Supporting Information

Controlling the phase formation in solids: Rational synthesis of phase separated Co@Fe₂O₃heteroparticlesand CoFe₂O₄nanoparticles

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Experimental Section

Materials and Methods

Iron(0) pentacarbonyl (Fe(CO)₅, 99.5%, Acros), cobalt(II) acetate tetrahydrate (Co(ac)₂.4H₂O, 99%, Fluka), oleic acid (90%, Aldrich), oleylamine (90%, Acros), 1-octadecene (ODE, 90% Acros), di-tert-butyl dicarbonate ((Boc)₂O, >99%, Aldrich), dioxane (p.A., Fisher), H₂N-PEG₍₈₀₀₎-NH₂ (Aldrich), triethylamine (>99%, Aldrich), 3-hydroxy tyramine hydrochloride (Dopamine.HCl) (98%, Aldrich), trifluoroacetic acid (TFA) (99%, Aldrich), ethanol (99.8%, Roth), toluene (>99%, Aldrich), hexane (p.A., Fisher), dichloromethane DCM (p.A., Fisher), dimethylformamide (DMF) (extra dry, >99.8%, Acros) and diethyl ether (p.A. Fisher) were used as received without further purification.

Synthesis of rhomboid Co@Fe₂O₃ heterodimer nanoparticles

1 mmolof cobalt acetate Co(ac)₂, 3 mmolof oleic acid, 3 mmolof oleylamine and 10 mLof octadecane were mixed for 20 min before heating under a constant flow of argon (Ar) and using mechanical stirrer. The solution was heated to 245°C with a constant rate of 3°C/min. After reaching to this temperature, 2 mmolof Fe(CO)₅ was added and the temperature was kept at this temperature for 30 minutes. The product was precipitated by addition of excess of ethanol and collected by centrifugation (9000 rpm, 10 min, RT). The nanoparticles were repeatedly washed by dissolving them in hexane, precipitating them with ethanol and centrifugation (9000 rpm, 10 min, RT). Finally, the product was dissolved in hexane.

Synthesis of spherical CoFe₂O₄ nanoparticles

1 mmolof cobalt acetate Co(ac)₂, 3 mmol of oleic acid, 3 mmolof oleylamine, 10 mLof octadecane and 2 mmolof Fe(CO)₅ were mixing together for 20 min under argon and with mechanical stirrer. The reaction mixture was heated to 245 °C(heating rate of 3°C/min)for 1 hour, and the resulting solution was washed and precipitated by ethanol. The product was characterized using TEM as shown in Figure S4, which confirms the formation of spherical nanoparticles. However to improve the crystallinity of the nanoparticles, after discarding the ethanol, the rest product was dissolved again in 5 mLof octadecane, 1.5 mmolof oleyamine and 1.5 mmolof oleic acid and then heated again to 300°C for another 1 hour. The second heating period improved the crystallinity of the nanoparticles. The product was precipitated by addition of excess of ethanol and collected by centrifugation (9000 rpm, 10 min, RT). The nanoparticles were repeatedly washed by dissolving them in hexane, precipitating them with ethanol and centrifugation (9000 rpm, 10 min, RT). Finally, the product was dissolved in hexane.

Synthesis of Boc protected Bis-Amine PEG₍₈₀₀₎ (NBoc-PEG₍₈₀₀₎-NH₂)

A solution of $(Boc)_2O$ (0.02 mol) in 30 mL of anhydrous dioxane was added drop wise to a solution of NH₂-PEG₍₈₀₀₎-NH₂ (0.1 mol) in 50 mL of anhydrous dioxane. The resulting solution was stirred overnight at room temperature. The solvent was evaporated, and the oily product obtained was dissolved in 50 mL of water and extracted thrice using 50 mL of CH₂Cl₂. The combined organic phases were washed with a conc. solution of NaCl and dried over anhydrous Na₂SO₄. The resulting organic phase was concentrated by rotary evaporation and viscous, colourless oil was obtained. Further purification was achieved by flash chromatography on silica using a CH₂Cl₂/ethanol mixture (2:1) as eluent.

Preparation of the polymer

The poly (active ester) poly(pentafluorophenylacrylate) (PFA) was prepared as reported earlier.²⁹ GPC analysis of the obtained polymer (THF, light scattering detection) gave the following values: $M_n = 16,390$ g/mol, with PDI = 1.39, with an average of 70 repeating units. For the synthesis of the multifunctional poly(acrylamides), poly(active ester)poly(pentafluorophenyl acrylate) (700 mg, 2.94 mmol repeating units) was dissolved in a mixture of 9 mL of dry DMF and 0.7 mL of triethylamine. After that 3-hydroxytyramine hydrochloride (24 mg) dissolved in 3 mL of DMF and 0.4 mLof triethylamine was added and the reaction mixture was stirred for 3 hours at 50°C. In the final step the remaining active ester groups were substituted using an excess of NBoc-PEG₍₈₀₀₎-NH₂ (dissolved in 3 mL of dry DMF) and stirring for 5 h at 50°C. The solution was concentrated to about 2 mL and the polymeric ligand was precipitated by addition of cold ethyl ether. The precipitated polymer

was centrifuged (9000 rpm, 10 min and RT) and the solvent was decanted. Upon drying, 286

Cleavage of the Boc group

mg of colourless oil was obtained.

The polymer obtained above was dissolved in CH_2Cl_2 (30 mL). After that trifluoroacetic acid (2.0 mL) was added and the mixture was stirred at room temperature for 2 h. After that the reaction solution was treated with mixture of water and hexane (30 mL/50 mL) and vigorously stirred for 30 minutes. The aqueous phase containing the polymer was separated and concentrated to 2 mL and dialysed against deionized water for 2 days at room temperature (cellulose membrane, MWCO = 3,500). Finally, the water was evaporated and the product was redissolved in CHCl₃ and to make a stock solution which was kept at +4°C.

Functionalization of Co@Fe₂O₃and CoFe₂O₄ nanoparticles

 $Co@Fe_2O_3$ and $CoFe_2O_4$ nanoparticles(10 mg) were dispersed in 15 mL of CHCl₃ by slowly dropping over 1 h into the above synthesized polymeric ligand solution (20 mg/10 mL,

chloroform). The reaction was continuously stirred overnight at room temperature, under inert conditions. The functionalized nanoparticles were precipitated by addition of hexane and separated from unbound polymer and surfactants by centrifugation. These nanoparticles were washed twice by dissolving them in chloroform and precipitating them with hexane. Finally, the particles were stored in or DMF at $+4^{\circ}$ C.

Physical Characterization

Electron Microscopy. The size and morphology of the as synthesized $Co@Fe_2O_3$ and $CoFe_2O_4$ nanoparticles were investigated using transmission electron microscopy (TEM, Philips EM 420 instrument with an acceleration voltage of 120 kV). Samples for transmission electron microscopy were prepared by placing a drop of dilute nanoparticle solution in hexane on a carbon coated copper grid. Low-resolution TEM images were recorded on a Philips EM420 microscope operating at an acceleration voltage of 120 kV. High-resolution TEM data and ED patterns were obtained on a FEI Tecnai F30 S-TWIN with a 300 kV field emission gun.

X-ray Diffraction.X-ray diffraction patterns were recorded with a Bruker AXS D8 Advance diffractometer equipped with a SolX energy dispersive detector in reflection mode using unfiltered MoK α radiation. Samples were prepared between two layers of Scotch ® Magic tape. X-ray diffraction patterns were recorded in the range of $5 \le 2\Theta$ /deg ≤ 40 at a step size of $\Delta 2\Theta = 0.025^{\circ}$ and a step time of $\Delta t = 10.2$ s. A set of six pattern was accumulated in order to gain an appropriate signal to noise ration. Crystalline phases were identified according to the PDF–2 database PDF2 using Bruker AXS EVA 10.0 software. Full profile pattern fitting according to Rietveld was performed with TOPAS Academic 4.1 applying the fundamental parameter approach.¹The magnetic properties of powder samples were measured with a superconductive quantum interference device (SQUID, Quantum Design MPMS XL).

Mössbauer Spectroscopy. Mössbauer spectra were obtained at room temperature and 80 K with a constant acceleration transmission Mössbauer spectrometer and ⁵⁷Co (Rh) source. A α -Fe foil was used to calibrate the Mössbauer spectrometer in a velocity range of ±12 mms⁻¹.

Magnetic Resonance Imaging.MR signal enhancement effects were measured for the aqueous solutions of functionalized Co@Fe₂O₃ and CoFe₂O₄nanoparticles at different Fe concentrations (measured with AAS) on a clinical 3.0 T MRI scanner (Magnetom Trio, Siemens Medical Solutions, Erlangen, Germany). Signal reception and radio frequency (RF) excitation was performed using 8-channel knee coil. For T_1 -measurement, a saturation prepared (SR) snapshot fast low angle shot (SR-TurboFLASH) pulse sequence with repetition

time (T_R) / echo time / flip angle = 3.0 ms/1.5 ms/20° was used with varying saturation times starting from 20 ms up to 8000 ms. For measuring the T_2 relaxation time, a multi-echo spinecho pulse sequence (CPMG, Carr-Purcell-Meiboom-Gill) with a total of 32 echos and $T_R = 5000$ ms was used, the echo time was varied from 7 ms to 224 ms. In a second T_2 measurement T_E was varied from 15 ms up to 480 ms.

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Fig. S1.STEM mode images and EDX line scan of $Co@Fe_2O_3$ heterodimer and ternary phase $CoFe_2O_4$ nanoparticles. (a)STEM mode image of $Co@Fe_2O_3$ heterodimer nanoparticles where cobalt shows a bright spotand also Fe_2O_3 shows a dark contrast.(b) Corresponding EDX line scan, which confirms cobalt to be the bright spot and also the presence of iron and oxgen for less bright nanoparticles. (c) STEM mode image of $CoFe_2O_4$ nanoparticles and (d) the corresponding line scan EDX which confirm that cobalt is distributed uniformly.



Fig. S2.SAED electron diffraction pattern of a $CoFe_2O_4$ nanoparticle.



Fig. S3.Co@Fe₂O₃ nanoparticles after (a) 15 min and 1 h at 245°C.



Fig. S4.CoFe₂O₄ nanoparticles after 1 h at 245° C.



Fig. S5.⁵⁷Fe Mössbauer spectra of (a) CoFe₂O₄ NPs recorded at 295 K (b) at 110 K and (c) Co@Fe₂O₃ nanodimers recorded at 80K.