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Terphenyl based ‘Turn On’ fluorescent sensor for mercury

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ABSTRACT

New terphenyl-based derivative **4** with pyrene as a fluorophore has been synthesized and examined for its cation recognition abilities toward various cations by NMR and fluorescence spectroscopy. The results show that it has very high binding affinity (log $\beta = 5.12$) and selectivity for mercury. A fluorescence enhancement of 375% was observed for the 4-Hg^{2+} system in THF. A Hg^{2+} selective electrode (ISE) was also formed which showed excellent selectivity over all the other cations tested. The lower limit of detection is 2.1×10^{-6} M.

The development of selective sensors for heavy and soft metal ions is very important because pollution due to them poses severe risks for human health and environment.[1] Among heavy and soft metal ions, mercury contamination is widespread and occurs through a variety of natural and soft metal anthropogenic sources[2] including oceanic and volcanic emission,[2,3] gold mining,[4] solid waste incineration, and combustion of fossil fuels.[5] Even the low dose exposure of mercury may lead to digestive, kidney and especially neurological diseases.[6] Keeping in view the roles played by mercury in day-to-day life, the development of techniques for mercury hazard assessment and mercury pollution management is in great demand. Fluorescence signaling is one of the first choices due to its high detection sensitivity and simplicity which translates molecular recognition into tangible fluorescence signals.[7] Thus, designing fluorescent sensors for mercury[8] has drawn worldwide attention. In most of the fluorescent sensors reported for mercury, so far, the binding of the mercury with the ionophore results in nonspecific fluorescence quenching via spin–orbit coupling[8] associated with the heavy atom effect, which will facilitate the intersystem crossing process. Fluorescence quenching is not only disadvantageous for a high signal output upon recognition but also hampers temporal separation of spectrally similar complexes with time-resolved fluorometry.[9] Fluorescence enhancement on the other hand is an ideal phenomenon for the metal ion recognition. However, the designing of fluorescence ‘Turn On’ type sensors upon mercury binding is a challenging issue and only a few fluorescence ‘Turn On’ sensors for mercury have been reported.[10] One of the approaches to this phenomenon would be the design of receptor having an ’Off’ state of the fluorophore which upon addition of an external analyte causes fluorescence enhancement by turning ’On’ the fluorescence.

Our research involves the design, synthesis, and evaluation of (thia)calix[4]arene-based receptors for selective soft metal ions sensing. Recently, we reported a new ratiometric fluorescent sensor for mercury based on calix[4]arene of partial cone conformation.[11] The compound exhibited ratiometric sensing of Hg^{2+} and the receptor behaves as a fluorescent molecular switch upon chemical inputs of Hg^{2+} and Cu^{2+}. Now, we have prepared a ‘Turn On’ fluorescent sensor for Hg^{2+} ions based on terphenyl appended with pyrene moieties. Terphenyls are the key intermediates for the synthesis of symmetrically and unsymmetrically substituted triphenylenes which play an important role in supramolecular and material chemistry, as their liquid crystalline behavior can be modified by changing electronic properties of their substituents. Recently Lehmann co-workers reported a [15] crown-5 appended terphenyl which shows mesomorphic properties in the presence of sodium ions.[12] Thus, in the present letter, we report the synthesis, characterization, and mercury sensing properties of terphenyl-based compound **4** having pyrene moieties. We have chosen pyrene as fluorophore because of its high detection sensitivity.[13] In the presence of Hg^{2+} ions, the receptor **4** undergoes 375% increase in the emission band which is attributed to the receptor–Hg^{2+} complex (Fig. 1). A mercury ion-selective electrode has also been formed which showed excellent selectivity over all the other cations tested. To the best of our knowledge, this is the first report where pyrene-substituted-terphenyl based compound has been used for sensing of Hg^{2+} ions.

Compound **4** was synthesized in two steps (Scheme 1). Suzuki-Miyaura cross coupling of **1**[15] with **2**[16] catalyzed by Pd(II) furnished compound **3** (50%).[17] The ^{1}H NMR spectrum of compound **3** showed two singlets (18H, 12H) for *tert*-butyldimethylsilyl (TBS) group, one broad signal for amino (NH_2) group, one singlet, and two doublets (2H, 4H, 4H) for aromatic protons of terphenyl moiety. The FAB mass spectrum showed a parent ion peak at 520 (M^+) corresponding to coupled product **3**. Condensation of diamine **3** with 2.0 mol equiv. of 1-pyrene carboxaldehyde in ethanol gave

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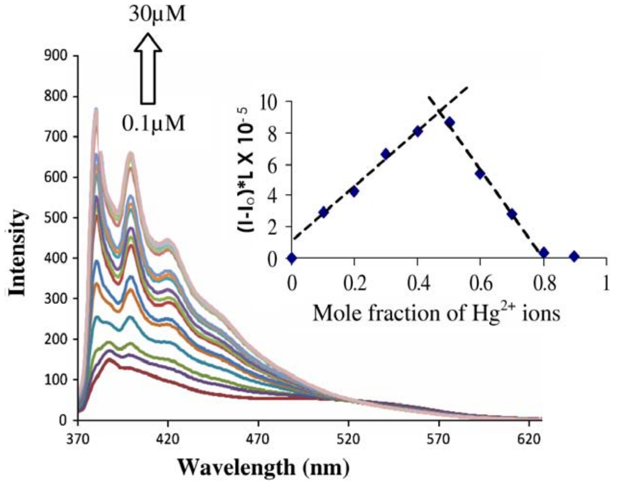


Figure 1. Fluorescence response of receptor 4 (1 μM) on addition of Hg^{2+} (0.1–30 equiv) in THF–H_2O (9.5:0.5) λ_{ex} = 345 nm. Inset: Job plot of receptor 4 with Hg^{2+} ions with a total concentration of ([L]+[Hg^{2+}]) 2.5 μM in THF.

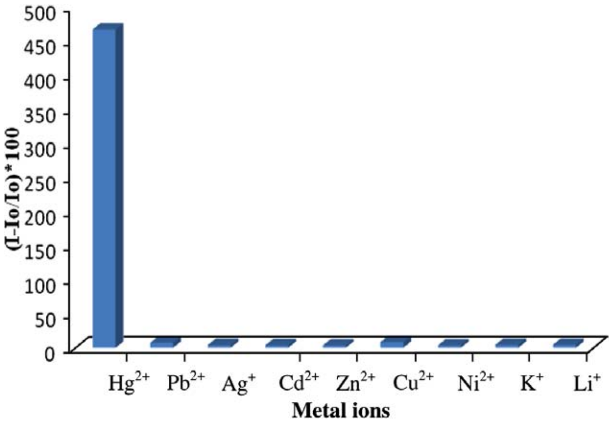


Figure 2. Fluorescence enhancement ratio [($I-I_o/I_o$) × 100] of receptor **4** (1.0 μM) at 345 nm upon addition of different metal ions (30 equiv, 30 μM) in THF–H_2O (9.5:0.5).

target compound **4**[18] in 50% yield (Scheme 1). The structure of compound **4** was confirmed from its spectroscopic and analytical data. The ^{1}H NMR spectrum of compound **4** showed two singlets (18H, 12H) for TBS group, two singlets and two doublets (2H, 4H, 2H, 2H) for aromatic protons of terphenyl moiety, one multiplet (18H) for pyrene protons, and one singlet (2H) for imine proton (N═C–H). A parent ion peak was observed at 945 $(M+1)^+$ in the FAB mass spectrum. These spectroscopic data corroborate with structure **4** for this compound.

The binding behavior of compound **4** toward different cations (Cu^{2+}, Hg^{2+}, Pb^{2+}, Zn^{2+}, Ni^{2+}, Cd^{2+}, Ag^+, K^+, Na^+, and Li^+) was investigated by fluorescence and NMR spectroscopy. In the fluorescence spectrum, compound **4** exhibits a weak monomer emission at 389 nm when excited at λ = 345 nm. This weak emission from compound **4** is due to photo-induced electron transfer (PET) from the imino nitrogen to the photo-excited pyrene which leads to poor emission. Upon addition of increasing amounts of Hg^{2+} from 0.1 to 30 μM to the solution of compound **4** in THF–H_2O (9.5:0.5), a significant increase (375%) in the emission band attributed to the receptor–Hg^{2+} complex is observed (Fig. 1). Such fluorescence enhancement observed for **4** in the presence of Hg^{2+} is attributed to the co-ordination of imino nitrogens of **4** with Hg^{2+} ions leading to the formation of co-ordination complex as a result of which the PET from imino nitrogen to pyrene moiety is suppressed which results in fluorescence enhancement. Under the same conditions as used above for Hg^{2+}, we also tested the fluorescence response of **4** to other metal ions such as Pb^{2+}, Ag^+, Cd^{2+}, Zn^{2+}, Cu^{2+}, Ni^{2+}, K^+, and Li^+ besides Hg^{2+}, and as shown in Figure 2, no significant fluorescence change of **4** occurred in the presence of these metal ions which indicates that all these metal ions were not coordinating with the imino nitrogen atoms of the compound **4**. The addition of potassium iodide to the solution of **4**-Hg^{2+} resulted in quenching of fluorescence intensity which was revived again on addition of Hg^{2+} ions indicating that the change in fluorescence on addition of mercury is reversible. The stoichiometry of the complex formed between compound **4** and Hg^{2+} ion was evaluated by the method of continuous variation (Job's plot) and it was found to be 1:1 (H:G) which indicated that one Hg^{2+} ion was interacting with receptor **4**. The association constant (log β) of compound **4** with Hg^{2+} ions was calculated from fluorescence titration experiments by means of SPECFIT program (global analysis system V3.0 for 32-bit Window system), which uses singular value decomposition and non-linear regression modeling by the Lever berg–Marquardt method[19] and was found to be 5.12. The global analysis showed that the titration curves were consistent with the formation of 1:1 (H:G) complex.

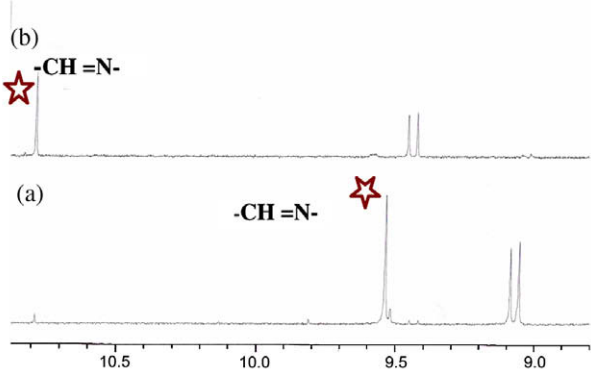
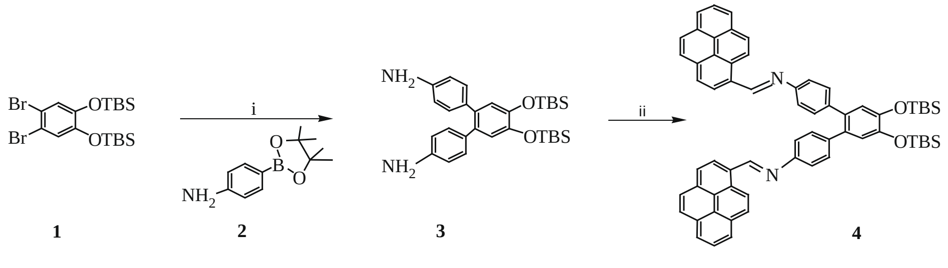


Figure 3. Partial ^{1}H NMR spectrum ($CDCl_3$–CD_3CN, 8:2) of receptor **4** before (a) and after (b) addition of Hg^{2+} ions.



Scheme 1. Synthesis of receptor **4**. Reagents and conditions: (i) [$Pd(PPh_3)_2(Cl)_2$], dioxane, H_2O, K_2CO_3, overnight refluxing[17]; (ii) 1-pyrene carboxaldehyde, absolute ethanol, rt.[18]

The detection limit of **4** as a fluorescent sensor for the analysis of Hg^{2+} was found to be 2.1×10^{-6} mol L^{-1} which is sufficiently low for the detection of submillimolar concentrations of Hg^{2+} ions as found in many chemical systems.

To elucidate the binding mode of receptor **4** with Hg^{2+}, the ^1H NMR spectrum of its complex with mercury perchlorate was also recorded. A significant downfield shift of 1.26 ppm is observed for the imino protons, which indicates that the imino nitrogens are coordinating with Hg^{2+} ions through their lone pairs of electrons (Fig. 3). Thus, from this NMR study, we may conclude that mercury is interacting with receptor **4** as supported by fluorescence studies.

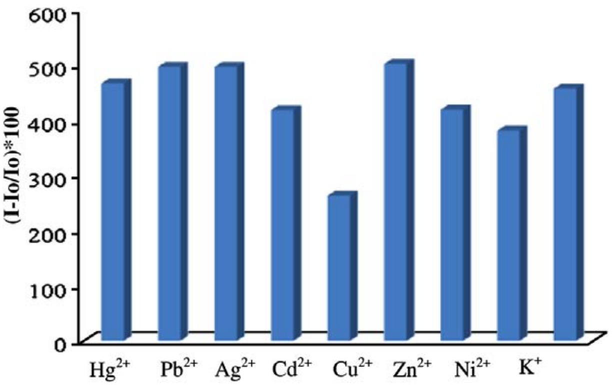


Figure 4. Competitive selectivity of receptor 4 (1.0 μM) toward Hg^{2+} (30 equiv, 30 μM) in the presence of other metal ions (300 equiv, 300 μM).

Table 1
Composition and potential response characteristics of mercury ion-selective electrode

PVC (mg)	DOS (mg)	NaTPB (mg)	Ionophore (mg)	Linear range (M)	Slope (mV/decade)
101.2	201.1	1.3	5.4	1.0×10^{-1}–5.0×10^{-6}	28.86

NaTPB: Sodium tetraphenylborate.
DOS = Dioctyl sebacate as plasticizer.

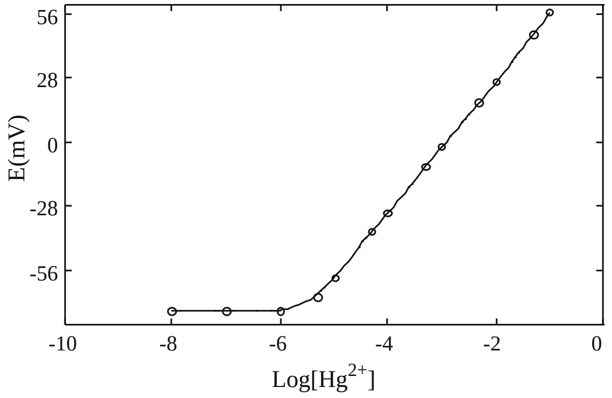


Figure 5. Potentiometric response curve of ISE based on receptor **4**: Hg^{2+} selective electrode.

The practical applicability of compound **4** as a Hg^{2+} selective fluorescence sensor was tested by carrying out competitive experiments in the presence of Hg^{2+} at 30 μM mixed with Li^+, K^+, Ni^+, Cu^{2+}, Zn^{2+}, Cd^{2+}, Ag^+, and Pb^{2+} at 300 μM. As shown in Figure 4 no significant variation in fluorescence intensity change ($I - I_o/I_o \times 100$) was found by comparison with or without the other metal ions besides Hg^{2+} ions, except for Cu^{2+} ions which interfere with the detection of Hg^{2+} ions.

Thus, from the fluorescence and NMR studies it may be concluded that mercury ions selectively complex with **4** in comparison to other cations. Based on the results of these binding studies we envisaged that it should be possible to construct mercury ion selective PVC membranes based on **4**. Thus, a sensor membrane for **4** was prepared and assembled as previously reported from our laboratory for mercury ions.[14] The composition of this membrane is listed in Table 1. The PVC membrane of the cation receptor generated a stable potential when placed in contact with mercury nitrate solution. The emf response of the membrane in the presence of a wide range of mercury ion solutions is shown in Figure 5. The electrodes demonstrate a linear response for Hg^{2+} ions in the concentration range from 1.0×10^{-1} to 5.0×10^{-5} mol dm^{-3}.

The slope of the plot was approx. 28.86 mV per decade of concentration which indicates the near Nernstian nature of the electrode. The response time of the membrane was measured at different concentrations and was found to be less than 10 s and no change was observed up to 5 min. Potentials were measured periodically at a fixed concentration and the standard deviation of ten identical measurements was ±1 mV. The dependence of the membrane potentials on pH was studied at 1.0×10^{-3} mol dm^{-3} Hg^{2+} ion concentration. The potential remained constant from pH 1.3 to 4.3 which may be taken as the operational pH range of the sensor. The most important feature of an ion-selective electrode is its response to its primary ion in the presence of various other cations. This is measured in terms of the potentiometric selectivity coefficient ($K^{pot}{}_{A,\ B}$) which was evaluated by the fixed interference method at 1.0×10^{-2} mol dm^{-3} concentrations of various interfering ions. Table 2 shows the potentiometric selectivity coefficient data of the imine derivatized terphenyl-based PVC membrane electrode for the interfering cations relative to Hg^{2+}. $K^{pot}{}_{A,\ B}$ was fairly low for all the cations tested which indicates that there is no interference present with the determinant ion (Hg^{2+}).

The electrode assembly was tested as an indicator electrode to determine the end point in the potentiometric titration of Hg^{2+} with a standard solution of sodium iodide. A 20 ml solution of 1.0×10^{-2} mol dm^{-3} mercury nitrate was titrated against 1.0×10^{-2} mol dm^{-3} sodium iodide solution. The sharp rise in the potential indicates the end point (Fig. 6).

Thus, we have prepared a new pyrene-substituted terphenyl-based sensor **4** in high yield and its binding behavior toward different metal ions was investigated by ^1H NMR and fluorescence spectroscopy. Minimization of PET mechanism on addition of Hg^{2+} ions resulted in pronounced Off-On-type fluorescent signaling behavior. The receptor can be used to form a mercury selective PVC membrane. The mercury selectivity is due to the formation of coordination between the imino moieties and the mercury ions. The prepared compound may be utilized as a sensor for the analysis of Hg^{2+} ions in the submillimolar concentration range.

Table 2
Selectivity coefficient values of mercury ion-selective electrode **4**

Secondary ions	Na^+	K^+	NH_4^+	Ag^+	Co^{2+}	Ca^{2+}	Mg^{2+}	Cd^{2+}	Cu^{2+}	Pb^{2+}	Ni^{2+}	Zn^{2+}	Fe3+
$\log K^{Pot}_{Hg^{2+},B}$	−1.05	−1.08	−0.95	−0.15	−2.85	−3.10	−2.80	−3.02	−2.75	−2.78	−2.75	−2.95	−4.34

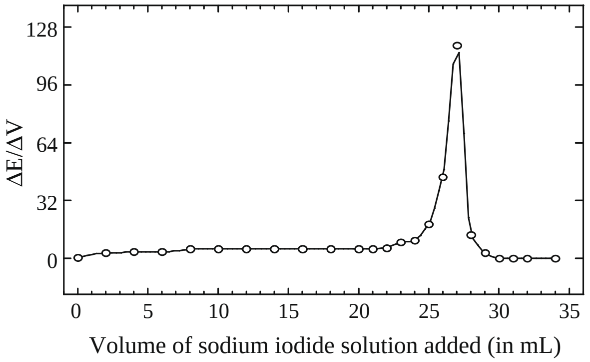


Figure 6. Derivative curve for the titration of 1.0×10^{-2} M Hg^{2+} solution with 1×10^{-2} M NaI solution.

Acknowledgments

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16. *Synthesis of* ***2***: To a suspension of [$PdCl_2(PPh_3)_2$] (5.08 g, 39.73 mmol) in dioxane (15 ml) were added 4-bromoaniline (2.5 g, 14.45 mmol), 4,4,5,5-tetramethyl-1,3,2-dioxaborolane (5.087 g, 39.74 mmol), and triethylamine (5.83 g, 57.8 mmol) under argon. After stirring for 5 h at 80 °C, the dioxane was removed under vacuum and the residue so obtained was treated with water, extracted with dichloromethane, and dried over anhydrous Na_2SO_4. The organic layer was evaporated and the compound was purified by column chromatography using dichloromethane as an eluent to give 2.3 g (75%) of compound **3** as brown solid. Mp: 160 °C; ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 1.32 (s, 12H), 3.83 (s, 2H), 6.61 (d, J = 6 Hz, 2H), 7.62 (d, J = 6 Hz, 2H); ^{13}C NMR (300 MHz, $CDCl_3$): δ 24.82, 83.28, 114.06, 136.39, 149.26; FAB-MS *m/z*: 219 (M^+).
17. *Synthesis of* ***3***: To a solution of compound **2** (1.1 g, 5.03 mmol) and compound **1** (1.0 g, 2.20 mmol) in dioxane were added K_2CO_3 (1.10 g, 8.02 mmol), distilled H_2O (10 ml), and [$Pd(Cl)_2(PPh_3)_2$] (0.21 g, 0.302 mmol) under argon and the reaction mixture was then refluxed overnight. The dioxane was then removed under vacuum and the residue so obtained was treated with water, extracted with dichloromethane, and dried over anhydrous Na_2SO_4. The organic layer was evaporated and the compound was purified by column chromatography using dichloromethane–ethyl acetate mixture (10:1, v/v) as an eluent to give 0.627 g (60%) of compound **3** as light yellow solid. Mp = 150 °C; ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 0.23 (s, 12H), 1.00 (s, 18H), 3.57 (s, 4H), 6.53 (d, J = 9 Hz, 4H), 6.80 (s, 2H), 6.87 (d, J = 9 Hz, 4H); ^{13}C NMR (300 MHz, $CDCl_3$): δ −4.02, 18.42, 25.96, 114.66, 122.84, 130.69, 132.20, 133.41, 144.30, 145.37; FAB-MS *m/z*: 520 (M^+), 522 $(M+2)^+$; Anal. Calcd for $C_{30}H_{44}N_2O_2Si_2$: C, 69.18; H, 8.51; N, 5.38. Found: C, 68.98; H, 8.23; N, 5.09.
18. *Synthesis of* ***4***: 1-Pyrenecarbaldehyde (0.046 mg, 0.201 mmol) was added portion wise to a stirred solution of diamine **3** (0.050 mg, 0.096 mmol) in ethanol (15 ml). The resulting reaction mixture was refluxed for one hour during which a yellow solid was obtained. The solid compound was filtered and washed with ethanol (10 ml) to give 0.068 mg of **4** (75%). Mp: > 280 °C; IR υ_{max} (KBr, cm^{-1}): 1632 (C = N); ^{1}H NMR (300 MHz, $CDCl_3$, ppm): δ 0.31 (12H, s), 1.06 (18H, s), 6.99 (2H, s), 7.27 (4H, s), 7.60–8.36 (18H, m), 8.91 (2H, d), 9.05 (2H, s); ^{13}C NMR (300 MHz, $CDCl_3$, cm^{-1}): δ −3.93, −3.97, 18.52, 26.01, 114.80, 120.69, 120.87, 122.49, 123.03, 123.20, 124.62, 124.90, 125.05, 125.86, 126.09, 126.18, 126.68, 127.05, 127.47, 127.58, 128.97, 130.58, 130.83, 131.25, 133.29, 133.37, 139.45, 150.66, 158.32; FAB-MS *m/z*: 945 $(M+1)^+$; Anal. Calcd for $C_{64}H_{60}N_2O_2Si_2$: C, 81.31; H, 6.40; N, 2.96. Found: C, 81.03; H, 6.06; N, 2.7.
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