Dynamically Self-Assembling Carriers Enable Guiding of Diamagnetic Particles by Weak Magnets

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Ⓦ *Web-Enhanced Feature* Ⓢ *Supporting Information*

ABSTRACT: We show that diamagnetic particles can be remotely manipulated by a magnet by the reversible adsorption of dual-responsive, light-switchable/superparamagnetic nanoparticles down to their surface. Adsorption occurs upon exposure to UV light, and can be reversed thermally or by ambient light. The dynamic self-assembly of thin films of the dual-responsive nanoparticles induces attractive interactions between diamagnetic particles. We demonstrate that catalytic amounts of the dual-responsive nanoparticles are sufficient to magnetically guide and deliver the diamagnetic particles to desired locations, where they can then be released by disassembling the dynamic layers of superparamagnetic nanoparticles with visible light.

The ability to manipulate the position of small objects remotely (using an external stimulus) has widespread applications in physical and life sciences which enable goals as diverse as the transport of Bose−Einstein condensates[1] and control of the topological state of DNA.[2] Of particular interest is the approach involving optical trapping and manipulation;[3,4] however, this technique suffers from several limitations including lack of selectivity[4] as well as limitations associated with the high intensity of the trapping laser, such as local heating[5] and photodamage of the trapped species.[6] Many of these problems can be overcome by the use of a magnetic field for guiding. This strategy has enabled several interesting applications, including control of calcium signaling[7] and magnetofection;[8] however, only materials with high absolute values of magnetic susceptibility ($|\chi| \gg 0$) can be effectively guided by magnets. To overcome this limitation, and to allow random particles to be manipulated with magnetic fields, we envisaged a methodology (Figure 1) which would allow for the reversible formation of a thin paramagnetic coating on the surface of diamagnetic particles, thus rendering them responsive to magnetic fields. The resulting *diamagnetic core−paramagnetic shell* assemblies would be stable in the dark and could be magnetically delivered to a desired location, whereupon the diamagnetic "cargo" could be released simply by exposure to visible light, which "strips off" the thin paramagnetic shell.

In order to realize this goal, we decided to take advantage of the previously reported[9] dual-responsive nanoparticles (NPs), which comprise superparamagnetic (SPM) Fe_3O_4 cores, ~11 nm in diameter, functionalized with monolayers of *trans*-azobenzene molecules ($Fe_3O_4 \cdot AC$ in Figures 1 and 2a). Solutions of these NPs in apolar solvents are stable for
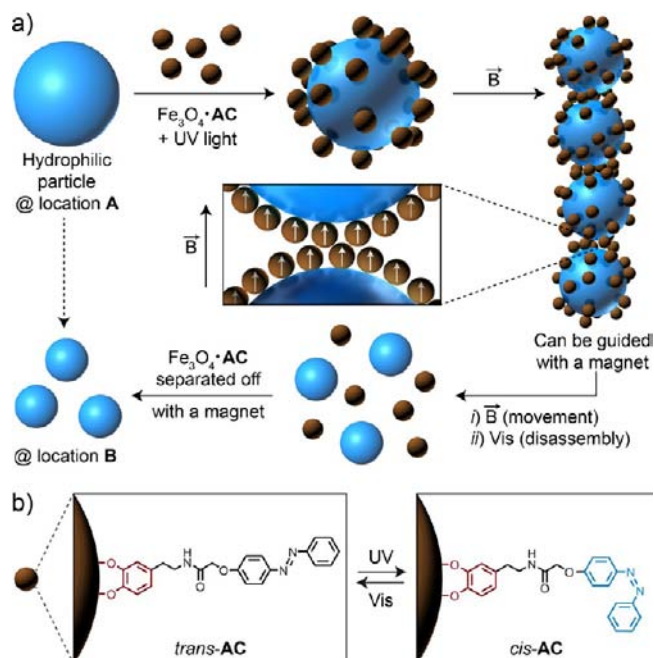

Figure 1. (a) Guiding of diamagnetic particles with magnets is enabled by the reversible, light-controlled formation of a dynamic paramagnetic coating on their surfaces. (b) Reversible, light-induced isomerization of azobenzene on the surface of an SPM iron oxide nanoparticle.

prolonged periods of time (e.g., no signs of aggregation in toluene can be seen after several months in the dark) due to the hydrophobic nature of *trans*-azobenzene on their surfaces. Interestingly, the NPs also do not aggregate after exposure to external magnetic fields:[10] even though the magnetic dipole moments of the particles align in the direction of the applied field, the NPs' thermal energy at room temperature overcomes interparticle magnetic dipole−dipole interaction (in other words, the magnetic Bjerrum length of the NPs, λ_B,[11,12] is smaller than their diameter, $2r$; in our case $\lambda_B \approx 0.33r$). At the same time, the particles are responsive to light: UV irradiation ($\lambda \approx 365$ nm; $I \approx 0.7$ mW/cm^2) induces a rapid *trans*→*cis* isomerization of azobenzene on the surfaces of nanoparticles[13] and causes their self-assembly into spherical aggregates[14] with diameters approximately 1 order of magnitude larger than those of single NPs (Figure 2a, right). Since the spherical aggregates interact with each other via *multiple* NP−NP pairs (cf. Figure
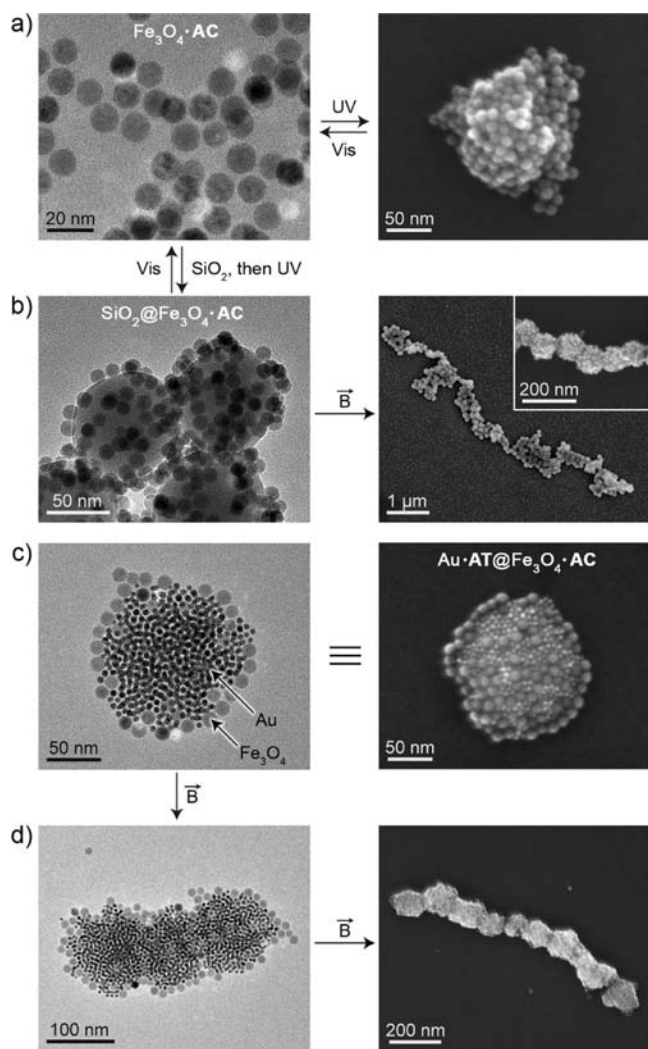
Figure 2. (a) Light-controlled self-assembly of azobenzene-coated Fe₃O₄ (Fe₃O₄·**AC**) nanoparticles. (b) UV light-induced occlusion of silica particles with Fe₃O₄·**AC** (left) and magnetic field-induced aggregation into linear structures (right). (c) Core−shell assemblies prepared by exposing a mixture of Au·**AT** and Fe₃O₄·**AC** NPs to UV light. (d) Linear structures obtained by exposing the core−shell assemblies to a magnetic field.

1a, center), the strength of these aggregate−aggregate interactions is sufficient to overcome the thermal energy, and the spherical aggregates align into larger, linear assemblies. In other words, the magnetic interactions in this system can be turned "on" and "off" using UV and visible light, respectively.

The light-induced self-assembly process occurs as a result of a combination of attractive electric dipole−dipole interactions between the *cis*-azobenzene groups[15] and the solvophobic effect.[16] Therefore, we hypothesized that hydrophilic particles intentionally introduced to a UV-irradiated solution of Fe₃O₄·**AC** NPs would serve as preferential attachment sites for these NPs, whose self-aggregation would then be suppressed. Proof-of-concept experiments were performed on mixtures of Fe₃O₄·**AC** NPs and ~90 nm silica particles[17] dispersed in toluene containing 5% v/v ethanol. As Figure 2b, left, shows, exposure of this mixture to UV light indeed resulted in rapid (within 30 s) formation of SiO₂@Fe₃O₄ assemblies, and, notably, no aggregates of free Fe₃O₄·**AC** were found (provided the Fe₃O₄·**AC**/SiO₂ ratio was low enough[18]).

Furthermore, the addition of Fe₃O₄·**AC** NPs to pre-formed SiO₂@Fe₃O₄ assemblies, followed by UV irradiation, resulted in the thickening of the Fe₃O₄ shell (multilayers comprising at least four layers of Fe₃O₄ NPs were observed), and, again, no self-aggregation of Fe₃O₄ NPs was observed.[18] It should be emphasized, however, that the composition of the solvent mixture played an important role in determining the outcome of the light-induced self-assembly process: when the solvent was too apolar (e.g., a 9:1 toluene−tetrahydrofuran mixture), Fe₃O₄·**AC** NPs, in addition to occluding the surface of silica, formed aggregates on their own (Figure S4), whereas in a much more polar 4:1 toluene−ethanol mixture, iron oxide remained in a disaggregated state, even upon exposure to UV light (due to the polar solvent's stabilizing effect on *cis*-**AC**; Figure S6). Only in mixtures of intermediate polarity, e.g., 19:1 toluene−ethanol, Fe₃O₄·**AC** selectively covered the surface of SiO₂ (Figure 2b, left; also Figure S5).

To demonstrate the generality of this approach, we attempted to encapsulate small (5 nm) gold NPs inside a monolayer of Fe₃O₄·**AC**. Toward this end, we functionalized Au NPs with an azobenzene-terminated thiol, **AT** (see SI, section 2). The surface concentration of **AT** on Au (~3.7 azobenzene units/nm²) was intentionally higher than that of **AC** of Fe₃O₄ (~2.0 azobenzenes/nm²), such that the energy of interaction between two NPs would be, $E_{Au-Au} > E_{Au-Fe_3O_4} > E_{Fe_3O_4-Fe_3O_4}$. The higher azobenzene surface coverage on Au also led to a faster aggregation of Au·**AT** as compared to Fe₃O₄·**AC**. As a consequence, UV irradiation of a mixture of these two types of particles resulted in selective formation of Au@Fe₃O₄ core−shell assemblies (Figure 2c).[19] Again, no aggregates comprising only Fe₃O₄ could be seen,[18] although such aggregates formed readily (Figure 2a) in the absence of Au·**AT**.

We further speculated that, since in the presence of external magnetic field the diamagnetic (= SiO₂; Au) core−paramagnetic shell assemblies interact with each other via *multiple* Fe₃O₄ NP dipole−dipole interactions (analogous to the interactions between all-Fe₃O₄ NP assemblies[9]), these structures could further assemble into one-dimensional aggregates. (It should be noted that the magnetic dipole interactions between assemblies comprising both diamagnetic and SPM components are maximized when the SPM components are located at their surfaces.) Indeed, application of low-intensity magnetic field to a solution of these assemblies results in the formation of linear aggregates, as shown in Figure 2b, right, and 2d. Notably, only a small, "catalytic" amount of ~11 nm Fe₃O₄ NPs (corresponding to a loose monolayer; cf. Figure 2b) is sufficient to induce further aggregation of these core−shell assemblies—for example, we have determined that assemblies comprising as little as 4% m/m of Fe₃O₄·**AC** NPs (96% being the Au·**AT** "cargo") form larger, linear aggregates when external magnetic field is applied.

As these larger aggregates form, the magnetic force acting on them becomes large enough to overcome the Brownian force,[20,21] and the aggregates move toward the regions of maximum magnetic field, quickly concentrating near the magnets. The resulting precipitate remains attracted to a magnet and can readily be transported from one location to another in nearly quantitative yield with speeds of up to ~1 cm/s for up to 1 day in the dark, and for at least several days under UV illumination. At the same time, the formation of all of the aggregates described here is fully reversible due to their dynamic nature: both the core−shell assemblies and their linear
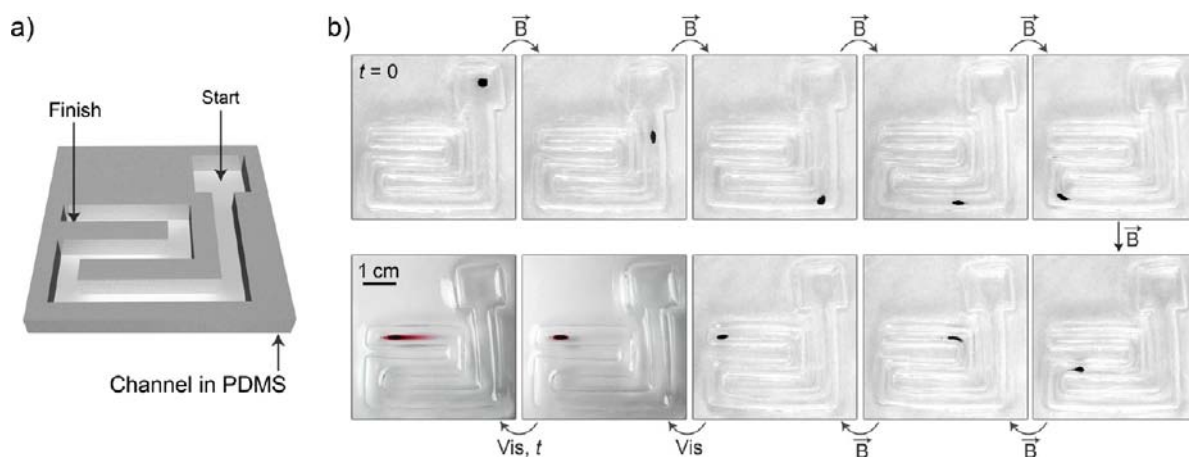
Figure 3. (a) PDMS mold used in the delivery and release experiment. The Au·**AT**@Fe₃O₄·**AC** assemblies are placed in one end of the channel and remotely transported to the other end. (b) A series of pictures showing that the assemblies are readily attracted by a hand-held magnet despite being composed of, in this case, 88% Au. The pictures were taken under ambient light. Once the aggregates reached the "end" point, intense visible light was turned on, triggering the disassembly of the aggregates and release of the red-colored gold nanoparticles. The series of pictures is from a movie attached in the online versions.

aggregates slowly disassemble in the dark due to thermal *cis→trans* azobenzene re-isomerization, which cancels out the attractive interactions holding NPs together within the aggregates. This re-isomerization reaction and the disassembly process can be greatly accelerated by exposing the system to visible light. Overall, the strategy described here—depicted in Figure 1a—enables us to (i) rapidly "trap" diamagnetic particles using UV light, (ii) guide them with a magnet, and (iii) release them at a desired location using visible light.

To demonstrate the proof-of-concept, we placed a UV-pre-exposed mixture comprising 88% (m/m) of gold nanoparticles (Au·**AT**) "cargo" and 12% Fe₃O₄·**AC** "carriers" at one end of a channel molded from PDMS (Figure 3a). The precipitate was then transported to the other end of the channel using a small, hand-held neodymium magnet which was moved manually underneath the channel. Subsequent exposure to intense (∼1.0 mW/cm²) visible light induced quantitative disassembly of the solids and released the "cargo", manifested by the appearance of an intense red color characteristic of gold nanoparticles. Finally, the core–shell assemblies could be re-formed and transported again upon re-exposure to UV light and the magnetic field. A movie of this procedure is available online; still shots are shown in Figure 3b.

In summary, we have demonstrated the capability to magnetically guide diamagnetic particles by reversibly coating them with a thin, dynamic paramagnetic "film". This guiding is achieved by the simultaneous action of two external stimuli: light and a magnetic field. We envision that the methodology presented here could be extended to an "inverse" dynamic self-assembly system whereby the apolar Fe₃O₄·*trans*-**AC** NPs placed in polar solvents spontaneously aggregate due to the solvophobic effect but can be *dynamically disassembled* upon exposure to UV. This modified system could enable the opposite—that is, to occlude and magnetically manipulate *apolar* diamagnetic particles under thermally equilibrated conditions and to release them, at a desired location, with UV light. At the same time, the present study is also the first example wherein well-defined (core–shell) binary nanoparticle assemblies are generated in a single step using UV light. Current efforts are underway in our laboratories in order to extend this strategy to prepare even more complex (e.g.,

ternary) assemblies and to study the properties of these new materials.

■ ASSOCIATED CONTENT

ⓢ Supporting Information
Synthesis of nanoparticle ligands, preparation and functionalization of nanoparticles, additional nanoparticle self-assembly studies. This material is available free of charge via the Internet at http://pubs.acs.org.

Ⓦ Web-Enhanced Feature
A movie in .avi format demonstrating the assembly/disassembly process is available in the online versions.

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Notes
The authors declare no competing financial interest.

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(18) This conclusion was reached by thorough inspection of the samples by means of SEM. We emphasize that whether or not $Fe_3O_4 \cdot AC$ NPs self-aggregate depends on their concentrations relative to the concentrations of the more hydrophilic particles.

(19) We verified by SEM that the process consists of two steps: first, Au·**AT** aggregates nearly quantitatively within ∼30 s of exposure to UV light, followed by a rapid (∼30−35 s) adsorption of $Fe_3O_4 \cdot AC$ on the Au aggregates. For comparison, pure $Fe_3O_4 \cdot AC$ showed no signs of aggregation before 150 s of UV irradiation under the same experimental conditions.

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