

Orthogonal Light-Induced Self-Assembly of Nanoparticles using Differently Substituted Azobenzenes**

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Abstract: Precise control of the self-assembly of selected components within complex mixtures is a challenging goal whose realization is important for fabricating novel nanomaterials. Herein we show that by decorating the surfaces of metallic nanoparticles with differently substituted azobenzenes, it is possible to modulate the wavelength of light at which the self-assembly of these nanoparticles is induced. Exposing a mixture of two types of nanoparticles, each functionalized with a different azobenzene, to UV or blue light induces the selective self-assembly of only one type of nanoparticles. Irradiation with the other wavelength triggers the disassembly of the aggregates, and the simultaneous self-assembly of nanoparticles of the other type. By placing both types of azobenzenes on the same nanoparticles, we created unique materials (“frustrated” nanoparticles) whose self-assembly is induced irrespective of the wavelength of the incident light.

The ability to induce communication between selected components of complex mixtures of chemical species is a hallmark of biological systems,^[1–3] and one of the key challenges in the field of systems chemistry.^[4] Within the environments of living cells, such communication is often initiated and governed by small-molecule entities (for example, phosphorylation,^[5] nitrosylation,^[6] and acetylation,^[7]). Compared with natural systems, synthetic chemists have the advantage of not being limited to the biomolecular pool of building blocks, thus having the potential to engineer systems featuring novel properties, such as responsiveness to external stimuli. For instance, remote control of nanoparticle (NP) aggregation using (electro)magnetic fields has enabled scientists to pursue goals as diverse as inducing apoptosis in vivo,^[8] and creating self-erasing images with metastable NP aggregates.^[9] (Note: the formation of such aggregates is usually referred to as the self-assembly of nanoparticles.) In the self-erasing images example, azobenzene-functionalized NPs, placed in a nonpolar environment, self-assembled upon exposure to near-ultraviolet (UV) light ($\lambda = 365$ nm).^[9–11] The self-assembly process was initiated by the UV-induced isomerization of *trans*- to *cis*-azobenzene, which gave rise to attractive interparticle interactions through a combination of

solvophobic interactions^[12] and attractive dipole–dipole interactions between *cis*-azobenzene moieties.^[13]

Compared to UV radiation, blue light has several advantages as an external stimulus, for example, it leads to reduced photodegradation of the switchable moieties^[14,15] and it is less invasive in the context of biological environments.^[16,17] Previously, it was demonstrated^[18–21] that modulating the substitution pattern on molecular photoswitches could shift their absorption bands, thus affecting the energy of light required to induce photoisomerization processes. For example, installing the electron-donating methoxy substituents in the *para* positions could red-shift the π – π^* absorption band of azobenzene by as much as 30 nm.^[22] However, the ability to induce self-assembly of NP aggregates using visible light has thus far remained an unresolved challenge. Herein, we show that metallic NPs functionalized with a red-shifted azobenzene self-assemble in response to blue light. Combining these novel particles with the previously reported NPs decorated with the parent azobenzene allowed us to create the first system whereby either of the two components could be addressed and assembled with high selectivity, depending on the wavelength of the incident light.

To verify the feasibility of our approach, we first calculated the electric dipole moments of energy-minimized conformations of a model compound, 4-(3-mercaptopropyl-1-oxy)-4'-(dimethylamino)azobenzene (see the Supporting Information, Section S1). In comparison with the *trans* form of this compound ($\mu = 4.65$ D), the *cis* isomer has a much higher dipole moment ($\mu = 6.70$ D), which suggests that it is possible to induce self-assembly of (dimethylamino)azobenzene-decorated NPs in non-polar solvents as a result of *trans*→*cis* isomerization. Next, we simulated the absorption spectra of both isomers and found that the peak arising from the π – π^* transition in the *trans* isomer appeared at approximately 400 nm (Figure S2)—that is, it was red-shifted by approximately 50 nm compared to the parent azobenzene. In contrast the *cis* isomer exhibited a pronounced absorption band centered at approximately 340 nm, indicating the possibility of inducing the *cis*→*trans* back-isomerization by irradiation with near-UV light.

Based on these considerations, we synthesized thiolated 4-(dimethylamino)azobenzene **1** (Figure 1a; Section S2). The UV/Vis absorption spectrum of the *trans* isomer of **1** displayed an intense π – π^* band centered at 407 nm. Upon irradiation with blue light (we used a Prizmatix mic-LED 420 nm light-emitting diode; light intensity ca. 1.0 mW cm^{–2}), the intensity of this band decreased markedly, whereas a new band at approximately 359 nm appeared, in good agreement with the calculated spectra (Figure S9a). Subsequent exposure to near-UV light (UVP UVGL-25 lamp, 365 nm; light intensity

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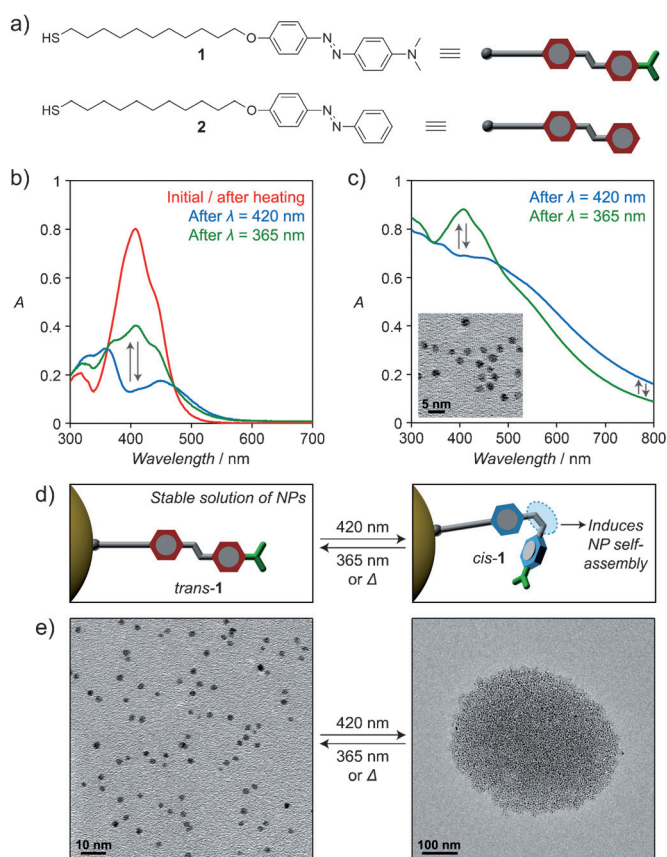


Figure 1. a) Structural formulas of the thiolated azobenzenes used in this study. b) Changes in the UV/Vis spectra of **1** (in toluene) upon exposure to blue light, then UV light. c) Reversible changes in the UV/Vis spectra of **1** assembled on gold nanoparticles, 2.5 nm in diameter. Inset: TEM image of **1**-functionalized 2.5 nm Au NPs. d) Reversible isomerization of **1** on the surface of a nanoparticle; the formation of *cis*-**1** initiates the self-assembly of nanoparticle aggregates. e) TEM images of **1**-functionalized Au NPs before (left) and after (right) exposure to blue (420 nm) light. Aggregates such as the one on the right could be disassembled using UV (365 nm) light or by gentle heating.

ca. 0.7 mW cm^{-2}) partially restored the original spectrum of *trans*-**1**; based on the absorption profiles, we estimate that the photostationary states contain about 12 % and around 48 % of *trans*-**1** at 420 nm and 365 nm, respectively. Although the *trans* $\rightarrow$ *cis*, and in particular, *cis* $\rightarrow$ *trans*, isomerization yield was far from complete, we hypothesized that the change in the overall NP polarity might be large enough to induce a reversible transformation between free and aggregated NPs.

We worked with relatively monodisperse, dodecylamine-capped gold NPs of approximately 2.5 nm in diameter, prepared by reducing a gold(III) salt with a borohydride in the presence of a mixture of surfactants (Section S3).^[23] Addition of **1** to a toluene solution of these NPs resulted in the particles precipitating almost instantaneously, presumably because of a large dipole moment of *trans*-**1**, and poor solvation of NPs decorated with this ligand. To solve this issue, we employed a two-step procedure, in which we first prepared NPs protected with a monolayer of a “dummy” thiol, *O*-phenyl-11-mercaptoundecanol,^[24] and then per-

formed a partial ligand-exchange reaction with **1** (Figure S10). The thiol-to-thiol replacement^[25,26] proceeds markedly slower than the amine-to-thiol exchange, which allowed us to terminate the reaction before the NPs began to precipitate. For example, we found that the NPs remain toluene-soluble after incubation with **1** for up to 24 h, at which point the mixed monolayer contains approximately 70 % of **1**.

Figure 1c shows the UV/Vis spectra of a toluene/hexane (7:3 v/v) solution of **1**-functionalized NPs (2.5 nm NP-**1**) exposed to 1) blue and 2) UV light. Upon exposure to blue light for 3 min, the band at approximately 410 nm decreased markedly, whereas the overall absorption in the low-energy portion of the spectrum increased, indicating the formation of nanoparticle assemblies. NP aggregation was supported by dynamic light scattering (DLS) measurements (Figure S11), as well as by transmission electron microscopy (TEM). The TEM images revealed that self-assembly proceeded in a near-quantitative fashion (i.e., virtually no free NPs could be found; Figure 1e). Subsequent irradiation with UV light caused the aggregates to disassemble, that is, these NPs display, in the same medium, a behavior *opposite* to that of particles functionalized with the parent azobenzene, whose assembly and disassembly are induced by UV and blue light, respectively.^[27,28] Alternatively, disassembly could be triggered thermally: we found that gentle heating (45°C for 7 min) of free or NP-immobilized **1** resulted in a quantitative *cis* $\rightarrow$ *trans* conversion, which canceled out the attractive interactions between the NPs.

Next, we considered selective self-assembly of specific components of a system comprising NPs having two different sizes, each functionalized with a different azobenzene ligand. To this end, we prepared a mixture of **1**-decorated 2.5 nm Au NPs and 5.5 nm Au NPs functionalized with **2**—a parent azobenzene (2.5 nm NP-**1** and 5.5 nm NP-**2**, respectively, in Figure 2a). Although both of these types of NPs were readily solvated in a non-polar solvent (7:3 v/v toluene-hexane), exposure to blue light induced the *trans* $\rightarrow$ *cis* isomerization of **1**, which triggered the self-assembly of aggregates of the 2.5 nm NPs (Figure 2c and top panel in Figure 2e). Subsequent exposure to UV resulted in partial recovery of absorption at 407 nm, concomitant with a decrease in absorption at 350 nm (Figure 2c, inset), which could be attributed to simultaneous *cis* $\rightarrow$ *trans* back-isomerization of **1**, and *trans* $\rightarrow$ *cis* isomerization of **2**. Nevertheless, absorption at high wavelengths remained high, indicative of the presence of NP aggregates. Under UV light, however, it was the 5.5 nm NPs that were aggregated—that is, exposure to UV allowed us to simultaneously disassemble aggregates of the smaller NPs, and to assemble aggregates of the larger ones.

To obtain mechanistic insights into this intriguing process, we quenched the reaction at different time intervals, and inspected the samples by TEM (Figure 2e). Interestingly, we found that at short UV irradiation times (e.g. $t_{\text{UV}} = 1 \text{ min}$; Figure 2e, bottom right) 5.5 nm NP-**2** preferentially aggregated on top of the aggregates of 2.5 nm NP-**1**—in other words, aggregates of 2.5 nm NP-**1**, exposing the polar *cis*-**1** moieties, acted as “seeds” for the assembly of the larger particles, whose surface polarity gradually increased with the progress of the *trans*-**2** $\rightarrow$ *cis*-**2** isomerization. However, these

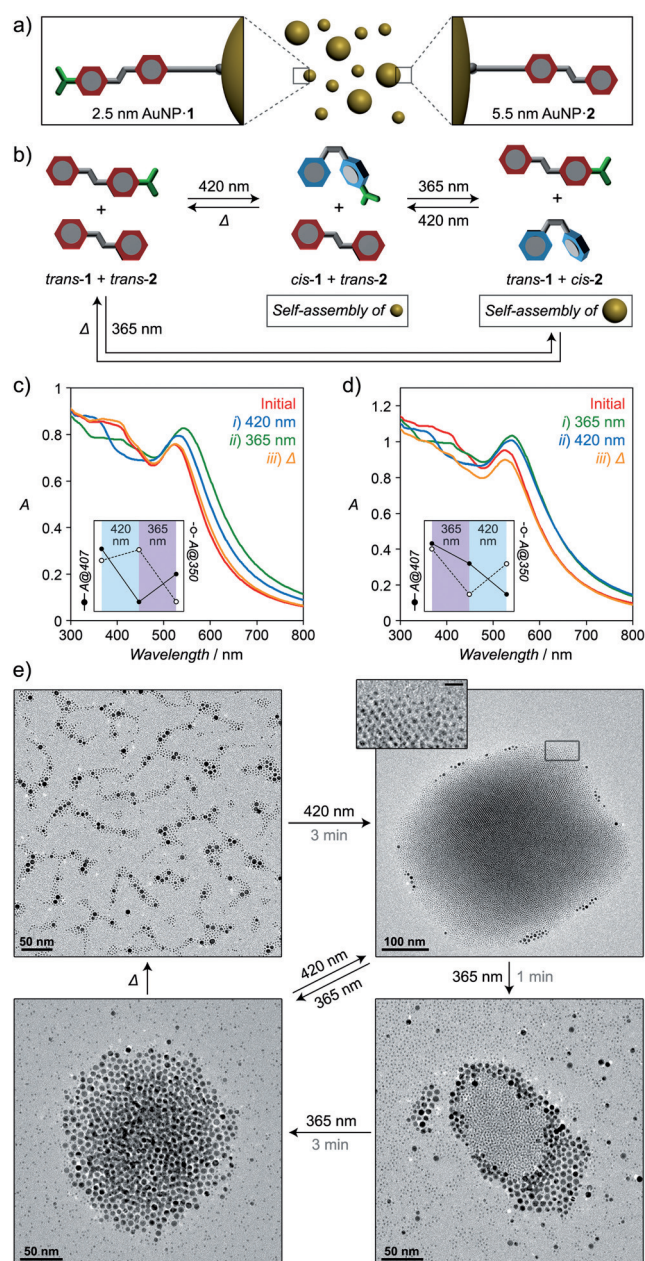


Figure 2. Light-controlled orthogonal self-assembly in a mixture of nanoparticles. a) Components of the system: 1-functionalized 2.5 nm Au NPs and 2-functionalized 5.5 nm Au NPs. b) Irradiation of a mixture of azobenzenes with blue light leads to the selective isomerization of *trans*-1, giving rise to the self-assembly of 2.5 nm NPs. Subsequent exposure to UV light triggers a simultaneous *cis*-1 $\rightarrow$ *trans*-1 and *trans*-2 $\rightarrow$ *cis*-2 isomerization, resulting in the disassembly of the aggregates of 2.5 nm NPs, concomitant with the self-assembly of 5.5 nm NPs. Gentle heating induces *cis* $\rightarrow$ *trans* isomerization of both 1 and 2 and “resets” the system. c,d) Changes in the UV/Vis spectra of mixtures of the NPs shown in (a) upon exposure to different wavelengths of light and then thermal treatment. Insets: changes in absorbance at the wavelength of maximum absorbance of *trans*-1 and *trans*-2. e) Following light-induced self-assembly in a mixture of NPs by TEM. See text for details.

seeds were ephemeral in that they gradually disintegrated, whereas the aggregates of 5.5 nm increased in size (we found that the intermediate products comprised comparable

amounts of 2.5 nm and 5.5 nm; see, for example, $t_{UV} = 2$ min in Figure S14). The final product of the process ($t_{UV} \geq 2$ min) consisted of aggregates composed of 5.5 nm NP-2 (Figure 2e, bottom left). We also studied the opposite process—that is, blue-light-mediated self-assembly of 2.5 nm NP-1 in the presence of disassembling aggregates of 5.5 nm NP-1. Similar to the previous sequence, UV/Vis spectroscopy showed 1) isomerization of both types of azobenzenes and 2) the existence of NP aggregates both before and after exposure to blue light. Representative TEM images taken at different stages of the process are shown in Figure S15 in the Supporting Information.

Finally, we considered NPs functionalized with mixed self-assembled monolayers of both 1 and 2. We envisioned that these NPs could form stable solutions in non-polar solvents provided that they are decorated with the *trans* form of both ligands. However, exposure to either UV or blue light would induce isomerization of one type of azobenzene, thus initiating self-assembly. Subsequent irradiation with the other wavelength would cancel out attractive interactions owing to one type of azobenzene, while concomitantly enabling binding because of the other azobenzene. As a result, the NPs remain “locked” in the assembled state irrespective of the irradiation wavelength; hence they are termed “frustrated” nanoparticles.

These “frustrated” NPs were prepared by treating 2-functionalized NPs in toluene with 1 (see Section S6 for details). When the molar content of 1 on NPs exceeded a critical value, the particles irreversibly precipitated; however, by terminating the reaction shortly before precipitation took place we established that this critical fraction of 1 amounts to about 35 %. The “frustrated” NPs shown in Figure 3 contained approximately 31 % of 1 and they were

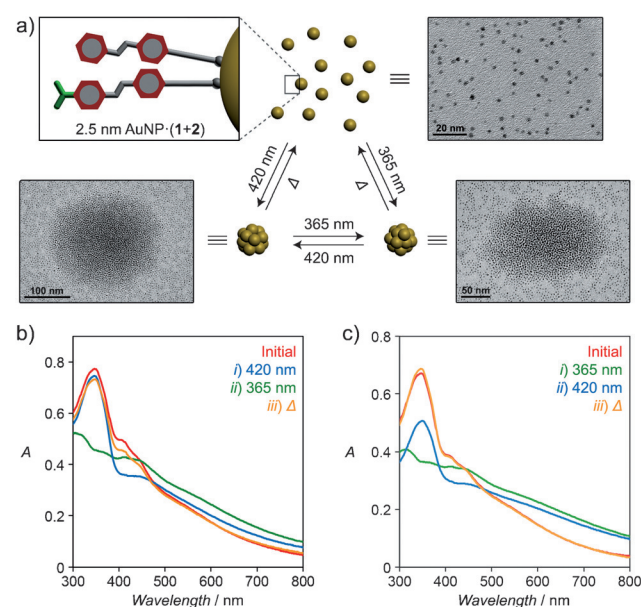


Figure 3. “Frustrated” nanoparticles. a) Schematic representation and TEM image of Au NPs co-functionalized with 1 and 2 (top). Bottom: TEM images of aggregates created upon exposure to blue and near-UV light. b,c) Changes in the UV/Vis spectra of “frustrated” NPs upon exposure to different wavelengths of light and then heating.

readily soluble in a 7:3 (v/v) toluene/hexane mixture. The red trace in Figure 3b is characterized by a pronounced band at about 340 nm, accompanied by a shoulder at around 420 nm, which can be attributed to **2** and **1**, respectively. Exposure to either blue light or UV (Figure 3b,c, respectively) triggers self-assembly, as manifested by increased absorption in the low-energy part of the spectrum, as well as by DLS (Figure S19). The aggregates remained unaffected by different wavelengths of light (Figure 3 and Figure S20); however, they disassembled when heated to 45°C—a stimulus that converted both azobenzenes into their *trans* forms.

In summary, we have described the first example of orthogonal self-assembly driven solely by light. Selected components of a mixture comprising nanoparticles functionalized with 1) a parent, and 2) a red-shifted azobenzene self-assembled selectively upon exposure to UV or blue light. Our system is somewhat similar to the photoresponsive foldamers of Hecht and Yu,^[22] and to the polymeric microactuators of van Oosten et al.,^[29] in that each incorporates two types of azobenzenes, which can be addressed selectively. An interesting aspect of our system is that although the *trans*⇌*cis* isomerization process could be largely incomplete, the overall change in NP polarity was large enough to induce assembly/disassembly in a near-quantitative fashion. Future work will focus on systems incorporating three or more types of components responding to various colors of light. We envision that manipulating such multicomponent mixtures with light will give rise to more complex materials, for example, core-shell-shell (onion-like) assemblies. At the same time, efforts are being made to prepare NPs that self-assemble reversibly in aqueous environments.

Keywords: azo compounds · nanoparticles · photochemistry · self-assembly · stimuli-responsive materials

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