Noncovalent Interactions

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# Halogen Bonding: A Supramolecular Entry for Assembling Nanoparticles**

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Noncovalent interactions play an important role in the engineering of structurally well-defined assemblies. Important supramolecular forces, including hydrogen and halogen bonding, van der Waals interactions, and π–π stacking have been studied in much detail and used for the design of a vast number of synthons capable of forming task-specific structures having a high level of complexity.[1–4] Halogen bonding (XB) is an interesting noncovalent interaction in which halogens behave as acceptors of electron density.[5] Recent reports show the increasing significance of XB in liquid crystals,[6,7] solid-state reactivity,[8] nonporous solids,[9] inorganic chemistry,[10] materials science,[11,12] and biology,[13,14] to mention just a few. Remarkably, although XB is considered as a world parallel to hydrogen bonding[15–17] and a useful tool to construct supramolecular complexes and networks,[18] no studies to date have reported control of the formation and structure of large nanoparticle-based assemblies with this specific and directional interaction. XB interactions are kinetically labile but are considered to be relatively strong. Could, then, this intermolecular force be used to drive and engineer the formation of such assemblies?

Herein, we demonstrate the supramolecular assembly of gold nanoparticles (AuNPs) mediated by XB interactions. Our strategy is based on a versatile two-step process. In the first step, the AuNPs were functionalized with an XB donor ligand (**1**) while particles were kept isolated and their dimensions constant (Scheme 1). Large spherical assemblies were obtained by aging of this system (AuNP–**1**). Treating AuNP–**1** with a bifunctional XB acceptor linker (BPEB) resulted in the formation of chainlike structures or large, dense assemblies, depending on the concentration of BPEB. The dimensions of the spherical particles included in these AuNP–**1**/BPEB assemblies can be controlled by aging of the AuNP–**1** species prior to the reaction with BPEB. Thus, the primary time-dependent assembly of AuNP–**1** controls the inner structure, whereas the appearance of the overall structures can be engineered by varying the concentration of the linker (BPEB). Control experiments with an isostructural ligand (**2**) lacking XB donor capabilities and a monofunctional XB acceptor linker (PEB) highlight the importance of XB interactions in the observed assembly processes.

Compound **1** was selected to perform a double role: 1) the coordination of the *N*-oxide moiety to the surface of the AuNPs provides a relatively stable capping layer preventing the rapid, uncontrolled formation of large colloids, and 2) the $Ar_fI$ moieties allow the system to form larger structures by means of XB (Scheme 1). Fluorinated aromatic compounds akin to compound **1** containing aryl halides readily form cocrystals with pyridine-containing systems such as BPEB.[19–21] The order of such structures is often dominated by halogen-bonding interactions. Indeed, the crystal structure of compound **1** reveals that both of the $Ar_fI$ moieties are involved in XB.[22] Gold nanoparticles capped with tetraoctylammonium bromide (AuNP–TOAB) were used as starting material with an average diameter of (5.4 ± 0.4) nm and a typical surface plasmon band (SPB) at $\lambda_{max} \approx 522$ nm in toluene (Figure 1 a and Figures 1S and 2S in the Supporting Information).[23] Functionalized AuNPs (AuNP–**1**) were obtained at room temperature through exchange of TOAB with **1** in organic solvents. The formation of the new AuNP–**1** particles by coordination of the polar *N*-oxide moiety of **1** to the gold surface was verified by optical (UV/Vis) spectroscopy in the transmission mode, which reveals dampening and broadening of the SPB (Figure 1 b and Figure 3S in the Supporting Information). Such optical behavior has been reported for various ligand exchange processes, including with thiols, amines, and isothiocyanate.[23] The position of the SPB of metal nanoclusters is influenced by the surrounding media, particularly by the nature of the capping layer. The interactions between the ligands and NPs alter the electron density of the entire system, thus directly affecting the absorption of the surface-bound organic moiety as well as the SPB.[24–26] The formation of AuNP–**1** and the subsequent aggregation process was monitored by UV/Vis spectroscopy and transmission electron microscopy (TEM) during a 48 h time period. This UV/Vis data reveals that the dampening of the SPB develops gradually and is accompanied by a small red shift of approximately 7 nm and band broadening (Figure S3 in the Supporting Information). TEM measurements show that the formation of AuNP–**1** occurs within two hours, at which time the sample consists of mainly isolated particles having the same dimensions as the starting material (AuNP–TOAB; Figure 2 a and Figure 1S in the Supporting Information). The relative fast TOAB/**1** exchange process is followed

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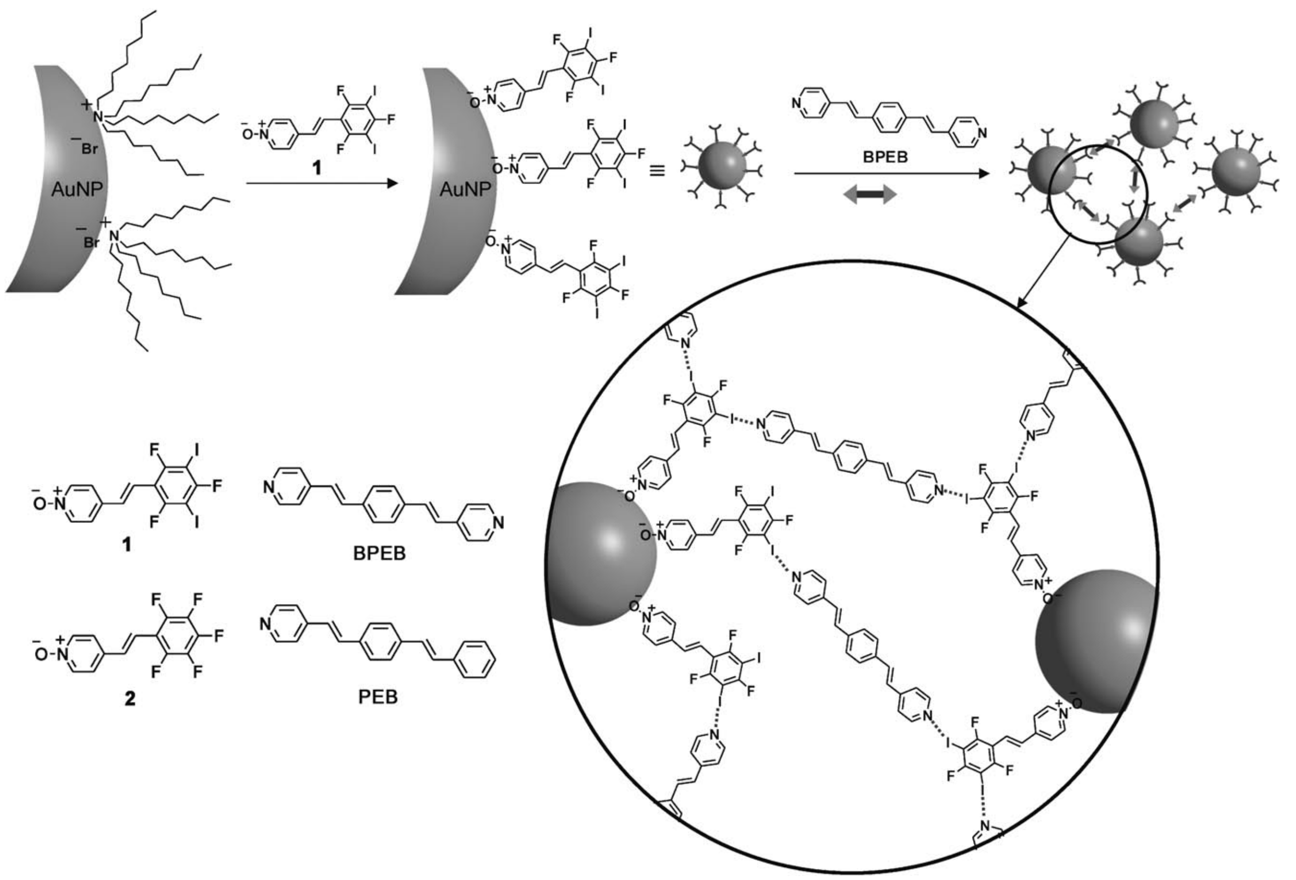

*Scheme 1.* The two-step process to direct the formation of halogen-bonding AuNP-based clusters. The AuNPs were functionalized with a halogen-bond donor (**1**) and subsequently exposed to a halogen-bond acceptor (BPEB) to generate large assemblies.

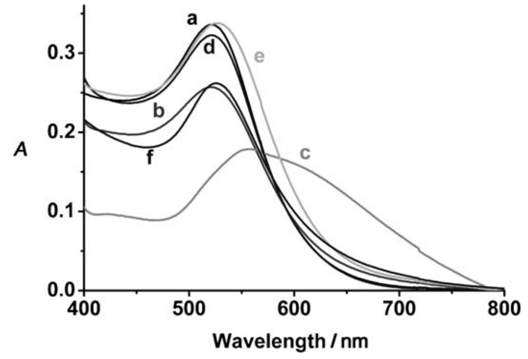

*Figure 1.* Representative UV/Vis spectra showing the surface plasmon absorption bands of the various AuNPs systems. a) AuNP–TOAB; b) AuNP–**1** (24 h aging) before and c) after adding BPEB; d) AuNP–**2** (24 h aging) before and e) after adding BPEB; f) AuNP–**1** (24 h aging) after adding PEB. The experimental details are provided in the Supporting Information.

by a slower diffusion-controlled coagulation of these primary particles into spherical aggregates with a diameter of 100 nm consisting of individual particles of AuNP–**1** (Figure 2 a,d). Some of these secondary particles are connected with chain-like structures. Spherical structures are generated because every nucleus gathers the neighboring primary particles within its individual field of attraction through intermolecular interactions.[27–29] Structures comprising bigger and more branched particles are formed after 24 h.

A perfluorinated system (AuNP–**2**) was prepared from AuNP–TOAB and compound **2** to evaluate to importance of the $Ar_fI$ units on the assembly process with the analogous AuNP–**1** (Figure 1 d and Figure 2 g). Interestingly, the individual particles of AuNP–**2** are stable in solution for prolonged periods of time and under conditions leading to the above-described aggregation of AuNP–**1**. The formation of individual isolated nanoparticles after exchange of the TOAB capping layer by compounds **1** or **2** and the lack of fusion indicates charge preservation and that the aggregation of AuNP–**1** is solely due to noncovalent interactions.

The supramolecular forces involved in this system may include π–π stacking and halogen bonding. These observations show that the supramolecular interactions of this setup, stability, and subsequent product formation can be controlled by structural variations of the capping layer at the molecular level (i.e. $Ar_fI$ vs. $Ar_fF$).

Interestingly, exposing AuNP–**1** at different stages of the aggregation to BPEB resulted in relatively fast formation of larger assemblies. For instance, addition of BPEB to a AuNP–**1** system aged for 24 h results within one hour in a decrease of the intensity of the SPB at $\lambda = 522$ nm and in the appearance of a broad, lower-energy band at $\lambda = 600$ nm (Figure 1 b,c). This process involves a gradual color change from red to

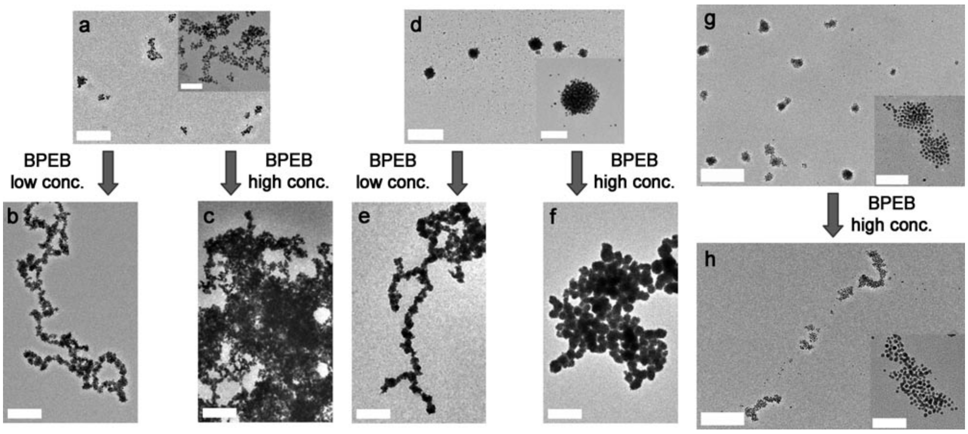

***Figure 2.*** TEM images of the various AuNPs systems. a) AuNP–**1** taken after 2 h aging and b, c) with low and high concentrations of BPEB, respectively. d) AuNP–**1** taken after 24 h aging and e, f) with low and high concentrations of BPEB, respectively. g, h) TEM images of AuNP–**2** (24 h aging) before and after adding BPEB. The scale bars correspond to 200 nm. The insets show enlarged areas with scale bars of 50 nm. There is an eightfold difference between the low and high concentrations of BPEB. The UV/Vis spectra shown in Figure 2 correspond to the higher concentrations. The experimental details are provided in the Supporting Information. A series of TEM images showing the results of these experiments at a different scale is provided in Figure 4S in the Supporting Information.

purple and then to blue as observed by the naked eye and manifested by the spectral evolution of the SPB. The significant red shift and broadening of the SPB indicates the formation of AuNP–**1**/BPEB assemblies. Prolonged reaction times result in a continual decrease in the 522 nm band along with a red shift and broadening in the lower-energy band. These optical changes occur concomitantly with the precipitation of large superstructures. The formation of AuNP–**1**/BPEB assemblies has also been studied by TEM as a function of BPEB concentration. The addition of relatively small amounts of BPEB to a AuNP–**1** system aged for two hours resulted in the formation of chainlike aggregates (Figure 2 a,b). An eight-fold increase of the BPEB concentration elevates the level of aggregation and produces very dense clusters (Figure 2 a,c). Similar structures were formed when BPEB was added to a AuNP–**1** system aged 24 h. At low BPEB concentrations, chainlike aggregation was observed that becomes denser with increasing amounts of BPEB (Figure 2 d–f). However, these latter assemblies formed from the aged AuNP–**1** system primarily consist of large spherical aggregates interconnected with BPEB. Thus, the dimensions of the supramolecular components (AuNP–**1**) of the AuNP–**1**/BPEB assemblies can be controlled by time, whereas the degree of colloidal association can be controlled by adjusting the concentration of BPEB in the medium. Apparently, linking of AuNP–**1** with BPEB does not drastically affect its structure (i.e. dimensions and shape; Figure 2 a–f and Figure 4S in the Supporting Information).

To verify the role of halogen-bonding interactions in formation of the AuNP–**1**/BPEB assemblies, we also treated AuNP–**2** (lacking the XB donor moieties) with BPEB as a control experiment. Importantly, no aggregation occurred for several weeks under conditions leading to the formation of the AuNP–**1**/BPEB assemblies. The color of the solution did not change, and UV/Vis spectroscopy did not reveal significant changes in the SPB (Figure 1 d,e). Moreover, TEM measurements showed well-separated AuNP–**2** particles with a uniform size distribution (Figure 2 g,h). Another control experiment was performed by treating PEB with AuNP–**1** to exclude possible nonspecific interactions in the formation of AuNP–**1**/BPEB assemblies. Within several hours, only a small increase in the optical absorption of AuNP–**1** occurs without any noticeable band broadening or color changes. This result demonstrates that the system undergoes little or no aggregation (Figure 1 b,f). TEM measurements confirm the presence of a lower level of aggregation than in the AuNP–**1**/BPEB assembly (formed with the same concentration of BPEB), which may result from π–π interactions between PEB molecules (Figure 5S in the Supporting Information).

In summary, we have demonstrated that XB interactions provide a new entry for constructing supramolecular assemblies of metal NPs. These assemblies were prepared by functionalization of AuNPs with a XB donor ligand (**1**) and their subsequent assembly using a bifunctional XB acceptor linker (BPEB). The level and morphology of the final aggregates (AuNP–**1**/BPEB) can be controlled by varying the time during the first assembly step to afford larger particles of AuNP–**1** and by varying the concentration of the linker (BPEB) during the second assembly step. Noncovalent assembly of nanoparticles is of much current interest.[30–34] Hydrogen-bond-mediated assembly,[35,36] polarity-driven assembly,[37] or electrostatic coupling using bifunctional spacer molecules have been demonstrated.[38] We believe that this versatile two-step XB assembly process opens up an alternative and powerful strategy for creating highly structured hybrid materials in solution and on surfaces.[24,39,40]

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**Keywords:** halogen bonding · nanoparticles · noncovalent interactions · self-assembly · supramolecular chemistry

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