A new chemosensor that signals Hg(II), Cu(II) and Zn(II) at different emission wavelengths: selectivity toward Hg(II) in acetonitrile†

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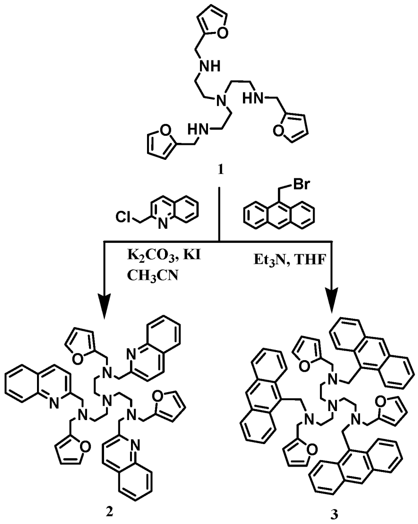
A new tripodal fluoroionophore bearing furan and quinoline moieties, 2, senses Hg^{2+}, Cu^{2+} and Zn^{2+} in acetonitrile by displaying enhanced fluorescence at distinct wavelengths. Chemosensor 2 also shows selectivity toward Hg^{2+} and senses Hg^{2+} even in the presence of acid in the media. When quinoline is replaced with a non-coordinating signaling unit like an anthryl moiety, the fluoroionophore fails to sense Hg^{2+} selectively.

Molecular fluorescent chemosensing of metal ions is a promising field in chemistry with proven roles in environmental, biological and clinical applications.[1,2] Hg^{2+} is a well known global pollutant and remains a danger to human health; exposure of the human body to even a low concentration of Hg^{2+} can lead to neurological diseases, various cognitive and motion disorders, and damage to the prenatal brain, digestive system and kidney.[3a–c] A huge amount of mercury is released to the environment by natural and anthropogenic sources including oceanic and volcanic emission, gold mining, solid waste incineration, combustion of fossil fuels and the chlor-alkali industry. Furthermore the water soluble Hg^{2+}, $MeHg^{+}$ cations, and highly toxic Me_2Hg are of serious environmental concern.[3d–g] On the other hand, Cu^{2+} and Zn^{2+} have crucial roles in biological systems.[4] A large number of studies of fluorescence-based sensing of different metal ions have been reported, which deal with different aspects of chemosensing *e.g.* sensitivity, selectivity *etc.*[1,3d,5] In recent times, a number of Hg^{2+} selective chemosensors have also been developed.[3d,6] Sensing of multiple metal ions by a single chemosensor and using a single technique *via* displaying distinct outputs for different ions is desirable. Of course, a "quadruple-channel sensing" of Cu^{2+}, Pb^{2+} and Hg^{2+}, and the "lab-on-a-molecule" that simultaneously responds to the electrolyte inputs like Zn^{2+}, H^{+} and Na^{+} have recently been described.[7] Two important mechanisms, photoinduced electron-transfer (PET)[1a–d] and chelation enhanced fluorescence (CHEF), are popular in the development of sensors for metal ions.[8] Herein, we report a tris(2-aminoethyl)amine (tren) based, furan and quinoline functionalized tripodal fluoroionophore (**2**), as a fluorescence enhancement based chemosensor for Hg^{2+}, Cu^{2+} and Zn^{2+} in acetonitrile. We also show that **2** has selectivity toward Hg^{2+} and can detect Hg^{2+} in the presence of acid.

Chemosensor **2** is composed of an ionophore having N7O3 donor sets for binding of metal ion, contributed by tren, quinoline and furan units. Fluorophore (quinoline) and furan units are attached to three nitrogen centers of tren through a methylene spacer. On the other hand, **3** is composed of N4O3 donor sets from tren and furan moieties where anthryl units act as fluorophoric centers. These two fluoroionophores were synthesized following the procedure in Scheme 1. In brief, **2** and **3** were prepared by one-step reaction of furan attached tren ligand, **1**, with 3.1 equiv. of 2-chloromethylquinoline hydrochloride in acetonitrile (CH_3CN) and 9-bromomethylanthracene in tetrahydrofuran (THF), respectively. The crude products **2** and **3** were purified by column chromatography using $CHCl_3$–EtOAc and $CHCl_3$–CH_3OH gradient, giving **2** and **3** in 32% and 37% yield, respectively. The reaction between tren and 3 equiv. of furfuraldehyde followed by sodium borohydride reduction in methanol yielded **1** as a yellow oil. Details of these syntheses and characterization data of all new compounds (**1–3**) are provided in the ESI.†

Fluoroionophore **2** showed modified UV-absorbance and emission spectral characteristics (Fig. 1), when compared with standard quinine bisulfate, though in both cases λ_{max} was observed at 315 nm. A low intense emission (band positions at 393, 415 and 441 nm) was observed on excitation with 315 nm light. The low emission intensity was due to the PET process



Scheme 1 Syntheses of fluoroionophores **2** and **3**.

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† Electronic supplementary information (ESI) available: Syntheses, characterization data of **1–3** along with copies of ^{1}H-NMR, ^{13}C-NMR and HRMS(ESI) spectra. Fluorescence data of **2** and **3** in presence of different inputs. See DOI: 10.1039/b9nj00204a

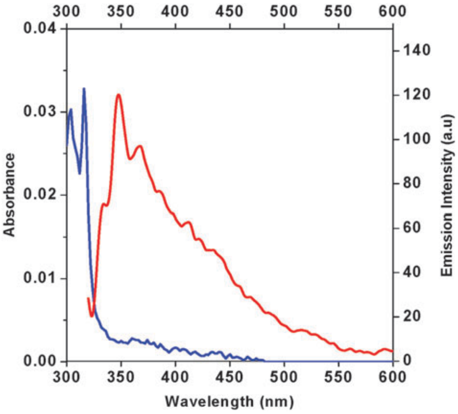

Fig. 1 UV-absorbance and emission spectra of **2** (5×10^{-6} M) in CH_3CN at 298 K. λ_{exc} = 315 nm.

between the excited state fluorophore and lone pair electrons of nitrogen and oxygen centers. The ionophore **2** having four tertiary nitrogen atoms, three quinoline nitrogen atoms and three furan oxygen atoms would be expected to promote different coordination with different metal ions. **2** displayed a new broad emission peak in the presence of $Hg^{2+}/Cu^{2+}/Zn^{2+}$ as an input in CH_3CN where a broad peak was centered at 421, 405 and 393 nm, respectively (Fig. 2). The difference in spectral shifts may be attributed to the different coordination environments and geometries of these three metal ions towards the soft donor N7O3 coordination environment. Furthermore, Hg^{2+}, being a soft metal ion compared to Cu^{2+} and Zn^{2+}, prefers to form a stronger metal ligand complex. In the cases of inputs like Li^+, Na^+, Ca^{2+}, Ni^{2+}, Ag^+, Cd^{2+} and H^+, **2** did not show much difference in the fluorescence output, when compared to Hg^{2+}, Cu^{2+} and Zn^{2+} as inputs (Fig. 2). The fluorescence intensity enhancement factors at 421, 405 and 393 nm in the cases of Hg^{2+}, Cu^{2+} and Zn^{2+} were 8.3, 2.8 and 3.6, respectively with respect to the emission of **2** at the corresponding wavelength. The enhancement of fluorescence along with a shift in the spectral position was attributed to the combined effect of PET and CHEF of **2** in presence of these ions. Maximum fluorescence enhancement as well as maximum spectral shift of **2** was observed with Hg^{2+} input. We have also examined the effect of different metal ions on chemosensor **2** in $CH_3CN–H_2O$ = 8 : 2 (v/v) binary solvent mixture. The emission output observed was similar to that observed in CH_3CN (Fig. S18, ESI†). In contrast, chemosensor **2** fails to sense any metal ion in $CH_3CN–H_2O$ = 1 : 1 (v/v) binary solvent mixture (Fig. S19, ESI†).

In order to find the selectivity of Hg^{2+} over Cu^{2+} and Zn^{2+}, we have performed the following two experiments. When 100 equiv. of Hg^{2+} were added to the CH_3CN solution of **2** (5×10^{-6} M) containing 100 equiv. of Cu^{2+} or Zn^{2+}, the resultant solution showed maximum fluorescence output with a maximum spectral shift as observed in the case of **2** in the presence of Hg^{2+} (Fig. 3). Secondly, a selectivity experiment was also carried out by adding 100 equiv. each of cations like Zn^{2+} and Hg^{2+} or Cu^{2+} and Hg^{2+} to **2** (5×10^{-6} M) in CH_3CN. In all cases fluorescence output was slightly higher but closely matched the **2.Hg^{2+}** emission (Fig. S10, ESI†). These two control experiments suggested selectivity of **2** toward Hg^{2+} over other cations tested in this system. Selectivity toward Hg^{2+} could be due to the soft nature of the ligand donor set N7O3 which is composed of tertiary nitrogen centers as well as furan oxygen atoms. Hence, chemosensor **2** prefers the softer metal ion Hg^{2+} compared to Cu^{2+}/Zn^{2+} which are hard in nature.

To evaluate the binding constant of Hg^{2+} with **2**, we carried out fluorescence titration experiments in CH_3CN (Fig. 4). 5×10^{-6} M solution of **2** was titrated with different aliquots of Hg^{2+} solution (5×10^{-4} M). Chemosensor **2** in CH_3CN displayed a very weak fluorescence. However, on titration of **2** with Hg^{2+} ions (up to 100 equiv.), the fluorescence intensity of **2** was enhanced gradually along with a gradual shift in the spectral positions. The binding constant value of **2** with Hg^{2+} was determined from the emission intensity data following the modified Benesi–Hildebrand equation[9] (ESI†). From the plot of $(I_{max} - I_{min})/(I - I_{min})$ against $[Hg^{2+}]^{-1}$, the value of K ($+10\%$) extracted from the slope was 1.7×10^4 M^{-1}. Similar titration experiments on sensor **2** with Zn^{2+} and Cu^{2+} in CH_3CN showed binding constants 3.3×10^3 M^{-1} and 1.0×10^4 M^{-1}, respectively (Fig. S14–S17, ESI†). These binding constants quantitatively suggest that **2** has selectivity toward Hg^{2+} over Cu^{2+}/Zn^{2+} in CH_3CN.

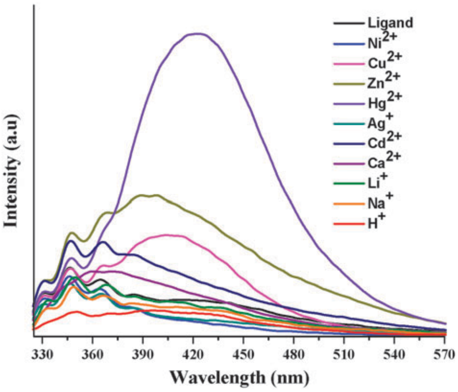

Fig. 2 Fluorescence response of **2** (5×10^{-6} M) with various metal ions in CH_3CN at 298 K. λ_{exc} = 315 nm.

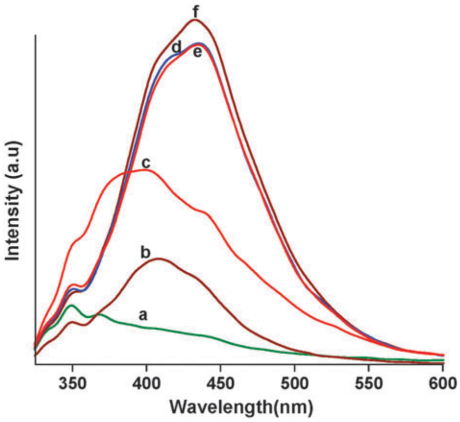

Fig. 3 (a) Emission spectra of (5×10^{-6} M) of **2** in CH_3CN; (b) (5×10^{-6} M) of **2** in presence of 100 equiv. of Cu^{2+}; (c) Zn^{2+}; (d) Hg^{2+}; (e) addition of 100 equiv. of Hg^{2+} to 'b'; (f) addition of 100 equiv. of Hg^{2+} to 'c'.

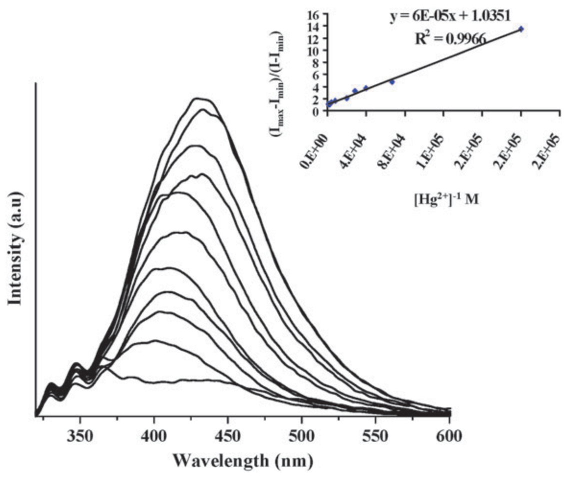

Fig. 4 Fluorometric titration of **2** (5×10^{-6} M) with different concentrations of Hg^{2+} in CH_3CN. Inset showing Benesi–Hildebrand linear plot for **2** with different concentrations of Hg(II) at 298 K. λ_{exc} = 315 nm.

Generally, in PET based systems, the presence of acid interferes with the sensing of metal ions because H^+ can also act as an input like metal ions. Upon protonation at the PET center, the PET process can be stopped similarly to metal ion as an input. Here, **2** showed characteristic emission with intensity enhancement ($\lambda_{emission}$ at different wavelengths) in presence of Hg^{2+}/Cu^{2+}/Zn^{2+} whereas H^+ as an input showed slight quenching of emission bands when compared to **2** (Fig. 2). This indicates that protonation did not block all the PET centers in this system. We have also performed detailed studies on the emission behavior of **2** in presence of different H^+ concentrations (0.004 M, 0.008 M, 0.012 M, 0.02 M and 0.025 M hydrochloric acid, HCl) (Fig. S20, ESI†). Though there is a slight enhancement of the emission of **2** in presence of 0.004 M HCl, gradual quenching of emission bands is observed with the increase of acid concentration. Specially, in presence of 0.02 M or higher concentration of HCl, **2** (5×10^{-6} M) in CH_3CN displayed a very weak fluorescence. It might be due to the partial protonation at the nitrogen centers of **2** and therefore the photoinduced proton transfer (PPT) quenching process takes place from the protonated nitrogen centers of **2** to the excited state unprotonated quinoline nitrogen centers.[10] Based on this observation we were interested to study the fluorescence switching effect of Hg^{2+} in presence of acid in the medium.

Upon gradual addition of Hg^{2+} to this acidic solution (0.02 M HCl) of **2**, gradual enhancement of fluorescence (Fig. 5) was shown up to a certain concentration of Hg^{2+} (1.8×10^{-3} M) and further addition showed the quenching of fluorescence. Of course, the enhancement factor in the case of the acidic medium was almost half that of **2.Hg^{2+}** in non-acidic conditions. Chemosensor **2** has multiple protonating sites (N7) but in non-aqueous medium partial protonation takes place and the PPT process shows quenching of fluorescence. When Hg^{2+} is added as an input to this system, it could have access to bind to the rest of the unprotonated nitrogen centers as well as three furan oxygen atoms and that partially blocks PPT and PET processes.

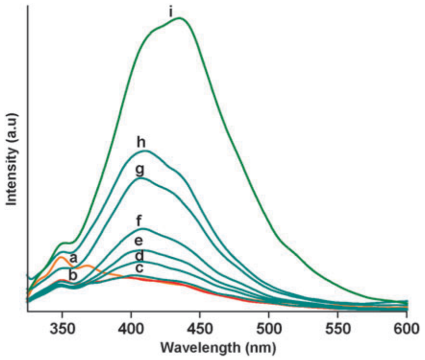

Fig. 5 (a) Emission spectra of **2** (5×10^{-6} M) in CH_3CN; (b) **2** (5×10^{-6} M) in CH_3CN in presence of 0.02 M HCl; (c) solution 'b' in presence of 2×10^{-4} M Hg^{2+}; (d) 1×10^{-3} M Hg^{2+}; (e) 1.2×10^{-3} M Hg^{2+}; (f) 1.4×10^{-3} M Hg^{2+}; (g) 1.6×10^{-3} M Hg^{2+}; (h) 1.8×10^{-3} M Hg^{2+}; (i) **2** (5×10^{-6} M) in presence of 5×10^{-4} M Hg^{2+}.

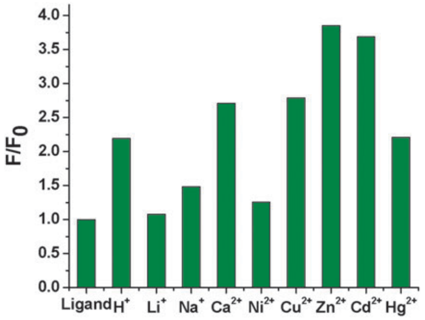

Fig. 6 Fluorescence responses of **3** (1×10^{-7} M) in THF with the addition of 100 equiv. of various metal ions and H^+.

To establish the role of the coordinating signaling unit, we have synthesized chemosensor **3**, in which the coordinating quinoline fluorophore in **2** was replaced by a non-coordinating anthryl moiety. The fluoroionophore **3** (1×10^{-7} M) in THF showed fluorescence peaks characteristic of the anthryl moiety, centered at 391, 412 and 436 nm (Fig. S11, ESI†). In the case of inputs like Li^+, Na^+ and Ni^{2+} with **3**, there was almost no effect in the fluorescence output but Ca^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+} and H^+ showed enhancement of fluorescence intensities (2–4 times) (Fig. 6) and with a slight spectral shift (2–6 nm) (Fig. S12, ESI†). Furthermore, addition of Hg^{2+} displayed quenching of fluorescence of **3** in the presence of acid (Fig. S13, ESI†).

In conclusion, the present study demonstrates that fluoroionophore **2**, bearing three quinoline moieties as coordinating signaling units attached to the nitrogen centers *via* a methylene spacer and three furan moieties in close proximity to the PET unit, is a viable candidate for sensing of Hg^{2+}, Cu^{2+} and Zn^{2+} in acetonitrile at different wavelengths. This study also shows that **2** has a preference for binding with Hg^{2+} over other metal ions and it can also sense Hg^{2+} in acidic conditions.

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