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A Molecular Keypad Lock Based on the Thiacalix[4]arene of 1,3-*Alternate* Conformation

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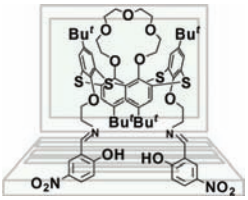
ABSTRACT



A chemosensor based on the thiacalix[4]arene of 1,3-*alternate* conformation has been designed and synthesized. The binding behavior of this chemosensor has been studied toward different metal ions by fluorescence spectroscopy, and it was observed that the chemosensor selectively senses Cu^{2+} ions. The chemical inputs of Cu^{2+} and F^- in a sequential manner generate an output which mimics the functions of a security keypad lock.

Fluorescent sensors that change their fluorescence behavior upon binding with heavy transition metal ions and anions are one of the most widely used analytical tools on the basis of which various molecular switches and logic gates have been proposed.[1] These molecular logic gates and circuits play an important role in electronic devices from digital computers, calculators, video games, and store automation to music equipment.[2]

Recently, the combination of molecular logic gates and logic circuits has also been used for developing a keypad lock[3] at the molecular level. This is an electronic device which is capable of processing password entries, hence access to an object or data can be restricted to a limited number of people. In other words, one needs to know the password which opens the lock. Such molecular devices which can distinguish between the sequences of different chemical inputs are expected to be better than simple logic gates. The development of such a molecular scale keypad lock is a particularly attractive goal as it represents a new approach for protecting information at the molecular scale. Such sequential logic circuits can also be used to design molecular keyboards capable of crossword puzzles.[4] Thus, keeping in view the role played by soft transition metal ions and

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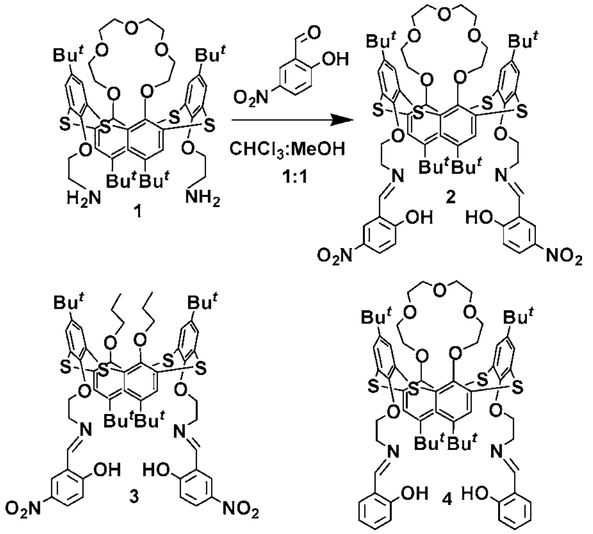
electronic devices in day to day life, the development of fluorescent sensors for their applications in electronic devices is very important.

Our research work involves the development of fluorescent sensors[5] for soft metal ions, and we recently reported[6] a ratiometric fluorescent sensor for mercury ions based on the *partial cone* conformation of calix[4]arene which behaves as a NOR logic gate with YES logic function upon chemical inputs of Hg^{2+} and Cu^{2+} ions. Now we have synthesized a chemosensor based on a thiacalix[4]arene of 1,3-*alternate* conformation which upon chemical inputs of Cu^{2+} and F^- in a sequential manner generates an output which mimics the functions of a security keypad lock. Such a type of security keypad lock based on thiacalix[4]arene is unprecedented.

Condensation of diamine **1** with 2.0 mol equiv of 2-hydroxy-5-nitrobenzaldehyde furnished target compound **2** in 84% yield (Scheme 1). The diamine **1** was synthesized from a known precursor (for synthetic details, see Supporting Information S3−S5 and S23−S25). The structure of compound **2** was confirmed by its spectroscopic and analytical data (see Supporting Information S5−S6 and S16−S18). The ^1H NMR spectrum of compound **2** showed two singlets (18H each) at 1.28 and 1.34 ppm corresponding to the *tert*-butyl protons, four triplets (4H each) at 3.0 ppm for NCH_2 protons and at 3.14, 3.94, and 4.12 ppm for OCH_2 protons, two broad signals (4H each) at 3.39 and 3.59 ppm corresponding to OCH_2 protons, four singlets (4H and 2H each) corresponding to the aromatic and imino protons at 7.36, 7.39, 8.17, and 8.26 ppm respectively, two doublets (2H each) at 6.99 and 8.20 ppm corresponding to the aromatic protons, and a broad signal corresponding to the phenolic proton at 14.16 ppm (see S16, Supporting Information). The IR spectrum of compound **2** showed a C═N stretching band at 1630 cm^{-1}. A parent ion peak at m/z 1264 $(M + 1)^+$ corresponding to the 1:2 condensation product was observed in the FAB mass spectrum. These spectroscopic data corroborate the structure **2** for this compound.

Scheme 1



The binding behavior of compound **2** toward different cations (Cu^{2+}, Pb^{2+}, Hg^{2+}, Zn^{2+}, Cd^{2+}, Ni^{2+}, Ag^+, K^+, Na^+, and Li^+) was investigated by fluorescence spectroscopy. The fluorescence spectrum of compound **2** (10 μM) shows an emission band at 313 nm in THF:H_2O (9.5:0.5,v/v). The fluorescence is quenched upon addition of Cu^{2+} ions (100 μM) to the solution of compound **2** (Figure 1). The quenching of fluorescence could be attributed to a photoinduced charge transfer mechanism (PCT).[7] Under the same conditions as used above for Cu^{2+}, we also tested the fluorescence response of **2** to other metal ions such as Pb^{2+}, Hg^{2+}, Zn^{2+}, Cd^{2+}, Ni^{2+}, Ag^+ , K^+, Na^+, and Li^+ (Figure 2). No significant variation was observed except in the case of K^+ ions where a 25% enhancement in the emission intensity was observed

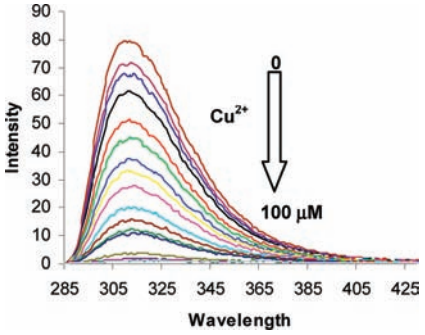


Figure 1. Fluorescence spectra of **2** (10 μM) in response to the presence of Cu^{2+} ions (100 μM) in THF:H_2O (9.5:0.5,v/v) buffered with HEPES, pH = 7.0; λ_{ex} = 269 nm.

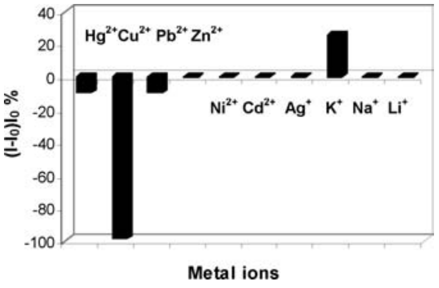


Figure 2. Fluorescence intensity changes $[(I - I_0)/I_0 \times 100]$ of receptor **2** (10 μM) in THF:H_2O (9.5:0.5, v/v) upon addition of 100 μM of various metal perchlorates. The excitation wavelength was 269 nm. I_0 is the fluorescence intensity at 313 nm of each free host, and I is the fluorescence intensity after adding metal ions.

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(see Supporting Information S11). The enhancement in the case of K^+ ions can be ascribed to the fact that the K^+ ions bind to the polyether ring, and as a result, photoinduced electron transfer (PET) from the polyether ring to the photoexcited nitro phenyl moiety is suppressed. Earlier, Kim et al. have reported similar fluorescence enhancement in the presence of K^+ ions where the K^+ ions bound to the crown ether ring of a calix[4]arene of 1,3-*alternate* conformation bearing pyrene moieties.[8] We also synthesized a reference compound **3** from a known precursor[9] without incorporating the crown ether moiety (for synthetic details, see Supporting Information S6−S7 and S20−S22). No change in fluorescence was observed on addition of K^+ ions to the receptor **3** (see Supporting Information S12) confirming that the fluorescence enhancement observed in the case of **2** with K^+ ions is due to interaction of the crown ring with K^+ ions.

Fitting the changes in the fluorescence spectra of compound **2** with copper ions, using the nonlinear regression analysis program SPECFIT,[10] gave a good fit and demonstrated that 1:1 stoichiometry (host:guest) was the most stable species in the solution with a binding constant $\log \beta_1 = 4.16$. The method of continuous variation (Job's plot) was also used to prove the 1:1 stoichiometry (see Supporting Information S9).

To test the practical applicability of compound **2** as a Cu^{2+}-selective fluorescence sensor, competitive experiments were carried out in the presence of Cu^{2+} ions at 100 μM mixed with Li^+, Na^+, K^+, Ni^+, Zn^{2+}, Cd^{2+}, Ag^+, and Pb^{2+} at 100 μM. No significant variation in the intensity was found by comparison with and without the other metal ions (see Supporting Information S10).

In addition to cation binding properties, we also investigated the sensing properties of **2** toward different anions (F^-, Cl^-, Br^-, I^-, HSO_4^-, CH_3COO^-, $H_2PO_4^-$, and NO_3^-) using tetrabutylammonium as a countercation. There was no change in the fluorescence behavior of compound **2** on adding these anions except in the case of fluoride ions where a 16% enhancement in the fluorescence intensity was observed (see Supporting Information S13). We propose that the fluorescence enhancement of **2** on addition of fluoride ions probably occurs by the deprotonation of the phenolic hydroxyl group by F^- which results in the formation of an anion. This promotes the delocalization of π electrons in the nitrophenyl moiety which results in fluorescence enhancement. To confirm this assumption and evaluate the intermolecular interactions between the compound **2** and fluoride ions, we carried out NMR studies in $CDCl_3$. It was found that on addition of small amounts of tetrabutylammonium fluoride to a solution of compound **2** in $CDCl_3$ the hydroxyl protons completely disappeared indicating that the deprotonation of the hydroxyl group is taking place in the presence of fluoride ions (see Supporting Information S19). Similar results were obtained when a relatively strong base such as Bu_4NOH was employed (see Supporting Information S14). To further investigate the proposed deprotonation, we synthesized compound **4** which contains relatively weakly acidic phenolic protons (for synthetic details, see Supporting Information S7−S8 and S26−S28). When binding studies of compound **4** were performed in the presence of different cations and anions under the same conditions as used for the receptor **2**, the profound selectivity of compound **4** was observed for Cu^{2+} ions (see Supporting Information S15); however, no change in emission was observed in the presence of any anion. Thus, we can conclude that the presence of the nitro groups in receptor **2** makes the phenolic protons relatively more acidic, deprotonation of which by F^- ions results in changes in the emission spectra being observed, whereas no such phenomenon was observed in compound **4** which has relatively less acidic phenolic protons due to the absence of a nitro group.

Recently, there has been a lot of interest in the development of materials which could protect information at the molecular level. However, there are only a few reports of such systems which can function as security or memory devices. Das et al. have recently reported a chemosensor which functions as a molecular keypad lock using Cu^{2+} and F^- as ionic inputs.[3b] Tian et al. recently reported a fluorophore capable of crossword puzzles and logic memory.[4] Since there has not been any report in which thiacalix[4]arene was used for such applications, we examined our system as a molecular keypad lock. For construction of such devices, we performed fluorescence experiments in the simultaneous presence of Cu^{2+} and F^- ions in dry THF, and spectra were taken immediately after the addition of analytes. The addition of Cu^{2+} ions to solution of **2** containing F^- ions results in quenching of the fluorescence (Figure 3), whereas on addition of F^- ions to the $\mathbf{2}{\cdot}Cu^{2+}$ complex, a new red-shifted band is formed at 370 nm (Figure 4). When Cu^{2+} ions are added to a solution of **2** containing F^- ions, Cu^{2+} ions bind to the imino nitrogens and F^- ions, and the PCT comes into operation which quenches the fluorescence emission. On the other hand, when F^- ions are added to a solution of the $\mathbf{2}{\cdot}Cu^{2+}$ complex, presumably binding of F^- to the Cu^{2+} center

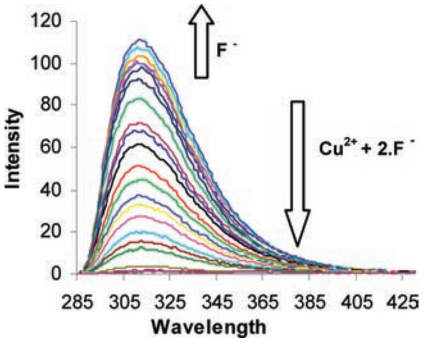

Figure 3. Fluorescence spectra of **2** (10 μM) in response to the addition of F^- ions (300 μM) and further addition of Cu^{2+} ions in THF; $\lambda_{ex} = 269$ nm.

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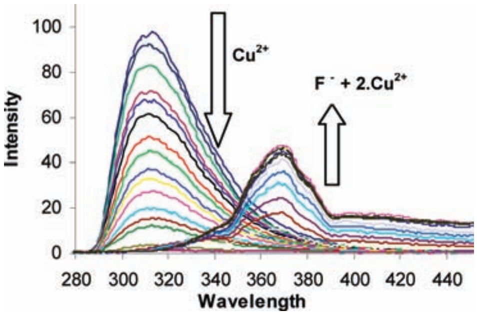

Figure 4. Fluorescence spectra of **2** (10 μM) in response to the addition of Cu^{2+} ions (100 μM) and further addition of F^- ions in THF; $\lambda_{ex} = 269$ nm.

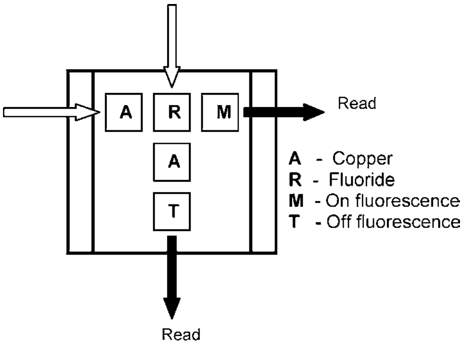

Figure 5. Fluorescence keypad to access a secret code at 370 nm.

of the **2**·Cu^{2+} complex causes redistribution in the energy levels of the **2**·Cu^{2+} complex, and as a result one of the two degenerate orbitals of the Cu^{2+} ions d_{z^2} and $d_{x^2-y^2}$ gets stabilized and the other gets destabilized. Due to this energy difference in the d-orbitals of the Cu^{2+} ions, their participation in the emission quenching decreases which leads to the revival of fluorescence intensity. Furthermore, the coordination of Cu^{2+} ions to the receptor **2** probably decreases the energy of the LUMO of the nitrophenyl moiety which reduces the HOMO−LUMO gap of the **2**·Cu^{2+} complex. This lowering of energy of the **2**·Cu^{2+} complex accounts for the emission at a longer wavelength upon the addition of fluoride ions.[3b] With the above fluorescence outputs, we have used our system for the construction of a security keypad lock. To generate an input sequence as a password entry for a keypad lock, inputs Cu^{2+} and F^- were designated as "**A**" and "**R**" (Figure 5). For the first input sequence, "**A**" followed by "**R**" gave emission "**ON**" at 370 nm and created a secret code "**ARM**" where "**M**" defines the "**ON**" state. When the input sequence is reversed, i.e., the first input is "**R**" and then "**A**", fluorescence was in the "**OFF**" state at 370 nm. Thus, this sequence is a wrong entry "**RAT**" (**T** defines the OFF state) which failed to open the keypad lock (Figure 5). Numerical digits (0−9) or letters from (A−Z) can be used as password entries. In total, 90 combinations of numerals and 650 combinations of letters can be formed, with each number or letter specifying each input. Thus, an access code would be made possible by assigning the correct starting (Cu^{2+}) and ending (F^-) ions to two specific letters "**A**" and "**R**", respectively, and different ions to all of the other letters, to ensure that only one code would work. However, there are many combinations to try which adds to the complexity of opening the keypad lock. Thus, the sequence dependence of inputs is mandatory for the construction of the molecular keypad lock.

In conclusion, we have designed and synthesized a chemosensor based on a thiacalix[4]arene of 1,3-*alternate* conformation which behaves as a molecular keypad lock with sequential chemical inputs of Cu^{2+} and F^- ions.

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Supporting Information Available: Experimental details and spectroscopic data of compounds **1**, **2**, **3**, and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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