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## Dual-responsive nanoparticles that aggregate under the simultaneous action of light and CO<sub>2</sub>†

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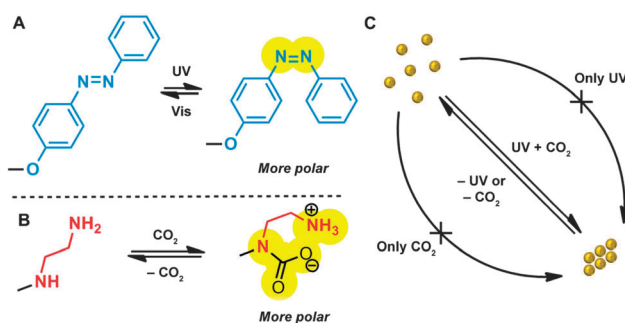
**Metallic nanoparticles co-functionalised with monolayers of UV- and CO<sub>2</sub>-sensitive ligands were prepared and shown to respond to these two types of stimuli reversibly and in an orthogonal fashion. The composition of the coating could be tailored to yield nanoparticles capable of aggregating exclusively when both UV and CO<sub>2</sub> were applied at the same time, analogously to the behaviour of an AND logic gate.**

Stimuli-responsive nanomaterials<sup>1</sup> that self-assemble in a reversible fashion are important because of their emerging applications in diverse fields, such as switchable catalysis,<sup>2,3</sup> water purification,<sup>4</sup> detection of analytes,<sup>5</sup> and time-sensitive information storage.<sup>6</sup> Accordingly, a variety of nanoparticles (NPs) have been engineered to aggregate in response to different external stimuli, such as a magnetic field,<sup>7</sup> pH,<sup>8,9</sup> or chemical fuel.<sup>10</sup> For example, dynamic aggregation of metallic NPs was accomplished by reversibly photo-switching the electronic states and geometries of surface-bound chromophores.<sup>11–14</sup> New applications could arise, however, for NPs that respond to two (or more) different external stimuli at once, such as the recently reported dual-responsive NPs that aggregate when either a magnetic field or light is applied.<sup>15–18</sup> Whereas such dual-responsiveness is, in principle, relatively easy to “encode” in the NPs, it is more challenging to design systems capable of aggregating only when two types of external stimuli are applied at the same time.<sup>19,20</sup> Here, we describe the first system exhibiting such behaviour with light and carbon dioxide as the two “inputs”.

Carbon dioxide is a biocompatible, naturally abundant gas that has several advantages over other chemical stimuli: (i) facile reactivity with various nucleophilic Lewis base functional groups such as amines, NHCs (N-heterocyclic carbenes), or guanidines, (ii) easy removal from the above complexes by mild heating, sonication, or purging with an inert gas, (iii) no by-product formation through the reversible complex formation, and (iv) potential applicability to reversible CO<sub>2</sub> capture and/or transformations.<sup>21–24</sup> In addition,

nanomaterials that aggregate reversibly in the presence of CO<sub>2</sub> are potentially important as possible anti-cancer therapeutics (taking advantage of the increased production of CO<sub>2</sub> in cancer cells<sup>25,26</sup>). Although many CO<sub>2</sub>-sensitive materials,<sup>27</sup> in particular, organic polymers,<sup>28,29</sup> have been reported, the application of amine-functionalised metallic NPs as CO<sub>2</sub>-responsive materials remains unknown. Here, we presumed that control of the NP surface polarity by using fine-tuned amounts of photo- and CO<sub>2</sub>-sensitive ligands could induce selective and reversible aggregation of NPs with two orthogonal stimuli (Fig. 1).

It is well established that mixtures of  $\omega$ -functionalised long-chain alkanethiols can form mixed self-assembled monolayers (*ms*SAMs) on the surfaces of metallic NPs<sup>30</sup> (here, we focused on gold NPs). We commenced our study with AuNPs functionalised with *ms*SAMs comprising an azobenzene-terminated thiol (*AzoSH*) and a “background” ligand, 1-dodecanethiol (C<sub>12</sub>SH) (Fig. 2a). As the UV-Vis spectra in Fig. 2c show, NPs decorated with critical (>50%) amounts of *AzoSH* aggregated in toluene upon exposure to long-wave ( $\lambda = 365$  nm) UV light,<sup>31</sup> whereas they exhibited no detectable response to CO<sub>2</sub> (confirmed by dynamic light scattering (DLS) measurements; see ESI,† Fig. S2 in Section S5). Furthermore, we observed that the *trans*-to-*cis* photoisomerisation of *AzoSH* did not affect the affinity of these NPs towards CO<sub>2</sub> (Fig. S2, ESI†). Therefore, we concluded that those AuNPs

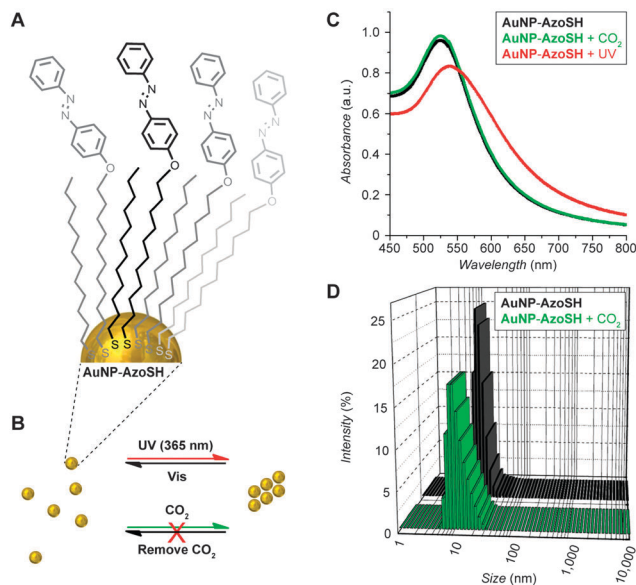


**Fig. 1** (A) Reversible isomerisation of a photoswitchable ligand. (B) Reversible CO<sub>2</sub> complexation by a diamine ligand. (C) A dual-stimuli-responsive AND logic gate.

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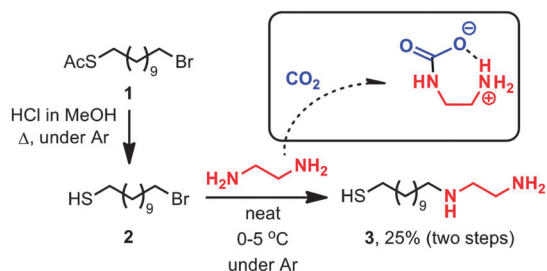




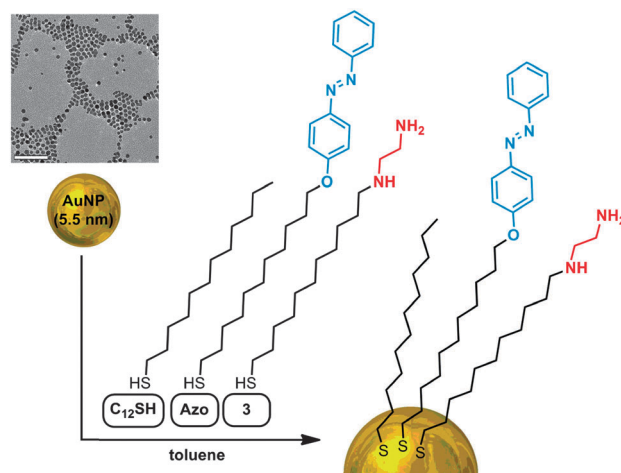
**Fig. 2** Light-sensitive ligand (**AzoSH**)-decorated gold nanoparticles (**AuNP-AzoSH**) (A) aggregate in response to light while showing no response to  $\text{CO}_2$  (B). UV-Vis absorption spectra (C) and DLS (D) of toluene solutions of **AuNP-AzoSH** before and after exposure to UV and bubbling  $\text{CO}_2$ .

bearing only the **AzoSH** and **C<sub>12</sub>SH** ligands are inert towards the  $\text{CO}_2$  stimulus under these conditions.

The lack of general knowledge on the construction of  $\text{CO}_2$ -sensitive metal-nanoparticle surfaces encouraged us to investigate the synthesis and application of thiol-terminated amine ligands (Fig. 1b).<sup>32</sup> Based on previous literature reports,<sup>33–36</sup> we presumed that ethylenediamine derivatives are capable of  $\text{CO}_2$  complexation under low-pressure conditions. To verify the effect of  $\text{CO}_2$  binding on the solubility in toluene, we synthesised and studied the behaviour of a model compound, *N*-decylethylenediamine. As detailed in the ESI† (Section S3), this diamine was readily soluble in toluene; however, rapid precipitation commenced upon bubbling  $\text{CO}_2$  through the solution (Fig. S1, ESI†). The process was reversible: the addition of an inert gas (e.g.  $\text{N}_2$ ) caused the precipitate to redissolve. Encouraged by these results, we then proceeded to synthesise AuNPs decorated with the diamine moieties. Although diamine-functionalised NPs were previously prepared by reacting 11-bromoundecane-1-thiol (**2**)-decorated NPs with 1,2-ethylenediamine, we began our investigation by preparing a well-defined thiol bearing the diamine moiety. As shown in Scheme 1, the



**Scheme 1** Synthesis of diamine ligand **3**.



**Fig. 3** Preparation of dual-responsive AuNPs functionalised with an *mSAM* comprising **C<sub>12</sub>SH**, **AzoSH** and diamine **3** (the scale bar in the TEM image is 50 nm).

synthesis of diamine **3** was straightforward, starting with a known material **1**.<sup>37–39</sup>

With the diamine-functionalised thiolate ligand **3** in hand, we prepared a family of dual stimuli-responsive AuNPs by varying the ratio of the two responsive ligands (**AzoSH** and diamine **3**) and the background ligand 1-dodecanethiol (**C<sub>12</sub>SH**), as shown in Fig. 3. Although **3** could potentially bind to AuNPs *via* both the mercapto and the amine functionalities, the latter scenario is unlikely given the *ca.* two-orders-of-magnitude higher affinity of Au to thiols as compared to amines.<sup>12</sup> In addition, binding to Au *via* the amine functionalities would cause NP crosslinking and irreversible aggregation, which we did not observe.<sup>40</sup>

Owing to the high polarity and low toluene solubility of the diamine ligand **3**, the ligand exchange reaction was conducted under dilute (*ca.* 10 times) conditions, compared with typical ligand exchange reaction conditions.<sup>41</sup> Moreover, **3** was always used after drying under vacuum at 40 °C to ensure that it was not complexed with  $\text{CO}_2$ . The functionalised AuNPs were precipitated with methanol (1:1 v/v) in the presence of didodecyltrimethylammonium bromide (0.5 mg per 0.716 mg of Au), washed extensively with methanol to remove any unbound molecules, dried under vacuum and kept in an inert atmosphere prior to use. A good indication of the presence of **3** in the functionalised AuNPs is their good solubility in polar solvents (e.g., ethanol, methanol and even water), which confirms a successful ligand-exchange reaction (for comparison, **AuNP-AzoSH** is soluble only in non-polar solvents such as toluene, chloroform, or dichloromethane). The functionalisation procedure did not affect the size or size distribution of the NPs, whose monodispersity was confirmed by transmission electron microscopy (Fig. 5a).

Fine-tuning of the ratio of the three ligands was critical for obtaining NPs exhibiting the behaviour shown in Fig. 1c (in this context, it is worth mentioning that the previously adapted<sup>32,34</sup> on-nanoparticle reaction between ethylenediamine and **2**-functionalised AuNPs would hardly be applicable). We found that when the molar percentage of **3** in the NPs exceeded 25%, the particles were insoluble in toluene due to their high







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- 40 This conclusion is supported by an experiment in which we incubated AuNPs co-functionalized with **3** and C<sub>12</sub>SH under oxygen for an extended period of time. Under oxidative conditions, the presence of free SH groups on the outer surfaces of NPs would likely cause crosslinking due to disulfide bridge formation. No such crosslinking was observed by DLS or UV-Vis spectroscopy.
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- 42 In addition to the increasing NP surface polarity in the nonpolar medium, attractive forces between the NPs could originate from direct interactions (e.g. due to dipole–dipole interactions of the *cis*-azobenzene dipoles).

