Amphiphiles alter the energy of surfaces, but the extent of this feature is typically constant. Smart systems with amphiphilicity as a function of an external, physical trigger are desirable. As a trigger, the exposure to a magnetic field, in particular, is desired because it is not shielded in water. Amphiphiles like surfactants are well known, but the magnetic response of molecules is typically weak. Vice-versa, magnetic particles with strong response to magnetic triggers are fully established in nanoscience, but they are not amphiphilic. In this work colloids with Janus architecture and ultra-small dimensions (25nm) have been prepared by spatial control over the Thiol-Yne click modification of organosilica-magnetite core-shell nanoparticles. The amphiphilic properties of these anisotropically modified particles are proven. Finally, a pronounced and reversible change in interfacial stabilization results from the application of a weak (<<1T) magnetic field.
Stimuli-Responsive Particle-Based Amphiphiles as Active Colloids Prepared by Anisotropic Click Chemistry
Cornelia Lanz[a] Moritz Schlötter,[a] Nele Klinkenberg,[a] Patricia Besirske[a] and Sebastian Polarz[a,b]*

Abstract: Amphiphiles alter the energy of surfaces, but the extent of this feature is typically constant. Smart systems with amphiphilicity as a function of an external, physical trigger are desirable. As a trigger, the exposure to a magnetic field, in particular, is desired because it is not shielded in water. Amphiphiles like surfactants are well known, but the magnetic response of molecules is typically weak. Vice-versa, magnetic particles with strong response to magnetic triggers are fully established in nanoscience, but they are not amphiphilic. In this work colloids with Janus architecture and ultra-small dimensions (25nm) have been prepared by spatial control over the Thiol-Yne click modification of organosilica-magnetite core-shell nanoparticles. The amphiphilic properties of these anisotropically modified particles are proven. Finally, a pronounced and reversible change in interfacial stabilization results from the application of a weak (<1T) magnetic field.

The prototypes for amphiphilic compounds originate from molecular chemistry, like surfactants or block-copolymers. Unique properties and important applications result from the combination of relevant parts such as hydrophobic and hydrophilic in one molecular entity. The latter is responsible for interfacial activity within amphiphiles and the capability for complex self-organization.[3] The degree of interfacial activity is constant for the vast majority of molecular systems, because it is difficult to alter the molecular configuration to such an extent, amphiphilic properties may become stimuli-responsive. However, amphiphiles that can be turned on and off by demand would be highly interesting.

The higher sensitivity of nanoparticles towards external triggers is only one argument, why particle-based amphiphiles have raised interest.[3] While only few publications can be found for a literature survey on particle-based amphiphiles, an impressive amount of publications exist for particles with so-called Janus design.[3] The classic examples for a Janus particle (JP) involve colloidal beads with the two hemispheres differing in chemical composition.[4] Therefore, the successful preparation of a JP requires some sort of symmetry break. One can roughly differentiate between two preparation approaches. The JP can be assembled from two individual and chemically different species, which are joint together. This approach is also described as compartmentalization.[3] The alternative strategy is a partial (1) modification of the surface of the original particle. This can be achieved by restricting the accessibility of one hemisphere by immobilization of the particle(s) on a surface or by imbedding them in a matrix like a polymer or wax.[3] Clearly, these methods work better the larger and less mobile the particles are. This is one of the reasons, why JPs smaller than 50nm in diameter are hard to find in literature.[7] However, thinking of stimuli-responsive, particle-based amphiphiles, minimization of the size/ mass of the JPs is desirable. A smaller size and mass would increase the sensitivity towards the external trigger and, thus, lead to more versatile active colloids than currently known.[8] As amphiphiles operate in water, it would also be an advantage, if the system could react to a magnetic field, because it is not shielded in an aqueous electrolyte.[9] The latter arguments define the target system for the current work: A nano-sized (<50nm) JP-based amphiphile, which reacts on an externally applied magnetic field. The blueprint of the target JPs is shown in Scheme 1.

![Scheme 1. Stimuli-responsive particle-based amphiphiles. Silica encapsulated magnetite nanoparticles are covered with a shell of alkyne-modified organosilica. The anisotropic modification of the alkyne groups by click chemistry leads to JPs. Amphiphilicity originates from suitable selection of R (= hydrophobic group). The application of a magnetic field is expected to orient the magnetic dipoles of the superparamagnetic cores, which induces an additional force. This could have an influence on the way, the particles stabilize the interface.](Image)

Two, preliminary achievements are important to mention. Others have published impressive work on the encapsulation of single-domain magnetite nanoparticles in silica.[10] The advantage
of a silica shell is, it is chemically robust, the particles become dispersible in polar solvents and, last but not least, many routes are known for the modification of silica surfaces.\textsuperscript{[11]} Our group could recently establish an organosilica system which is suitable by modification using the so-called click chemistry.\textsuperscript{[11a, 12]} The advantages of click chemistry have been discussed in several review articles and could not be better represented than by the Nobel Prize in 2001.\textsuperscript{[13]}

Monodomain magnetite (Fe$_3$O$_4$) nanoparticles (NPs) with a diameter of 9.8 nm (polydispersity index (PDI) = 6\%) were prepared according to a method published by Sturm et al. in 2017.\textsuperscript{[14]} The unambiguous characterization is summarized in Supporting Information Fig. S1. Next, we adapted the method published by Ding et al. for encapsulating the Fe$_3$O$_4$-NPs with a shell of silica.\textsuperscript{[11c, 11d]} The resulting particles are shown in Supporting Information Fig. S2. The thickness of the SiO$_2$ shell can be minimized by controlling the amount of tetraethyl orthosilicate (TEOS) added to the synthesis mixture. The smallest value of the SiO$_2$ layer is only 1 nm.

The alkyne-containing shell was prepared by sol-gel process with a novel, phenylacetylene-bridged silsesquioxane precursor (4) shown in Scheme 2 (see also the experimental section). We start from the phenylbromide-bridged sol-gel precursor (1), which can be transformed to multiple other groups exploiting the full potential of aromatic substitution chemistry.\textsuperscript{[11a, 11c, 12a, 12b, 15]} Here, the bromide is substituted by a trimethylsilyl-protected acetylene (2) catalyzed by copper(I) iodide/1,1’-bis(diphenylphosphino)ferrocenedichloropalladium(II).\textsuperscript{[16]} The trimethylsilyl group is removed from (3) by treatment with AgNO$_3$ leading to the new sol-gel precursor (4). (4) was characterized by $^{1}$H- , $^{13}$C- and $^{29}$Si-NMR spectroscopy (Supporting Information Fig. S3). The NMR spectra prove the purity of the compound, in particular the presence of only one $^{29}$Si-signal at -62.93 ppm. The signals at 3.08 ppm / 84.51 ppm and 77.36 ppm ($^{1}$H, $^{13}$C) show the presence of the acetylene function. The successful synthesis is also demonstrated by electron spray ionization mass spectrometry (ESI-MS) (Supporting Information Fig. S3). Hydrolysis and condensation lead to the phenylacetylene containing organosilica material (AlkySil). The chemical nature of the material was characterized by $^{13}$C- and $^{29}$Si-NMR, ATR-IR, FT Raman spectroscopy and thermogravimetric analysis (TGA) (see Supporting Information Fig. S4).

![Scheme 2](image)

Scheme 2. Reaction sequence leading to organosilica materials modified by a bridging phenylacetylene group. R = iso-Pr.

The final, core-shell-shell particles were prepared as described in detail in the experimental section (Fig. 1a). The size and morphology of the synthesized Fe$_3$O$_4$/SiO$_2$/AlkySil particles were characterized by TEM (see Fig. 1b). The particle diameter increased from 20.8 nm (Fe$_3$O$_4$/SiO$_2$ particles, PDI = 8\%) to 22.9 nm (PDI = 5\%). The successful formation of the AlkySil shell is confirmed by the different imaging contrast seen in TEM. In TEM the particles seem to be agglomerated. However, this can be excluded by analytical ultracentrifugation (AUC) measurements. The resulting particle size distribution curve (d$_{h,max}$ = 26.1 nm) is shown in Fig. 1c, and is consistent with the TEM data when compared to isolated particles. Complete characterization of the particles is summarized in Supporting Information Fig. S5.

The alkyne-functionalized core-shell-shell particles can be further modified via two different types of click reactions, the Huisgen cycloaddition and the Thiol-Yne click reaction.\textsuperscript{[17]} Both types were used for the isotropic modification of the particles as a proof-of-concept. An example for the Cu-catalysed Huisgen cycloaddition of the dye Cumarin-343 is shown in Supporting Information Fig. S6. The photochemical Thiol-Yne variant discussed is demonstrated using mercaptopentadecanoic acid (Fig. 2). As it is not possible by electron microscopy to visualize the presence of the organic constituents directly, Zn$_{2}$O ions were coordinated to the carboxylic acid groups to increase the imaging contrast. A bright field STEM image is shown in Fig. 2b. Compared to the Fe$_3$O$_4$/SiO$_2$/AlkySil particles (Fig. 1b), a thin, dark rim at the exterior surface can be clearly identified. An energy-dispersive X-ray spectroscopy (EDX) linescan (see Fig. 2c) confirms that this dark rim consists of Zn. Additional data is shown in Supporting Information Fig. S7. The reference
experiment, where Fe$_3$O$_4$/SiO$_2$/AlkySil particles are treated with Zn$^{2+}$ (Supporting Information Fig. S8) proves that the coordination of the metal at the surfaces is due to the successful click reaction with mercaptoundecanoic acid.

After successfully proving the preparation of ultra-small Janus nanoparticle, we can (anisotropically) modify the particles with alternative clickable compounds like pentafluorothiophenol next. The existence of the pentafluorothiophenol entity can be proven by IR- and EDX spectroscopies (Supporting Information Fig. S10). The corresponding JPs were prepared using the methodology described above. For demonstration of the amphiphilic properties of the JPs, the pendant drop method was used and the liquid-vapor surface tension ($\gamma_{lv} = 20.4$ mN/m) was calculated (see Supporting Information Fig. S11). However, more interesting is, if and how the amphiphilicity changes in the presence of a magnetic field. Experiments were performed using the sessile drop method (Fig. 4a). A magnet (< 1T) is placed beneath the substrate and the difference in the contact angle $\theta$ is recorded. Surface tensions solid-gas (constant), liquid-gas and solid-liquid enter $\gamma$. Thus, the spreading of the drop is indicative for a change in the interfacial energy. As nothing has changed, except for exposure to the magnet, this change in surface energy has to originate in a difference in amphiphilicity of the JPs (Scheme 1). The phenomenon can be described as follows: The magnetite cores of the JPs are superparamagnetic. Thus, in absence of an external magnetic field, the moments are randomly distributed. In the presence of a magnetic field, the domains become oriented resulting in a force on the particles (see also Supporting Information Fig. S6). Because one interpretation of the surface tension, is the force per distance $f$ acting at the interface, the additional, magnetic influence can eventually change $\gamma$.
One also has to consider, there are gradients in the magnetic field applied in the experiment described in Fig. 4a. Because particles migrate in such a gradient (Supporting Information Fig. S6), it can not be excluded there are also local changes of the composition of the interface. Migration does not occur in a homogeneous magnetic field. Instead, rotation happens. The reaction to a homogeneous magnetic field was probed by determination of the Cotton Mouton effect (CME), which is the emergence of birefringence caused by a magnetic field. The CME curve (Fig. 4b) shows a rapid and strong answer of the dispersion of the JPs exposed to a weak field (0.05 mT). In addition, dynamic light scattering (DLS) indicates the presence of aggregates of the JPs (Fig. 4c). The diffusion coefficient and the resulting hydrodynamic radius $R_h$ were determined paralell and perpendicular to the field. For $B = 0$ both values are almost equal, which speaks for spherical aggregates like vesicular structures. A distinct anisotropy is found for $B = 0.5T$, with the extension of the aggregates almost doubled in direction of the field. This speaks for a deformation and/or alignment of the aggregates.

Starting from core-shell-shell nanoparticles, we showed that the Thiol-Yne click reaction can be used for the spatially resolved modification leading to a Janus architecture. The anisotropic modification using hydrophobic moieties leads to particle-based amphiphilic properties. Addressing the magnetite core by an external field changed the inter-particle interaction, which had a direct influence on the degree of amphiphilicity. The system presented herein is not only a versatile platform for new particle-based amphiphiles, considering click chemistry will allow to modify the surfaces with almost any group and the remaining hemisphere of the JPs (Scheme 1) can still be modified differently.

Figure 4. Contact angle determination using sessile drop method of a water drop on a glass substrate in the presence of the JPs modified by perfluorothiophenol (a). Left image show the drop in absence of a magnetic field compared to a magnet (<1T) placed beneath the substrate (right). CME measurement (b) and DLS results (c) of the JPs at $B = 0$ and 0.5 T vertical and parallel to the magnetic field.

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Keywords: organosilica nanoparticles • core-shell structures • Janus structures • active colloids • smart materials

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Stimuli-Responsive Particle-Based Amphiphiles as Active Colloids Prepared by Anisotropic Click Chemistry

Cornelia Lanz, Moritz Schlötter, Nele Klinkenberg, Patricia Besirske and Sebastian Polarz

[a] C. Lanz, M. Schlötter, N. Klinkenberg, P. Besirske, Prof. Dr. S. Polarz
Department of Chemistry
University of Konstanz
Universitätsstrasse 1, D-78457 Konstanz

[b] Institute of Inorganic Chemistry
Leibniz-University Hannover
Callinistrasse 9, D-30167 Hannover
E-mail: sebastian.polarz@ieca.uni-hannover.de

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Experimental

**Synthesis of 1,3-Bistri(isopropoxysilyl)-benzene-5-acetylene (4)**

To a mixture of Pd-DPPF (0.2 mmol, 0.1 eq), DPPF (0.27 mmol, 0.15 eq) and Cul (0.35 mmol, 0.2 eq) in 13.3 mL THF and 6.6 mL NEt₃, 1,3-Bistri(isopropoxysilyl)-5-bromobenzene (1) (1.8 mmol, 1 eq) was added. The reaction mixture was degassed for 15 min and trimethylsilylacetylene (28.9 mmol, 16.3 eq) was added before capping the microwave vial. The microwave was heated to 110°C over 20 min, the temperature was held for 45 min before cooling down to 55 °C. The obtained precursor 1,3-Bis(isopropoxysilyl)-benzene-5-trimethylsilylacetylene (3) was filtrated and purified via column chromatography.

1H-NMR (400 MHz, CDCl₃): δ(ppm) = 7.93 (t, 1H, p-arom. CH); 7.80 (d, 2H, o-arom. CH); 4.24 (hept, 6H, OCH); 1.20 (d, 36H, CH₃); 0.26 (s, 9H, Si-(CH₃)₃).

13C-NMR (100 MHz, CDCl₃): δ(ppm) = 141.19 (p-arom. CH); 139.90 (o-arom. CH); 132.10 (arom. C-Si); 121.94 (C-C≡C); 105.87 (C-C≡C); 93.87 (C-C≡C); 65.49 (OCH); 25.48 (CH₃); 0.04 (Si-(CH₃)₃).

29Si-NMR (79 MHz, CDCl₃): δ(ppm) = 141.65 (p-arom. CH); 140.18 (o-arom. CH); 132.10 (arom. C-Si); 121.03 (C-C≡C); 84.51 (C-C≡C); 77.36 (C-C≡C); 65.68 (OCH); 25.63 (CH₃).

HR-ESI-MS: m/z = 605.3043, (simul. 605.3047) [M+Na⁺]; deviation: 0.3 ppm.

To deprotect precursor (3) a solution of AgNO₃ (1.73 mmol, 2 eq) in 20 mL aceton (317.22 eq), 0.9 mL dest. H₂O (60 eq) and 2.09 mL pyridine (30 eq) was produced. 0.5 g precursor (3) (0.86 mmol, 1 eq) was mixed with the solution under vigorous stirring and heated to 40 °C for 40 h. For purification AgCl was precipitated by addition of brine and precursor (4) was extracted with Et₂O. After removal of the solvent and further purification with column chromatography a colourless oil was obtained.

1H-NMR (400 MHz, CDCl₃): δ(ppm) = 7.97 (t, 1H, p-arom. CH); 7.84 (d, 2H, o-arom. CH); 4.25 (hept, 6H, OCH); 3.08 (s, 1H, C-C≡C-H); 1.20 (d, 36H, CH₃).

13C-NMR (100 MHz, CDCl₃): δ(ppm) = 141.65 (p-arom. CH); 140.18 (o-arom. CH); 132.50 (arom. C-Si); 121.03 (C-C≡C); 84.51 (C-C≡C); 77.36 (C-C≡C); 65.68 (OCH); 25.63 (CH₃).

29Si-NMR (79 MHz, CDCl₃): δ(ppm) = -17.91 (C-Si-(CH₃)₃); -62.69 (C-Si-O). HR-ESI-MS: m/z = 533.2722 (simul. 533.2725) [M+Na⁺]; deviation: 0.5 ppm.

**Preparation of AlkySil material**

0.3 g precursor (4) were dissolved in 1 mL ethanol and with 50 µL 0.1 M HCl prehydrolysed for 2 h. By addition of 50 µL conc. ammonia the condensation started. Afterwards the mixture was transferred into a syringe and closed with parafilm overnight. The yellow material was obtained by drying the gel under standard conditions.

**Preparation of Fe₃O₄/SiO₂ core-shell particles**

A total of 5.0 g Igepal CO-520 dissolved in 110 mL cyclohexane was sonicated for 15 min before adding 10 mL (3.4 mg/mL in cyclohexane) Fe₃O₄ cores and 0.9 mL conc. ammonia.
Under continuous stirring 0.5 mL tetraethylorthosilicat (TEOS) were added with 50 mL/h rate of addition. The reaction was stopped by addition of 30 mL methanol and purification by centrifugation in ethanol. The Fe₃O₄/SiO₂ core-shell particles were redispersed in ethanol.

Preparation of Fe₃O₄/SiO₂/AlkySil core-shell-shell particles

For the prehydrolysation, 40 mg precursor (4), 1.0 mL n-propanol and 50 µL 0.1 M HCl were stirred for 2 h. A total of 20 mg Fe₃O₄/SiO₂ particles dispersed in 140 mL ethanol were stirred and the prehydrolysed precursor (4) was added via a syringe pump with 0.1 mL/h rate of addition. The particles were purified by centrifugation in ethanol.

Preparation of isotropic-clicked Fe₃O₄/SiO₂/AlkySil/Cumarin particles

A total of 4.9 mg Tetrakis(acetonitrile)copper(I)hexafluorophosphate and 5.0 mg Cumarin-343-azide were solved in 1.0 mL ethanol and added to 5 mL of 1.0 mg/mL Fe₃O₄/SiO₂/AlkySil particles in ethanol. The reaction mixture was stirred for 24 h and afterwards washed several times by centrifugation in ethanol.

Preparation of isotropic-clicked Fe₃O₄/SiO₂/AlkySil/Zn particles

A total of 125 mg mercaptoundecanoic acid and 1 mg Benzildimethylketal (DMPA) were added to 3 mg Fe₃O₄/SiO₂/AlkySil particles in 3 mL ethanol in a quartz tube. The UV lamp was turned on for 1 min. The obtained clicked particles were washed several times in ethanol. Afterwards Zn ions were coordinated by addition of 30 mg Zn(NO₃)₂·6H₂O to the particle dispersion and heated to 70°C for 5 min. The resulting Fe₃O₄/SiO₂/AlkySil/Zn particles were washed by centrifugation in ethanol.

Preparation of anisotropic-clicked Fe₃O₄/SiO₂/AlkySil/a-Zn particles

For the assembly, 120 µL of a 0.8 mg/mL Fe₃O₄/SiO₂/AlkySil particles dispersion in ethanol were dried on a 2x2 cm Si substrate with a 50 nm amorphous ZnO layer. The substrate with the assembled particles was placed in a petri dish containing a solution of 125 mg mercaptoundecanoic acid and 0.5 mg Benzildimethylketal (DMPA). The UV lamp was positioned directly above the petri dish and turned on for 1 min. The obtained particles were removed from the substrate by addition of 150 µL 0.01 M HCl and purified by centrifugation and redispersed in ethanol. Afterwards, Zn ions were coordinated by addition of 15 mg Zn(NO₃)₂·6H₂O to the particle dispersion and heated to 70°C for 5 min. The resulting Fe₃O₄/SiO₂/AlkySil/a-Zn particles were washed by centrifugation in ethanol.
Preparation of anisotropic-clicked Fe$_3$O$_4$/SiO$_2$/AlkySil/a-F-thiol particles

For the assembly, 120 µL of a 0.8 mg/mL Fe$_3$O$_4$/SiO$_2$/AlkySil particles dispersion in ethanol were dried on a 2x2 cm Si substrate with a 50 nm amorphous ZnO layer. The substrate with the assembled particles was placed in a petri dish containing a solution of 10 µL pentafluorothiophenol (F-thiol) and 0.5 mg Benzildimethylketal (DMPA). The UV lamp was positioned directly above the petri dish and turned on for 1 min. The obtained particles were removed from the substrate by addition of 150 µL 0.01 M HCl and purified by centrifugation and redispersed in ethanol.

Analytical methods

For the microwave synthesis a microwave from Anton Paar Monowave 300 and 30 mL microwave tubes with cap were used. NMR spectra were measured on a Varian Unity INOVA 400 MHz spectrometer. MAS-NMR spectra were obtained with a Bruker DRX 400 spectrometer with a spinning frequency of 10 kHz. ESI-MS spectra were recorded with Bruker micrOTOF II. TGA measurements were obtained with a Netzsch STA F3 Jupiter. SEM images were acquired with a Zeiss Gemini 500. Raman spectra were acquired using a Raman station 400 from Perkin Elmer. X-ray diffraction was performed with a Bruker AXS D8 advance diffractometer using Cu-Kα radiation. IR spectra were obtained with a Perkin-Elmer Spectrum 100. HR-TEM images, EDX spectra and linescan were acquired with a JEOL, JEM 2200FS at an accelerating voltage of 200 kV. UV/Vis spectra were acquired using an Agilent Cary60. The fluorescence spectra were measured with a PicoQuant FT300. AUC measurements were performed with an Optima SL-I analytical centrifuge (Beckman-Coulter, Palo Alto, CA, USA) with Rayleigh interference in a titania measuring cell (Nanolytics, Potsdam, Deutschland) and centrepiece with 12 mm optical waylength. The field- and temperature-dependant SQUID measurements have been acquired using a Quantum Design MPMS XL 5 magnetometer. The surface tensiometry and contact angle were measured at 20 ± 1 °C using a Krüss drop shape analysis DSA1 apparatus. The instrument calculates the surface tension and contact angle with spatial coordinated of the drop shape and size. Measurements of the particle dispersion in water were taken on the same drop with and without a magnet. The used NdFeB (cube, 10 mm, magnetic field density of ~ 1 T) was positioned 1 mm from the bottom of the drop. The measurement apparatus is a combination of two classical dynamic light scattering (DLS) systems and a birefringence detection setup. The sample is placed in an electro magnet and illuminated with a laser (HeNe 632nm, 10mW). One DLS detection optic is aligned at a scattering angle of 9°, with the scattering vector parallel to the magnetic field. The second DLS detection optic is aligned with the same scattering angle but the scattering vector is perpendicular to the magnetic field. The scattered light is picked up by mono-mode fibers and detected with single photon detectors.
(ALV SO-SIPD) that are connected to a hardware correlator (Flex02-12D/C from correlator.com). The intensity autocorrelation functions are analyzed separately, by fitting a mono-exponential relaxation. By the use of the Stokes-Einstein relation, the directional diffusion coefficients yield the respective hydrodynamic radius. The birefringence is detected from the transmitted beam. Enhanced detection sensitivity is achieved by the use of a photoelastic modulator (PEM II/FS84 from Hinds Instruments), two Glan-Thompson polarizers (aligned at ±45° with respect to the magnetic field) and a Lock-In amplifier (Stanford Research SR830-DSP). The value of birefringence is measured by compensation of the signal with a pockels cell. For a more detailed description, see e.g. [doi:10.1016/0378-4363(77)90800-2].
Results

Figure S1. Analytical data for the magnetite particles.

(a) TEM-images (left: scalebar 50 nm, right: scalebar 10 nm).

(b) Histogram counted from TEM-images, d = 9.78 nm, PDI = 6.0%.
AUC measurement, $d_h = 11.6$ nm.

PXRD data (blue: magnetite reference, black: magnetite particles).
Wavenumber (cm$^{-1}$) vibration

\~ 3400 H$_2$O (KBr matrix)
2770-2960 CH$_3$ streching
1630 CO streching
580 FeO streching

IR spectrum.

Temperature-dependent SQUID measurement, blocking temperature $T_B = 100.7$ K.
Field-dependent SQUID measurement, blue: measurement at 4 K, \( m = 39.7 \text{ emu/g} \), ferromagnetic behaviour; black: measurement at 300 K, \( m = 38.0 \text{ emu/g} \), superparamagnetic behaviour.
**Figure S2.** Fe$_3$O$_4$/SiO$_2$ core-shell NPs.

TEM micrographs of Fe$_3$O$_4$/SiO$_2$ core-shell particles with thin (a) and thick shell (b); scalebars = 50nm. Correlation of particle diameter with amount of TEOS used during synthesis (c).
(d) Histogram of the used Fe₃O₄/SiO₂ particles counted from TEM-images, d = 20.8 nm, PDI = 8.0%.

(e) AUC measurement of the used Fe₃O₄/SiO₂ particles, dₜₐₜ = 23.6 nm with a particle density of \( \rho = 3.1 \text{ g/cm}^3 \).
PXRD data (blue: magnetite reference, grey: Fe$_3$O$_4$/SiO$_2$ particles).

IR spectrum of Fe$_3$O$_4$/SiO$_2$ particles.

| Wavenumber (cm$^{-1}$) | vibration               |
|------------------------|-------------------------|
| ~ 3400                 | H$_2$O (KBr matrix)     |
| 2770-2960              | CH$_3$ streching        |
| 1630                   | CO streching            |
| 1080                   | SiO streching           |
| 580                    | FeO streching           |
EDX linescan of Fe₃O₄/SiO₂ particles; measured: Fe (grey) with Gauss-fit (black) and Si (blue) with Pearson VII-fit (light blue).
Figure S3. Analytical data for the sol-gel precursor (4).

(a) $^1$H-NMR spectrum in CDCl$_3$.

(b) $^{13}$C-NMR spectrum in CDCl$_3$. 
$^{29}$Si-NMR spectrum in CDCl$_3$.

ESI-MS pattern for [M+Na$^+$]; measured (black): m/z = 533.2722 (simul. (grey): 533.2725) [M+Na$^+$]; deviation: 0.5 ppm.
Figure S4. Analytical data for the organosilica material (AlkySil).

(a)

SEM (left, scalebar 500 nm) and TEM (right, scalebar 50 nm) image of AlkySil-material.

(b)

| Wavenumber (cm⁻¹) | vibration             |
|-------------------|-----------------------|
| 3295              | CH valence            |
| 1030              | SiO stretching        |
| 840               | Ring deformation      |

ATR-IR spectrum.
(c) Raman shift (cm\(^{-1}\)) vibration

| Raman shift (cm\(^{-1}\)) | vibration         |
|---------------------------|-------------------|
| 2101                      | C≡C               |
| 1230                      |                   |
| 1575                      | aromatic ring     |
| 994                       |                   |
| 550                       | Si-O-Si           |

Raman spectrum.

(d) TGA curve, organic amount 49.1%
\( ^{13}\text{C-MAS-NMR spectrum.} \)

\[ \delta (\text{ppm}) = 139.3 \text{ (p-arom. CH)}, 131.4 \text{ (o-arom. CH)}, 122.2 \text{ (arom. C-Si)}, 82.9 \text{ (C-C≡C)}, 79.0 \text{ (C-C≡C)}, 59.4 \text{ (C-C≡C)}, 40.4 \text{ (OCH)}, 16.9 \text{ (CH3)}. \]

\( ^{29}\text{Si-MAS-NMR spectrum.} \)
Figure S5. Analytical data for the Fe$_3$O$_4$/SiO$_2$/AlkySil core-shell-shell particles.

(a) TEM image overview of Fe$_3$O$_4$/SiO$_2$/AlkySil particles, scalebar 50 nm.

(b) Histogram of the Fe$_3$O$_4$/SiO$_2$/AlkySil particles counted from TEM-images, $d = 22.9$ nm, PDI = 5.0%.
Comparison of the diameter of the different particle types from TEM images (black) and AUC measurements (blue).

EDX spectrum of Fe$_3$O$_4$/SiO$_2$ (black) and Fe$_3$O$_4$/SiO$_2$/AlkySil particles (blue). Referenced to Fe-signal; Fe$_3$O$_4$/SiO$_2$ particles less Si than Fe; Fe$_3$O$_4$/SiO$_2$/AlkySil particles more Si than Fe.
Wavenumber (cm⁻¹) | vibration
---|---
~ 3400 | H₂O (KBr matrix)
2770-2960 | CH₃ stretching
1630 | CO stretching
1080 | SiO stretching
580 | FeO stretching

IR spectrum of Fe₃O₄/SiO₂/AlkySil particles.

PXRD data (blue: magnetite reference, grey: Fe₃O₄/SiO₂/AlkySil particles).
EDX-Linescan of the Fe$_3$O$_4$/SiO$_2$/AlkySil particles; Fe (black) and Si (grey).

Field-dependant SQUID measurement Fe$_3$O$_4$/SiO$_2$/AlkySil particles at 1.8 K (black) and 300 K (grey). Fe$_3$O$_4$/SiO$_2$/AlkySil particles show same behaviour as the magnetite particles (see S1).
Comparison of the Blocking temperature ($T_B$, blue), magnetic moment (m, black) and remanence (grey) of $\text{Fe}_3\text{O}_4$, $\text{Fe}_3\text{O}_4/\text{SiO}_2$ and $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{AlkySil}$ particles. With introducing non-magnetic silica as first shell the blocking temperature, magnetic moment and remanence decreases and further decreases with the second shell consisting of AlkySil.

|                  | $T_B$ / [K] | m / [emu g$^{-1}$] | R / [emu g$^{-1}$] |
|------------------|-------------|---------------------|-------------------|
| $\text{Fe}_3\text{O}_4$ | 199.2       | 39.7                | 8.8               |
| $\text{Fe}_3\text{O}_4/\text{SiO}_2$ | 145.9       | 22.7                | 8.0               |
| $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{AlkySil}$ | 144.28      | 15.6                | 4.7               |
**Figure S6.** Analytical data for the isotropic click modification of the Fe$_3$O$_4$/SiO$_2$/AlkySil particles by the copper-catalyzed 1,3-dipolar Huisgen cycloaddition.

(a) TEM image of Cumarin-343-clicked Fe$_3$O$_4$/SiO$_2$/AlkySil particles, scalebar 50 nm. Morphology is unchanged after click reaction.

(b) Magnetic separation of Fe$_3$O$_4$/SiO$_2$/AlkySil/Cumarin particles. (c) Magnetic separation of negative control with dissolved dye. Due to chemically-bound dye the solution of the dispersion is colourless (b) whereas the negative control (c) is yellow coloured after magnetic separation of the particles. (d) UV/Vis spectra of Cumarin-343-azide (black), Fe$_3$O$_4$/SiO$_2$/AlkySil/Cumarin particles (blue) and negative control (grey). The particles show high scattering at low wavelengths because of the magnetite cores, as well as an absorption band measured at 437 nm (blue), which conforms to the absorption band of the dye Cumarin-343-azide (black).
The negative control experiment (click reaction with Fe$_3$O$_4$/SiO$_2$ particles) shows that the dye is covalently-bound and not just adsorbed on the surface of the particles.

Fluorescence spectra of Fe$_3$O$_4$/SiO$_2$/AlkySil/Cumarin particles (blue), Cumarin-343-azide (black) and negative control (grey).
Figure S7. Analytical data for the isotropic click modification of the Fe$_3$O$_4$/SiO$_2$/AlkySil particles by the photochemical Thiol-Yne reaction with mercaptoundecanoic acid.

Comparison between bright-field and dark-field STEM images of the particles modifies using mercaptoundecanoic acid after coordination of Zn$^{2+}$, scalebar 20 nm.
Figure S8. Reference experiment: Treatment of unmodified Fe$_3$O$_4$/SiO$_2$/AlkySil with Zn$^{2+}$.  

Left: STEM-micrograph, EDX line scan (black = Fe; blue = Si; light blue = Zn; dark blue: position of linescan), right: EDX spectrum. Reference experiment shows no coordinated Zn ions.
**Figure S9.** Monolayer of Fe$_3$O$_4$/SiO$_2$/AlkySil on a silicon substrate.

SEM micrographs, left: scalebar 500 nm, right: scalebar 200 nm.
Figure S10. Analytical data for the click modification of the Fe$_3$O$_4$/SiO$_2$/AziSil particles by the photochemical Thiol-Yne reaction: pentafluorothiophenol.

(a) IR spectra of Fe$_3$O$_4$/SiO$_2$/AziSil/F-thiol (grey), Pentafluorothiophenol (black). By comparing the IR spectra of pentafluorothiophenol (black) and the fluoro-modified core-shell-shell particles (grey) we see the characteristic C-F vibration band at 1488 cm$^{-1}$.

(b) EDX spectrum of Fe$_3$O$_4$/SiO$_2$/AziSil/F-thiol particles of the click reaction with pentafluorothiophenol.
**Figure S11.** Analytical data for the anisotropic click modification of the Fe₃O₄/SiO₂/AlkySil particles by the photochemical Thiol-Yne reaction with pentafluorothiophenol.

Pendant drop method for calculation of the surface energy of the Fe₃O₄/SiO₂/AlkySil/a-F-thiol particle dispersion in ethanol, $\gamma_v = 20.4$ mN/m.
