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An analytical method for detecting toxic metal cations using cyclotriveratrylene derivative capped gold nanoparticles

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ABSTRACT

Cyclotriveratrylene-oxime (CTV-oxime) derivatives that terminate with a dithiolate linker were synthesized enabling the supramolecular scaffold to adhere to gold nanoparticles (AuNPs) with the bowl-shaped cavity of the CTV scaffold exposed for utilization in host–guest chemistry. Exposure of these CTV functionalized AuNPs to varying concentrations of di- and trivalent metal cations resulted in the formation of large CTV-AuNP polymeric clusters and an accompanying a shift in the plasmon resonance. These interactions between the CTV-AuNPs and the metal cations in solution provides proof-of-concept that supramolecular functionalized AuNPs can be used as a simple and straightforward, on-site detection system for toxic metal cations in solution. The order of binding affinity of the metals studied based on observed K_d values is $Cu^{2+} > Zn^{2+} > Pb^{2+} > Hg^{2+} > Eu^{3+} > Cd^{2+}$.

Introduction

Due to the environmental and biological impact of metal ion contamination, the development of sensitive and selective detection systems for colorless metal ions is of great importance. The toxicity of heavy metals is well known, yet even essential metals are toxic at higher concentrations including zinc[1] and also copper, which is implicated in neurodegenerative diseases.[2] A variety of analytical devices have been developed for the detection of metal ions, including systems based on direct chemosensors,[3] atomic fluorescence spectrometry (AFS),[4] inductively coupled plasma mass spectrometry (ICP-MS),[5] and atomic absorption spectroscopy (AAS).[6] Although these techniques offer sensitive and selective analytical approaches, they are expensive, require sophisticated equipment, and lack the portability for on-site detection.

Unlike traditional organic fluorescent dyes, gold nanoparticles (AuNPs) have much stronger molar absorptivities that are 3–5 orders of magnitude higher than organic fluorescent dyes[7,8] and are of great interest in chemical and biological sensing[9] as well as for in vitro diagnostics.[10] The optical properties of AuNPs are due to their unique surface plasmon resonance (SPR) where electrons on the surface of a AuNP are in collective oscillation and become in resonance with incident electro-magnetic radiation.[11,12] Modified AuNPs make excellent colorimetric analytical platforms because AuNP aggregation due to analyte detection results in a distinct color change from red to blue.[13–16] AuNPs with various surface-bound ligands have been previously employed to detect K^+,[17] and Ca^{2+},[18] divalent heavy metals (Hg^{2+}, Pb^{2+}, Cd^{2+}),[19,14] Cr^{3+},[20] and trivalent lanthanide ions.[21] Herein we describe cyclotriveratrylene (CTV)-functionalized AuNPs that provide the basis for the design of an analytical tool that can be used for the detection of di- and trivalent metal ions in solution for the detection of metal ions of environmental concern.

Cyclotriveratrylene (CTV, Fig. 1) is a bowl-shaped supramolecular scaffold[22,23] that we have previously employed through apex derivatization to provide a supramolecular scaffold with the concave bowl receptor pointed *away* from the surface, enabling CTV to function as a gold surface-bound host molecule.[24] The crown and saddle conformers are comparable in energy and interconvert in solution.[25]

CTV derivatives have been shown to bind both divalent and trivalent metal ions with their peripheral ortho di-methoxy ether groups creating coordination polymers as well as clathrate crystalline materials.[26,27] Hardie and co-workers obtained crystal structures of CTV bound to alkali-earth metal cations (Na^+, K^+, Rb^+, and Cs^+)[28] forming large crystalline coordinate polymers through binding the methoxy group of CTV, and revealed that lanthanide metal ions can also bind to CTV-methoxy groups.[29] X-ray crystallographic data on CTV-lanthanide complexes indicated that the water molecules of the capped triangular dodecahedral $[Eu(H_2O)_9]^{3+}$ cations are at distances favorable for hydrogen

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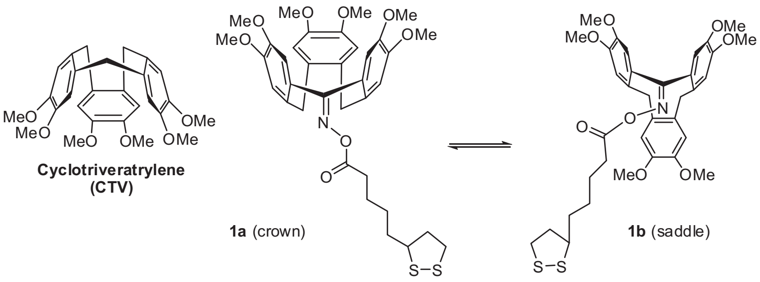


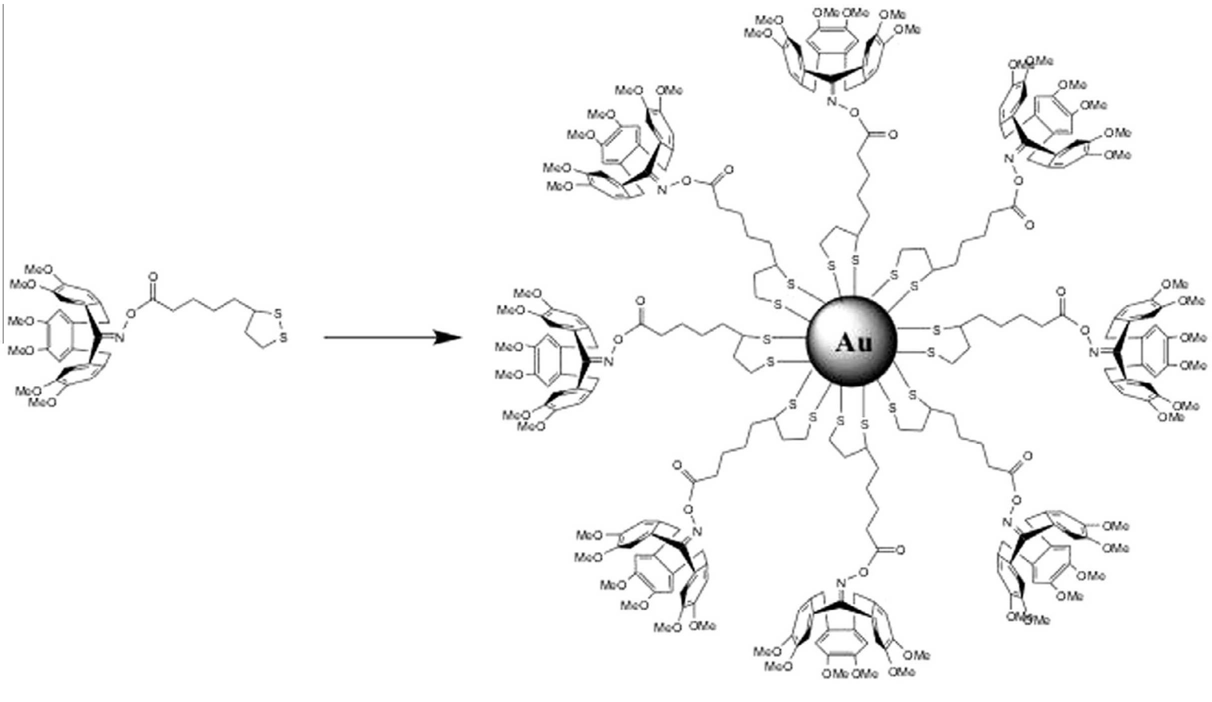
Figure 1. CTV, and apex-modified CTV-oxime lipoate ester.

bond formation with the CTV perimeter methoxy lone-pairs. Combining these technologies, we designed a colorimetric analytical device for the detection of di- and trivalent metal ions employing CTV bound to gold nanoparticles (AuNP). An apex-modified CTV supramolecular scaffold head group with a dithiolane tail installed as the lipoic acid ester of CTV oxime for binding to a gold surface with the CTV bowl shaped cavity directed *away* from the surface was synthesized and bound to AuNPs.

Results and discussion

With the successful design and synthesis of an apex modified CTV supramolecular scaffold head group with a dithiolane tail, 15 nm AuNPs were functionalized by the addition of a 2.7 mM solution of CTV-dithiolane ligand **1a**/**b** in a 1% polysorbate 20 acetonitrile (ACN) solution (Scheme 1).[13] These samples were then vortexed for 20 s to ensure homogeneity throughout the solution. The AuNP/CTV-dithiolane solution was allowed to sit at room temperature for ~24 h to allow full functionalization of the AuNPs. In order to remove the excess CTV-dithiolane, the AuNPs were centrifuged at 14,000 rpm for ~30 min. The dense CTV-dithiolane functionalized AuNPs precipitated and the excess CTV-dithiolane remained in solution. The supernatant was carefully removed and the functionalized AuNPs were resuspended in a 1% polysorbate 20/ACN solution. This process was repeated three times to ensure complete removal of any excess CTV-dithiolane from the AuNP solution. Transmission electron microscopy (TEM) was used to confirm that the AuNPs were intact after functionalization with the CTV-dithiolate ligand (Fig. 2). TEM images reveal that the CTV-functionalized AuNPs retain their roughly spherical shape. Due to the differences in the refractive indices between the water and acetonitrile solvents, the UV–Vis spectra were red shifted upon modification of AuNPs with CTV in ACN. The SPR maximum absorbance of the AuNP solution had shifted from 522 nm in water to the expected 550 nm in ACN solution (Fig. 3).[30] The decrease in absorbance is due to the loss of nanoparticles from the washing and extracting of solvent to remove excess CTV after modification.

With the successful functionalization of stable CTV-dithiolane 15 nm AuNPs, a series of colorless di- and trivalent metal ions (Cu^{2+}, Pb^{2+}, Hg^{2+}, Zn^{2+}, Cd^{2+}, and Eu^{3+}) were titrated into a solution of CTV-ditholane modified AuNPs in polysorbate 20/ACN. Various concentrations of each metal ion (0 μM, 10 μM, 20 μM, 50 μM, 60 μM, 90 μM, and 100 μM) in nanopure water were pipetted into the CTV-dithiolane AuNP solution. The solution was incubated at room temperature (~21 °C) in order to allow for complexation between CTV-methoxy moieties and the divalent and trivalent metal cations, which resulted in the formation of a purple precipitate. The system was responsive to varying metal ion



Scheme 1. Route to functionalizing the AuNPs with the CTV-dithiolane ligand.