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Small Molecular Chromogenic Sensors for Hg^{2+}: A Strong "Push-Pull" System Exists after Binding

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Two small molecular chromogenic sensors **1** and **2** for detection of Hg^{2+} are described. After coordination with Hg^{2+}, a red shift of about 100 nm was observed in the UV/Vis spectra and the color of the solution changed from pale yellow to red which could easily be detected by the naked eye. The results indicate a strong push-pull system was formed after coordination of Hg^{2+}. The ^1H NMR spectra and control experiments showed the binding sites of **1** and **2** to be the aniline groups rather than the azine bridge. Moreover, mercury test papers were made by adsorbing **1** onto filter paper, allowing heterogeneous sensing of Hg^{2+} in aqueous solution.

Introduction

There continues to be a need for new and improved methods for the detection of certain transition- and post-transition-metal ions that have detrimental effects on humans or other animals.[1,2] Of these metal ions, mercury is considered a highly toxic and hazardous pollutant that poses severe risk to human health and the environment.[3–5] Despite its toxicity, mercury and mercuric salts are widely used in industrial processes and products such as gold mining and fungicides.[6–8] Once elemental or ionic mercury has been converted by aquatic organisms into methylmercury, it can enter the food chain and be ingested by humans causing many mercury-pollution-related diseases.[9–11] Great efforts have been made to develop Hg^{2+} sensors using chromogenic,[12–18] fluorogenic,[19–27] or electrochemical methods.[28–30] However, most of these chemical sensors suffer from limitations, such as a tedious synthesis, an inability to be used in pure water thereby needing special or expensive apparatus instrument, and interference with other metal ions.

We are interested in exploring further the use of chromogenic sensors to selectively detect Hg^{2+} because 1) chromogenic detection can be carried out without spectroscopic instrumentation and therefore is simple, easy and low-cost, 2) UV/Vis titration shows the appearance of a new band and the disappearance of the initial band, the two bands directly giving the ratio of the species, and 3) mercury test devices can be made by adsorbing chromogenic sensors onto a substrate[31] (e.g., mercury test paper can be made by adsorbing a chromogenic sensor onto filter paper), which is convenient.

It is well known that the optical properties of a molecule are strongly dependent on its electron distribution. Bearing this in mind and considering the fact that amine is a good ligand to mercury ions, we have designed structure-simple receptors **1** and **2**. Both receptors are electron-rich compounds and contain two amino substituents. We reason that when these receptors are exposed to a mercury ion, one of the amine groups will coordinate with the ion and a strong metal-induced intramolecular electron transfer (MICT) will occur and a push-pull system will be formed (the other amine group acts as a donor and because of MICT this amine will have a very low affinity for the mercury ion) causing a distinct change in the optical properties of the receptor.

In this paper, the syntheses, optical properties, and Hg^{2+} binding properties of receptors **1** and **2** (Scheme 1) are described. The binding site of these receptors was confirmed by ^1H NMR spectra and control experiments. Moreover, the application of mercury test papers made by adsorbing sensor **1** onto filter paper in aqueous solution is also presented.

Results and Discussion

Synthesis

The syntheses of compounds **1** and **2** as well as model compounds are outlined in Scheme 1. Compounds **1**–**4** were obtained in moderate yields by reacting corresponding aldehydes with hydrazine hydrate. Compound **5** was synthesized

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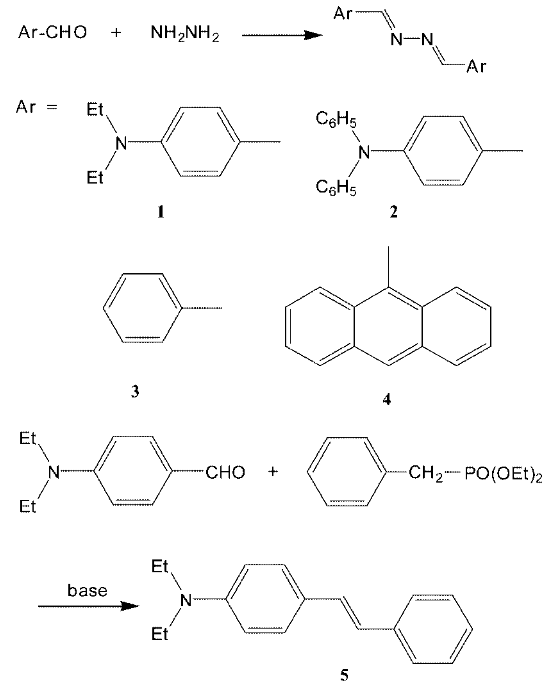

Scheme 1. Structures and synthetis of compounds **1**–**5**.

by the Wittig–Horner reaction. All of the compounds were totally characterized by ^{1}H NMR, MS, and elementary analysis.

Absorption Spectra

Figure 1 shows the UV/Vis response of compound **1** upon addition of a mercury ion. As expected, a new band at 496 nm appeared with the disappearance of the initial band at 393 nm. The new band was red-shifted by about 103 nm in the visible light region causing the color of the solution to change from pale yellow to red which could be detected easily by the naked eye. This new band was ascribed to a MICT absorption. The presence of a well-defined isosbestic point indicated the existence of a two-state equilibrium, which means there is only one stable complex in solution. The UV/Vis titration profile showed the formation of a 1:1 adduct between receptor **1** and Hg^{2+}, as expected because of the existence of the MICT absorption. The binding constant was calculated to be 2.6×10^4 M. A μM detection limit of receptor **1** for Hg^{2+} was deduced from the absorption spectrum.

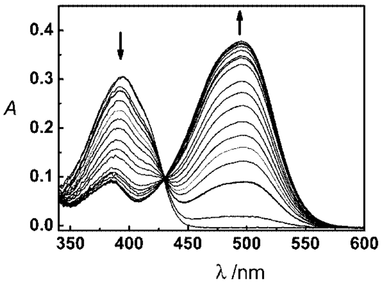

Figure 1. The UV/Vis response of **1** (CH_3CN, 5×10^{-6} M) upon addition of Hg^{2+}.

The sensing specificity of **1** for the mercury ion over interference metal ions, including Ni^{2+}, Co^{2+}, Zn^{2+}, Cd^{2+}, Cu^{2+}, Ag^+ and main-group metal ions Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, and Ba^{2+}, was tested. Figure 2 shows the UV/Vis response and color change of **1** upon addition of metal ions (main-group metal ions have been omitted). From Figure 2 (top, inset) we could see that MICT absorptions were also observed with Zn^{2+}, Co^{2+}, and Mg^{2+}. However, their MICT absorptions were very weak, indicating the low affinity of receptor **1** for these ions. With the addition of Cu^{2+}, a new peak in the UV/Vis spectrum was observed at 336 nm with the disappearance of the absorption at 393 nm. Control experiments showed Cu^{2+} was not complexed by **1**, however, it did induce the decomposition of **1**, as proved by UV/Vis spectroscopy (see the Supporting Information). The detection limit of Cu^{2+} at 336 nm was 2×10^{-5} M.

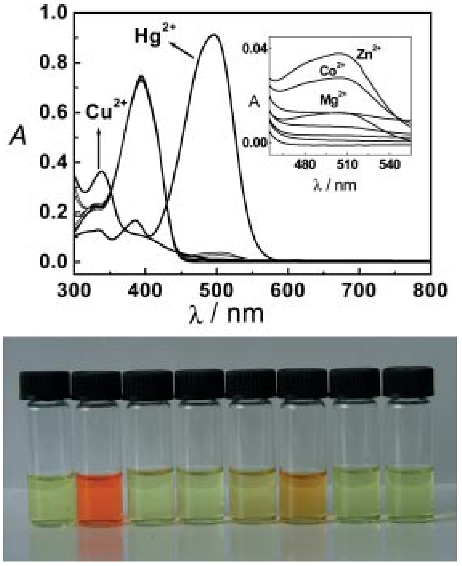

Figure 2. Top: UV/Vis response of **1** (CH_3CN, 1×10^{-5} M) upon addition of different metal ions (including Hg^{2+}, Cu^{2+}, Cd^{2+}, Co^{2+}, Ni^{2+}, Pb^{2+}, Zn^{2+}, Ag+, Mg^{2+}, and Zn^{2+}). Insert: Partial UV/Vis spectra in the range of 450–600 nm (the spectra of Hg^{2+} has been omitted). Bottom: color changes observed for **1** ($MeCN/H_2O$ = 2:1, 1×10^{-4} M) upon addition of 2 equiv. of metal ions. From left to right: free **1**, Hg^{2+}, Zn^{2+}, Ni^{2+}, Co^{2+}, Cu^{2+}, Ag^+, and Cd^{2+}.

The UV/Vis spectra (Figure 3) recorded on addition of mercury ions to receptor **2** are similar to those obtained with **1**. The absorption at 400 nm decreased gradually with the observation of a new absorption at 500 nm and the color of the solution changed from pale yellow to red (see the Supporting Information). UV/Vis titration experiments indicated a 1:1 adduct was formed between **2** and Hg^{2+} with a binding constant of about 6×10^4 M. No change in the fluorescence spectrum was observed after the addition of Hg^{2+} (see the Supporting Information).

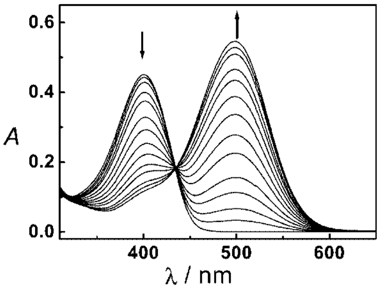

Figure 3. UV/Vis response of **2** (MeCN, 1×10^{-5} M) upon addition of Hg^{2+}.

The reversibility of the binding of receptors **1** and **2** to Hg^{2+} was then tested. On addition of thiourea, adducts **1·Hg^{2+}** and **2·Hg^{2+}** decomplexed quickly, as confirmed by UV/Vis spectroscopy and color recovery of the solutions (see the Supporting Information). From the above results, we concluded that receptors **1** and **2** are good chemosensors for mercury ions.

Binding Site Study

1,4-Disubstituted azines have recently been used as recognition sites for Hg^{2+} detection.[32,33] As compounds **1** and **2** contain both an azine bridge and aniline groups, these two compounds have multiple binding sites. On the basis that no fluorescence change was observed on addition of Hg^{2+} ions to **2**, we supposed the binding sites of compounds **1** and **2** to be the aniline groups rather than the azine bridge. In order to confirm this supposition, ^1H NMR studies as well as control experiments were carried out. Before the addition of mercury ions (Figure 4), compound **1** showed two doublets arising from the protons on the phenyl rings and one quartet due to the NCH_2 protons owing to the symmetry of **1**. On addition of mercury ions, the signals arising from the protons on the phenyl rings and NCH_2 were shifted downfield. From the splittings and chemical shifts of these protons, we could conclude that the electron densities on the two phenyl rings were different after the addition of the mercury ions, indicating a lack of symmetry in the adduct. If compound **1** coordinated to the mercury ion at the azine bridge, the adduct would have a similar symmetry to that of **1**, which means the ^1H NMR spectrum of the adduct should be similar to that of free **1** but with different chemical shifts. The ^1H NMR experiment therefore further confirmed our supposition.

For the control experiments, model compounds **3**, **4**, and **5** were designed and synthesized. Compounds **3** and **4** only contained an azine bridge, whereas compound **5** only contained an aniline nitrogen atom. In the titration of compounds **3** and **4** with Hg^{2+}, the UV/Vis spectra showed no absorption response (Figure 5). Also, the fluorescence spectra of **4** before and after addition of mercury ions were nearly same (see the Supporting Information). The UV/Vis spectrum of compound **5** exhibited an absorption band at about 353 nm with a shoulder at 328 nm. On addition of Hg^{2+}, the absorption band at 353 nm gradually red-shifted

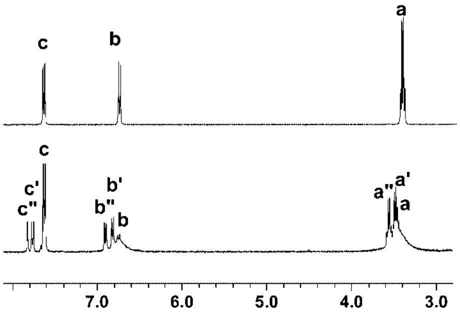

Figure 4. ^1H NMR spectra of **1** before and after the addition of 0.2 equiv. of Hg^{2+}. Top: free **1**. Bottom: **1** + 0.2 equiv. of Hg^{2+}.

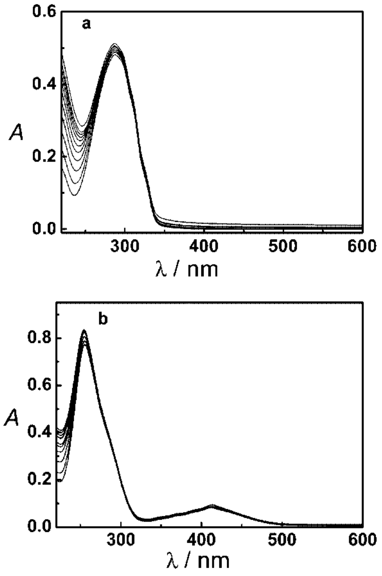

Figure 5. UV/Vis responses of compounds **3** and **4** (MeCN, 1×10^{-5} M) upon addition of Hg^{2+} (0–10 equiv.). **a**: compound **3**. **b**: compound **4**.

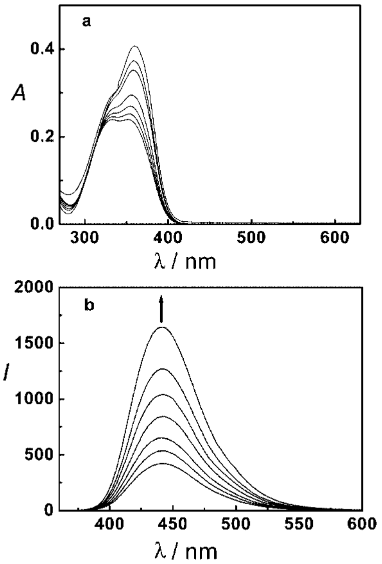

Figure 6. **a**: The UV/Vis response of **5** (MeCN, 1×10^{-5} M) upon addition of Hg^{2+} (0–6 eqiv.). **b**: Fluorescent titration profile of **5** with 0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 equiv. of Hg^{2+}.

to 360 nm. Moreover, the addition of Hg^{2+} induced significant fluorescence enhancement (Figure 6). The fluorescence titration profiles of **5** with Hg^{2+} are consistent with a supposed 1:1 adduct and the association constant was about 1.9×10^4 M, indicating that **5** could be used as a fluorescent sensor for Hg^{2+}. From both the ^1H NMR spectra and the control experiments, we believe there is no doubt that the binding sites in receptors **1** and **2** are the aniline groups rather than the azine bridges.

Mercury Test Papers

As receptors **1** and **2** are not soluble in aqueous solution, to confirm the potential application of these receptors, mercury ion test papers based on compound **1** were prepared by immersing filter papers (4×1 cm^2) into **1** in CH_2Cl_2 (4 mg/mL) and drying them in air. Figure 7 shows the changes in the color of the test papers on immersion in aqueous solutions containing different amounts of Hg^{2+} at pH = 7. Clearly, the test paper could detect Hg^{2+} in aqueous solution at a concentration of about 2.5×10^{-5} M. Other ions such as Ag^+, Ni^{2+}, Co^{2+}, Zn^{2+}, Cd^{2+}, Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, and Ba^{2+} did not cause any detectable changes, indicating the high selectivity of the test papers for Hg^{2+}.

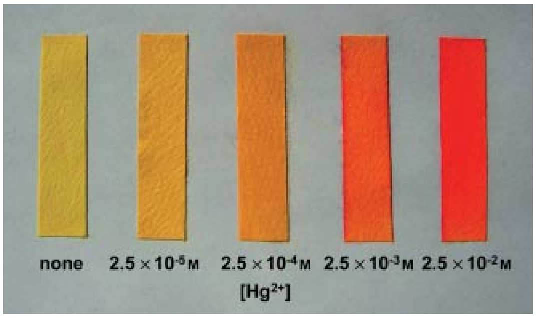

Figure 7. Changes in the colors of the test papers based on **1** for detecting Hg^{2+} in neutral aqueous solutions with different Hg^{2+} concentrations.

Conclusions

Structure-simple and electron-rich chromogenic sensors **1** and **2** for mercury ions have been described. Upon binding with Hg^{2+}, they become strong push-pull systems and color changes could easily be detected by the naked eye. Control experiments showed the binding site in sensors **1** and **2** to be the aniline group rather than the azine bridge. Furthermore, mercury ion test papers were prepared by adsorbing **1** onto filter paper and showed high selectivity towards the mercury ion in aqueous solution. As George S. Hammond mentioned "The most fundamental and lasting objective of synthesis is not production of new compounds, but production of properties" (Norris Award Lecture, 1968), we believe design strategies that use structure-simple, electron-rich compounds and MICT effects to avoid tedious syntheses will be helpful in the design of other kinds of sensors for specific ions.

Experimental Section

Materials and Instrumentation: Chemicals and reagents were purchased from commercial suppliers and used without further purification unless otherwise noted. UV/Vis absorption spectra were recorded with a Hitachi U3500 spectrometer. Fluorescence spectra were obtained with a Hitachi F-4500 spectrometer. ^1H NMR spectra were obtained with a Bruker DMX-400 spectrometer.

Compound 1: Hydrazine hydrate (0.17 g, 4.2 mmol) was added dropwise to a solution of 4-(diethylamino)benzaldehyde (1.5 g, 8.4 mmol) in acetic acid (50 mL). The reaction mixture was stirred at room temperature for 5 h. The solvent was evaporated and the residue purified by column chromatography (CH_2Cl_2 as eluent). Compound **1** was obtained as a yellow solid. Yield 1.085 g (57.4%). M.p. 193 °C. ^1H NMR (300 Hz, $CDCl_3$): δ = 8.54 (s, 2 H), 7.67 (d, 4 H), 6.67 (d, 4 H), 3.42 (m, 8 H), 1.19 (m, 12 H) ppm. $C_{22}H_{30}N_4$ (350.25): calcd. C 75.43, H 8.57, N 16.00; found C 75.73, H 8.77, N 15.54.

Compound 2: Compound **2** was synthesized in a similar procedure to that used for **1** and obtained as a light yellow solid. Yield 52%. M.p. 243 °C. ^1H NMR (300 Hz, $CDCl_3$): δ = 8.57 (s, 2 H), 7.65 (d, 4 H), 7.34–7.27 (m, 8 H), 7.16 (d, 8 H), 7.11–6.96 (m, 8 H) ppm. $C_{38}H_{30}N_4$ (542.25): calcd. C 84.13, H 5.54, N 10.33; found C 83.78, H 5.83, N 9.92.

Compound 3: Compound **3** was synthesized in a similar procedure to that used for **1** and obtained as a light yellow solid. Yield 72%. M.p. 98 °C (ref.[34] 98 °C). ^1H NMR (300 Hz, $CDCl_3$): δ = 8.66 (s, 2 H), 7.83 (m, 4 H), 7.44 (m, 6 H) ppm.

Compound 4: Compound **4** was synthesized in a similar procedure to that used for **1** and obtained as an orange solid. Yield 70%. M.p. 280 °C (ref.[35] 276 °C). ^1H NMR (300 Hz, $CDCl_3$): δ = 10.15 (s, 2 H), 8.88 (d, 4 H), 8.61 (d, 2 H), 8.09 (d, 4 H), 7.67–7.63 (m, 4 H), 7.58–7.54 (m, 4 H) ppm.

Compound 5: 4-(Diethylamino)benzaldehyde (2.818 g, 15.9 mmol) was dissolved in anhydrous THF (50 mL) and then NaH (0.8 g, 16.6 mmol, 50% w/w) was added. A solution of diethyl benzylphosphonate (3.6 g, 15.8 mmol) in anhydrous THF (50 mL) was then added to the reaction mixture over 5 min, which was then stirred overnight. Excess NaH was destroyed and solvent removed. The residue was purified by column chromatography and compound **5** was obtained as a yellow solid. Yield 1.3 g (32.6%). M.p. 96 °C (ref.[36] 98 °C). ^1H NMR (300 Hz, $CDCl_3$): δ = 7.47 (d, 2 H), 7.39 (d, 2 H), 7.32 (m, 2 H), 7.19 (m, 1 H), 7.04 (d, 1 H), 6.88 (d, 1 H), 6.66 (d, 2 H), 3.37 (m, 4 H), 1.20 (m, 6 H) ppm. $C_{18}H_{21}N$ (251.17): calcd. C 86.05, H 8.37, N 5.57; found C 85.73, H 8.65, N 5.15.

Supporting Information (see also the footnote on the first page of this article): UV/Vis titration profiles of sensors **1** and **2** with Hg^{2+} and Cu^{2+}, fluorescence spectra, color changes.

Acknowledgments

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