### Supplementary Information

Core-shell hybrid upconversion nanoparticles carring stable nitroxide radicals as potential multifunctional nanoprobes for upconversion luminescence and magnetic resonance dualmodality imaging

Chuan Chen, <sup>a</sup> Ning Kang, <sup>b</sup> Ting Xu, <sup>a</sup> Dong Wang, <sup>ab</sup> Lei Ren<sup>\*b</sup> and Xiangqun

Guo\*a

<sup>a</sup> The MOE Key Laboratory of Spectrochemical Analysis and Instrumentation, State Key Laboratory of Physical Chemistry of Solid Surfaces, Department of Chemistry, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, P. R. China.
<sup>b</sup> Department of Biomaterials, College of Materials, Xiamen University, Xiamen 361005, P. R. China.

\* Corresponding author: E-mail: xqguo@xmu.edu.cn (X. Q. Guo); renlei@xmu.edu.cn (L. Ren); Tel: +86 0592 2181682; Fax: +86 0592 2181682.



**Fig. S1** FTIR spectra of (a) 3-aminopropyltriethoxylsilane (APTS), (b) 4-Carboxyl TEMPO radicals and (c) the silanizing TEMPO radical precursors. The spectrum of silanizing TEMPO radical precursors (c) show the presence of characteristic bands at <u>1643</u> cm<sup>-1</sup> corresponding to the stretching vibration of the C=O groups (amide I). The bands at <u>1549</u> cm<sup>-1</sup> are assigned to the N–H groups (amide II). The bands at <u>2936</u> and <u>2975</u> cm<sup>-1</sup> are attributed to the stretching vibrations of  $-CH_2-$  and  $-CH_3$  groups of the ethyl chains, respectively. Compared with 3-aminopropyltriethoxylsilane, the spectrum of silanizing TEMPO radical precursors (c) also shows the presence of two characteristic bands at <u>1075</u> and <u>800</u> cm<sup>-1</sup> assigned to the Si–O–Et groups. Moreover, it is worth noting that this successful amidation reaction was also revealed by the disappearance of stretching vibration of C=O groups at <u>1731</u> and <u>1690</u> cm<sup>-1</sup> of the 4-Carboxyl TEMPO radicals.



**Fig. S2** ESI-MS spectrum of the silanizing nitroxide radical precursor. (MS m/z: [M<sup>+</sup>] calcd for C<sub>19</sub>H<sub>39</sub>N<sub>2</sub>O<sub>5</sub>Si, 403.61; found [M + Na]<sup>+</sup>: 426.2.



Fig. S3 TEM image of TEMPO@SiO<sub>2</sub> nanoparticles.



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**Fig. S4** The ESR spectra recorded in aqueous solution of (a) silanizing TEMPO radical precursors, (b) TEMPO@SiO<sub>2</sub> nanoparticles, (c) supernatant after three cycles centrifugal separation of TEMPO@SiO<sub>2</sub> nanoparticles precipitate, (d) SiO<sub>2</sub> nanoparticles.



Fig. S5 Schematic illustration of the paramagnetic SiO<sub>2</sub> network formation.



Fig. S6 Low magnification TEM images of the core and core-shell UCNPs shown in Fig. 3. These results demonstrate the 2D assembly of UCNPs, confirming the high monodispersity and uniformity of the obtained core and core-shell UCNPs with different layers of  $NaYF_4$  shell. All scale bar are 200 nm.



**Fig. S7** Size distribution of core NaYF<sub>4</sub>:Yb,Er and core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with different layers of NaYF<sub>4</sub> shell. The length of the obtained UCNPs increased from  $19.6 \pm 1.1$  nm to  $23.3 \pm 0.8$  nm,  $25.5 \pm 1.1$  nm,  $27.2 \pm 1.1$  nm,  $29.3 \pm 1.0$  nm,  $31.2 \pm 1.1$  nm and  $33.4 \pm 1.2$  nm after growing different thickness of NaYF<sub>4</sub> shells on the core NaYF<sub>4</sub>:Yb,Er, and the width increased from  $19.6 \pm 1.1$  nm to  $20.2 \pm 0.8$  nm,  $21.1 \pm 0.9$  nm,  $21.7 \pm 0.9$  nm,  $23.1 \pm 1.0$  nm,  $24.1 \pm 0.9$  nm and  $25.1 \pm 1.1$  nm after growing different layers of NaYF<sub>4</sub> shells on the core NaYF<sub>4</sub>:Yb,Er.



Homogenous active core-inert shell UCNPs

**Fig. S8** Schematic of anisotropic shell growth of NaYF<sub>4</sub> shell on the core NaYF<sub>4</sub>:Yb,Er. Because  $\beta$ -NaYF<sub>4</sub> UCNPs has a highly anisotropic structure, the nanoparticles preferentially grow into the ellipsoidal shape.<sup>1, 2</sup>



**Fig. S9** XRD patterns of the core NaYF<sub>4</sub>:Yb,Er (a) and core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with 15 (b) and 30 (c) layers of NaYF<sub>4</sub> shell. Calculated line pattern for hexagonal phase NaYF<sub>4</sub> (bottom plot) is shown for reference (black). All diffraction peaks of these nanoparticles could be clearly indexed to hexagonal phase NaYF<sub>4</sub> crystals.



**Fig. S10** Selected-area electron diffraction (SAED) pattern of core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with 30 layers of NaYF<sub>4</sub> shell. This SAED pattern demonstrates a perfect hexagonal crystal structure of the resulted core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with 30 layers of NaYF<sub>4</sub> shell. The pattern shows clear polycrystalline diffraction rings corresponding to the (100), (110), (111), (201), (311), and (321) planes of hexagonal phase NaYF<sub>4</sub> lattice.



Fig. S11 The enhancement times of total integrated upconversion emission intensity from 350 nm to 700 nm of core-shell UCNPs versus the corresponding layers of inner NaYF<sub>4</sub> shell.



Fig. S12 XPS spectrum of UCNP@TEMPO@SiO<sub>2</sub> nanocomposites.



Fig. S13 EDX analysis of UCNP@TEMPO@SiO<sub>2</sub> nanocomposites.



Fig. S14 DLS size distribution of the UCNP@TEMPO@SiO<sub>2</sub> nanocomposites synthesized with variable amounts of silanizing TEMPO radical precursors added during the process of copolymerization.



**Fig. S15** Zeta potential of (a) UCNP@TEMPO@SiO<sub>2</sub>, (b) UCNP@TEMPO@SiO<sub>2</sub>-NH<sub>2</sub>, and (c) PEGylated UCNP@TEMPO@SiO<sub>2</sub>. (Performed in 1 mM pH 7.4 Tris-HCl buffer solution)



**Fig. S16** Inverted fluorescence microscope images of HeLa cells incubated with PEGylated UCNP@TEMPO@SiO<sub>2</sub> nanocomposites at different concentrations (0, 40, 80, 120, 160, 200  $\mu$ g/mL) for 6 h. Each group can be classified to the DIC image, nuclei of cells (being dyed by Hoechst 33258 for visualization), upconversion luminescence image (UCL) and the overlay of the three above, respectively.



**Fig. S17** UV-vis spectra of PEGylated UCNP@TEMPO@SiO<sub>2</sub> nanocomposites (15 mg/mL) in MeOH/H<sub>2</sub>O (1:1) solution (red line), the PEGylated UCNP@SiO<sub>2</sub> without the TEMPO radicals doping (15 mg/mL) were used as reference (black line). Photograph (a) shows the transparency of the PEGylated UCNP@TEMPO@SiO<sub>2</sub> nanocomposites (15 mg/mL) in MeOH/H<sub>2</sub>O (1:1) solution. Photograph (b) and (c) show the strong upconversion emission of this solution in the daylight and in the dark under excitation of 980 nm laser (power 0.6 W), respectively.

#### Geometric structure analysis of core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs

According to the TEM images, the average diameter of core NaYF<sub>4</sub>:Yb,Er UCNPs is  $19.6 \pm 1.1$  nm, the average length and width of rod-like core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with 30 layers of NaYF<sub>4</sub> are  $33.4 \pm 1.2$  nm and  $25.1 \pm 1.1$  nm, respectively. So the approximative volume ratio of NaYF<sub>4</sub>:Yb,Er core and NaYF<sub>4</sub> shell is calculated by following formula:

$$V_{core} / V_{shell} = \frac{4}{3} \pi \left(\frac{d}{2}\right)^3 \div \left[\pi \left(\frac{D}{2}\right)^2 \times H - \frac{4}{3} \pi \left(\frac{d}{2}\right)^3\right] = 1:3.19$$

This value is approximately equal to the molar ratio of the amount of lanthanide input for fabricate core and shell (1:3) respectively.

# Calculation of TEMPO radicals loading in core-shell UCNP@TEMPO@SiO<sub>2</sub> nanocompocites (molar TEMPO:UCNP ratio)<sup>3</sup>

The amount of TEMPO radicals conjugated in the outer SiO<sub>2</sub> shell of NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs is estimated using the following procedures:

• A hexagonal phased ( $\beta$ ) NaYF<sub>4</sub> unit cell has the following parameters: a=0.596 nm, c=0.353 nm. Since Y<sup>3+</sup> (0.0880 nm), Yb<sup>3+</sup> (0.0859 nm), Er<sup>3+</sup> (0.0881 nm) have a quite similar ion radius, the dopant induced lattices distortions in hexagonal phased ( $\beta$ ) NaYF<sub>4</sub> could be negligible. The UCNPs had monodisperse size distribution and uniform geometric structure. The average diameter of sphere-like NaYF<sub>4</sub>:Yb,Er core UCNPs is 19.6 ± 1.1 nm (d) , the average length and width of rod-like core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs are 33.4 ± 1.2 nm (H) and 25.1 ± 1.1 nm (D), respectively. Based on these preconditions, we calculate the "molecular weight" of NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> core-shell UCNPs firstly.

Volume of NaYF<sub>4</sub>:Yb,Er core UCNPs unit cell (Na<sub>1.5</sub>Y<sub>1.5</sub>F<sub>6</sub>, a=0.596 nm, b=0.353 nm)

$$V_{cell} = 3^{1/2} \times a^2 \div 2 = 0.1086 \ nm^3$$

Volume of core and shell (d=  $19.6 \pm 1.1$  nm, D=  $25.1 \pm 1.1$  nm, H=  $33.4 \pm 1.2$  nm)

$$V_{core} = \frac{4}{3}\pi \left(\frac{d}{2}\right)^3 = 3942 \ nm^3$$
$$V_{shell} = \pi \left(\frac{D}{2}\right)^2 \times H - \frac{4}{3}\pi \left(\frac{d}{2}\right)^3 = 12585 \ nm^3$$

The number of unit cell in core and shell

$$N_{core} = 1.5 \times V_{core} / V_{cell} = 5.4 \times 10^4$$
  $N_{shell} = 1.5 \times V_{shell} / V_{cell} = 1.2 \times 10^5$ 

The "molecular weight" of NaYF<sub>4</sub>:18%Yb,2%Er/NaYF<sub>4</sub> core-shell UCNPs

$$M_{UCNPs} = N_{core} \times (M_{Na} + 80\% M_{Y} + 18\% M_{Yb} + 2\% M_{Er} + 4 \cdot M_{F}) + N_{shell} \times (M_{Na} + M_{Y} + 4 \cdot M_{F})$$
  
=  $N_{core} \times 204.6g / mol + N_{shell} \times 187.9g / mol = 3.36 \times 10^{7} g / mol$ 

■ The absorption of PEGylated UCNP@TEMPO@SiO<sub>2</sub> nanocomposties (15 mg/mL) at 435 nm in MeOH/H<sub>2</sub>O (1:1) solution was 0.112. According to Beer–Lambert law (A= $\epsilon \times b \times c$ ) and the molar absorptivity coefficient ( $\epsilon$ ) of TEMPO radical (13.3 dm<sup>3</sup> mol<sup>-1</sup> cm<sup>-1</sup>),<sup>4, 5</sup> the concentration of TEMPO radicals was calculated to 8.4 mM (1.7 mg/mL). Furthemore, the concentration of Y element in this solution was 3.5 mg/mL measured by ICP-AES. In comparation with core NaYF<sub>4</sub>:Yb,Er UCNPs, the doping amounts of Yb and Er in the core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs with 30 layers of NaYF<sub>4</sub> is negligibly small. Thus, the concentration of core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs (Y %=47 %) was calculated to 3.5/0.47=7.5 mg/mL.

Numbers of core-shell NaYF<sub>4</sub>:Yb,Er/NaYF<sub>4</sub> UCNPs in the MeOH/H<sub>2</sub>O (1:1) solution of UCNP@TEMPO@SiO<sub>2</sub> nanocomposties (15 mg/mL):

$$N_{UCNPs} = \frac{7.5 \times 10^{-3}}{M_{UCNPs}}$$

Numbers of TEMPO radicals in the MeOH/H<sub>2</sub>O (1:1) solution of UCNP@TEMPO@SiO<sub>2</sub> nanocomposties (15 mg/mL):

$$N_{TEMPO} = \frac{1.7 \times 10^{-3}}{M_{TEMPO}}$$

The average numbers of TEMPO radicals embedded in the compact  $SiO_2$  shell coated on the surface of per UCNP:

$$N_{TEMPO} / N_{UCNPs} = \frac{\frac{1.7}{M_{TEMPO}}}{\frac{7.5}{M_{UCNPs}}} = 3.8 \times 10^4$$

#### **References in Supplementary Information**

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