
Supporting information

Polysulfonate Cappings on Upconversion Nanoparticles Prevent their Disintegration in Water and Provide Superior Stability in a Highly Acidic Medium

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Synthesis of oleate-capped NaYF₄:Yb³⁺(16%),Er³⁺(2%) nanoparticles (UC_{Er}@OA). In a 1000 mL three-necked flask, YCl₃·6H₂O (15.6 mmol), YbCl₃·6H₂O (4.0 mmol), ErCl₃·6H₂O (0.4 mmol), oleic acid (160 mL) and octadecene (300 mL) were stirred at 160 °C under an atmosphere N₂ until lanthanides salts were completely dissolved. The reaction was then cooled to room temperature and 100 ml of methanol containing NaOH (0.5M) and NH₄F (0.8M) were added at once. The colloidal suspension was stirred for 30 min at 120 °C, under a flow of nitrogen and then heated to reflux at 305-308 °C for 90 minutes. Afterwards, the mixture was cooled to room temperature. The formed UCNPs were precipitated by addition of ethanol and isolated via centrifugation at 7000 rpm for 5 minutes. The white pellet was washed three times by dispersion of the UCNPs in chloroform and then precipitated by addition of excess of ethanol, additionally washed three times by dispersion in cyclohexane, and then precipitated by addition of excess of acetone. Finally, the purified UC_{Er}@OA were dispersed in cyclohexane.

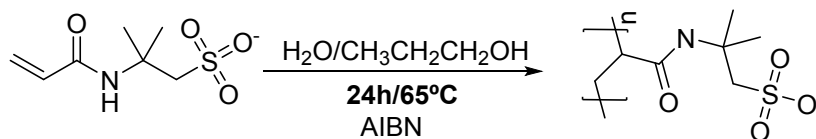
Synthesis of oleate-capped NaYF₄:Yb³⁺(16%),Tm³⁺(0.35%) nanoparticles (UC_{Tm}@OA). In a 1000 mL three-necked flask, YCl₃·6H₂O (15.0 mmol), YbCl₃·6H₂O (5.0 mmol), TmCl₃·6H₂O (0.06 mmol), oleic acid (160 mL) and octadecene (300 mL) were stirred at 160 °C under an atmosphere N₂ until lanthanides salts were completely dissolved. The reaction was then cooled to room temperature and 100 ml of methanol containing NaOH (0.5M) and NH₄F (0.8M) were added at once. The colloidal suspension was stirred for 30 min at 120 °C, under a flow of nitrogen and then heated to reflux at 305-308 °C for 90 minutes. Afterwards, the mixture was cooled to room temperature. The formed UCNPs were precipitated by addition of ethanol and isolated via centrifugation at 7000 rpm for 5 minutes. The white pellet was washed three times by dispersion of the UCNPs in chloroform and then precipitated by addition of excess of ethanol, additionally washed three times by dispersion in cyclohexane, and then precipitated by addition of excess of acetone. Finally, the purified UC_{Tm}@OA were dispersed in cyclohexane.

Ligand exchange with BF₄⁻. We used a ligand-exchange strategy using nitrosonium tetrafluoroborate (NOBF₄) to replace the original oleate ligands attached to the UCNPs.^{1,2} In particular, in 50 mL round bottom flask 10 mL of UC_{Ln}@OA [25 mg/mL] dispersed in cyclohexane and then 10 mL dimethylformamide (DMF) were added. This resulted in a two-phase system consisting of an upper layer of cyclohexane (containing the OA-coated UCNPs) and a subjacent layer of DMF. Subsequently 250 mg of NOBF₄ were added at once under vigorous stirring and the mixture was stirred for 60 minutes. This resulted in the phase transfer of the UCNPs from cyclohexane to DMF. The UCNPs in the slightly turbid DMF phase were precipitated by adding 100 mL of chloroform and were collected by centrifugation (7000 rpm, 5 minutes).

The transparent pellet was redispersed in 5 mL of DMF, precipitated again by addition of an excess of chloroform (50ml), and collected by centrifugation. This wash was repeated three times. Afterwards, the pellet was redispersed in 5 mL of DMF and centrifuged (2000 rpm, 3 minutes) in order to get rid of larger agglomerates to afford UC_{Ln}@BF₄.

Ligand removal with HCl. For this synthesis we used a protocol based on two-steps. The first one is the complete removal of the hydrophobic ligand oleate by treatment of hydrophobic UCNPs with hydrochloric acid that can strip the native ligands off the surface to generate ligand-free and water-dispersible particles.³ The UC_{Ln}@OA (50 mg) were dried and then, dispersed in 0.1 M HCl (10 ml, pH = 3), sonicated in an ultrasonic bath and stirred for 3 hours while adjusting the pH value to 3 by the addition of the HCl solution every 30 min. After this, the oleic acid was extracted with diethyl ether and the process was repeated until the solution became almost transparent. Naked UCNPs (UC_{Ln}) were precipitated with acetone and centrifuged (10000 rpm for 8 min), and collected by dried under vacuum.

Synthesis of poly(2-acrylamido-2-methyl-1-propanesulfonate acid, PAMPS) The polymer (PAMPS) has been prepared via free radical polymerization by using a high percentage of azobisisobutyronitrile (AIBN) as initiator as previously reported.⁴ The free radical polymerization and purification was carried out by following a previously described protocol.⁵



Scheme 1. Synthesis of PAMPS.

Briefly, polymerization was carried out in a deoxygenated mixture of milli-Q water/n-propanol (50: 50 v/v; total volume of 60 mL) containing, AMPS (14 g, 67mmol), and AIBN as initiator (500 mg, 3.00 mmol). The solution was deoxygenated with nitrogen for 2 hours and continuously stirred at 65 °C for 24 h. The reaction was cooled (using an ice-bath) Then, 50 mL chloroform were added and the mixture was vigorously stirred during 3 h. The reaction was stopped and two phases were observed, the denser phase (strong emulsion) was discarded. Organic solvents were removed at reduced pressure from the other one and, then, dried under vacuum.

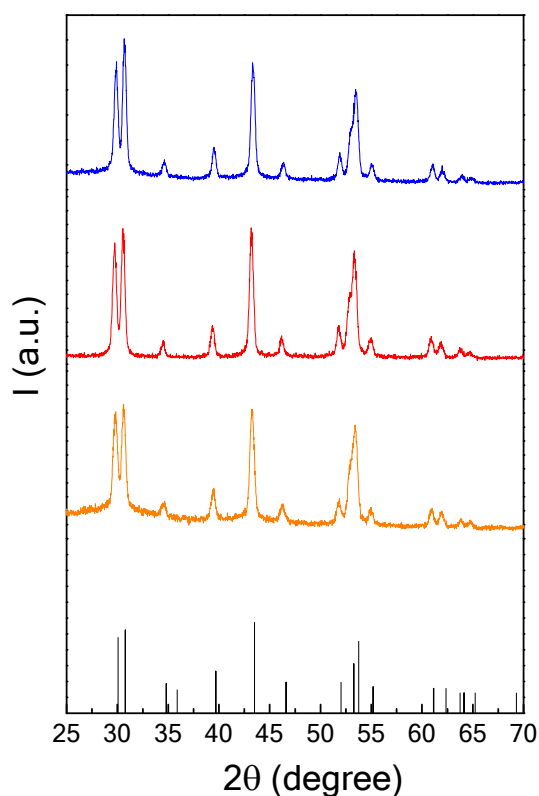


Figure S1. XRD spectra of: Orange-line: NaYF₄:Yb,Tm (UC_{Tm1}@OA); red line: NaYF₄:Yb,Tm (UC_{Tm2}@OA) and blue line: NaYF₄:Yb,Er (UC_{Er}@OA) and hexagonal NaYF₄ standard (JCPDS PDF number 16-0334).

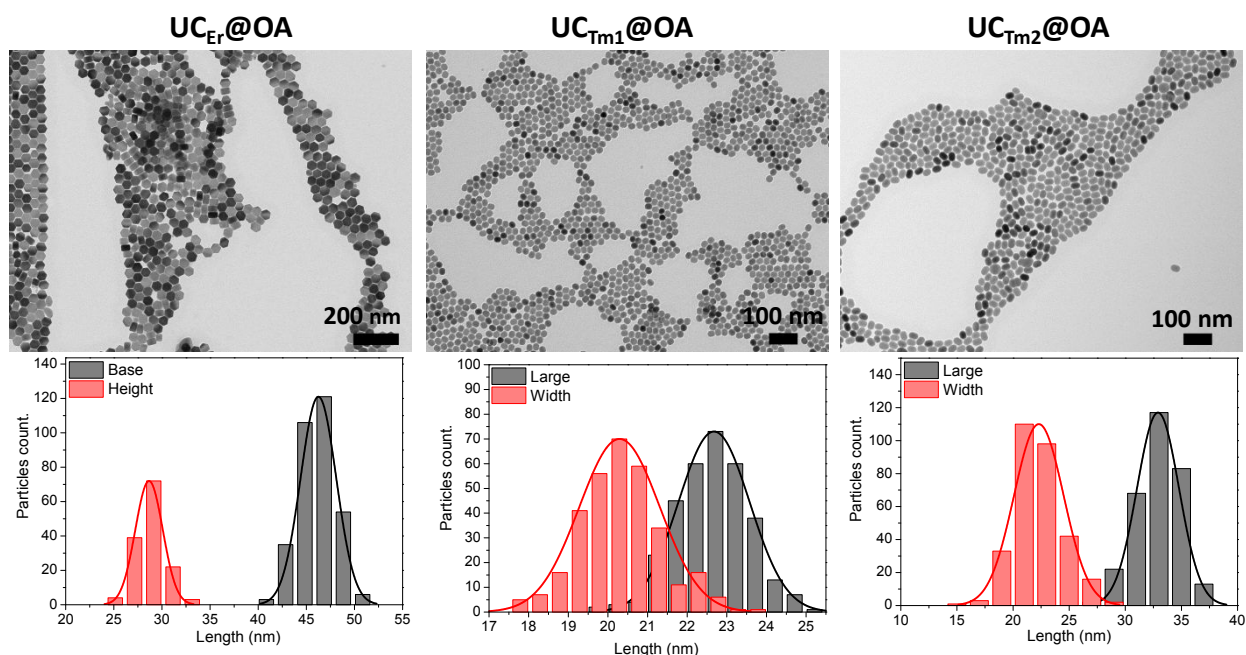


Figure S2. Representative low-resolution TEM images for UC_n together with size distribution histograms constructed from these TEM particle measurements: (left) $UC_{Er}@OA$, (Middle) $UC_{Tm1}@OA$ and (right) $UC_{Tm2}@OA$.

Table S1. Content of rare-earth ions of $UC_n@OA$ determined by ICP-MS.

Samples	Code	Er^{+3} [%mol]	Tm^{+3} [%mol]	Yb^{+3} [%mol]	Y^{+3} [%mol]
NaYF ₄ :Yb,Tm	$UC_{Tm1}@OA$		0.3	75.9	23.8
NaYF ₄ :Yb,Tm	$UC_{Tm2}@OA$		0.3	76.2	23.5
NaYF ₄ :Yb,Er	$UC_{Er}@OA$	2.1		16.9	81.0

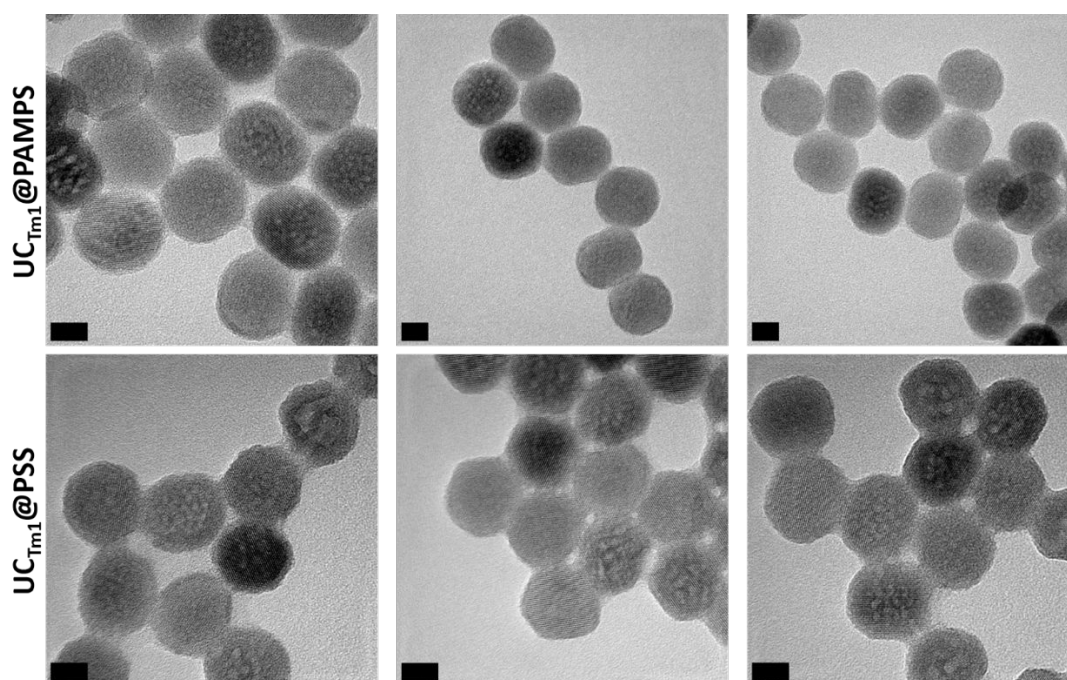


Figure S3. Representative HRTEM images of (top) $UC_{Tm1}@PAMPS$ and (bottom) $UC_{Tm1}@PSS$. Scale bar 10 nm.

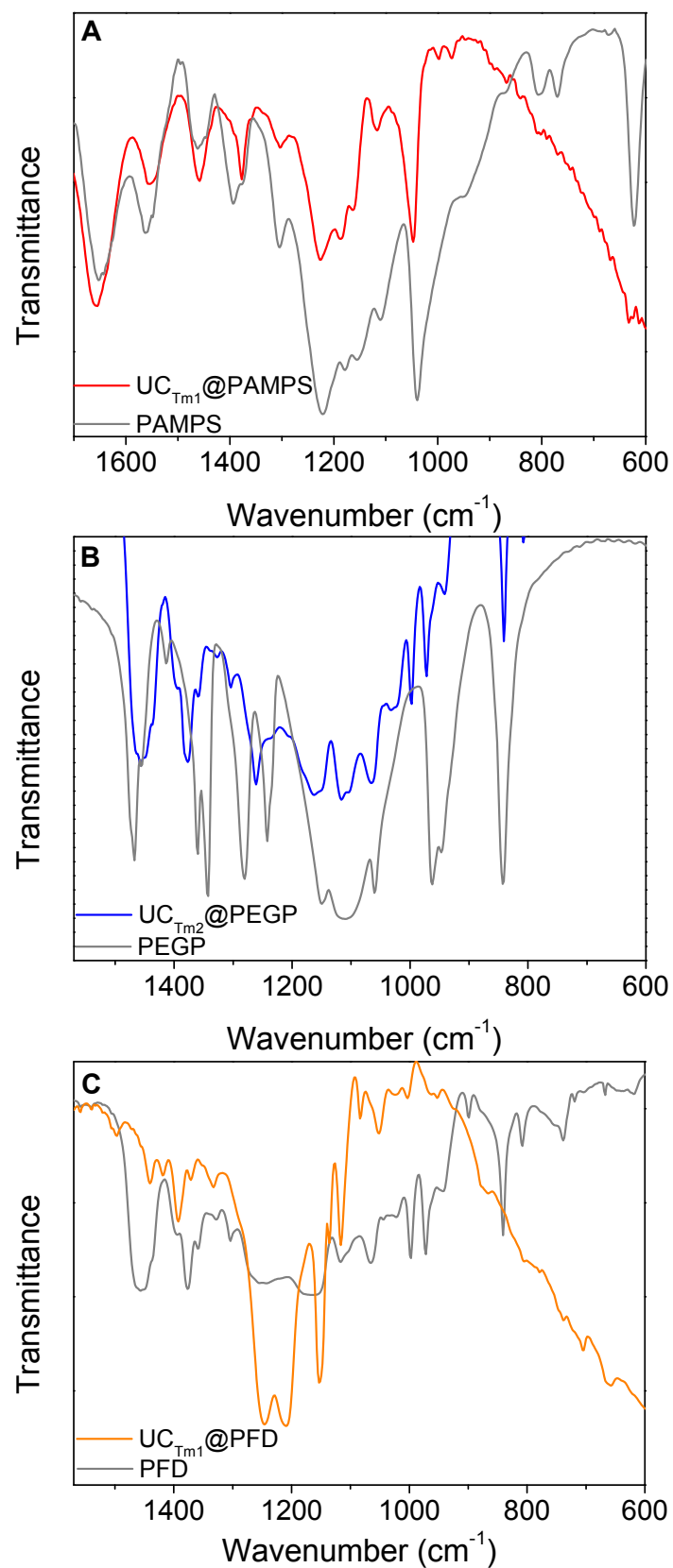


Figure S4. FTIR spectra of (A) UC_{Tm1}@PAMPS (red line), (B) UC_{Tm2}@PEGP (blue line) and (C) UC_{Tm1}@PFD (orange line). The grey line in A-C corresponds to PAMPS, PEGP and PFD, respectively.

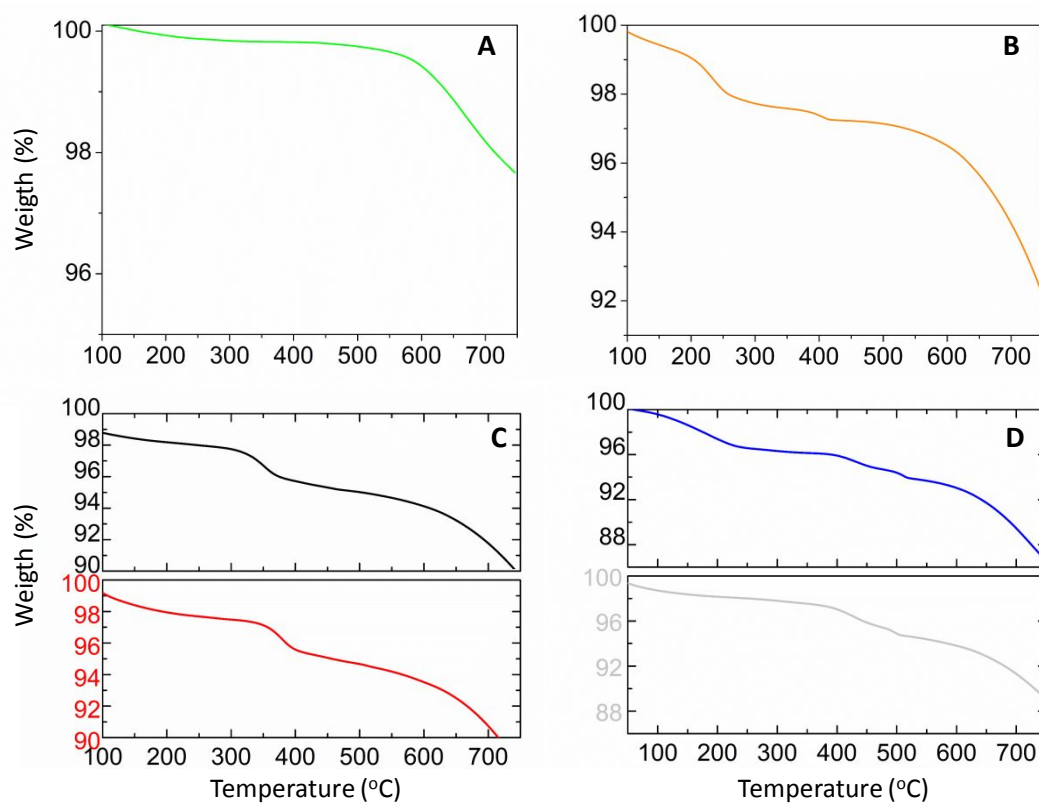


Figure S5. Thermograms of (A) UC_{Tm1}@BF₄ (green), (B) UC_{Tm1}@PFD (orange). UC_{Tm1}@AMPS (red), (C) comparison between UC_{Er}@AMPS (black) and UC_{Tm1}@AMPS (red) and (D) comparison between UC_{Er}@PSS (blue) and UC_{Tm1}@AMPS (gray).

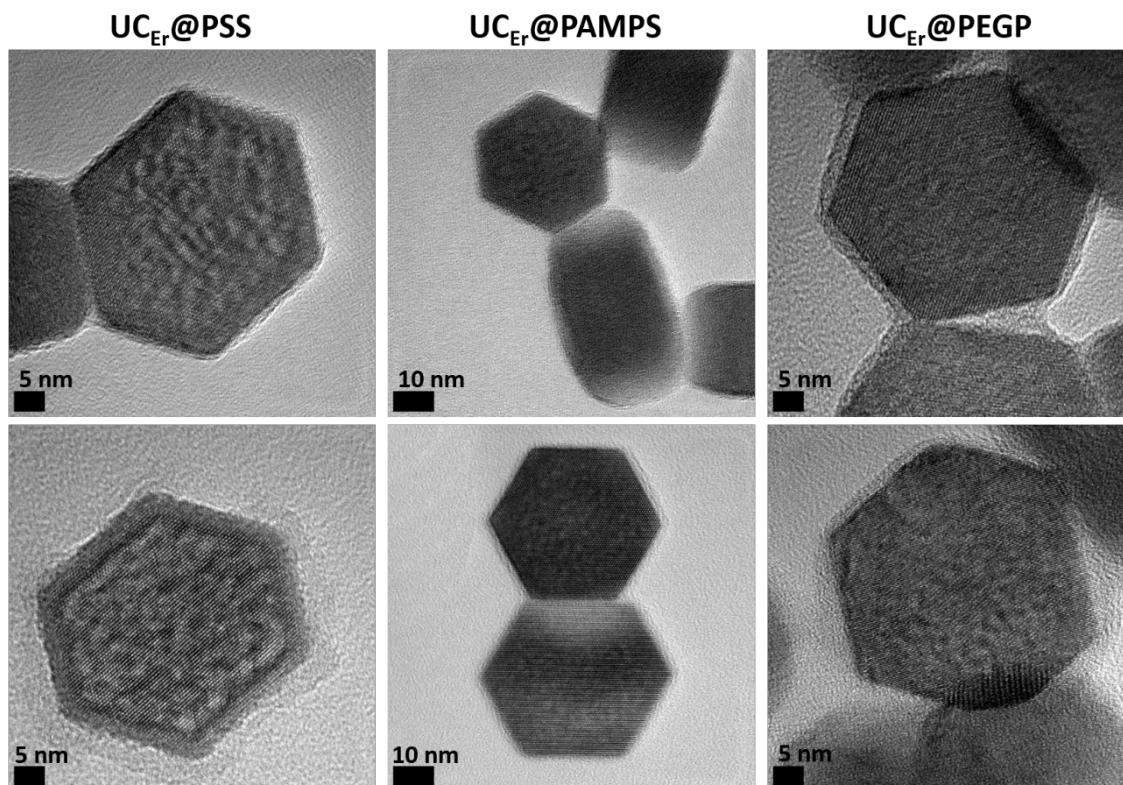


Figure S6. Representative HRTEM images of (left) UC_{Er}@PSS, (middle) UC_{Er}@AMPS and (right) UC_{Er}@PEGP.

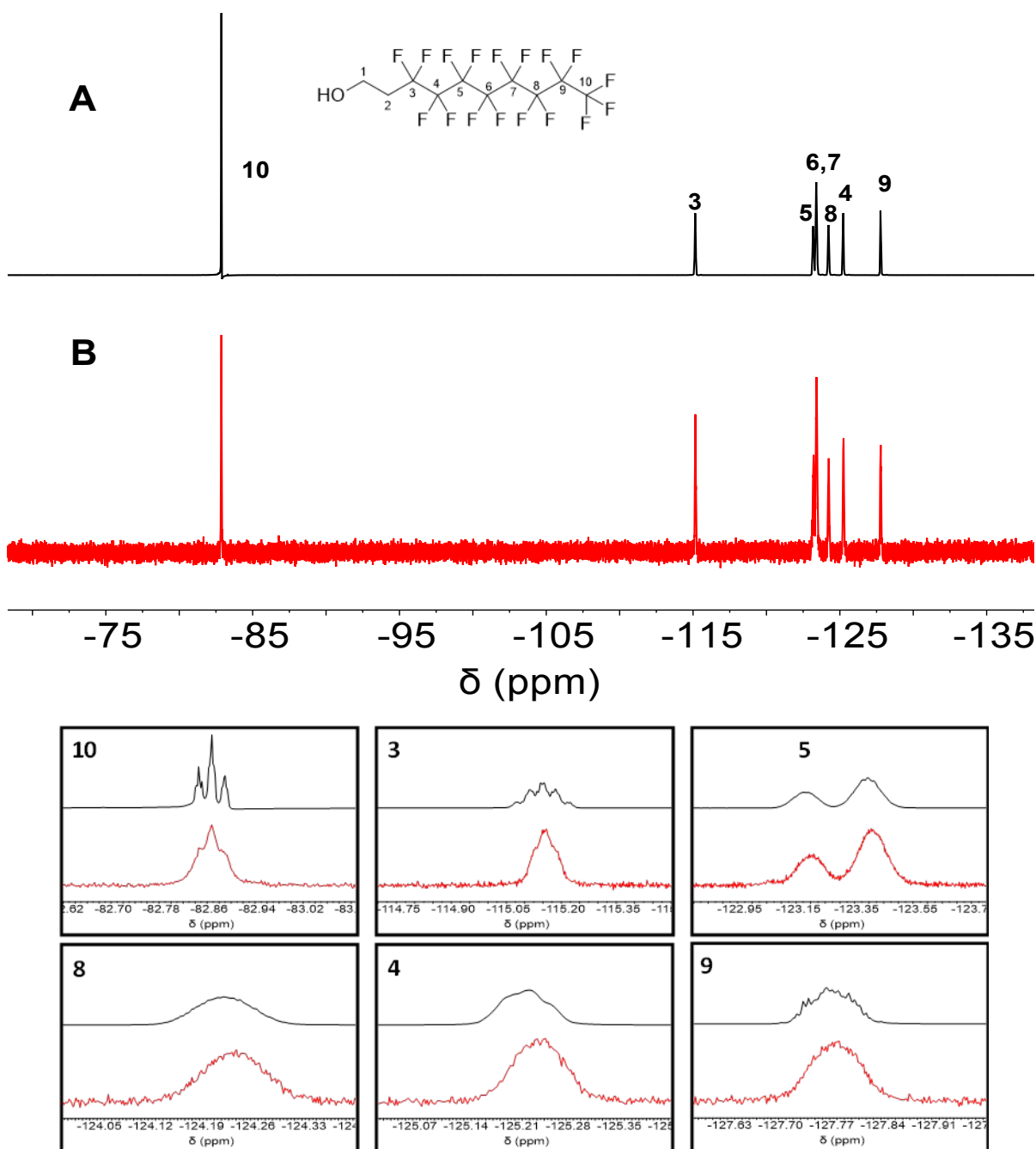


Figure S7. ^{19}F -NMR spectra of (A) PFD and (B) UC_{Tm1}@PFD in deuterated methanol. (C) Amplification of signals 1-7 of the ^{19}F -NMR spectra.

^{19}F -NMR of 1H,1H,2H,2H-perfluoro-1-decanol.

^{19}F -NMR (MEOD) δ_{F} , ppm: -82.85 (3F, t, CF₃), -115.15 (2F, m, CH₂-CF₂-CF₂), -123.15 and -123.40 (6F, m, CH-(CF₂)₂-CF₂, CH₂-(CF₂)₃-CF₂, CF₂-(CF₂)₂-CF₃), -124.20 (2F, m, CF₂-CF₂-CF₃), -125.25 (2F, m, CH₂-CF₂-CF₂), -127.75 (2F, m, CF₂-CF₃).

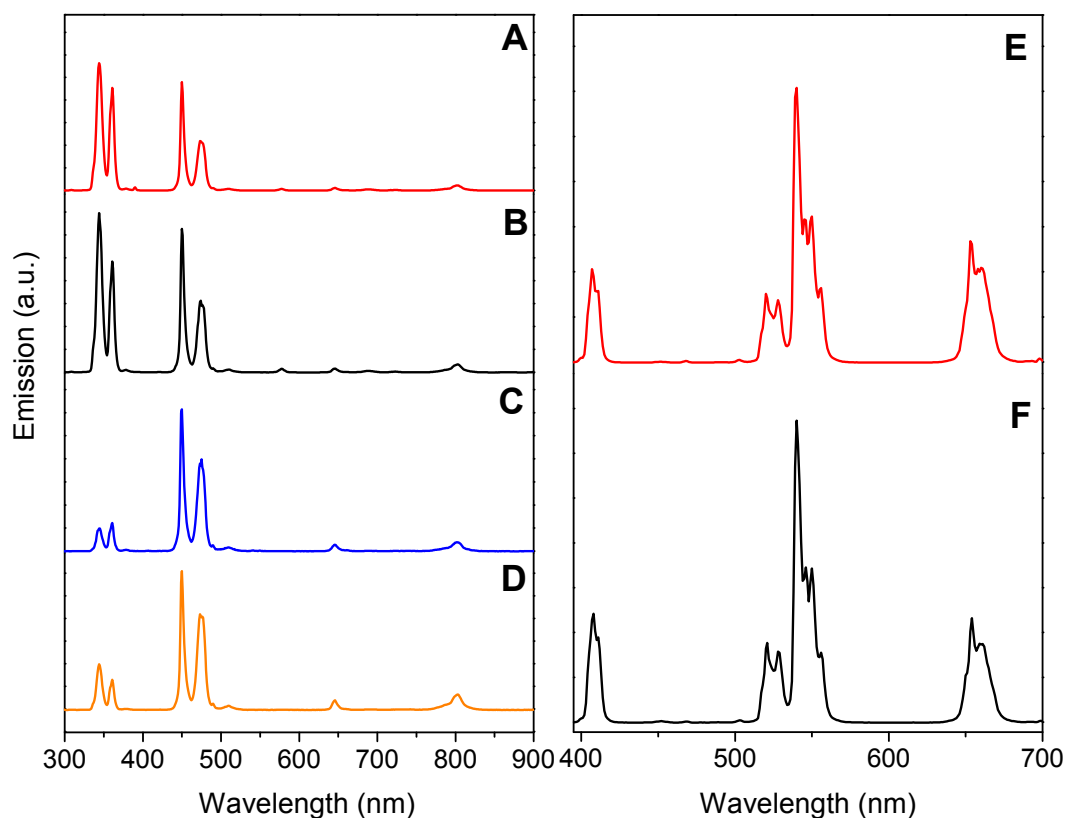


Figure S8. Emission spectra of (A) UC_{Tm1}@PAMPS [5mg/ml DMF], (B) UC_{Tm1}@PSS [5mg/ml DMF], (C) UC_{Tm2}@PEGP [2mg/ml H₂O], (D) UC_{Tm1}@PFD [5mg/ml DMF], (E) UC_{Er}@PAMPS [5mg/ml DMF] and (F) UC_{Er}@PSS [5mg/ml DMF]. ($\lambda_{\text{ex}}=975$ nm).

Stability of the polymer capping of UC_{Ln} in strongly acidic media

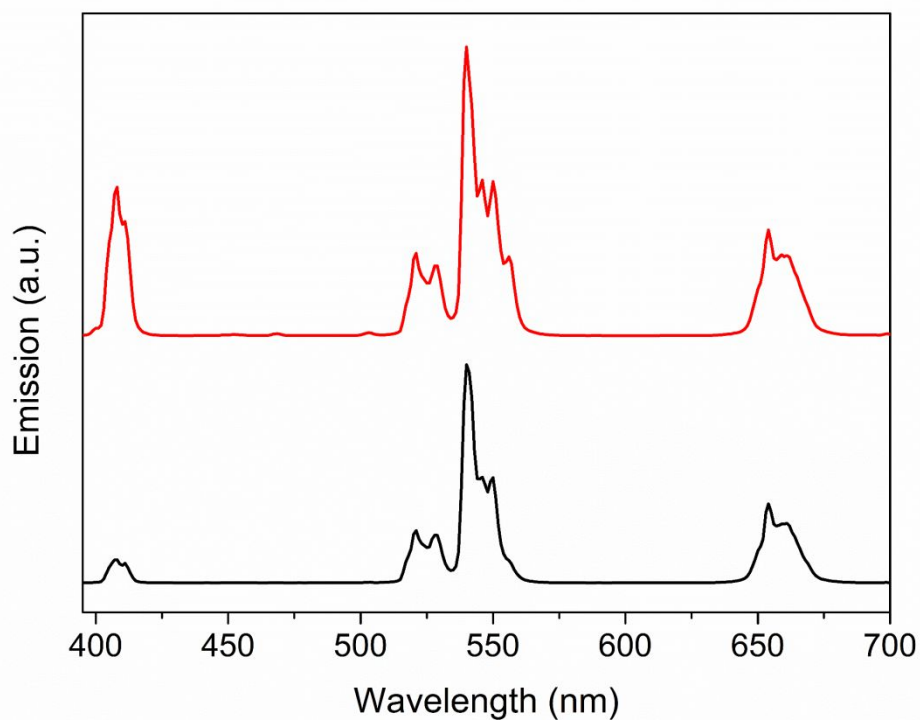


Figure S9. Emission spectra of UC_{Er}@PAMPS (top) and UC_{Er}@PSS (bottom) after acid treatment. The concentration of the solutions was 1 mg/mL in H₂O. ($\lambda_{\text{ex}}=975$ nm).

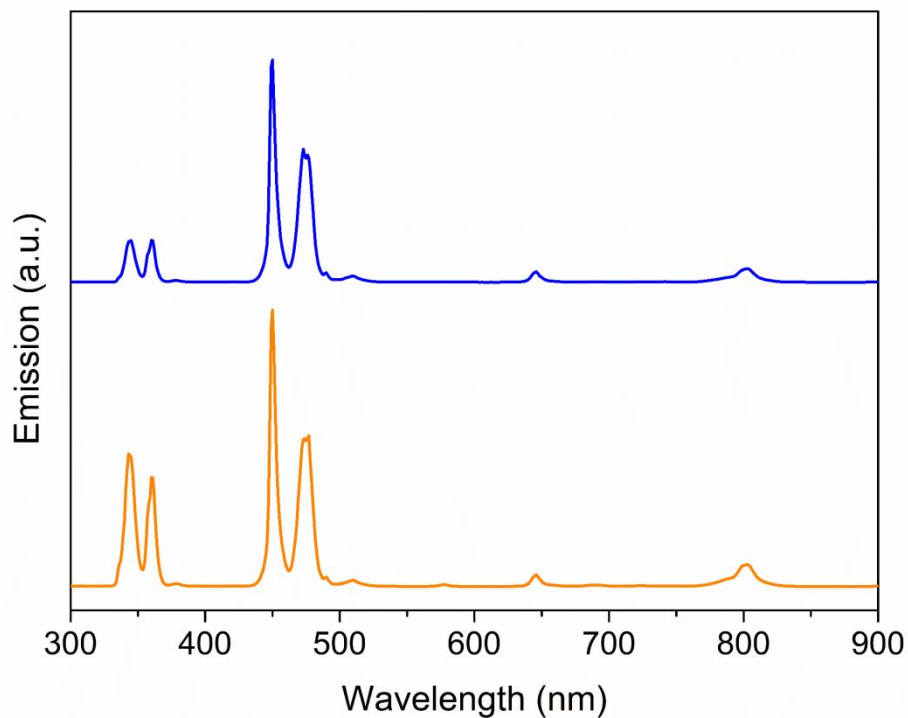


Figure S10. Emission spectra of UC_{Tm2}@PEGP (top) and UC_{Tm1}@PFD (bottom) after acid treatment. The concentration of the solutions was 1 mg/mL in H₂O. (λ_{ex} = 975 nm).

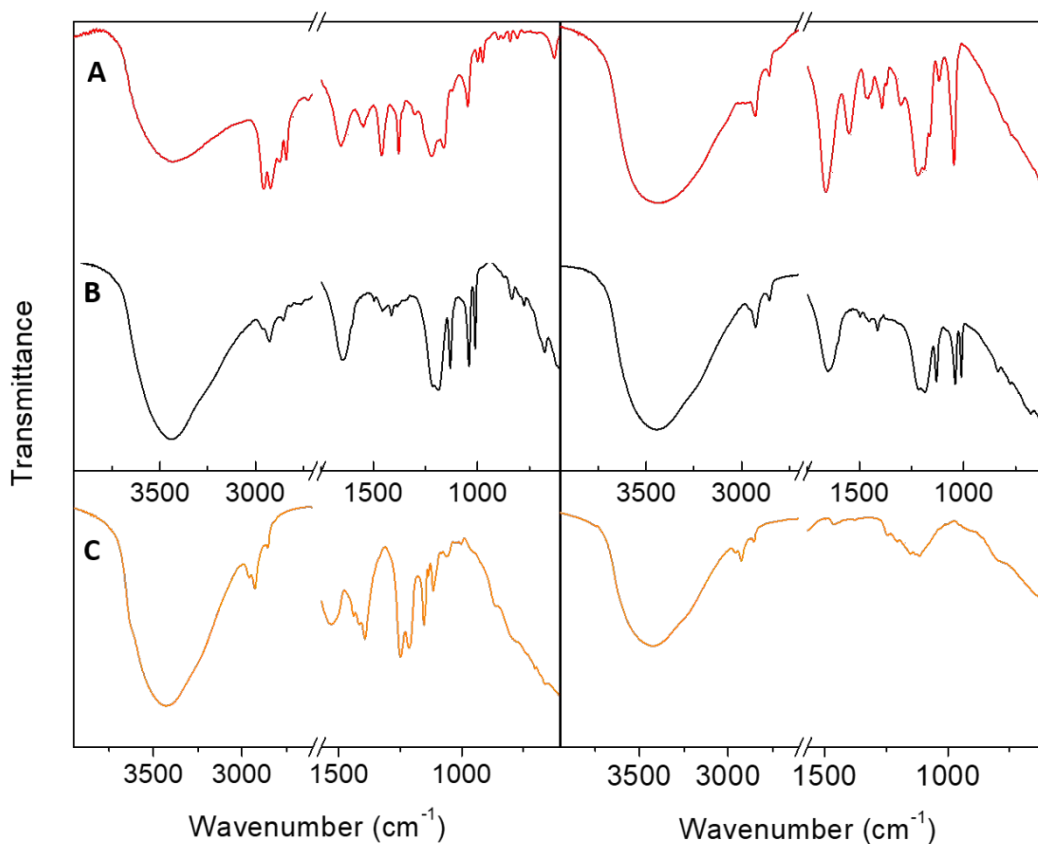


Figure S11. FTIR spectra of (A) UC_{Er}@PAMPS, (B) UC_{Er}@PSS and (C) UC_{Er}@PFD before (left) and after (right) acid treatment.

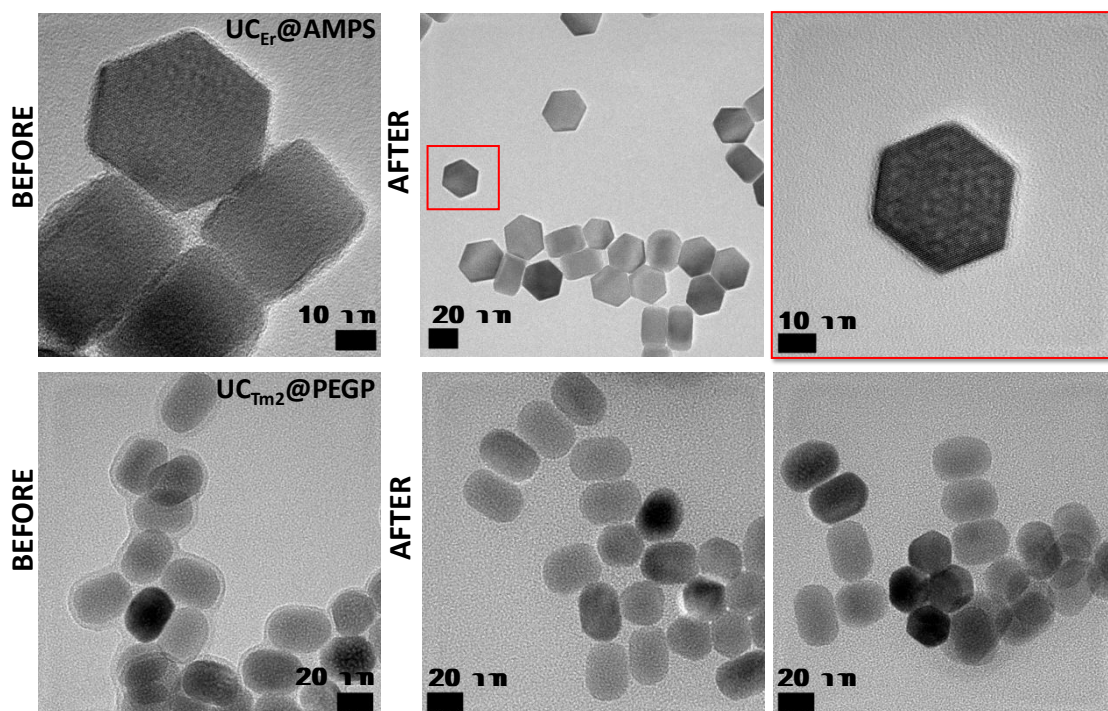


Figure S12. Representative HRTEM images of UC_{Er}@AMPS (top) and UC_{Tm2}@PEGP (bottom) before (left) and after (right) acid treatment.

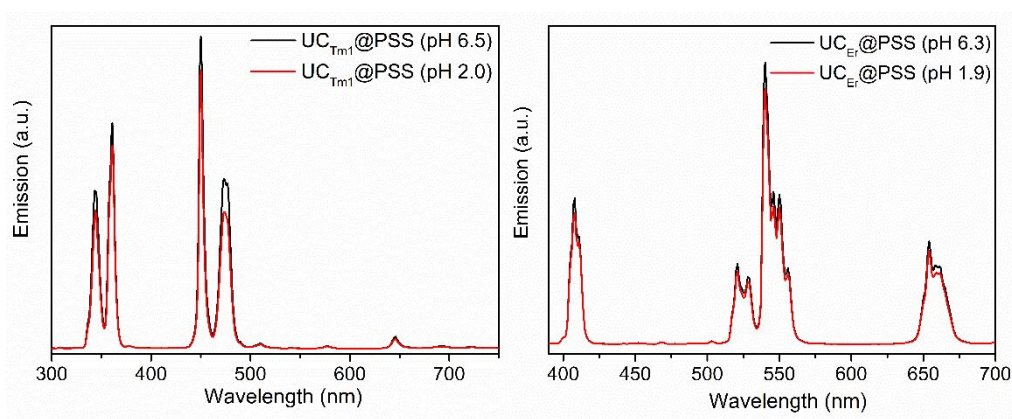


Figure S13. Comparison between emission spectra of Left: UC_{Tm1}@PSS (1.4 mg/mL) in water at pH 6.5 (black) and pH 2.0 (red) and Right: UC_{Er}@PSS (1.2 mg/mL) in water at pH 6.3 (black) and pH 1.9 (red). (λ_{ex} = 975 nm).

Table S2. Values of zeta potential (ζ) of UC_{Ln}@ligand nanoparticles.

Sample	Zeta potential (ζ)/ mV	
	Before acid treatment	After acid treatment ^a
UC _{Er} @PAMPS	-26.9±1.2	-25.9±1.4
UC _{Tm1} @PSS	-31.2±1.3	-32.0±1.4
UC _{Tm2} @PEGP	-2.6±0.3	14.8±0.5
UC _{Tm1} @PFD	11.5±0.6	18.6±0.5

^aSamples were dispersed in MQ-H₂O after acid treatment.

Table S3. Values of zeta potential (ζ) of bare UC_{L_n} dispersed in MQ-H₂O.

Sample	Zeta potential (ξ) _{pH=5.5} /mV
UC _{Tm1} @BF ₄	19.3±0.5
UC _{Tm2} naked	19.4±0.4
UC _{Er} @BF ₄	20.3±0.6

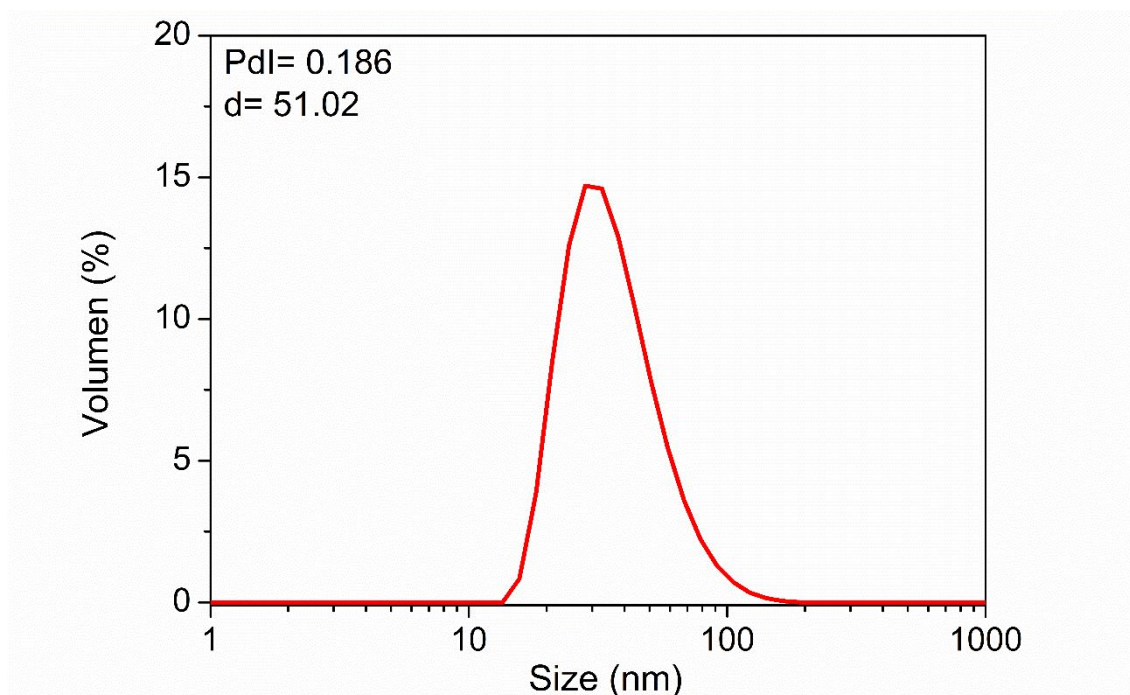


Figure S14. Dynamic scattering (DLS) of UC_{Tm1}@PSS dispersed in DMF.

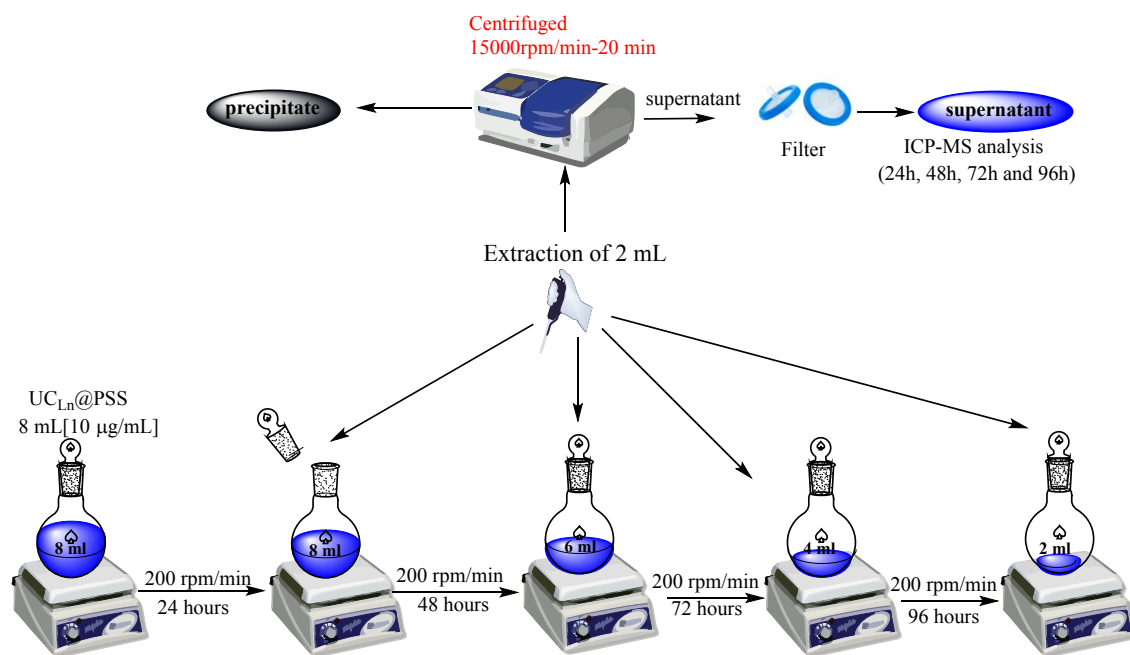


Figure S15. Schematic representation of the procedure followed to study the stability of the UCNPs in water

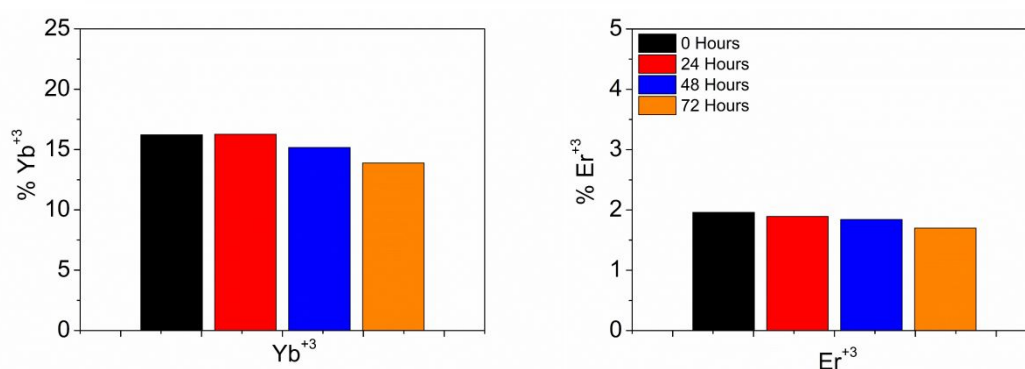
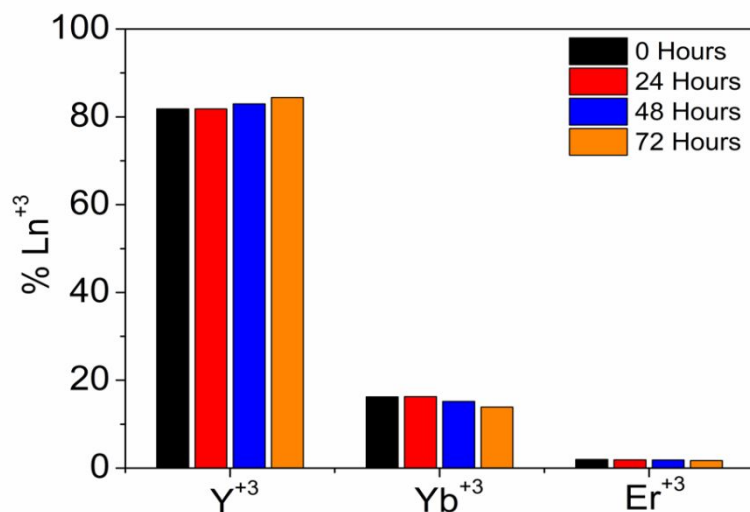


Figure S16. Ratio between lanthanides in bare UC_{Er} nanoparticles at different dissolution times: 24, 48, 72 and 96 h (calculated from ICP-MS results of the solid residue in the centrifuged samples).

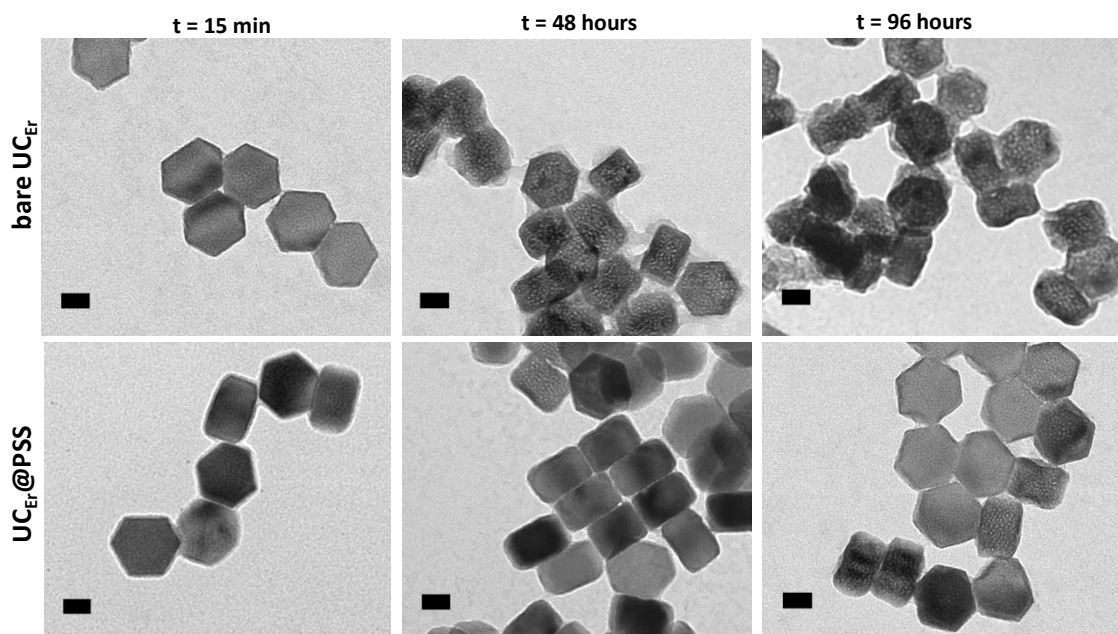


Figure S17. Representative low-resolution TEM images bare UC_{Er} (top) and UC_{Er}@PSS (bottom), 15 minutes (left), 48 hours (center) and 96 hours (right) in water dispersions at 5 μg/ml. Scale bar 20 nm.

References.

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