ARTICLE

A New Approach to Design Ratiometric Fluorescent Probe for Mercury(II) Based on the Hg^{2+}-Promoted Deprotection of Thioacetals

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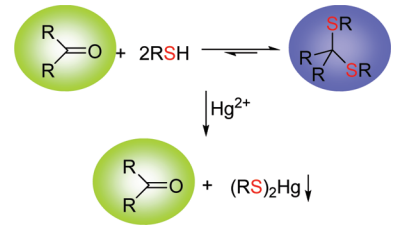
ABSTRACT On the basis of the protection reaction between ethanethiol and aldehyde, we designed and synthesized two new ratiometric fluorescent chemosensors, **3** and **4**, by using intramolecular charge transfer (ICT) as a signaling mechanism. Upon the addition of Hg^{2+} ion, both probes displayed apparent luminescence color changes, which could be observed by naked eyes under a UV lamp. Unexpectedly, both chemosensors also gave response to the addition of trace silver ions, making this kind of chemosensors as the first example of ratiometric fluorescent probe that showed dual channel fluorescence for both Hg^{2+} and Ag^{+}. The test strips experiments suggested that **3** and **4** could serve as practical fluorescent probes for rapid detection of Hg^{2+} ion.

KEYWORDS: chemosensor • mercury • deprotection of thioacetals • intramolecular charge transfer • fluorescence • high selectivity

INTRODUCTION

As one of the highly toxic metal ions, mercury can affect many different areas of the human body (1) (i.e., brain, heart, kidney, stomach, and intestines) as well as their associated functions (2), and cause a wide variety of symptoms, including digestive, cardiovascular, and especially neurological diseases (3). Despite the recent reduction of its industrial use due to more stringent regulations, mercury pollution still arises from diverse sources including nature and human activities (4). It is estimated by the U.S. Environmental Protection Agency (EPA) that the total mercury released into the environment reaches ~7500 tons per year (5). Therefore, to prevent the possible mercury pollutions, mainly from food and water, the monitoring of mercuric ions (Hg^{2+}), one of the most usual and stable form of mercury pollution, becomes an increasing demand. Thanks to the great efforts of scientists, a number of Hg^{2+} sensors have been developed with good performance, for example, the redox, colorimetric and fluorescent Hg^{2+} sensors by using proteins (6), nucleic acids (7), DNAs (8), nanoparticles (9), and several types of small molecules and some other biomacromolecules (10–12) as Hg^{2+} acceptors. On the other hand, ratiometric fluorescent probes could enable the measurement of emission intensities at two different wavelengths, providing a built-in correction for environmental effects and could also increase the dynamic range of fluorescence measurement. This was considered as a good approach to overcome the major limitation of intensity-based probes, in which variations in the environmental sample and probe distribution were problematic for quantitative measurements. However, so far, the ratiometric fluorescent probes for Hg^{2+} were still very scarce (13).

Scheme 1. Mechanism of Hg^{2+}-Promoted Deprotection Reaction



As we knew from the textbook of basic organic chemistry (Scheme 1), the protected aldehyde group by mercaptan could be converted to the previous aldehyde one only with the addition of Hg^{2+}, thus, this reaction could be considered as the selective reaction toward Hg^{2+}. Also from the textbook, it was known that aldehyde was an electron-withdrawing group, after protected by mercaptan, the formed moieties in thioacetal might be regarded as an electronic donor. Therefore, considering the good performance of the ratiometric fluorescent probes and the selectivity of Hg^{2+}-promoted deprotection reaction of the thioacetal, we would like to develop a ratiometric fluorescent chemosensor toward Hg^{2+}, by using intramolecular charge transfer (ICT) as a signaling mechanism, in which the luminophore moiety acted as an electron donor and aldehyde group as the acceptor one. It was expected that after the deprotection reaction promoted by Hg^{2+}, the electronic property of the resultant aldehyde would be changed; as a result, the ICT

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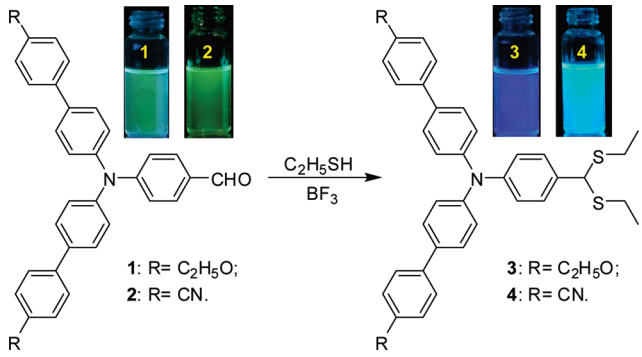
Scheme 2. Synthetic Route to Compounds 3 and 4



efficiency could be regulated before and after the deprotection reaction. This would lead to the change of their fluorescent behavior. Thus, we designed two new thioacetals, **3** and **4**, conveniently from the protection reaction between ethanethiol and aldehyde **1** or **2**, which emitted green luminescence upon excitation (Scheme 2). After the addition of the aqueous solution of Hg^{2+} to the diluted solutions of **3** and **4**, the deprotection reaction happened immediately, accompanying with apparent luminescence color change, which could be observed by naked eyes under normal illumination. Unexpectedly, both chemosensors also gave response to trace silver ions, making this kind of chemosensor the first example of a ratiometric fluorescent probe that showed dual channel fluorescence for both Hg^{2+} and Ag^{+}. Herein, we report the synthesis, characterization, and sensing behavior of **3** and **4** in detail.

MATERIALS AND INSTRUMENTATION

Dichloromethane was dried over and distilled from CaH_2 under an atmosphere of dry nitrogen. Tetrahydrofuran (THF) was dried over and distilled from K−Na alloy under an atmosphere of dry nitrogen. All other reagents were used as purchased. The ^{1}H NMR and ^{13}C NMR spectra were measured on Bruker 400 and Varian Mercury300 spectrometer using tetramethylsilane (TMS; $\delta = 0$ ppm) as internal standard. The Fourier transform infrared (FTIR) spectra were recorded on a PerkinElmer-2 spectrometer in the region of 3000−400 cm^{-1} on NaCl pellets. Matrix-assisted laser desorption ionization time-of-flight mass spectra were measured on a Voyager-DE-STR MALDI-TOF mass spectrometer (MALDI-TOF MS; ABI, American) equipped with a 337 nm nitrogen laser and a 1.2 m linear flight path in positive ion mode. UV−visible spectra were obtained using a Schimadzu UV-2550 spectrometer. Photoluminescence spectra were performed on a Hitachi F-4500 fluorescence spectrophotometer. Compounds **5** (14a), **6** (14b), and **7** (14c) were prepared according to the literature procedure.

Synthesis of Compound 1. Compound **7** (683 mg, 1.3 mmol), compound **5** (472 mg, 2.86 mmol), and K_2CO_3 (1.8 g, 13 mmol) were dissolved in dry THF (15 mL) and degassed H_2O (5 mL) with $Pd(PPh_3)_4$ as catalyst. After being stirred at 80 °C overnight, the reaction was stopped. The resultant mixture was extracted with chloroform for several times, the organic layer was combined, and the product was purified by gel column chromatography using petroleum ether/chloroform (1/4, v/v) as eluent to afford compound **1** as yellow solid (382 mg, 57.2%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.43−1.47 (t, J = 6.0, 6H), 4.07−4.10 (q, J = 4.0, 4H), 6.96−6.99 (d, J = 8.5, 4H), 7.10−7.13 (d, J = 9.0, 6H), 7.23−7.26 (d, J = 9.0, 4H), 7.70−7.72 (d, J = 6, 4H), 9.83 (s, 1H).

Synthesis of Compound 3. Under an atmosphere of dry argon, compound **1** (72 mg, 0.14 mmol) and ethanethiol (0.026 mL, 0.35 mmol) were dissolved in dry dichloromethane (5 mL) with $BF_3 \cdot Et_2O$ (0.05 mL, 0.42 mmol) as the Lewis acid. After being stirred at 0 °C for 2 h, 0.1 mol/L aqueous $NaHCO_3$ was added to adjust the pH value of the resultant mixture to 8−9. The resultant mixture was extracted with ether for several times, the organic layer was combined, and the product was purified by column chromatography using petroleum ether/ethyl acetate (6/1, v/v) as eluent to afford compound **3** as yellow solid (66 mg, 76.4%). ^{1}H NMR (400 MHz, acetone-d_6): δ 1.09−1.11 (t, J = 3.5, 3H), 1.25−1.28 (t, J = 5.5, 3H), 2.41−2.53 (q, J = 8.0, 4H), 3.93−3.98 (q, J = 8.0, 4H), 4.98 (s, 1H), 6.85−6.87 (d, J = 8.0, 4H), 6.93−6.96 (d, J = 12.0, 2H), 6.99−7.02 (d, J = 11.5, 4H), 7.28−7.31 (d, J = 11.5, 2H), 7.43−7.46 (m, 8H). ^{13}C NMR (400 MHz, DMSO-d_6): δ 14.08, 14.39, 25.57, 50.96, 62.90, 114.62, 123.00, 124.11, 127.03, 127.18, 128.56, 131.84, 134.59, 134.95, 145.65, 146.35, 157.89. MALDI-TOF MS calcd for $C_{64}H_{66}N_8O_{10}$, 619.2579; found, 618.0571.

Synthesis of Compound 2. Compound **7** (525 mg, 1 mmol), compound **6** (321 mg, 2.2 mmol), and K_2CO_3 (1.38 g, 10 mmol) were dissolved in dry THF (10 mL) and degassed H_2O (3 mL) with $Pd(PPh_3)_4$ as catalyst. After being stirred at 80 °C overnight, the reaction was quenched with water. The resultant mixture was extracted with chloroform several times, the organic layer was combined, and the product was purified by gel column chromatography using petroleum ether/chloroform (1/4, v/v) as eluent to afford compound **2** as yellow solid (328 mg, 69%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.17−7.20 (d, J = 8.5, 4H), 7.26−7.30 (m, 4H), 7.57−7.60 (d, J = 9.0, 4H), 7.67−7.78 (m, 8H), 9.88 (s, 1H).

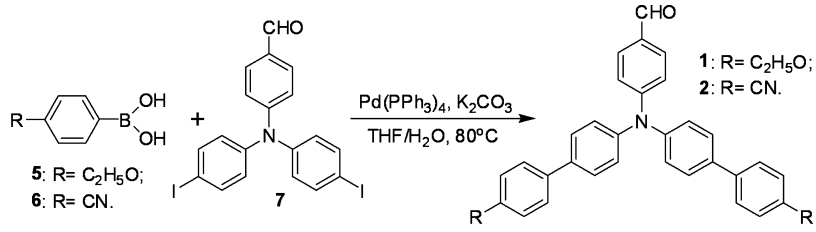
Synthesis of Compound 4. Under an atmosphere of dry argon, compound **2** (67 mg, 0.14 mmol) and ethanethiol (0.026 mL, 0.35 mmol) were dissolved in dry dichloromethane (5 mL) with $BF_3 \cdot Et_2O$ (0.05 mL, 0.42 mmol) as the Lewis acid. After stirred at 0 °C for 3 h, 0.1 mol/L aqueous $NaHCO_3$ was added to adjust the pH value of the resultant mixture to 8−9. The resultant mixture was extracted with ether for several times, the organic layer was combined, and the product was purified by column chromatography using petroleum ether/ethyl acetate (5/1, v/v) as eluent to afford compound **4** as yellow solid (64 mg, 79%). ^{1}H NMR (400 MHz, acetone-d_6): δ 1.22−1.26 (t, J = 4.0, 6H), 2.56−2.69 (m, 4H), 5.16 (s, 1H), 7.16−7.18 (d, J = 8.0, 6H), 7.50−7.52 (d, J = 8.0, 2H), 7.74−7.76 (d, J = 8.0, 4H), 7.84−7.91 (m, 8H). ^{13}C NMR (400 MHz, acetone-d_6): δ 14.81, 26.81, 52.50, 111.21, 119.48, 124.99, 125.73, 128.00, 129.13, 129.98, 133.59, 134.12, 137.84, 145.43, 147.15, 148.77. MALDI-TOF MS calcd for $C_{64}H_{66}N_8O_{10}$, 581.1959; found, 581.0406.

Preparation of Solutions of Metal Ions. One millimole of eath inorganic salt ($NaNO_3$, KNO_3, LiCl, $Ba(NO_3)_2$, $AgNO_3$, $Cr(NO_3)_3 \cdot 9H_2O$, $CoCl_2 \cdot 6H_2O$, $Ca(NO_3)_2 \cdot 4H_2O$, $Pb(NO_3)_2$, $Ni(NO_3)_2 \cdot 6H_2O$,$Zn(NO_3)_2 \cdot 6H_2O$,$Cu(NO_3)_2 \cdot 3H_2O$,$Al(NO_3)_3 \cdot 9H_2O$, $Fe(NO_3)_3 \cdot 9H_2O$, $MnSO_4 \cdot 2H_2O$, $Cd(SO_4) \cdot 8H_2O$, $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$, $MgSO_4$, and $Hg(ClO_4)_2 \cdot 3H_2O$) was dissolved in distilled water (10 mL) to afford 1×10^{-1} mol/L aqueous solution. The stock solutions were diluted to desired concentrations with distilled water when needed.

Fluorescence Titration of 3 with Hg^{2+} Ions. A solution of **3** (5.0×10^{-6} mol/L) was prepared in THF. The solution of Hg^{2+} (1×10^{-3} mol/L) was prepared in distilled water. A solution of **3** (3.0 mL) was placed in a quartz cell (10.0 mm width) and the fluorescence spectrum was recorded. The Hg^{2+} ion solution was introduced in portions and fluorescence intensity changes were recorded at room temperature each time (Excitation wavelength: 370 nm).

Fluorescence Intensity Changes of 3 with Different Metal Ions. A solution of **3** (1×10^{-5} mol/L) was prepared in THF. The solutions of metal ions (1×10^{-1} mol/L) were prepared in distilled water. A solution of **3** (3.0 mL) was placed in a quartz cell (10.0 mm width) and the fluorescence spectrum was

Scheme 3. Synthetic Route to Compounds 1 and 2



recorded. Different ion solutions were introduced (1.5 μL) and the changes of the fluorescence intensity were recorded at room temperature each time (excitation wavelength 370 nm).

RESULTS AND DISCUSSION

Synthesis and Structural Characterization. The synthetic route to compounds **3** and **4** was depicted in Scheme 2. It was easily seen that the target compounds **3** and **4** were prepared conveniently through the general protection reaction between mercaptan and aldehydes **1** and **2**, which could be easily obtained by the Suzuki reactions as shown in Scheme 3. The whole synthetic route was very simple, and the purification was very easy. Thus, it should be an easy thing to prepare more thioacetals through this route if needed.

Compounds **3** and **4** exhibited good solubility in common organic solvents, such as chloroform, acetone, THF, etc. They were characterized by spectroscopic methods, and all gave satisfactory spectral data (see Materials and Instrumentation and Figure S1−6 in the Supporting Information).

Optical Properties. As shown in Figure 1, the aldehyde **1** emitted green light with the maximum emission wavelength centered at about 512 nm. After the reaction with ethanethiol, the obtained thioacetal **3** emitted deep blue luminescence (centered at about 397 nm), indicating that after the protection reaction of aldehyde, the electronic property of the resultant thioacetal changed, leading to the

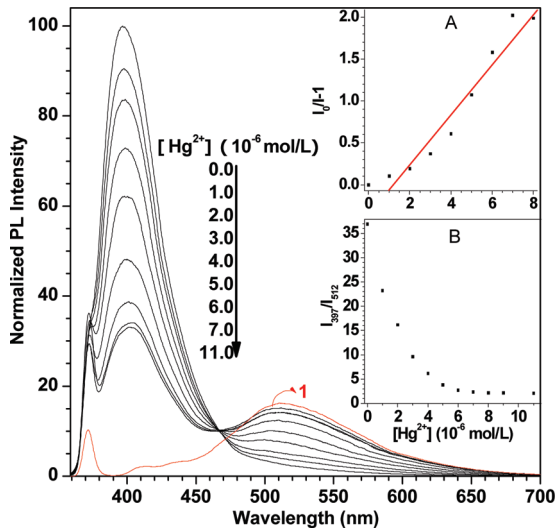


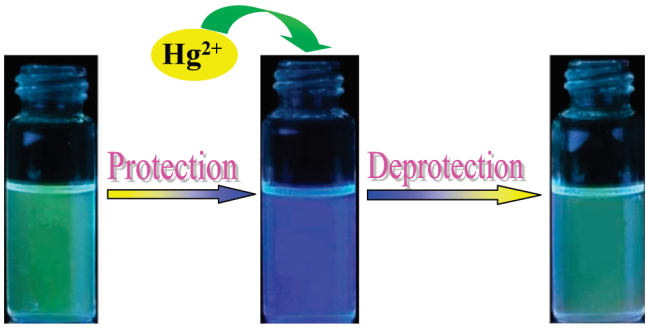
FIGURE 1. Normalized emission spectra of 1 (5 μM, red line) and 3 (5 μM, black line) in the presence of increasing concentration of Hg^{2+}. Insets: (A) plot of fluorescence titration of 3 with Hg^{2+}; (B) fluorescence difference I_{397}/I_{512} of 3 versus the concentration of Hg^{2+}.

different fluorescent behavior due to the different intramolecular charge transfer (ICT) efficiency. We then tried to add Hg^{2+} ions into the diluted solution of thioacetal **3**, excitingly, the emission intensity at 397 nm decreased immediately to about 90% of the original one at the concentration of Hg^{2+} ions as low as 1 μM. With the increasing concentration of Hg^{2+} ions in the test system, the intensity decreased correspondingly. However, when the concentration reached 7 μM, further increasing the concentration of Hg^{2+} ions to 11 μM, no big difference could be observed. Also, it was noticed that accompanying with the decreasing intensity at 397 nm, the fluorescent intensity at 512 nm increased, and when the concentration of Hg^{2+} ions became higher, the intensity was closer to that of aldehyde **1** with the same concentration.

Considering that the introduced trace water in the added Hg^{2+} solution might affect the intensity of thioacetal **3** during the fluorescence titration experiments, we studied the influence of the added trace water (see Figure S7 in the Supporting Information). The intensity really decreased upon the addition of trace water; however, only at a very limited degree, which would not affect the results of the titration experiment. Thus, these results indicated that upon the addition of Hg^{2+} ions, the Hg^{2+}-promoted deprotection reaction of thioacetal **3** really occurred as expected, and aldehyde **1** was formed step-by-step. To see the results more visually, we could summarize the intensity change as a function of Hg^{2+} ion concentration. As demonstrated in the inset A of Figure 1, there was a nearly linear relationship between the intensity change and the concentration of Hg^{2+} ions. A linear regression curve could be simulated, and the point at which this line crossed the abscissa axis was taken as the detection limit and equaled approximately 1 μM (15). By comparing the intensities at different wavelengths of 397 and 512 nm, we could concluded the obtained experimental results as another curve as shown in Figure 1 (inset B). Actually, the fluorescence difference for the solution of thioacetal **3** before and after the addition of Hg^{2+} ions could easily be distinguished by the naked eye as displayed in Chart 1 and Figure S8 in the Supporting Information, realizing our thought of the design of new chemosensors toward Hg^{2+} ions based on the ITC mechanism and the Hg^{2+}-promoted deprotection reaction of thioacetals.

To further confirm the deprotection reaction of thioacetal **3** upon the addition of Hg^{2+} ions in solutions, we measured the UV−vis and IR spectra of thioacetal **3** before and after the addition of Hg^{2+} ions, compared with that of aldehyde **1**. As shown in Figure 2, no absorption peak centered at about 1685 cm^{-1} was observed in the IR spectrum of

Chart 1. Protection and Deprotection Reactions of Aldehyde



thioacetal **3**, in good accordance to the absence of aldehyde groups. But after the addition of Hg^{2+} ions, a typical absorption peak of aldehyde groups at 1685 cm^{-1} appeared in the IR spectrum as the result of the reaction between **3** and Hg^{2+} ions, and this spectrum was nearly the same as that of aldehyde **1**, proving the successful deprotection reaction of thioacetal **3** in the presence of Hg^{2+} ions. The UV−vis spectra of **3** before and after the addition of Hg^{2+} ions also gave some proof (see Figure S9 in the Supporting Information).

To test the reproducibility of the sensing behavior of thioacetal **3** toward Hg^{2+} ions, we studied the fluorescence properties of thioacetal **3** at the presence and absence of Hg^{2+} ions at different concentrations. As demonstrated in Figure S10−13 in the Supporting Information, at higher concentrations, for example, 50 and 10 μM, the sensitivity was not good as shown in Figure 1 (5 μM). This was understandable: the sensing property of thioacetal **3** toward Hg^{2+} ions was according to the ICT mechanism; only after some needed amount of thioacetal **3** was converted to aldehyde **1** with the aid of Hg^{2+} ions could the fluorescence change be monitored. The higher concentration of thioacetal **3**, the more conversion needed, and thus, the relatively lower sensitivity. This might be another advantage of this kind of chemosensors: the linear range for the detection of Hg^{2+} ions could be adjusted conveniently by controlling the concentrations of the chemosensors, just as exhibited in Figures S11 and S13 in the Supporting Information and the inset of Figure 1. However, as shown in Figure S14, at the concentration of 1 μM, thioacetal **3** nearly gave no response to the addition of Hg^{2+} ions, possibly because of the low

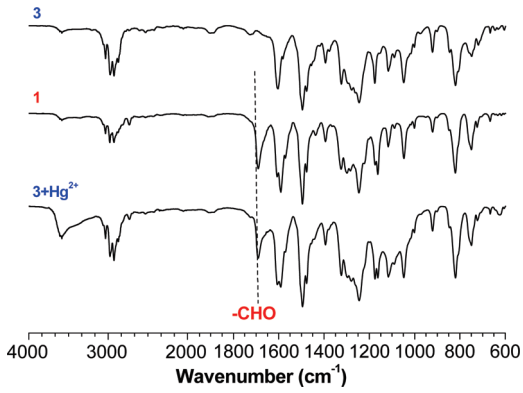


FIGURE 2. IR spectra of 3, 1, and the product of reacting 3 with Hg^{2+}.

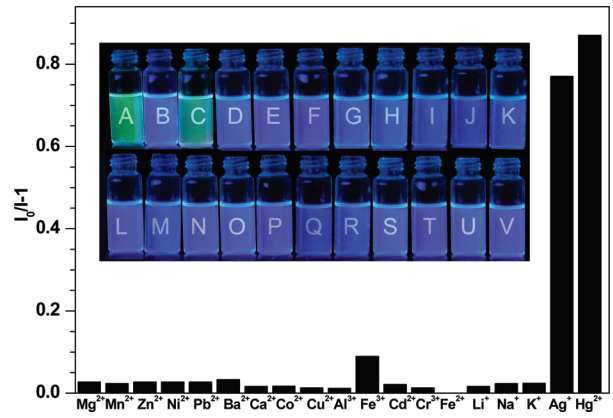


FIGURE 3. Fluorescence responses of 3 (10 μM) to various metal ions ([Hg^{2+}], 10 μM; [Fe^{3+}], 30 μM; [Ag^{+}], 30 μM; other ions, 50 μM). Excited at 370 nm. Inset: Fluorescence photograph of 3 to various metal ions ([Hg^{2+}], 7 μM; other ions, 25 μM). (A) 1 (5 μM); (B) 3 (5 μM); (C−V) 3+Hg^{2+}, Ba^{2+}, Ni^{2+}, Co^{2+}, Ca^{2+}, Cd^{2+}, Mg^{2+}, Zn^{2+}, Pd^{2+}, Mn^{2+}, Cr^{3+}, Fe^{3+}, Fe^{2+}, K^{+}, Na^{+}, Li^{+}, Al^{3+}, Cu^{2+}, Ag^{+}, mixture.

reacting activity of the deprotection reaction at this low concentration. Thus, 5 μM should be the optimized concentration of thioacetal **3** to act as a good chemosensor toward Hg^{2+} ions, correspondingly, the detection limit should be 1 μM. To further increase the sensitivity of this kind of Hg^{2+} chemosensors based on the deprotection reaction, there might be two approaches: one was to develop more reactive thioacetals, another was to design conjugated polymer-based chemosensors, because the "molecular wire effect" in conjugated polymers usually greatly enhanced the sensitivity because of the enhanced electronic communication among them. The related work was under progress in our laboratory.

To evaluate the Hg^{2+}-selective nature of **3**, the influence of other metal ions was investigated (see Figure S15 in the Supporting Information). As shown in Figure 3, except a little influence from Fe^{3+} (the response of Ag^{+} ions would be discussed later), other metal ions such as Ba^{2+}, Ni^{2+}, Co^{2+}, Ca^{2+}, Cd^{2+}, Mg^{2+}, Zn^{2+}, Pd^{2+}, Mn^{2+}, Cr^{3+}, Fe^{2+}, K^{+}, Na^{+}, Li^{+}, Al^{3+}, Cu^{2+} gave nearly no disturbance to the selective sensing of Hg^{2+}, indicating that the selectivity for Hg^{2+} was relatively high, and also proving the selectivity of the deprotection reaction of thioacetal for the metal ions. Also, as demonstrated in the inset of Figure 3, the different sensing behaviors could be easily seen by the naked eyes with the aid of a normal UV lamp. During the preparation of this paper, we found a report concerned on a thioacetal-based chemosensor for Cu^{2+} ions (16a); however, in our case, copper ions did not give any influence to the detection of Hg^{2+} ions, possibly because of the different chemical structure and testing conditions. Also, there was a report of the detection of Hg^{2+} (16b), but no influence from Ag^{+} ions reported as we investigated in the following part. Thus, to obtain more information of thioacetal-based chemosensors, much work is still needed.

As an interesting phenomenon, not all of the reported papers of Hg^{2+} chemosensors involved the possible influence from silver ions (17), and sometimes the Hg^{2+} chemosensors really gave response to the addition of trace silver ions. Although in the textbook, it was said that only in the

presence of mercury ions could the thioacetal undergo the deprotection reaction and convert to its original aldehyde, we still investigated the possible influence of silver ions. As shown in Figures S16 and 17 in the Supporting Information, upon the addition of silver ions, similar phenomena as in the case of Hg^{2+} ions were observed: the fluorescent intensity at 397 nm decreased, whereas that at 512 nm increased a little. However, the sensitivity was not as high as that toward Hg^{2+} ions. The results were unexpected, but reasonable if we considered carefully. As demonstrated in Scheme 1, thioacetals could be converted to aldehydes upon the addition of Hg^{2+} ions, because Hg^{2+} ions could form insoluble salts, $(RS)_2Hg$, with alkyl sulfide. As we knew, the solubility of RSAg was bad though a little better than $(RS)_2Hg$, thus, similar to Hg^{2+} ions, the Ag^+ ions should promote the deprotection reaction of thioacetals. The IR and UV−vis spectra of thioacetal **3** before and after the treatment with Ag^+ ions confirmed the conversion of thioacetal to aldehyde, in comparison with that of aldehyde **1** (see Figure S18 and 19 in the Supporting Information). This conversion was not mentioned in the textbook; however, our obtained experimental results indicated that in the deprotection reaction of thioacetal, Ag^+ ions could be an alternative choice to promote the reaction instead of Hg^{2+} ions in some special cases in which Hg^{2+} ions were prohibited. On the other hand, it was also important to probe the Ag^+ ions because it could inactivate sulfhydryl enzymes and combine with amine, imidazole, and carboxyl groups of various metabolites (18), and thus, thioacetal **3** could also be regarded as a good probe toward Ag^+ ions with relatively good detection limit of 6×10^{-6} mol/L. However, as shown in Figure 3, although the fluorescence intensity of the solution of thioacetal **3** changed at a large extent upon the addition of Ag^+ ions, the emission color of the resultant solution almost remained unchanged, even at the concentration of 25 μM, possibly because of the lower increasing of the emission at 512 nm (see Figure S17b in the Supporting Information), in comparison with that for Hg^{2+} ions. This, perhaps, was not a bad thing for the detection of Hg^{2+} ions. As discussed above, we would like to develop the ratiometric fluorescent probes for Hg^{2+} ions; although thioacetal **3** gave response toward Ag^+ ions when observed by the naked eye with the aid of a UV lamp, at concentrations lower than 25 μM, Ag^+ ions would give no disturbance to the detection of Hg^{2+} ions.

Considering the low concentration of thioacetal **3** used for the probing of Hg^{2+} ions (5 μM), we attempted to conduct the sensing process in aqueous solutions with a little amount of organic solvent in presence. As shown in Figure S20 and 21, thioacetal **3** did work in the aqueous solutions with the ratio of water/THF at 19:1. Other metal ions, including Ba^{2+}, Ni^{2+}, Co^{2+}, Fe^{3+}, Ca^{2+}, Cd^{2+}, Mg^{2+}, Zn^{2+}, Pd^{2+}, Mn^{2+}, Cr^{3+}, Fe^{2+}, Ag^+, K^+, Na^+, Li^+, Al^{3+}, Cu^{2+}, did not give apparent influence. Even in the presence of different metal ions mixture, thioacetal **3** could still give response to Hg^{2+} ions selectively (see Figure S22 in the Supporting Information). But the aqueous solution of thioacetal **3** was not very stable, and the reproducibility of the results was not as

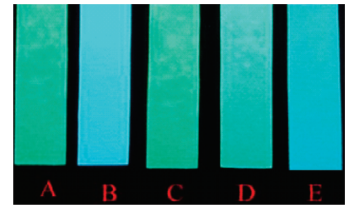


FIGURE 4. Fluorescence photographs of 1 (10^{-3} mol/L, A), 3 (1×10^{-3} mol/L, B), 3+Hg^{2+} (1×10^{-3} mol/L, C), 3+Hg^{2+} (1×10^{-4} mol/L, D), and 3+Hg^{2+} (1×10^{-5} mol/L, E).

good as those obtained in the organic solutions discussed above, which should be possibly ascribed to the different size of the formed nanoparticles of thioacetal **3** in the mixture solutions. Further research on the water-soluble sensors by utilizing this idea is under work in our laboratory. It should be pointed out that according to the mechanism of the deprotection of thioacetal with Hg^{2+}, water was the nucleophile that assisted the reaction in the presence of Hg^{2+} ions. Thus, in the mixture solvents, the deprotection reaction should be much faster than that in pure THF, because of the presence of large amount of water. However, interestingly, we could not distinguish the different response time in different test systems, because the readout time in the case of pure THF was very fast (upon the addition of Hg^{2+} ions, immediately, the emission color changed). This should be an advantage of this kind of probes: ultra fast response speed.

To investigate the practical application of thioacetal **3**, we prepared test strips by immersing filter paper into the THF solution of thioacetal **3** (1×10^{-3} mol/L) and then dried in air. When dipped into the solutions of Hg^{2+} ions with different concentrations, the test strips containing thioacetal **3** demonstrated apparent color changes excited at 365 nm under a UV lamp, which were similar to that of **1** and the discernible concentration of Hg^{2+} ions could be as low as 1.0×10^{-4} mol/L (Figure 4). Thus, these strips could be conveniently handled at any moment for the detection of Hg^{2+} ions.

To check the above experimental results from another aspect, we further designed and synthesized another thioacetal, compound **4**, with similar molecular structure to thioacetal **3** (Scheme 2), in which the previous ethoxy group was replaced by the cyano one. As a result, the ICT property in thioacetal **4** was different from that in **3**, because the cyano group was an electronic withdrawing moieties while ethoxy was donor one. This difference could be partially proved by the different maximum emission wavelength of **4** (457 nm) in comparison with that of **3** (397 nm). Figure 5 demonstrated the fluorescent behavior of thioacetal **4** in the presence and absence of Hg^{2+} ions. It was easily seen that upon the addition of Hg^{2+} ions, the emission intensity decreased immediately; with the increase in concentration of the added Hg^{2+} ions, the intensity further decreased. When the concentration of Hg^{2+} ion was 18 μM, the intensity was similar to that of aldehyde **2**. In the case of thioacetal **3**, upon the addition of Hg^{2+} ions, the fluorescence intensity at 512 nm increased, leading to the color change of the fluorescence. However, here, after the addition of Hg^{2+} ions

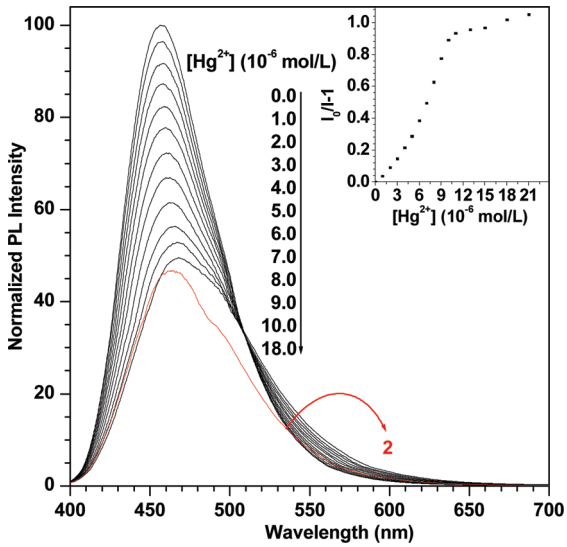


FIGURE 5. Normalized emission spectra of **2** (5 μM, red line) and **4** (5 μM, black line) in the presence of increasing concentration of Hg^{2+}, excited at 370 nm in THF.

into the diluted solution of thioacetal **4**, besides the decrease in the fluorescent intensity, the profile changed only a little, and no new peak appeared. But interestingly, under the excitation of a UV lamp at the wavelength of 365 nm, we could easily see the obvious different luminescence of thioacetal **4** and aldehyde **2** by naked eyes (see Chart S1 in the Supporting Information). To conduct the sensing experiments at different concentrations of thioacetal **4**, we obtained similar results, whereas the linear range for the detection of Hg^{2+} ions was different (see Figures S23−26 in the Supporting Information), and the detection limit was determined to be 5.0×10^{-7} mol/L.

As shown in Figures S27 and 28 in the Supporting Information, the introduced trace water and metal ions nearly did not cause apparent influence, indicating the good selectivity of thioacetal **4** toward Hg^{2+} ions. The sensing process could also be observed visually as demonstrated in Figure 6. The Ag^{+} ion could promote the conversion reaction of thioacetal **4** to aldehyde **2**, similar to what is observed in the case of thioacetal **3** (see Figures S29−S33 in the Supporting Information). Similar to thioacetal **3**, thioacetal **4** could give a response to Hg^{2+} ions in aqueous solution and solid state with relatively good performance (see Figures S34−S40 and Chart S2 in the Supporting Information).

Thus, the obtained experimental results of thioacetal **4**, on the one hand, further proved our idea for the development of good chemosensors toward Hg^{2+} ions; moreover, on the other hand, they indicated that by simply adjusting the chemical structure, the fluorescence properties of the resultant luminophores could be conveniently modified. Although **3** and **4** could be used in the mixture solvents of THF and water to probe the possible presence of Hg^{2+} ions, it was still a pity that they were not soluble in water without the aid of organic solvents. However, by modifying the structure, for example, to introduce some hydrophilic groups to them, the water-soluble chemosensors could be obtained. Therefore, it was believed that after optimizing the structural design, more Hg^{2+} ions chemosensors with better performance could be obtained, by utilization of the Hg^{2+}-promoted deprotection reaction coupled with the ICT mechanism. Further study is still in progress in our laboratory.

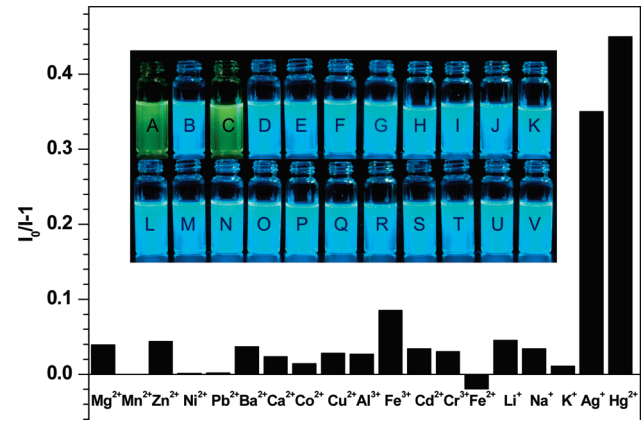


FIGURE 6. Fluorescence responses of **4** (10 μM) to various metal ions ([Hg^{2+}], 10 μM; [Ag^{+}], 40 μM; other ions, 50 μM). Excited at 370 nm. Inset: Fluorescence photograph of **4** to various metal ions ([Hg^{2+}], 20 μM; [Ag^{+}], 25 μM; other ions, 50 μM). (A) **2** (10 μM); (B) **4** (10 μM); (C−V) **4** + Hg^{2+}, Ba^{2+}, Ni^{2+}, Co^{2+}, Ca^{2+}, Cd^{2+}, Mg^{2+}, Zn^{2+}, Pd^{2+}, Mn^{2+}, Cr^{3+}, Fe^{3+}, Fe^{2+}, K^{+}, Na^{+}, Li^{+}, Al^{3+}, Cu^{2+}, Ag^{+}, mixture.

CONCLUSIONS

In summary, two new ratiometric fluorescent chemosensors **3** and **4** were constructed with the concept of aldehyde group protection/deprotection reaction. Both probes displayed high sensitivity and selectivity for Hg^{2+} and Ag^{+} over other metal ions because of the distinct deprotection reaction of thioacetal. In addition, **3** and **4** could serve as practical fluorescent chemosensors for rapid detection of Hg^{2+} ion by virtue of test strips.

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Supporting Information Available: NMR and MALDI-TOF spectra; UV−vis and fluorescent spectra; photos (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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