

Nanoparticle–Gel Hybrid Material Designed with Bile Acid Analogues

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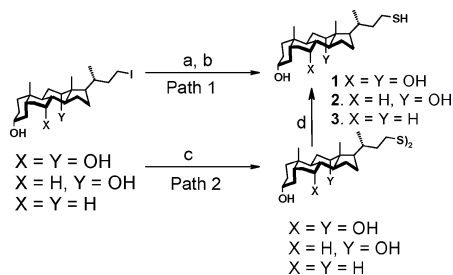
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There is considerable interest in research directed toward the tailoring of metal nanoparticles (NPs) due to their futuristic applications. Surface functionalized metal NPs have been used for a variety of applications, such as in nanoscale electronics,¹ biomedical sciences,² sensor technology, and chemical catalysis.³ Metal NPs are known for their unusual optical, electrical, magnetic and catalytic properties compared to those of the bulk metal.⁴ Among the various metals, gold NPs have been studied in greater detail owing to their stability and ease of synthesis. Brust et al. set the stage for a rapid exploration of gold NPs using organic thiols.⁵ Subsequently, several other alkyl thiols⁶ and thiol derivatives of synthetic⁷ and biopolymers, dendrimers/dendrons,⁸ porphyrin,⁹ water soluble thiol derivatives,¹⁰ and so forth have been described as capping agents to stabilize gold NPs. Phosphine,¹¹ pyridine,¹² and selenide¹³ stabilized NPs have also been explored.

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Scheme 1. Synthesis of Steroidal Thiols^a



^a (a) $(\text{NH}_2)_2\text{S}$, dry DMF. (b) NaOH, DMF/H₂O. (c) $(\text{BnNEt}_3)_2\text{MoS}_4$ /dry DMF. (d) Zn/5% HCl, MeOH–THF.

Ordered assemblies of nanometer-sized particles belong to an interesting class of nanomaterials that provide exceptional potential to achieve one-, two-, and three-dimensional organization for a wide variety of applications ranging from photonic devices to memory devices, arrays of magnetic NPs,¹⁴ and single-electron microelectronic devices, among others.¹⁵ An increasing number of efforts have been documented in the current literature to design various types of organic–inorganic hybrid materials.¹⁶ In this communication, we describe a novel design of NP–hydrogel hybrid material using facially amphiphilic steroid analogs.

Our interest in bile acid based gelators¹⁷ led us to explore the synthesis and properties of bile analogs with the side chain carboxylic acid replaced by a thiol to stabilize metal NPs. We reasoned that the specific self-aggregation modes of facially amphiphilic steroids would enable a metal NP capped by such a thiol to “lock” onto a gel fiber derived from a structurally related molecule.

The syntheses of 24-*nor*-23-mercapto-3 α ,7 α ,12 α -trihydroxycholeane (**1**), 3 α ,12 α -dihydroxycholeane (**2**), and 3 α -hydroxycholeane (**3**) were accomplished in a straightforward manner as shown in Scheme 1 (see Supporting Information for details). Attempts to synthesize gold NPs using facially

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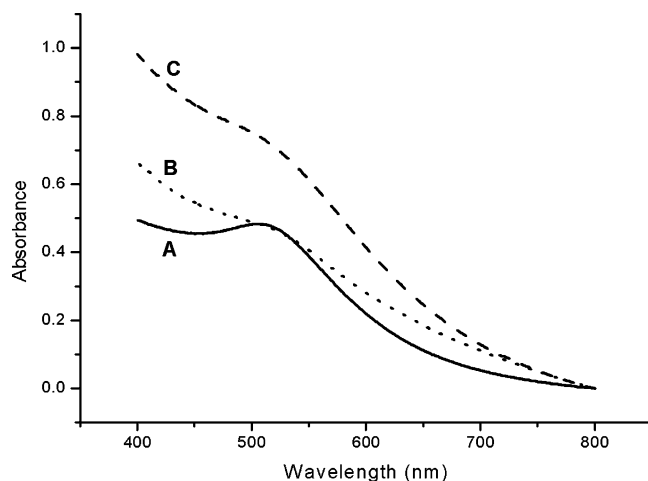


Figure 1. Absorption spectra of gold NPs capped with bile acid-derived thiols **1** (A), **2** (B), and **3** (C) in 1:1 EtOH/CHCl₃.

amphiphilic thiols **1–3**, via the biphasic method,⁵ resulted in dark brown dispersions that did not show the characteristic gold surface plasmon resonance band due to the limited solubility of steroidal thiols **1–3** in toluene. Therefore, the gold NPs were prepared by the NaBH₄ reduction of the yellow homogeneous solution of HAuCl₄ in the presence of steroidal thiols in methanol, keeping a 1:1 molar ratio between the gold salt and the steroidal thiol. The identity and homogeneity of the caps on the NPs were confirmed by ¹H NMR of the dispersions in DMSO-*d*₆, IR, and elemental analysis. As calculated from the elemental analysis, the 2 nm steroid-capped Au NPs are stabilized by approximately 20–30 steroidal units depending on the cap.¹⁸

These steroid-capped AuNPs are stable through several cycles of drying and re-dissolution. They could be easily dispersed in protic and polar aprotic organic solvents but were nondispersible in water and in chloroform, ethyl acetate, hexane, and toluene alone. Stable dispersions in these solvents may, however, be obtained in the presence of small quantities (2–5%) of ethanol or methanol.

These NPs showed a surface plasmon resonance band at 520 nm, characteristic of gold colloid (Figure 1).^{19–21} The shapes of the observed plasmon resonance bands were dependent on the structure of the steroidal capping agent.

The size and shape of the steroid-capped NPs were studied by transmission electron microscopy (TEM). The TEM images (Figure 2A–C) revealed spherical particles with the size depending on the nature of the capping unit. The average sizes of the **1**-, **2**- and **3**-stabilized gold NPs were found to be 3.5, 2.5, and 1.5 nm, respectively. This may explain the observed shapes of the plasmon absorption bands.¹⁹ The bulkiness of the capping agent has been given some importance in determining the size of the metal particles. Thus, we suggest that the bulkiness of the cap and the capped

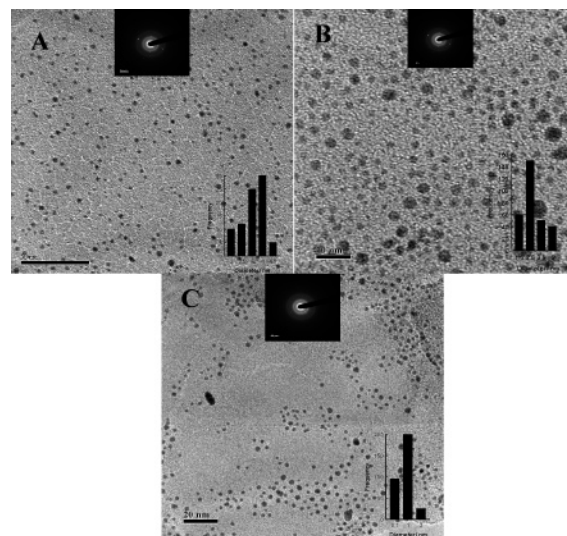
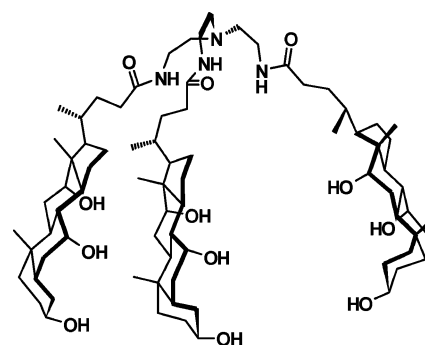


Figure 2. TEM images of gold NPs capped with bile acid-derived thiols **1** (A), **2** (B), and **3** (C), respectively (scale bars: for A, 50 nm; B, 10 nm; and C, 20 nm).

Chart 1. Structure of Gelator Molecule 4



NP size follow the same sequential decrease as we move from thiol **3** to thiol **1**.²²

To explore the possible immobilization of the steroid-capped NPs on a steroid gel, bile acid-derived hydrogelator **4** was selected.²³ This super hydrogelator forms a fibrillar network (*d ca.* 50 nm) upon aggregation in the AcOH/water medium (Chart 1).^{17c}

Because gels derived from **4** have been extensively studied in AcOH/H₂O, we selected the same medium to study the stability of the steroid-capped NPs. The NP dispersions (>0.05 mg/mL) in 20% AcOH/H₂O were unstable beyond 5 h and separated out of the medium. But to our delight, the NP–gel (GN) composite was found to be stable for several months even at higher NP loading (>2 mg/mL). This hybrid material was prepared by dissolving the NPs and the gelator (above the critical gelation concentration) in AcOH first and then diluting with 4 volumes of water. This dispersion formed a gel in 4–5 h.

The incorporation of the steroid-capped AuNPs into the gel showed no change in the melting behavior of the gel (NP loading up to 0.1%, w/v). On the other hand, melting

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(23) Immobilization of **1**-capped NPs in a polar medium containing a non-steroidal gelator was difficult to achieve. The **3**-capped NPs (above 0.02%, w/v) were non-dispersible in the gel of **4**. Immobilization of dodecane thiol stabilized gold NPs in gel **4** was not achieved because these NPs were completely insoluble in the AcOH/H₂O medium.

the gel at 50 °C caused the NPs to separate from the medium (0.05 mg of **1**-capped NPs in 1 mL of the 0.2% gel of **4**). In addition, NP dispersion in a medium containing gelator **4** below the critical gel concentration was unstable and caused the NPs to separate from the AcOH/H₂O medium within 24 h of preparation (0.05 mg of **1**-capped NPs in 1 mL of 0.1% solution of **4**). A similar observation was experienced while dispersing the steroid-capped NPs into 20% AcOH/H₂O containing a steroidal *non-gelator* (methyl deoxycholate). This clearly demonstrated that the steroid-capped AuNPs are significantly stabilized by the supramolecular structures present in the gel. The stability of the NPs observed in gel is likely to result from the association of the steroid units present both on the NP and on the gelator. Gelator **4** contains an amine functionality which is known to stabilize metal particles. Hence, the interaction of the amine functionality on the gelator may help stabilize the metal particles in the gel better.

The observed plasmon absorption band of steroid-capped AuNPs did not show any significant change in their λ_{max} values upon dispersing in the gel, suggesting that there is no drastic environmental change around the metal core of the embedded AuNPs in the gel.

TEM and atomic force microscopy (AFM) were used to analyze the morphology of the NP–gel hybrid material. For TEM imaging, samples were prepared by smearing the copper grid over the NP–gel composite taken on the glass plate, in such way that a fine layer appeared over the grid. TEM imaging of the NP–gel (GN) composite showed that steroid-capped NPs arranged well on the gel fibers of **4** (Figure 3). Even though TEM showed a regular arrangement of the capped NPs on the outer wall of the gel fibers, the possible incorporation of the capped NPs *inside* the gel fiber cannot be ruled out. Because gold NPs used here were much smaller than the diameter of the fibers of **4**, they could be physically arrested between the aggregates during fiber formation. A few aggregated spherical NP clusters could be seen (either on or outside the gel fibers) at times depending on the preparation. Regardless of the specific arrangements of the particles, this work clearly shows the immobilization of the NPs on the gel fibers.

The hybrid material was also analyzed by AFM. No additional details could be obtained from the AFM studies done so far (for preliminary results, see Supporting Information).

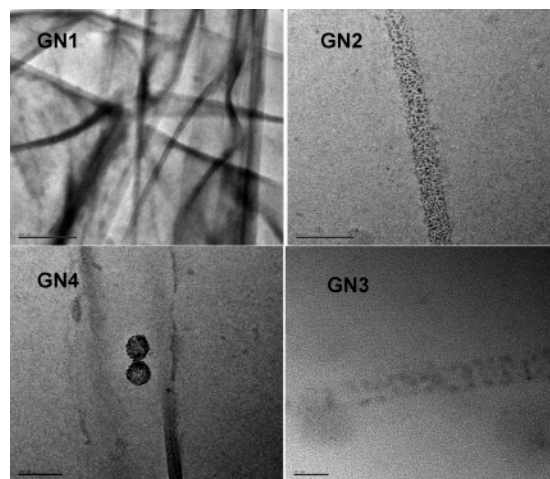


Figure 3. TEM images of the NP–gel composites (GN) scanned separately at various levels of magnification (0.05 mg of **1**–Au NP in 1 mL of the 0.2% gel of **4**). Scale bars: GN1, 200 nm; GN2, 100 nm; GN3, 20 nm; and GN4, 100 nm.

In summary, we have developed the synthesis of a series of facially amphiphilic thiols as capping agents to stabilize gold NPs. The free hydroxyl groups on the steroid moiety may be exploited to attach active groups for performing specific functions like catalysis, energy transfer, sensing, and so forth.

A steroid-derived gel was shown as an excellent medium for stabilizing the structurally “analogous” NPs, which emerged as a novel method for obtaining the composite materials. This design of the NP–gel composite opens up many opportunities for future studies and possible applications.

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Supporting Information Available: Synthetic procedures and experimental details (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

Note Added in Proof. For a recent work on the study of viscoelastic properties of a nanoparticle doped physical gel, see: Bhattacharya, S.; Srivastava, A.; Pal, A. *Angew. Chem., Int. Ed.* **2006**, *45*, 2934.

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