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Water-Soluble NaYF$_4$:Yb,Er(Tm)/NaYF$_4$/Polymer Core/Shell/Shell Nanoparticles with Significant Enhancement of Upconversion Fluorescence

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Research on NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm,[1−4] especially preparation and upconversion fluorescence of their nanocrystals,[5−10] has been active due to potential applications as sensitive bio-probes.[7,11−13] NaYF$_4$:Yb,Er(Tm) is one of the most efficient 980 nm near-infrared (NIR) to visible (green and blue) upconversion phosphors.[14,15] As bio-probes for imaging and detection, conceivable advantages include improved signal-to-noise ratio due to absence of autofluorescence and reduction of light scattering,[16,17] easy in vivo imaging by noninvasive and deep penetration of NIR radiation,[18] low photobleaching,[19] and feasibility of multiple labeling with different emissions under the same excitation. A compact, power-rich, and inexpensive 980 nm NIR laser may be used as the excitation source,[7] potentially replacing the currently expensive ultrafast pulse laser in the multiphoton fluorescent microscopy.

Commercial bulk NaYF$_4$:Yb,Er(Tm) is usually prepared by solid-state[1,14,15] or hydrothermal reaction.[2] A universal bio-probe, small (≤10 nm) with narrow size distribution, should be water soluble with high fluorescent efficiency.[19,20] Very recently, three groups reported the preparation of NaYF$_4$:Yb,Er(Tm) nanoparticles, adopting a similar strategy by co-thermolysis of rare earth trifluoroacetate (RE(CF$_3$COO)$_3$) and sodium trifluoroacetate (NaCF$_3$COO) in high temperature organic solutions.[8−10] In Capobianco et al.'s report,[10] cubic NaYF$_4$:Yb,Er(Tm) particles with a broader size distribution of 10−50 nm were prepared. The efficiency of the cubic phase is 1 order of magnitude lower than the desirable hexagonal phase. In Yan et al.'s method,[9] hexagonal phase NaYF$_4$:Yb,Er(Tm) particles were prepared. However, the hexagonal plates of NaYF$_4$:Yb,Er (187 nm × 71 nm) and NaYF$_4$:Yb,Tm (100 nm × 51 nm) were too large as bio-probes. In our parallel effort,[8] hexagonal phase NaYF$_4$:Yb,Er(Tm) nanoparticles with smaller size and narrow size distribution (10.5 ± 0.7 nm) were synthesized. However, all of the above-reported nanoparticles were hydrophobic with lower fluorescence compared to the bulk counterparts.

In this communication, hexagonal phase nanoparticles of NaYF$_4$:Yb,Er(Tm) core and NaYF$_4$:Yb,Er(Tm)/NaYF$_4$ core/shell (C/S) were prepared. Remarkable upconversion fluorescence enhancements of ~7 and ~29 times were observed for NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm, respectively, after coating with an undoped NaYF$_4$ shell. These hydrophobic C/S nanoparticles were further rendered hydrophilic by a layer of amphiphilic polymer. These attractive features of the nanoparticles make them suitable bio-probes for bio-applications.

The core and C/S of the nanoparticles were prepared using our recently reported method with modification.[8] The polymer coated C/S nanoparticles were synthesized by coating the C/S nanoparticles with an amphiphilic layer, 25% octylamine and 40% isopropylamine modified poly(acrylic acid) (PAA).[21,22] Details for the preparation of core, C/S, and PAA coated C/S of the nanoparticles are in Supporting Information.

Figure 1a shows the structure of NaYF$_4$:Yb,Er(Tm) core, C/S, and PAA coated C/S nanoparticles. The coating of PAA arose from the hydrophobic interactions of the octyl and isopropyl groups of PAA with the octadecyl group of oleylamine on the nanoparticles surface. After coating, the hydrophilic carboxyl group of PAA extended outward, rendering nanoparticles water soluble and allowing attachment of biomolecules. Figure 1b shows the fluorescence images of NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm cores, C/S, and PAA coated C/S nanoparticles of the same particle concentrations dispersed in chloroform, chloroform, and water solutions, respectively. Excited with a 980 nm NIR laser, significant fluorescence enhancement was observed for C/S nanoparticles, as compared with their respective cores. PAA coated C/S nanoparticles showed a decreased fluorescence.

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(1) Kramer, K. W.; Biner, D.; Frei, G.; Gudel, H. U.; Hehlen, M. P.; Luthi, S. R. *Chem. Mater.* **2004**, *16* (7), 1244−1251.
(2) Liang, L. F.; Wu, H.; Hu, H. L.; Wu, M. M.; Su, Q. *J. Alloy Compd.* **2004**, *368* (1−2), 94−100.
(3) Suyver, J. F.; Grimm, J.; van Veen, M. K.; Biner, D.; Kramer, K. W.; Gudel, H. U. *J. Lumin.* **2006**, *117* (1), 1−12.
(4) Wang, Z. J.; Tao, F.; Yao, L. Z.; Cai, W. L.; Li, X. G. *J. Cryst. Growth* **2006**, *290* (1), 296−300.
(5) Heer, S.; Kompe, K.; Gudel, H. U.; Haase, M. *Adv. Mater.* **2004**, *16* (23−24), 2102−2105.
(6) Zeng, J. H.; Su, J.; Li, Z. H.; Yan, R. X.; Li, Y. D. *Adv. Mater.* **2005**, *17* (17), 2119−2123.
(7) Yi, G. S.; Lu, H. C.; Zhao, S. Y.; Yue, G.; Yang, W. J.; Chen, D. P.; Guo, L. H. *Nano Lett.* **2004**, *4* (11), 2191−2196.
(8) Yi, G. S.; Chow, G. M. *Adv. Funct. Mater.* **2006**, *16* (18), 2324−2329.
(9) Mai, H. X.; Zhang, Y. W.; Si, R.; Yan, Z. G.; Sun, L. D.; You, L. P.; Yan, C. H. *J. Am. Chem. Soc.* **2006**, *128* (19), 6426−6436.
(10) Boyer, J. C.; Vetrone, F.; Cuccia, L. A.; Capobianco, J. A. *J. Am. Chem. Soc.* **2006**, *128* (23), 7444−7445.
(11) van de Rijke, F.; Zijlmans, H.; Li, S.; Vail, T.; Raap, A. K.; Niedbala, R. S.; Tanke, H. J. *Nat. Biotechnol.* **2001**, *19* (3), 273−276.
(12) Lim, S. F.; Riehn, R.; Ryu, W. S.; Khanarian, N.; Tung, C. K.; Tank, D.; Austin, R. H. *Nano Lett.* **2006**, *6* (2), 169−174.
(13) Wang, L. Y.; Li, Y. D. *Chem. Commun.* **2006** (24), 2557−2559.
(14) Menyuk, N.; Dwight, K.; Pinaud, F. *Appl. Phys. Lett.* **1972**, *21* (4), 159−160.
(15) Sommerdijk, J. L.; Bril, A. *Philips Tech. Rev.* **1974**, *34* (1), 1−32.
(16) Zijlmans, H. J. M. A.; Bonnet, J.; Burton, J.; Kardos, K.; Vail, T.; Niedbala, R. S.; Tanke, H. J. *Anal. Biochem.* **1999**, *267* (1), 30−36.
(17) Feijo, J. A.; Moreno, N. *Protoplasma* **2004**, *223* (1), 1−32.
(18) Waynant, R. W.; Ilev, I. K.; Gannot, I. *Philos. Trans. R. Soc. London, Ser. A* **2001**, *359* (1780), 635−644.
(19) Chan, W. C. W.; Nie, S. M. *Science* **1998**, *281* (5385), 2016−2018.
(20) Dubertret, B.; Skourides, P.; Norris, D. J.; Noireaux, V.; Brivanlou, A. H.; Libchaber, A. *Science* **2002**, *298* (5599), 1759−1762.
(21) Luccardini, C.; Tribet, C.; Vial, F.; Marchi-Artzner, V.; Dahan, M. *Langmuir* **2006**, *22* (5), 2304−2310.
(22) Gao, X. H.; Cui, Y. Y.; Levenson, R. M.; Chung, L. W. K.; Nie, S. M. *Nat. Biotechnol.* **2004**, *22*, 969−976.

10.1021/cm062447y CCC: $37.00

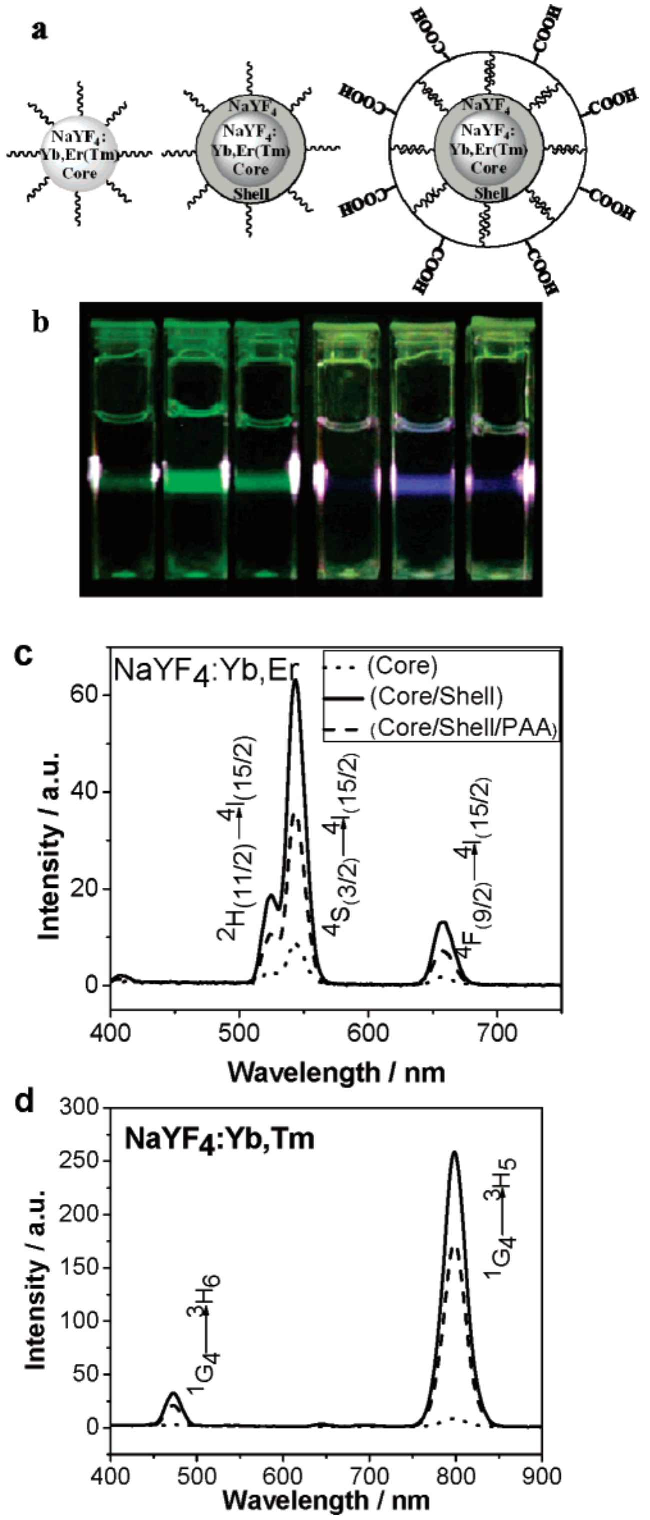

Figure 1. Structure scheme (a), upconversion fluorescence image (b, green from NaYF$_4$:Yb,Er and blue from NaYF$_4$:Yb,Tm), and upconversion fluorescence spectra (c and d) of the NaYF$_4$:Yb,Er(Tm) core, NaYF$_4$:Yb,Er(Tm)/NaYF$_4$ core/shell, and PAA coated NaYF$_4$:Yb,Er(Tm)/NaYF$_4$ core/shell nanoparticles. The excitation was a 1 W 980 nm NIR laser. Note that the NIR emission of NaYF$_4$:Yb,Tm at $\sim$800 nm is invisible to both human eyes and camera.

Figure 1c,d shows the fluorescence spectra of core, C/S, and PAA coated C/S of NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm nanoparticles, respectively. A 1 W external 980 nm NIR fiber laser with an average power density of $\sim$0.15 W/mm^{-2} was used as excitation. Using the same particle concentrations, we obtained upconversion fluorescence enhancements of 7.4 and 29.6 times for NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm, respectively, after coating with an undoped NaYF$_4$ shell. Compared with their bulk counterparts,[2] the integrated intensity of the emission peaks of the upconversion fluorescence output of NaYF$_4$:Yb,Er/NaYF$_4$ core/shell nanoparticles was $\sim$30% that of their bulk counterparts in our experiments. For the PAA coated C/S particles, fluorescence intensities of $\sim$57% for NaYF$_4$:Yb,Er and $\sim$66.9% for NaYF$_4$:Yb,Tm were observed, compared to those of the C/S counterparts.

To date, only down-conversion fluorescence enhancements such as CdSe and CePO$_4$:Tb have been reported, after coating with a second layer of ZnS[23] and LaPO$_4$.[24] Here we report a significant enhancement of upconversion fluorescence of nanoparticles after coating with an undoped NaYF$_4$ shell. It has been suggested that the organic surfactant with high vibrational energy on the nanoparticle surface quenched fluorescence.[5] A shell of hexagonal NaYF$_4$ with low phonon energy greatly reduced the quenching. The effects of PAA on fluorescence intensity were probed using UV−vis spectroscopy. The results showed that PAA did not exhibit absorption in the NIR or the visible wavelengths (Supporting Information, Figure S1). The observed decrease of fluorescence intensity (Figure 1b−d) by PAA coating would therefore likely arise from interactions of PAA with the upconversion nanoparticles, leading to fluorescence quenching. A decrease in the fluorescence quantum yield of $\sim$30% was also observed for PAA coated CdSe/ZnS C/S quantum dots (QDs).[21] Measurement of the lifetime of excited states would yield a better understanding of the mechanisms which warrant further work. The noticeable difference of enhancement from C/S of NaYF$_4$:Yb,Er (7.4 times) and NaYF$_4$:Yb,Tm (29.6 times) suggested different upconversion mechanisms. For NaYF$_4$:Yb,Er, two 980 nm NIR photons were needed to generated a visible photon by absorption at excited states, whereas for NaYF$_4$:Yb,Tm, three photons were needed to generate a visible photon.[8]

Figure 2a,b shows the transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) images of NaYF$_4$:Yb,Er core and NaYF$_4$:Yb,Er/NaYF$_4$ C/S nanoparticles, respectively. These nanoparticles were equiaxed with average diameters (from dynamic light scattering, DLS) of 8.5 ± 0.8 nm for core and 11.1 ± 1.5 nm for C/S, consistent with TEM results (counting $\sim$200 particles). HRTEM images confirmed the single crystallinity of these particles. The atomic compositions from energy-dispersive X-ray (EDX) analysis were Y/Yb/Er = 76.2:21.6:2.2 for NaYF$_4$:Yb,Er core and Y/Yb/Tm = 77.3:20.6:2.1 for NaYF$_4$:Yb,Tm core. The X-ray diffraction (XRD) results of the core and C/S (Figure 2c) showed the hexagonal phase of these nanoparticles. The average particle size, obtained by the Debye−Scherrer equation, was 7.7 nm for core and 10.5 nm for C/S, which was consistent with the results from DLS. Peak sharpening was also observed for the C/S in Figure 2c, as compared with the core nanoparticles, showing

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(23) Hines, M. A.; Guyot-Sionnest, P. *J. Phys. Chem.* **1996**, *100* (2), 468−471.

(24) Kompe, K.; Borchert, H.; Storz, J.; Lobo, A.; Adam, S.; Moller, T.; Haase, M. *Angew. Chem., Int. Ed.* **2003**, *42* (44), 5513−5516.

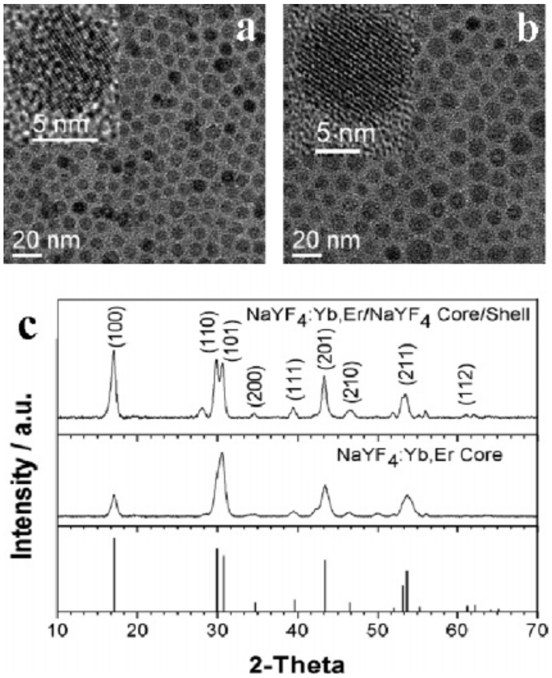

Figure 2. TEM results of NaYF$_4$:Yb,Er core (a) and NaYF$_4$:Yb,Er/NaYF$_4$ core/shell (b). XRD results of these nanocrystals (c). Bottom part of Figure 2c is the line pattern of the hexagonal phase NaYF$_4$ (PDF 28-1192).

a bigger grain size of the C/S nanoparticles. The same results were obtained for NaYF$_4$:Yb,Tm in our experiments.

The hydrophobic C/S nanoparticles were rendered hydrophilic by coating with PAA and easily dispersed in polar solvents like ethanol, water, and phosphate-buffered saline (PBS) to form stable transparent solutions. The stability of the PAA coated nanoparticles in water, pH 7.4 PBS, and pH 9.3 TBE buffer (Tris−borate−EDTA) was tested, respectively. In a 2-week observation, no aggregate was observed for the three solutions. In a 1-month observation, a very small amount of aggregate was observed in the bottom of the particle solution in water and PBS, whereas for nanoparticles in TBE buffer, no aggregate was observed. This suggested that, in pH 9.3 borate buffer, the PAA polymer was fully ionized and strong charge repulsion existed to prevent aggregation.[21] These PAA coated C/S nanoparticles were characterized with DLS and ζ-potential measurements. The hydrodynamic diameter of the PAA coated C/S was 30.2 ± 5.24 nm (Supporting Information, Figure S2), with a calculated polymer thickness of 8−10 nm, consistent with the literature of polymer coated QDs.[21] The ζ-potential of the C/S nanoparticles without PAA coating was +33.8, whereas after coating it was −14.4. This further confirmed the negatively charged PAA on the particle surface.

In summary, hexagonal phase NaYF$_4$:Yb,Er and NaYF$_4$:Yb,Tm core, core/shell, and PAA coated core/shell were prepared. Significant upconversion fluorescence enhancements of 7.4 times from NaYF$_4$:Yb,Er C/S and 29.6 times from NaYF$_4$:Yb,Tm C/S were observed. These hydrophobic core/shell nanoparticles were rendered hydrophilic by amphiphilic PAA coating. The high fluorescence efficiency (∼30% of that for bulk) and hydrophilicity with desirable carboxylic functional groups of these uniform, small nanoparticles give them great potential as bio-probes.

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Supporting Information Available: Details of synthesis of the core, core/shell, and PAA coated core/shell nanoparticles, UV−vis absorption spectrum of PAA (Figure S1), and DLS results of PAA coated core/shell nanoparticles (Figure S2; PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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