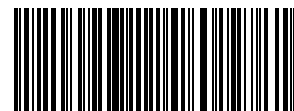**COMMUNICATION**
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Surface modification of gold nanorods through a place exchange reaction inside an ionic exchange resin†

Qiu Dai, Janelle Coutts, Jianhua Zou and Qun Huo*

A place exchange reaction between 11-mercaptoundecanoic acids (MUA) and cetyltrimethylammonium bromide (CTAB)-protected gold nanorods (GNRs) was conducted inside an ionic exchange resin; this modification resulted in functional gold nanorods soluble in both polar and nonpolar organic solvents.

Gold nanorods (GNRs) are an interesting class of nanomaterials with many promising application potentials such as surface enhanced Raman scattering,[1] bioimaging,[2] biosensor,[3] and cancer therapy.[4] GNRs show two distinct surface plasmon absorption bands. The transverse plasmon band around 520 nm is due to the excitation across the short dimension of the nanorods, and the longitudinal plasmon band is a result of excitation along the long axis of the nanorods. The surface plasmon resonance band of nanorods can be tuned from the visible to near infrared (NIR) wavelength range by changing the aspect ratio of nanorods.[5] The synthesis of GNRs with controllable size and aspect ratio have been extensively carried out both chemically [6] and electrochemically.[7] One of the most commonly used method is a templated growth of GNRs inside a rod-shaped liposome formed from cetyltrimethylammonium bromide (CTAB) surfactant. The as-synthesized nanorods are protected by a positively charged CTAB bilayer on the surface, which makes the nanorods soluble in aqueous solution.[8]

Unfortunately, the bilayer structure of GNRs has been a major problem that limits the further applications of GNRs. Similar to other biomembranes, the self-assembled bilayer structure is not robust and can be easily disrupted at high ionic strength or other conditions. This problem is detrimental to the biological application development of GNRs, which almost exclusively requires nanoparticles be used in high salt content buffer solutions. The surface chemistry modification of nanorods has remained as a significant challenge. So far only a very limited number of examples have been reported on the surface modification of GNRs, such as silica shell coating.[9]

Thiol ligand place exchange reaction in solution developed by Murray and co-workers has been used extensively for surface modification and functionalization of gold nanoparticles.[10] There have been several reports on surface modification of GNRs with thiol derivatives.[11] However such modification is often problematic for GNRs. The addition of a small amount of thiol ligands to a GNR solution will first replace the CTAB ligands located at the two poles of GNRs due to a relative high reactivity of surface gold atoms around these polar regions.[12] However, further increase of thiol ligands in solution failed to lead to successful and complete exchange of CTAB ligands with thiol ligands. Instead, this often results in an irreversible agglomeration of GNRs.[13]

Herein for the first time we report a solid-phase place exchange reaction for surface modification of GNRs with bifunctional thiol ligands inside an ionic exchange resin. An anionic exchange resin, Amberlite IRA-67, was used in the present study. This resin contains positively charged ammonium groups. As illustrated in Fig. 1, CTAB-protected nanorods were first loaded into the polymer resin beads suspended in an aqueous solution. Once trapped inside the polymer resin, a bifunctional thiol ligand such as 11-mercaptoundecanoic acid (MUA) was added to the polymer beads suspension. A place exchange reaction then took place between nanorods and MUA ligands inside the polymer beads. The successfully modified nanorods were then eluted from the polymer beads to the solution and collected.

During the solid-phase place exchange reaction, one can observe clearly a color change of the ionic exchange resin beads from white to black as shown in Fig. 2(A), which indicates a successful loading of GNRs into the pores of ionic exchange polymer beads. Although both GNRs and the anionic exchange resin are positively charged on the surface, we believe the capillary effect is the driving force for nanorods to enter into the pores of resin beads. After washing the beads with a copious
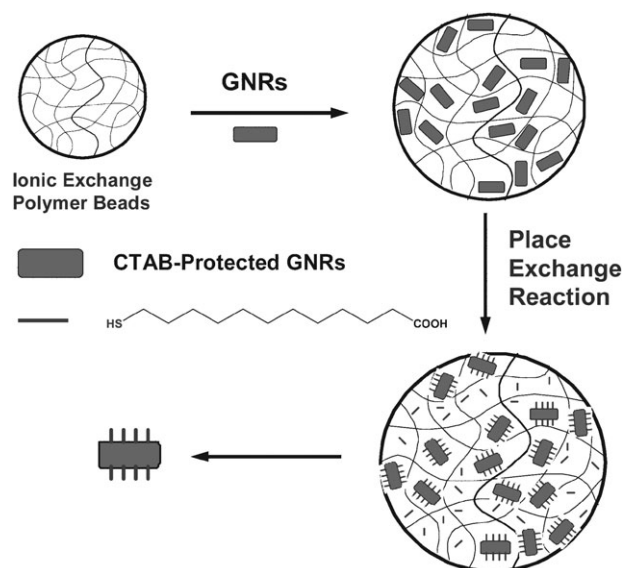
NanoScience Technology Center, Department of Chemistry, Department of Mechanical, Materials, and Aerospace Engineering, University of Central Florida, Orlando, FL 32826, USA. E-mail: qhuo@mail.ucf.edu; Fax: 407-882-2819; Tel: 407-882-2845
† Electronic supplementary information (ESI) available: Experimental section. Fig. S1: XPS spectrum of CTAB-GNRs. See DOI: 10.1039/b804797a

Fig. 1 Schematic illustration of surface modification of GNRs using thiol place exchange reaction inside ionic exchange polymer beads
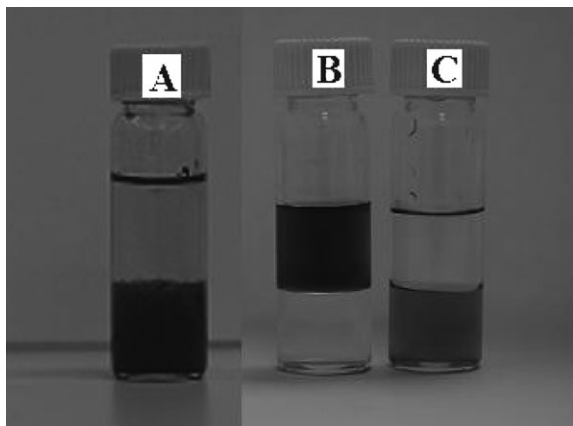
Fig. 2 (A) Photographs of GNRs absorbed into the ionic exchange polymer beads. (B), (C): Photographs of GNRs dissolved in water (B) and in chloroform after thiol place exchange reaction (C). For both (B) and (C), the top layer solvent is water and the bottom layer solvent is chloroform.

amount of water to remove the unloaded GNRs, the beads were washed with methanol and vacuum dried. The dried polymer beads were then suspend in a chloroform solution of MUA ligands. During the place exchange reaction, the nanorods slowly diffused out of the beads to the chloroform solution. The modified nanorods product can be dried from and re-dispersed in chloroform. Fig. 2(B) and (C) show CTAB-GNRs dissolved in water and MUA-GNR dissolved in chloroform.

The modified gold nanorods were then characterized by UV-Vis absorption spectroscopy and transmission electron microscopy. Fig. 3(A) and (B) show the UV-Vis absorption spectra of CTAB-GNRs and MUA-GNR, respectively. After solid-phase place exchange reaction, the traverse surface plasmon band of the nanorods remains at 525 nm, and the longitudinal surface plasmon band red shifted from 740 to 770 nm. It has been reported that the longitudinal surface plasmon band is more sensitive to the dielectric constant change of the environment than the traverse surface plasmon band.[14] We believe that the red shift of the longitudinal surface plasmon band is a result of solvent change of GNRs from water to chloroform.
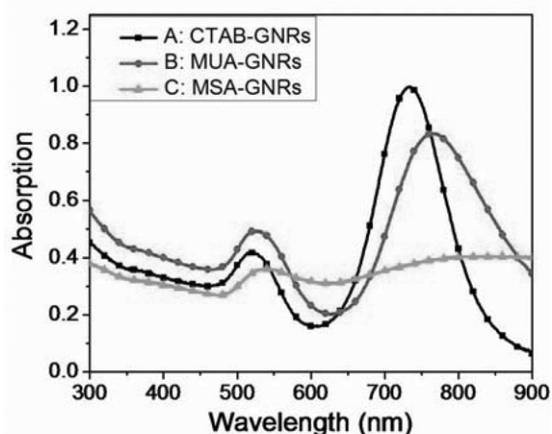

Fig. 3 UV-Vis absorption spectra of GNRs before and after thiol place exchange reaction.

As a comparison study, we also conducted a place exchange reaction on CTAB-GNRs with a mercaptosuccinic acid (MSA) ligand in aqueous solution. During the reaction, it was observed clearly that the color of the solution changed from a dark burgundy to blue with increased amount of MSA ligands. Fig. 3(C) is the UV-Vis absorption spectrum of nanorod product MSA-GNR obtained from the solution place exchange reaction. The transverse surface plasmon band of the nanorods red shifted to 530 nm, and the longitudinal surface plasmon band disappeared into a very broad band, a clear indication of nanorod aggregation. A similar spectral change was observed when an alkanedithiol was added to the GNR aqueous solution.[15]

TEM analysis further confirmed what was observed from UV-Vis spectroscopic study (Fig. 4). A severe aggregation occurred among the MSA-GNRs obtained from solution-phase place exchange reaction. A certain level of nanorods fusion into larger irregular shaped nanoparticles was also observed (Fig. 4(A)). In contrast, the MUA-GNRs as obtained from the solid-phase place exchange reaction remained as well-dispersed nanorods with the same aspect ratio as the original CTAB-GNRs (Fig. 4(B)).

The composition of the MUA-modified nanorods was analyzed by NMR spectroscopy and X-ray photoelectron spectroscopy (XPS). The ^{1}H NMR spectrum of MUA-protected GNRs in d-chloroform is shown in Fig. 5. the four peak assignments are 1.2–1.4 ppm (methylene protons at C_3–C_9), 1.5–1.7 ppm (methylene protons at C_2 and C_{10}), 2.3 ppm (methylene proton at C_{11}), 2.5 ppm (methylene proton at C_1). The XPS spectrum of MUA-GNRs in Fig. 6 revealed the presence of sulfur from MUA ligands and the absence of nitrogen and bromine from CTAB ligands, which further confirmed the successful replacement of CTAB with MUA. For CTAB-GNRs, XPS analysis detected clearly the presence of bromine element, but not sulfur (see ESI†).

The mechanism for the successful place exchange reaction between functional thiol ligands and CTAB-protected nano-rods in an ionic exchange resin is rather intriguing. In a free solution, we believed that the failed place exchange reaction between thiol ligands and CTAB-GNRs is due to the disruption of the charged surfactant bilayer structure during partial place exchange reaction. It has been reported by Hostetler et al. that the place exchange reaction between thiol ligands and gold nanoparticles takes at least 30 min to hours to complete.[16] After
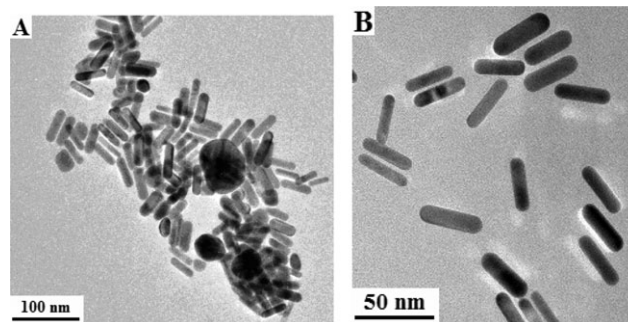

Fig. 4 (A) TEM image of the GNRs after solution thiol place exchange reaction with mercaptosuccinic acid. (B) TEM image of the GNRs after thiol place exchange reaction with MUA inside ionic exchange polymer beads.
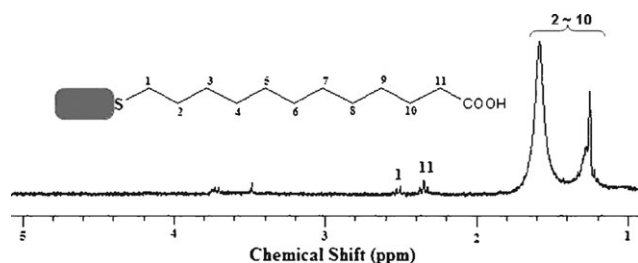
Fig. 5 ^{1}H NMR spectrum of MUA-protected GNRs. Spectrum was obtained from a Varian 300 MHz instrument.
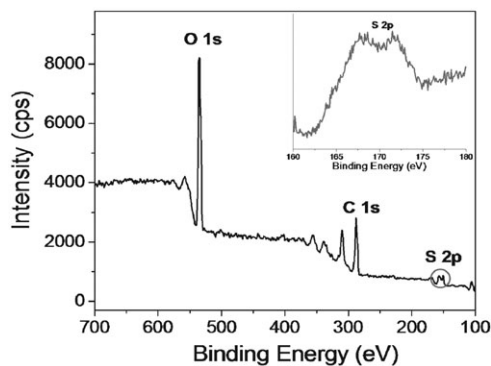

Fig. 6 XPS Spectrum of MUA-protected GNRs.

the nanorods are partially modified by the thiol ligands, the bilayer structure becomes unstable, and the thiol ligands have yet to form a stable protecting layer on the nanorod surface. Before this stable monolayer can be formed, the free movement of nanorods in solution results in an irreversible aggregation of the nanorods. In an ionic exchange resin, due to the same charge of the nanorods and the resin (both are positively charged), the nanorods are confined into the pores of the resin to form a meta-stable self-assembled structure, similar to what has been observed from charged colloidal arrays (CCAs).[17] The screening effect of the counter ions between the positively charged nanorods as well as the anionic exchange resin prevents the nanorods aggregation and irreversible adsorption of nanorods to the exchange resin. When a bifunctional thiol ligand such as MUA is loaded to the resin, the MUA ligands can gradually replace the CTAB ligands on the nanorods and form a stable monolayer on the nanorod surface.

As an additional support to this proposed mechanism, we conducted the following two experiments. In the first experiment, the ionic exchange polymer beads without GNRs being loaded were added and incubated in the MUA chloroform solution. After washing the polymer beads with chloroform and drying with N_2, the presence of MUA ligand inside the polymer beads was confirmed by the Ellman's agent (5,5′-dithio-bisnitrobenzoic acid) test.[18] In the second control experiment, polymer beads loaded with CTAB-GNRs were added to a pure chloroform solution. It is clear that no GNRs diffused out of the polymer beads into the chloroform solution without MUA ligands in the solution. These two experiments complementarily confirmed that a place exchange reaction between the MUA ligands and CTAB-GNRs inside the polymer beads has led to successful surface modification of GNRs.

In summary, we have developed a facile method for effective replacement of the CTAB surfactants on GNR surface with a bifunctional thiol ligand inside ionic exchange polymer beads. The resulting GNRs show a good solubility and stability against aggregation in organic solvents such as chloroform and methanol, or mixed solvents. The carboxylic acid groups on the GNRs surface provide anchor points for further modification and conjugation with other chemicals and bio-molecules by covalent and non-covalent chemistry.

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