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Thiaoxaaza-Macrocyclic Chromoionophores as Mercury(II) Sensors: Synthesis and Color Modulation

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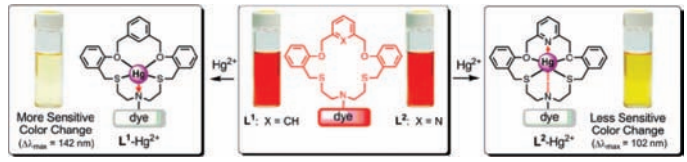
ABSTRACT



Azo-coupled macrocyclic chromoionophores incorporating benzene (L^1) and pyridine (L^2) subunits were synthesized, respectively. In a cation-induced color change experiment, both receptors showed Hg^{2+} selectivity. However, L^1 gave a larger cation-induced hypsochromic shift than L^2, suggesting that the presence of the pyridine unit in L^2 may inhibit the Hg···*N*-azo interaction. The observed Hg^{2+}-selective color changes for L^1 and L^2 were found to be controlled by anion-coordination ability. NMR titration of the proposed receptor ligand with Hg(II) salt was accomplished.

Synthetic receptors for sensing and recognizing environmentally and biologically important ionic species are currently of widespread interest.[1] In this category of sensor molecules, *N*-azo-coupled macrocyclic systems[2] represent a promising research area, not only in terms of their chromophoric function[3] but also because of their high selectivity for the metal species of interest, including heavy metal ions.[4]

Previously, we reported the synthesis of NO_2S_2 macrocycles[5] that show an affinity for Hg^{2+} and bind to this cation in an exo-[5b,6] or endo-coordination[5b,7] manner. More recently, we synthesized an *N*-azo-coupled analogue that shows Hg^{2+} selectivity with the color of the Hg^{2+} complex also controlled by the nature of the anion present. As an extension,

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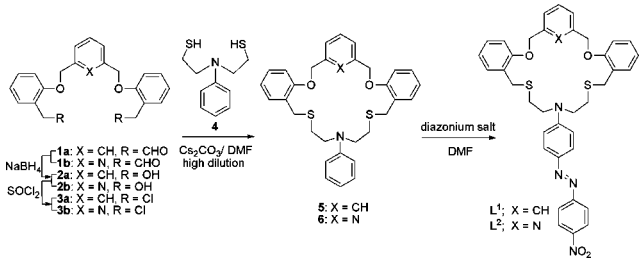
we are currently working on the synthesis of new macrocyclic chromoionophores for the selective detection of heavy metal ions and have undertaken a comparative structure−function analysis of metal sensing by the *N*-azo-coupled macrocycles incorporating benzene (**L**[1]) and pyridine (**L**[2]) subunits as part of their macrocyclic backbones (Scheme 1). We herein report the synthesis of **L**[1] and **L**[2] as an investigation of their structure−function relationship, with emphasis on the color-modulation in metal ion sensing.

Scheme 1. Synthesis of Azo-Coupled Macrocycles



As key precursors, *N*-phenylated macrocycles **5** and **6** were synthesized by dithiol−dichloride coupling reactions of **4** with **3a** or **3b**, employing Cs_2CO_3 under high dilution. **L**[1] and **L**[2] were synthesized by the reactions of the diazonium salt of *p*-nitronaniline with **5** and **6**, respectively. Red single crystals of **L**[2] were obtained by vapor diffusion of *n*-hexane into dichloromethane solution, and the crystal structure of this product was obtained (Figure 1). In **L**[2], the macrocyclic ring is flattened with the two torsion angles between the S and N donors indicating a propensity for each linkage to adopt an anti-anti conformation.

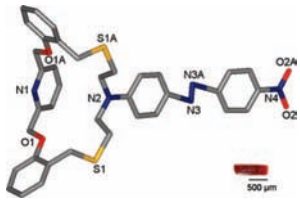


Figure 1. Crystal structure of **L**[2].

The metal-binding properties of **L**[1] and **L**[2] were examined by UV−vis spectrophotometry with respect to the induced color changes (Figure 2). **L**[1] and **L**[2] both exhibit intense absorptions at 480 nm (red, ε_{max}: 27300 for **L**[1] and 23300 for **L**[2]). Notably, the addition of Hg^{2+} resulted in the largest hypsochromic shift: to 339 nm for **L**[1] ($\Delta\lambda = 142$ nm) and 378 nm for **L**[2] ($\Delta\lambda = 102$ nm), changing their solution colors from red to colorless and pale-yellow, respectively (Figure 2). In contrast, no significant color changes were observed upon addition of other metal ions, except Cu^{2+} for **L**[1] and Ag^{+} for **L**[2] (Figure 2).

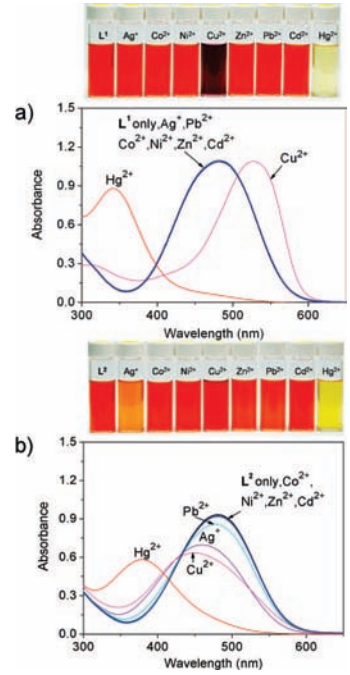


Figure 2. UV/vis spectra of (a) **L**[1] and (b) **L**[2] (40 μM) in the presence of metal perchlorates (5.0 equiv) in acetonitrile.

The titrations of **L**[1] and **L**[2] with $Hg(ClO_4)_2$ resulted in the absorption at 480 nm gradually decreasing whereas the absorptions at 378 and 339 nm gradually increased to give isosbestic points at 415 and 399 nm (Figure 3b), respectively.

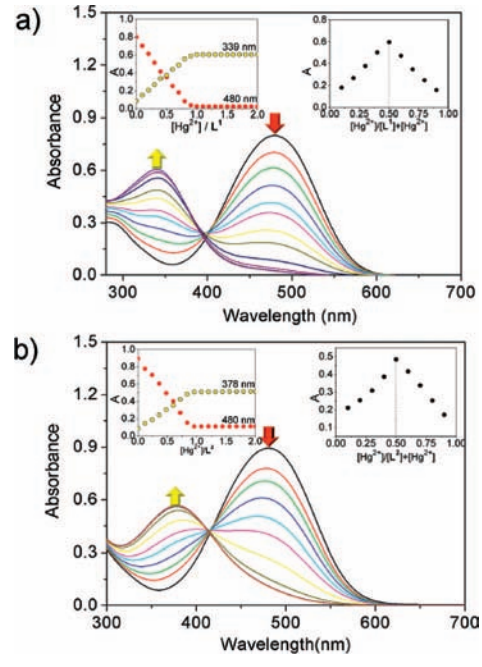


Figure 3. Spectrophotometric titrations of (a) **L**[1] and (b) **L**[2] (40 μM) with $Hg(ClO_4)_2$ in acetonitrile. Inset: (left) titration curves and (right) Job plots.

In both cases, a 1:1 (L/M) stoichiometry for complexation was evident from each titration curve and also from Job plots for each system. The titration plots were very sharp, and hence, the stablity constants are too high to be calculated using this data in least-squares nonlinear fitting programs.

In Hg^{2+} selectivity measurements, the absorbance of the $Hg^{2+}-\mathbf{L^1}$ complex was not affected in the presence of 10 equiv of other competing metal ions such as Ag^+, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Cd^{2+}, Li^+, K^+, Ca^{2+}, and Mg^{2+} (Figure S10, Supporting Information). These results are different from those obtained with other Hg^{2+} sensor molecules that have usually also been affected by Ag^+ and other heavy metal ions.[4] However, in contrast, the absorbance of the $Hg^{2+}-\mathbf{L^2}$ complex showed a 10−15% decrease when Ag^+, Co^{2+}, Ni^{2+}, and Cd^{2+} were added to the solution.

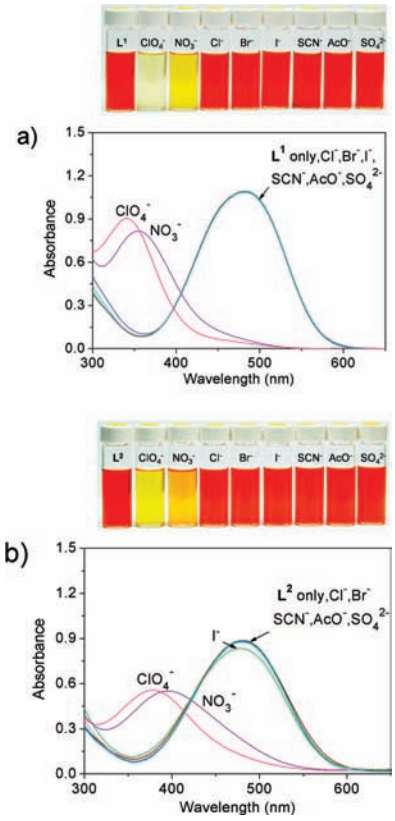


Figure 4. UV/vis spectra of (a) $\mathbf{L^1}$ and (b) $\mathbf{L^2}$ (40 μM) in the presence of Hg^{2+} salts (5.0 equiv) in acetonitrile.

We also found that the color change with Hg^{2+} may vary with the anion present. For instance, the addition of ClO_4^- or NO_3^- resulted in hypochromic shifts to 367 and 350 nm (pale yellow), respectively (Figure 4). However, no color change was observed upon addition of Cl^-, Br^-, I^-, AcO^-, SCN^-, or SO_4^{2-}. This is attributed to the significant coordinating ability of these latter anions to the Hg^{2+} ion.[2a] The results indicate that **1** not only can be useful as an efficient chromogenic reagent for cation sensing but also shows promise as a reagent for ClO_4^- and NO_3^- sensing in the presence of a range of other anions. The observed behavior undoubtedly reflects the structures of the respective complexes generated, and thus, we decided to attempt the preparation and crystal structure of each of the colored species.

We were successful in isolating yellow-red (**1**) and red (**2**) complexes as single crystals from solutions of $\mathbf{L^2}$ with $Hg(ClO_4)_2$ and $Hg(NO_3)_2$, respectively, and their structures were obtained by X-ray diffraction (Figure 5). The X-ray analysis revealed that **1** is a 1:1 complex of type $[Hg(\mathbf{L^2})](ClO_4)_2(DMF)$ (Figure 5a). The Hg atom is located at the center of $\mathbf{L^2}$ which adopts a bent arrangement. Hg1 is five-coordinate, being bound to two S, two O and one pyridine N atom. An intramolecular $\pi\cdots\pi$ stacking interaction (3.29 Å and 16.7°, dashed line in Figure 5a) occurs between two aromatic groups.

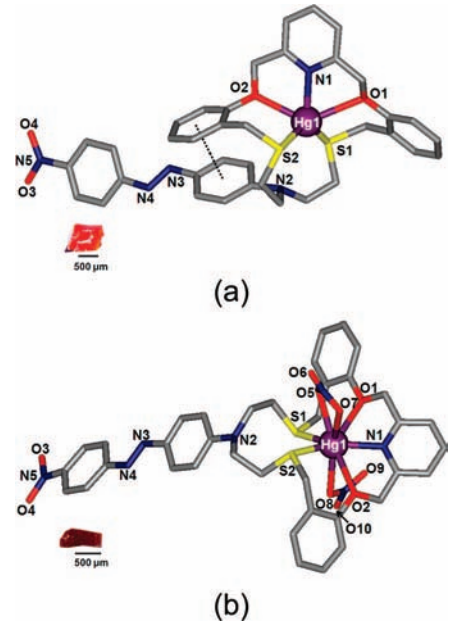


Figure 5. Crystal structures of $\mathbf{L^2}$ complexes with Hg^{2+} salts: (a) **1**, $[Hg(\mathbf{L^2})](ClO_4)_2(DMF)$ and (b) **2**, $[Hg(\mathbf{L^2})(NO_3)_2]$. Noncoordinated anions and solvent molecule are omitted.

On reaction with $Hg(NO_3)_2$, $\mathbf{L^2}$ forms the 1:1 endotype complex $[Hg(\mathbf{L^2})(NO_3)_2]$ (**2**). Unlike **1**, this dinitrato complex is a neutral species; the Hg center in the cavity is coordinated to an NS_2O_2 donor set from the macrocycle (but not to the *t*-N atom) as well as to two nitrato ions bound in a mono- and a bidentate manner. Considering the narrow bite angle [O5−Hg1−O7 44.94(3)°] of the bidentate nitrate ion, the geometry of the Hg coodination sphere is probably best described as pseudopentagonal bipyramidal. The NS_2O_2 donors of $\mathbf{L^2}$ define the equatorial plane, with the axial positions occupied by the two nitrato ligands.

In both complexes of $\mathbf{L^2}$, the distances between Hg and the *t*-N atom (3.290 Å for **1** and 4.478 Å for **2**) are too long to be considered as a regular bond,[8] with the longer distance in **2** than that in **1** being attributed to the presence of anion coordination. Consequently, it is the presence of the pyridine unit in $\mathbf{L^2}$ that may inhibit bond formation between Hg and the

t-N atom and results in this dye receptor being less sensitive than $\mathbf{L^1}$ as exemplified by the results presented in Figures 2 and 3 (see also Figure S11, Supporting Information).

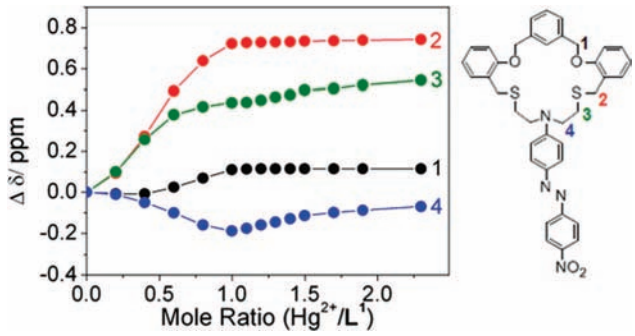


Figure 6. ^{1}H NMR titration curves for $\mathbf{L^1}$ with $Hg(ClO_4)_2$ in $CDCl_3$/CD_3CN (v/v 1:6).

Unfortunately, single crystals of the corresponding Hg^{2+} complexes of $\mathbf{L^1}$ were not able to be obtained. Instead, the binding behavior of $\mathbf{L^1}$ toward Hg^{2+} was further investigated by NMR titration (Figure 6). The signals of the methylene protons (H_{1-4}) in $\mathbf{L^1}$ (Figure S9a) were well resolved. Upon addition of $Hg(ClO_4)_2$ to a solution of $\mathbf{L^1}$, all of the protons display downfield shifts except for H_4, in keeping with $\mathbf{L^1}$ forming a stable complex with Hg^{2+}, which shows a fast-exchange rate between ligand and cation on the NMR time scale. The titration curves [plotting $\Delta\delta$ (ppm) vs added equiv of Hg^{2+}] for each proton clearly show an inflection point at a mole ratio (Hg/L) of 1.0, indicating a 1:1 solution stoichiometry for the complex. The order of magnitude of the chemical shift variation for the aliphatic region is H_2 ($\Delta\delta$: 0.74 ppm) > H_3 (0.54 ppm) > H_4 (0.19 ppm) > H_1 (0.11 ppm). The larger chemical shift changes shown by the H_2, H_3, and H_4 adjacent to the S and N atoms can be explained by the likelihood that the Hg^{2+} is strongly bound to the S and N donors, while the O donors interact with the Hg^{2+} relatively weakly.

The 1:1 (Hg/L) stoichiometry of the Hg^{2+} complexes with each ligand is also confirmed by their fast atom bombardment (FAB) mass spectra, which show peaks corresponding to $[Hg(\mathbf{L^1})ClO_4]^+$ (*m*/*z* 977.2) and $[Hg(\mathbf{L^2})ClO_4]^+$ (*m*/*z* 978.2), respectively (Figure 7). The relative abundance of their isotope peak patterns are in each case in good agreement with the corresponding simulated peak patterns.

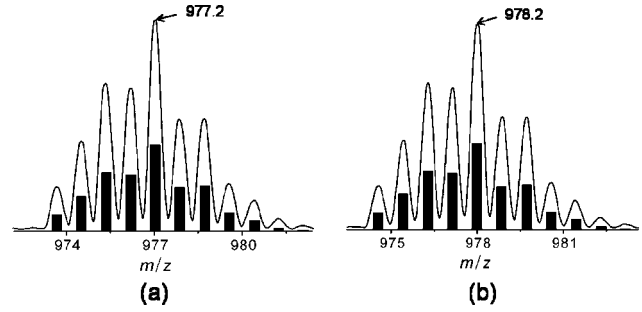


Figure 7. Observed isotope distributions for (a) $[Hg(\mathbf{L^1})ClO_4]^+$ and (b) $[Hg(\mathbf{L^2})ClO_4]^+$ in the FAB mass spectra of $Hg(ClO_4)_2$ complexes of $\mathbf{L^1}$ and $\mathbf{L^2}$, respectively. The bars represent the predicted mass spectral distributions for these ions.

In summary, the synthesis and comparative chromogenic behavior of the *N*-azo-coupled thiaoxaaza-macrocycles incorporating benzene ($\mathbf{L^1}$) and pyridine ($\mathbf{L^2}$) subunits are presented. $\mathbf{L^1}$ exhibits better Hg^{2+} selectivity and sensitivity than $\mathbf{L^2}$ because of the coordination of the pyridine nitrogen in $\mathbf{L^2}$ inhibiting the bond formation between Hg^{2+} and the macrocyclic *t*-N atom, with the observed induced color being very sensitive to this effect. This result may contribute not only to the design and synthesis of new chromoionophores for the selective detection of heavy metal ions but also in the development of related nanosensing materials based on the structure−function analysis.

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Supporting Information Available: Syntheses of $\mathbf{L^2}$, **1** and **2**; X-ray cystallographic files (CIF); NMR data. This material is available free of charge via the Internet at http://pubs.acs.org.

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