added to this solution. The reaction was carried out at 90 °C for 22 h. A solid was filtered off, and the solvent was removed

under reduced pressure. The residue was dissolved in chloroform and extracted with water twice. The organic layer was dried with CaCl₂ and was further purified by column chromatography (silica gel, 2% ethanol/chloroform). NL7 dendrimer was obtained as a liquid after the removal of the solvent. ESI-MS (m/z): 1069 ($M + H^+$). ¹H NMR (270 MHz, CDCl₃): δ 1.20 (m, 24H, CH₃), 2.91 (t, 4H, SCH₂CH₂N), 3.69 (t, 4H, SCH₂CH₂N), 4.12 (m, 40H, CH₂).

Parent Dendrimer of the G1-OH Dendrion. (SCH₂CH₂COCl)₂, 2.4 g (0.0097 mol), dissolved in 15 mL of DMF was added to the mixture of 1.8 g (0.0194 mol) of serinol and 2 g of triethylamine in 10 mL of DMF in the duration of 15 min. The mixture was stirred vigorously overnight at ambient temperature. After the completion of the reaction, the solvent was removed under reduced pressure. G1-OH was obtained. ESI-MS (m/z): 357 ($M + H^+$). ¹H NMR (270 MHz, CDCl₃): δ 2.50 (t, 2H, CH₂CO), 2.84 (t, 2H, SCH₂), 3.39 (d, 8H, CH₂OH), 3.70 (m, 1H, NHCH), 7.71 (d, 2H, NH).

Thiol Dendrons. The thiol dendrons were prepared by breaking the disulfide bond of the parent dendrimers. For example, the G2-COOC₂H₅ dendron was prepared as follows. Prior to surface modification, NL7 was cleaved by DTT to two thiol dendrons. Excess DTT was removed by extraction in the water/chloroform solvent system for the G2-COOC₂H₅ dendron, or in the water/ethyl acetate solvent system for the G1-OH dendron.

Scheme 2. Synthesis of Dendron Ligands through (Triphenylmethyl)thiol Protection. Synthesis of G3-OH. ((2-Triphenylmethyl)thio)ethylamine-trifluoroacetic acid (4.3 g, 0.01 mol) and 7.0 g (0.0226 mol) of BrDIA were dissolved in 50 mL of DMF. K₂CO₃ (2 g) in 2 mL of H₂O was added into the DMF solution. The mixture was stirred at 70 °C overnight. The solvent was removed under reduced pressures, and then ether and water were added into the flask. The ether layer was isolated and dried over anhydrous Na₂SO₄, and ether was removed under reduced pressure. A light-yellow liquid (7.8 g), TPNL7, was obtained.

The mixture of 1.8 g (0.0023 mol) of TPNL7, 1.4 g (0.015 mol) of serinol, and 2.5 g of DMF was heated at 120 °C overnight, and then it was allowed to cool to room temperature, and 20 mL of water was added. Consequently, 10 mL of ethyl acetate was added to extract the raw product. The organic layer was isolated and dried over anhydrous Na₂SO₄, and the solvent was removed. TFA, 10 mL, was added to the residue in an ice bath, followed by an addition of 0.3 g of triethylsilane. After this step, an immediate color discharge and the formation of a white precipitate were observed. The white solid was removed by filtration through Celite. The solvent of the final solution was evaporated under reduced pressure, and 2.0 g of G3-OH was obtained as a light-yellow liquid. ESI-MS (m/z): 716 ($M + H^+$). ¹H NMR (270 MHz, CDCl₃): δ 2.75 (m, 2H, SCH₂), 3.06 (m, 4H, CHNH), 3.31 (br, 2H, CH₂N), 3.36–3.60 (m, 16H, CH₂OH), 3.70–4.50 (m, 20H, NCH₂CO, OH), 7.82 (br, 4H, NH).

Synthesis of G2-OH. The synthesis of G2-OH followed a procedure similar to that of the synthesis of the G3-OH. ESI-MS (m/z): 340 ($M + H^+$). ¹H NMR (270 MHz, CDCl₃): δ 2.75 (m, 2H, SCH₂), 3.06.

Surface Modification of CdSe Nanocrystals by Dendrons. As shown in Figure 2, CdSe nanocrystals were modified by the hydrophilic dendrons through a modified procedure reported previously.^{14,15} Typically, the reaction time was set at an hour to 24 h. The initial pH of the reaction solution was set at pH = 10.3.

For NMR and IR measurements, the nanocrystals before and after the coupling reactions were dissolved and precipitated in adequate solvent systems about six times. The ester terminated dendron-nanocrystals were dissolved in chloroform and precipitated by ethyl ether. The dendron-nanocrystal precipitates were separated by centrifugation and decantation and dried by air. The final products were dried under vacuum for about 2 h to remove solvent residuals. After all these rigorous treatments, the dendron-nanocrystals were still completely soluble in desired solvents for the NMR measurements.

The water soluble dendron-nanocrystals were purified using the solvent system reported previously.¹⁴

An alternative two-phase surface modification procedure was developed for the dendrons only soluble in water. Typically, hydrophobic CdSe nanocrystals, 15 mg, were dissolved in 2 mL of ethyl ether, the dendrons, 0.14 mmol, were dissolved in 15 mL of water, and the pH value of the aqueous solution was adjusted to pH = 10.3. The nanocrystals were transferred from the organic phase to the aqueous phase by mixing the two solutions together. The ethyl ether phase became colorless, and the aqueous phase was optically clear and with the color of the nanocrystals. The aqueous phase was isolated, and, under Ar, either incubated overnight or heated to a desired temperature for a certain amount of time. Experimental results indicated that the room-temperature incubation for about 24 h worked very well for the CdSe dendron-nanocrystals coated by the G1-OH, G2-OH, or G3-OH dendrons. The final product of the CdSe dendron-nanocrystals with these three hydroxyl terminated dendrons was used for comparing the influence of the number of the generation of dendron ligands on the photochemical stability of the CdSe dendron-nanocrystals.

Surface Modification of Gold Nanocrystals by the Dendron Ligands. The dendron ligands were added into the citrate-stabilized gold nanocrystals synthesized by the procedure mentioned above. The atomic ratio between the dendron ligands and Au was 0.8:1. The gold nanocrystal concentration is simply determined by the absorbance at the surface plasmon peak position of the nanocrystal solution. After being stirred for about 5 h at room temperature, the nanocrystals were precipitated from the solution and isolated from the free ligands by the following centrifugation and decantation. For Au nanocrystals coated by single-chain thiols, the nanocrystals were separated by ultracentrifuge.

Coupling Reactions. In a typical coupling reaction, 3-fold of EDC relative to the dendron ligands on the surface of nanocrystals was mixed with the dendron-nanocrystals at pH = 6–7 for 30 min. The amount of ligands on the surface of nanocrystals was estimated by assuming a close packing of the ligands on the surface of a nanocrystal.¹⁴ Two equivalents of glycineamide were added into this mixture. The entire solution was incubated for 4 h at room temperature. For the ester-amine coupling, the CdSe dendron-nanocrystals were allowed to react with a 2-aminoethanol liquid for about 10 min at 100 °C. If the ester-amine coupling was carried out at room temperature overnight, significant hydrolysis of the ester groups was observed.

Gel Electrophoresis. Gel electrophoresis was carried out on 0.5% agarose gel in TBE electrophoresis buffer (Tris base 89 mM, boric acid 89 mM, EDTA 2 mM) with primarily purified samples. The voltage was normally set at 120–180 V. The nanocrystals at different bands were recovered back to solution as follows: cutting the corresponding spots on the gel plate and storing them separately in different vials, and melting the gel pieces in warm pure water or smashing the gel in cold pure water. An additional centrifugation step might take place to remove the insoluble and colorless gel residues from the colorful nanocrystal solution.

Results

Although dendron-nanocrystals may be used for many different systems, this work intends to prove its significance by rationally designing a class of dendron ligands belonging to the hydrophilic thiol family. The thiol group is chosen as the binding group to the surface cations of nanocrystals because of its versatile coordination chemistry to semiconductor^{12,13,15} and noble metal nanocrystals.^{18,20,24,25} The outer terminal groups of the dendron ligands are amides, carboxylic acids, alcohols, or

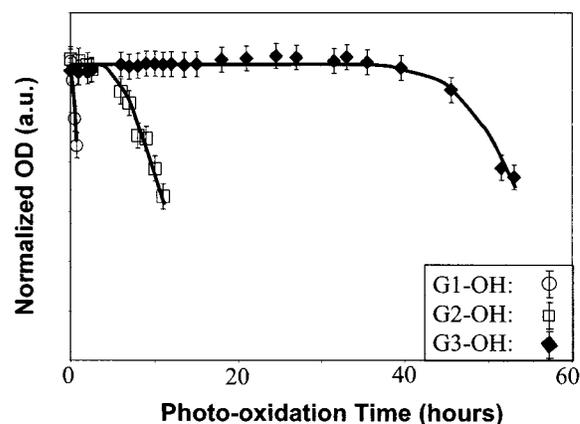


Figure 3. Photochemical stability (under UV radiation) of CdSe dendron-nanocrystals in air. The molecular structures of the dendrons are illustrated in Scheme 2.

esters, which resemble that of a hydrophilic protein or a sugar. The branches of a dendron ligand may not be completely symmetric, because it may potentially provide better steric crowding efficiency over the entire ligand shell and a more efficient coupling reaction. Experimental results indicate that the dendron ligands work well for differently sized CdSe nanocrystals and gold nanocrystals.

Photochemical, Thermal, and Chemical Stability of CdSe and Au Dendron-Nanocrystals. Photochemical, thermal, and chemical stability of CdSe and Au dendron-nanocrystals are exceptionally good in comparison to those of the nanocrystals coated by single-chain thiol ligands. The photochemical stability of dendron-nanocrystals was studied following the previously reported procedure.¹⁴ The normalized OD (optical density) at the original exciton absorption peak of CdSe nanocrystals was used as the indicator of the photooxidation of the nanocrystals.¹⁴ Figure 3 illustrates that the photochemical stability of the CdSe nanocrystals improves with the increase of the number of the generation of the dendron ligands with a similar structure. The molecular structures of the thiol dendrons are illustrated in Scheme 2. Without additional UV radiation, the aqueous solution of G2 and G3 dendron-nanocrystals after removing excess ligands can be stored under ambient conditions for at least several months without any precipitation. As described below, this exceptional stability of the CdSe nanocrystals coated by the G2 or G3 dendrons is sufficient for necessary coupling and purification procedures.

The previously reported results revealed that the photochemical stability of nanocrystal/ligand complexes can be improved significantly by simply increasing the molecular weight of the single-chain ligands.¹⁴ That is so because the longer the chain is, the thicker the ligand layer will be. For this reason, it is important to verify that the improved stability of dendron-nanocrystals shown in Figure 3 is not simply due to the increase of the molecular weight of the dendrons. We chose three ligands with a different degree of branches but with a similar molecular weight to clarify this issue. The experimental results (see Supporting Information) indicate that the stability of the CdSe nanocrystal/ligand complexes is strongly associated with the degree of the branching of the ligands.

The gold nanocrystals coated by single-chain thiols, such as MUA, are generally very fragile. They could not withstand the precipitation by sodium chloride solution, and the resulting

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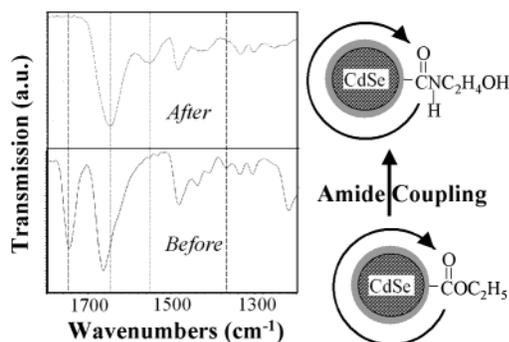


Figure 4. Infrared (IR) spectra of CdSe-NL7 dendron-nanocrystals before and after an amide coupling reaction.

precipitate became insoluble in pure water. They had to be purified by ultracentrifuge that did not convert the nanocrystal/ligand complex into solid/powder form. In contrast, the gold dendron-nanocrystals could be precipitated by sodium chloride solution and be redispersed in water repeatedly. In general, the gold dendron-nanocrystals were more stable against photooxidation than the corresponding CdSe dendron-nanocrystals.

Amide Coupling. The amide coupling of the dendron-nanocrystals through either the ester-amine coupling or the traditional EDC coupling worked well. Several types of primary amines, such as glycylamide, 2-aminoacetonitrile, benzylamine, 2-aminoethanol, and ammon, were successfully coupled to the outer surface of the dendron-nanocrystals. The solubility of the resulting dendron-nanocrystals is largely dependent on the resulting amide. For example, the ester-terminated CdSe dendron-nanocrystals were only soluble in organic solvents. After reacting with ammonia or 2-aminoethanol, the dendron-nanocrystals became only soluble in water. Infrared (IR) (Figure 4) and ^1H NMR (see Supporting Information) studies revealed that the ester-amine coupling reaction could be close to 100% completion. The ester stretching vibration band at around 1740 cm^{-1} and the methyl deformation mode at 1370 cm^{-1} disappeared completely after the CdSe dendron-nanocrystals reacted with aminoethanol liquid for about 10 min at $100\text{ }^\circ\text{C}$ (Figure 4).²⁶ The peaks which appeared at about 1640 and 1550 cm^{-1} in the spectrum of the resulting nanocrystals of the coupling reaction are due to the secondary amide vibration modes,²⁶ which indicates the formation of the new amide bonds. It should be mentioned that the IR spectra of the CdSe dendron-nanocrystals, either before or after the ester coupling reactions, are nearly identical to those of their corresponding free ligands (see Supporting Information). If dendron-nanocrystals were terminated with $-\text{COOH}$ groups, amide coupling was accomplished through the conventional EDC coupling,²⁶ and similar IR results were observed.

Separation and Purification. The separation and purification of dendron-nanocrystals can be carried out by conventional techniques. Both CdSe and Au dendron-nanocrystals can pass through an adequate chromatography column readily. We verified that the CdSe dendron-nanocrystals without any excess ligands were able to stay in a Sephadex G-25 (or NAP-10) column with room light for hours without leaving any residues after the nanocrystals were run through in a tight band. In

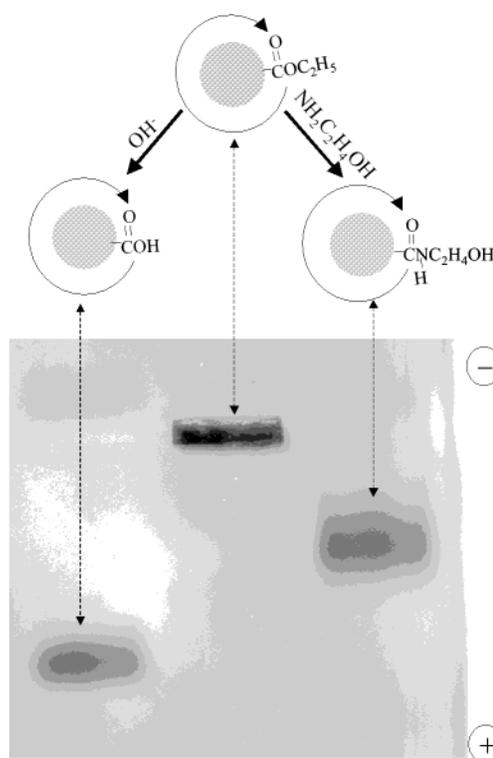


Figure 5. Gel-electrophoresis of CdSe dendron-nanocrystals. Middle: The original nanocrystals coated by NL7 (insoluble in water and not moved). Left: After the hydrolysis. Right: After the amide coupling reaction.

contrast, the CdSe nanocrystals coated by MPA were completely smeared and could not be washed out under the same conditions. However, we have not yet found a medium which shows significant separation by column chromatography for the dendron-nanocrystals with either different sizes or different terminal groups.

The CdSe dendron-nanocrystals can be purified and separated by gel-electrophoresis without any excess ligands. The negatively charged dendron-nanocrystals migrate toward the positive electrode. In Figure 5, the gel-electrophoresis results of the CdSe dendron-nanocrystals with different terminal groups are shown. The original ester-terminated dendron-nanocrystals did not move on the gel because they were insoluble in water. On the contrast, the two reaction products were moved in two tight bands on the gel with distinguishable mobilities. After gel-electrophoresis, the dendron-nanocrystals can be completely recovered back into pure water (see Experimental Section). A UV-vis study revealed that the nanocrystals recovered from the gel remained unchanged. However, it is helpful to cover the gel electrophoresis chamber during the electrophoresis to avoid the room light radiation because of the strong oxidation environment in the chamber. Coated with conventional single-chain thiol ligands, both CdSe and Au nanocrystals cannot survive the separation/recovery process without a large excess of free thiol ligands.

Discussion

The coupling reactions presented here are common ones for coupling functional organic/biological species onto solid substrates although they have been unachievable for the CdSe and other semiconductor nanocrystals coated by single-chain thiol ligands without excess free ligands in the solution. Similar to the coupling reactions, gel electrophoresis has also been very

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difficult to perform for semiconductor nanocrystals. Excess free ligands were found necessary for the gel electrophoresis of semiconductor and large-sized gold nanocrystals, and the nanocrystals were often not recoverable.

Evidently, the dendron ligands reported here have dramatically improved the photochemical stability of both types of nanocrystals. For other types of nanocrystals, such as magnetic oxides and metals, it would be worth to apply dendron ligands since their stability against a required environment is also a problem. In principle, uncross-linked dendrons as the ones described in this paper can stabilize the related nanocrystal/ligand complexes, if the stability is controlled by the diffusion of some small molecules into the interface between a nanocrystal and its ligand shell.

There is still some room to improve (see Figure 3) if one wants absolute stability for CdSe and Au nanocrystal/ligand complexes. If the resulting ligands generated by the photocatalytic oxidation occurred on the surface of nanocrystals were designed to be insoluble in the solvent, the oxidized ligands would still surround the inorganic core to form a micelle structure although there were no chemical bonds between the ligands and the inorganic cores.¹⁴ If the inorganic core was stable against photooxidation, the resulting nanocrystal/ligand complex would remain soluble and processable. In practice, an insoluble ligand shell may be achievable for the dendron ligands by intermolecular cross-linking between the chains by multiple hydrogen bonds, covalent bonds, or other relatively strong interactions. For the inorganic core, active semiconductor and metal nanocrystals can be coated by another inorganic component²⁹ prior to the surface modification by dendron ligands to convert them into being photooxidation inactive.

Certain types of dendron ligands can presumably be used for the synthesis of high-quality semiconductor nanocrystals, provided the recent discovery of many alternative routes toward high-quality semiconductor nanocrystals.^{2,3} With rationally designed ligands, one may directly prepare stable nanocrystals with desired functionality, such as being water soluble and chemically accessible. It should be pointed out that the thiol-based ligands described in this paper cannot be used for the synthesis of high-quality semiconductor nanocrystals because thiols were found to be not compatible with the existing synthetic schemes.^{2,3} We are currently designing and synthesizing dendron ligands using carboxylic acid, amine, phosphine oxide, or phosphonic acid groups as the coordinating sites for the direct synthesis of high-quality semiconductor nanocrystals and magnetic nanocrystals. The thiol-based dendrons presented in this paper may be applied for the synthesis of stable noble metal nanocrystals using the existing methods.²⁵

The results indicate that the inter- and intramolecular chain tangling between the branches of dendrons have played an important role for stabilizing the semiconductor nanocrystals, in addition to the steric crowding feature of the dendrons.²³ Dendron ligands have recently been used for the synthesis of gold nanocrystals using different generations of quinone-based ($-C=O$) hydrophobic dendrons with rigid branches in the hope

to control the size of gold nanocrystals by the different generation dendrons.²⁷ The results indicate that the gold nanocrystals synthesized with high generation dendrons have a strong tendency to aggregate, which is different from the results of this work. We think their results may be caused by the rigid branches of their dendrons,²⁷ which cannot provide sufficient steric crowding on the surface of nanocrystals and have difficulty possessing inter- and intramolecular chain tangling.²³ A series of similar structured dendrons with thiol as the binding group, whose branches are also quite rigid, was reported recently for the synthesis of gold nanocrystals.²⁸

Dendrimers have already been used for the synthesis of different types of colloidal nanocrystals.³⁰ In this case, nanocrystals are encapsulated inside dendrimers, which possess a different type of structure in comparison to that of the dendron-nanocrystals discussed in this paper. To our best knowledge, the quality of the resulting nanocrystals synthesized using dendrimers or dendrons, at least for semiconductor nanocrystals,^{31–33} is not comparable to the ones synthesized by the green chemical methods at high temperatures.^{2,3} For stabilizing nanocrystals as the surface ligands, dendrimers are not as ideal as dendrons. The cone-shaped structural feature and the single binding site of a dendron ligand should provide a better packing in the ligand shell and an unambiguous orientation of the ligands on the surface of nanocrystals, respectively.

Conclusion

In conclusion, dendron ligands are used for stabilizing CdSe and Au nanocrystals. The experimental results confirmed that the photochemical stability of semiconductor and noble metal nanocrystal/ligand complexes is the key for the development of reliable processing chemistry for these nanocrystals. The surface-modification chemistry of the nanocrystals with dendron ligands is simple and straightforward. The thickness of the ligand layer of the dendron-nanocrystals can be as thin as about 1 nm to achieve substantial stability for those dendron-nanocrystals to be manipulated as standard chemical reagents. The chemistry related to CdSe dendron-nanocrystals can be immediately applied for developing photoluminescence-based labeling reagents using semiconductor nanocrystals for biomedical applications.^{12,13} The chemistry presented also provides an alternative path to apply noble metal nanocrystals for chemical³⁴ and biomedical applications.^{16,17} The concept should also create many new opportunities in the field of colloidal nanocrystals and related materials since it carries the possibility to develop simple and affordable processing chemistry. For example, stable magnetic dendron-nanocrystals may represent a new avenue for using magnetic nanocrystals for drug delivery and enhanced magnetic resonance imaging.^{35,36}

Supporting Information Available: Synthesis and spectra of parent dendrimers (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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