Dalton Transactions

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/dalton

Journal Name

RSCPublishing

ARTICLE

Thiacalix[5]crown based chemosensor for Zn^{2+} and $H_2PO_4^-$: sequential logic operations at the molecular level

Cite this: DOI: 10.1039/x0xx00000x

Neetu Sharma, Shahi Imam Reja, Vandana Bhalla and Manoj Kumar*

Received ooth January 2012,
Accepted ooth January 2012

DOI: 10.1039/x0xx00000x

www.rsc.org/

A thiacalix[5]crown based di-topic receptor **3** possessing two types of binding sites *viz* crown-5 ring and imino moieties has been synthesized which undergoes fluorescence enhancement in the presence of Zn^{2+} ions. The selective binding of Zn^{2+} to compound **3** does not allow the K^+ ions to bind with crown-5 ring and thus a negative allosteric behaviour has been observed between Zn^{2+}/K^+ ions. In addition, **3**-Zn^{2+} complex can be used for the detection of $H_2PO_4^-$ ions with fluorescence "turn-off" response. Further based on the fluorescence response, a two input and one output sequential logic circuit has been constructed.

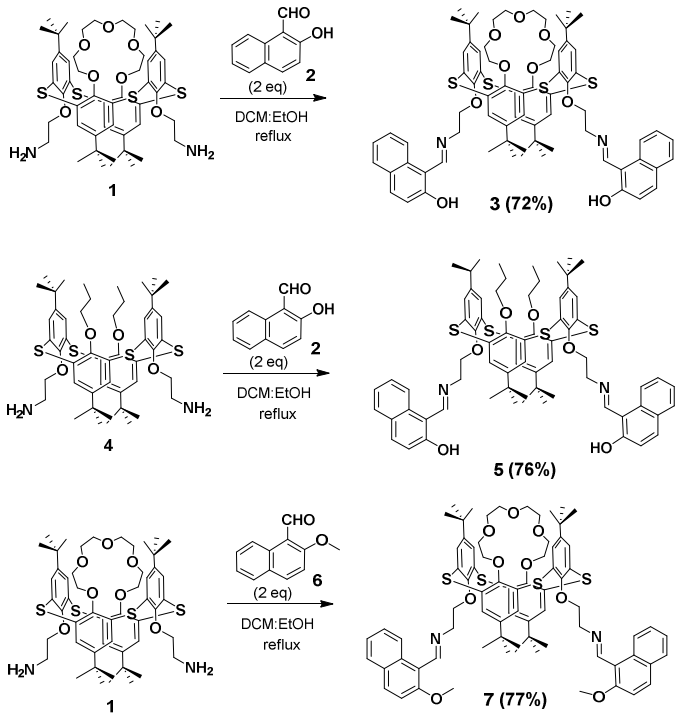
Introduction

Transition metal ions play an important role in a wide range of chemical reactions, including biological metabolisms as well as in environmental systems.[1] Among these transition metal ions, zinc is a crucial metal ion for normal growth and activities of numerous biological processes including catalytic activity of enzymes, neural signal transmission, apoptosis regulation, immune function, mammalian reproduction, cellular transport and metabolism.[2] The normal zinc ions concentration in blood plasma of humans is 12-16 μM.[3] The free zinc ion concentration which is not strongly bound to proteins is extremely low than that of total zinc ions concentration found in a cell. The imbalance of zinc ion concentration in the cells may lead to pathological processes such as Alzheimer's disease,[4] epilepsy,[5] ischemic stroke,[6] prostate cancer.[7] Therefore, simple and rapid detection of zinc ions is essential in biological as well as in environmental systems. Among various techniques such as atomic absorption, inductively coupled plasma-mass atomic emission, fluorescence and UV-vis absorption spectroscopy, fluorescence spectroscopy is widely used to quantify trace amount of metal ions because of its simple and sensitive nature.[8] Many of the Zn^{2+} sensors are reported in the past but most of them suffer from "turn-off" fluorescence response and only few exhibit fluorescence enhancement with some limitations such as poor detection limit, less water solubility, interference with other metal ions, especially Cd^{2+} ions since they both show similar chemical properties.[9] Therefore, it is highly desirable to develop a chemosensor which shows fluorescence enhancement as well as improved binding selectivity with Zn^{2+} ions in aqueous or mixed aqueous medium.

Our research work involves the design and synthesis of fluorescent sensors for the detection of soft metal ions, anions and evaluation of their logic behaviour for construction of molecular switches and logic gates.[10] Earlier from our lab we reported 1,3-alternate thiacalix[4]crown and thiacalix[5]crown based chemosensors which exhibit switching and negative allosteric behavior between Hg^{2+}/Li^+, Cu^{2+}/Li^+, Cu^{2+}/K^+, Fe^{3+}/Li^+, Hg^{2+}/K^+ and Fe^{3+}/K^+ respectively[11] but all of these chemosensors work only in organic medium. In continuation of this work, we have now synthesized thiacalix[5]crown based fluorescent chemosensor **3** appended with 2-hydroxy naphthalene moieties which works well in mixed aqueous media. Also we have prepared a model compound **5** from precursor **4** without crown-5 ring moiety. These chemosensors are non-emissive in nature and the addition of Zn^{2+} ions results in the fluorescence "turn-on" response in mixed aqueous media. Further, chemosensor **3** shows a switchable and negative allosteric behaviour between Zn^{2+}/K^+ and interestingly behaviour of these chemosensors with Zn^{2+} ions is not altered by the presence of other interfering metal ions. Some of the reports on zinc sensing are reported in the literature.[12] Also many of the phosphate anion sensors based on binuclear zinc complexes are reported in the literature,[13] so we used *in situ* prepared Zn^{2+} complex of these compounds for the fluorescence "turn-off" detection of phosphate ions. Based on the fluorescence response of **3** with Zn^{2+} and dihydrogenphosphate ions, a sequential logic circuit has been designed which can perform a logic operations similar to those implemented by their macroscopic counterparts.[14]

Results and Discussion

The condensation of compound **1**/**4** with 2.0 mol equiv. of **2** (**Scheme 1**) in dichloromethane: ethanol (1:1, v/v) furnished compound **3**/**5** respectively. The structures of compounds **3** and **5** were confirmed from their spectroscopic and analytical data.



Scheme 1. Synthesis of compounds 3, 5 and 7.

The ^{1}H NMR spectrum of compound **3** (see ESI S4†) shows six singlets (18 H, 18 H, 4 H, 4 H, 2 H and 2 H) at 1.32, 1.34, 7.38, 7.48, 8.78 and 14.47 ppm corresponding to the *tert*-butyl, aromatic, imino and hydroxy protons, two broad signals (4 H each) at 3.39 and 3.60 ppm corresponding to OCH_2 protons, four doublets (2 H each) at 6.92, 7.62, 7.69, 7.81 ppm corresponding to aromatic protons, six triplets (4 H, 4 H, 4 H, 4 H, 2H and 2 H) at 3.01, 3.13, 3.93, 4.16, 7.21 and 7.33 ppm for NCH_2, OCH_2 and aromatic protons. The ^{1}H NMR spectrum of compound **5** (see ESI S5†) shows six singlets (18 H, 18 H, 4 H, 4 H, 2 H, 2 H) at 1.23, 1.32, 7.42, 7.5, 8.84 and 14.46 ppm corresponding to tert-butyl, aromatic, imino and hydroxy protons, one multiplet (4 H) at 1.98 ppm for CH_2 protons, four doublets (2 H each) at 6.9, 7.62, 7.7, 7.85 ppm corresponding to aromatic protons, six triplets (6 H, 4 H, 4 H, 4 H, 2 H and 2 H) at 0.65, 3.31, 3.83, 4.22, 7.22 and 7.34 ppm for CH_3, NCH_2, OCH_2 and aromatic protons. IR spectrum of compound **3** shows stretching band at 1626 cm^{-1} corresponding to C=N group and there is no absorbance band corresponding to aldehyde and amine group which shows condensation has taken place (see ESI S6†). In the mass spectra parent ion peaks appear at m/z 1295.49 $(M+Na)^+$ and 1199.49 $(M+1)^+$ corresponding to the compounds **3** and **5**, respectively (see ESI S7-S8†). These spectroscopic data corroborate the structures for compounds **3** and **5**. The binding behavior of compounds **3** and **5** was studied toward different cations (Pb^{2+}, Hg^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Fe^{2+}, Fe^{3+}, Ag^+ , Zn^{2+}, Cd^{2+}, K^+, Na^+, Li^+ and Al^{3+}) as their perchlorate salts by UV-vis and fluorescence spectroscopy. The absorption spectrum of compound **3**/**5** (10.0 μM) in CH_3CN-H_2O (8:2, v/v) exhibits typical absorption bands for naphthyl moieties at 400/401 nm and 418/419 nm, due to the π-π* transitions of naphthyl moiety (see ESI S9†). The addition of increasing amounts of Zn^{2+} ions (0-100 equiv) to the solution of **3**/**5** results in the increase in absorption at 400/401 nm and decrease in absorption at 418/419 nm. The addition of other metal ions did not alter the absorption pattern of these receptors (see ESI S10†). In the fluorescence spectrum, compound **3**/**5** exhibits a very weak fluorescence emission at 445 nm when excited at 380 nm (**Figure 1a, 1b**). This weak fluorescence emission is ascribed to the excited state intramolecular proton transfer (ESIPT)[15] phenomenon involving fast enol-imine to keto-amine tautomerism (**Scheme 2**). The addition of Zn^{2+} ions to the compounds **3** and **5** leads to the enhancement in fluorescence

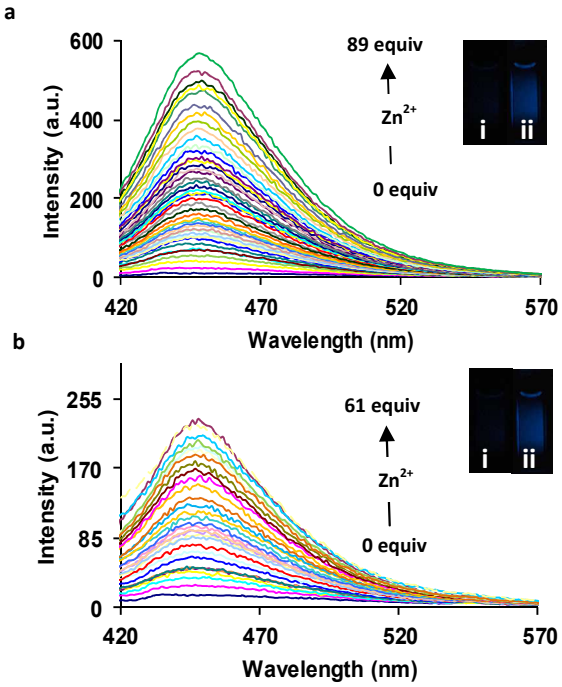
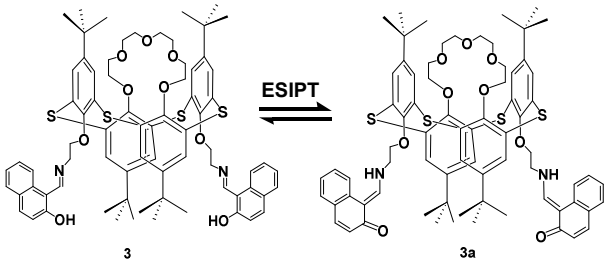


Figure 1. (a) Fluorescence emission spectra of **3** (10 μM) in presence of Zn^{2+} (0-89 equiv); (b) Fluorescence emission spectra of **5** (10 μM) in presence of Zn^{2+} (0-61 equiv) in CH_3CN/H_2O (8:2, v/v) buffered with HEPES, pH = 7.0; λ_{ex} = 380 nm. Inset showing fluorescence change (i) before and (ii) after the addition of Zn^{2+} ions.

intensity at 445 nm which is ascribed to the binding of imino nitrogen atoms of receptors **3** and **5** with Zn^{2+} ions inhibiting ESIPT phenomenon in the ligands. By considering the ratio of the fluorescence intensity (I/I_o) at 445 nm, we observed 42/14-fold fluorescence increase in the case of **3**/**5**-Zn^{2+} complex. Fitting the changes in the fluorescence spectra of compounds **3** and **5** with Zn^{2+} ions by using the nonlinear regression analysis program SPECFIT[16] gave a good fit and demonstrated that 1:2

stoichiometry (host: guest) was the most stable species in the solution with a binding constant (log β) = 6.97 ± 0.04/6.45 ± 0.04 (see ESI S11-S15†). The fluorescence quantum yield of **3**/**5**-Zn^{2+} complex is found to be 0.116/0.015 as compared to that of free ligand **3**/**5** (0.001/0.001) (see ESI S16†). The detection limit[17] of **3**/**5** for Zn^{2+} ions is found to be 1.38×10^{-8}/1.1×10^{-7} mol L^{-1} (see ESI S17-S18†) which is sufficiently low for the detection of Zn^{2+} ions found in many chemical systems.



Scheme 2. ESIPT phenomenon in compound **3**.

The binding of Zn^{2+} ions with imino nitrogen atoms is confirmed by ^{1}H NMR spectroscopy (see ESI S19†). It was observed that the addition of Zn^{2+} ions (2.0/2.0 equiv) to receptor **3**/**5** leads to the upfield shifting of OH protons (Δδ = 1.3/1.29 ppm) along with the downfield shifting of imino (Δδ = 2.05/2.00 ppm) and aromatic protons (Δδ = 0.59/0.66 ppm). This data confirms the binding of Zn^{2+} through imino-nitrogen atoms. The binding of Zn^{2+} to compound **3** and **5** is also confirmed from their mass spectra showing mass peak at m/z 560.31 and 523.33 corresponding to [**3**+2Zn^{2+}+Na^++2ClO_4^- +3H_2O] and [**5**+2Zn^{2+}+Na^++2ClO_4^-+H_2O] respectively (see ESI S20-S21†).

No change in the fluorescence emission was observed upon the addition of other metal ions to solution of compound **3**/**5** which indicate that these receptors are selective for only Zn^{2+} ions (see ESI S22†). To test the practical applicability of compound **3**/**5** as a selective sensor for Zn^{2+} ions, we have carried out the competitive experiments using fluorescence spectroscopy in the presence of Zn^{2+} ions at 89/61 equiv mixed with other cations (Pb^{2+}, Hg^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, Fe^{2+}, Fe^{3+}, Ag^+, Cd^{2+}, K^+, Na^+, Li^+ and Al^{3+}) at 200 equiv. No significant variation in the fluorescence emission was found by comparison with and without the other metal ions (see ESI S23-S24†). To confirm the ESIPT phenomenon in ligands **3**/**5**, we also prepared compound **7** by protecting phenolic hydroxyl groups of compound **3** with methyl groups (see ESI S25-S27†). Compound **7** when excited at 380 nm doesn't exhibit any emission band at 445 nm and also no change in emission spectra of **7** was observed after the addition of Zn^{2+} ions (see ESI S28†). However, the addition of K^+ ions (0-200 equiv) to the compound **3** results in slight fluorescence enhancement at 445 nm, whereas no change in emission was observed for compound **5** upon addition of K^+ ions (see ESI S29†). This contrasting behavior is ascribed to the presence of crown-5 ring in the case of receptor **3** which favours the binding of K^+ ions and this results in suppression of the photo-induced electron transfer (PET) from oxygen atoms of crown-5 ring to the photo-excited naphthyl moiety.[18] The presence of crown-5 ring as an additional binding site other than the imino moiety for metal ion complexation provides a platform to achieve di-topic

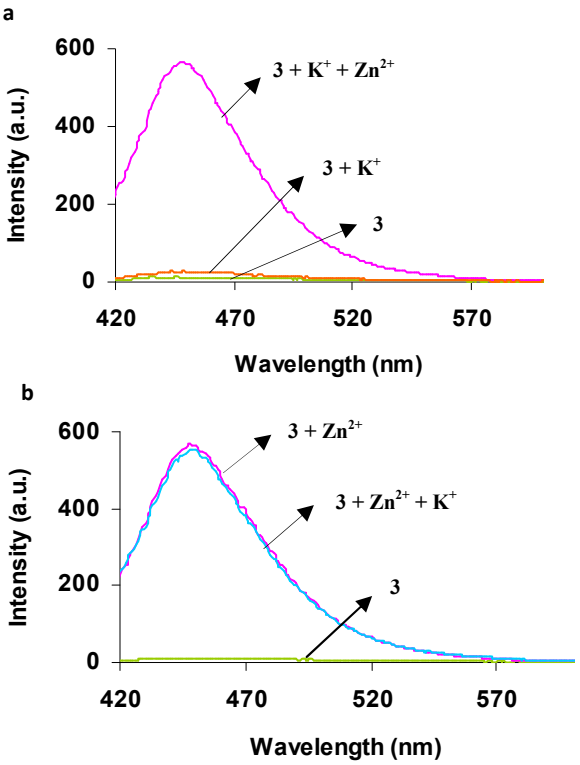


Figure 2. (a) Fluorescence emission spectra of **3**+K^+ complex in the presence of Zn^{2+} (100 equiv); (b) Fluorescence emission spectra of **3**+Zn^{2+} complex in the presence of K^+ (500 equiv) in CH_3CN/H_2O (8:2, v/v) buffered with HEPES, pH = 7.0, λ_{ex} = 380 nm.

complexation with allosteric regulation. The addition of Zn^{2+} (100 equiv) ions to the solution of **3**-K^+ complex results in the fluorescence behaviour similar to that of **3**-Zn^{2+} complex (**Figure 2**). This clearly indicates that Zn^{2+} moves in and K^+ moves out from receptor **3**. On reversing this metal ion exchange process, when K^+ ions (500 equiv each) were added to solution of **3**-Zn^{2+} complex, no change in emission spectrum was observed. This means that the addition of K^+ ions did not affect the binding of Zn^{2+} ions which is probably due to the strong binding of Zn^{2+} ions. The negative allosteric effect between K^+ and Zn^{2+} ions has also been confirmed from ^{1}H NMR study of **3** which shows coalescence and splitting of signals of crown ether moiety protons on addition of 1 equiv of K^+ ions to **3** due to the interaction of K^+ ions to the crown ether moiety. Further on addition of 2 equiv of Zn^{2+} ions into **3**-K^+ complex results the complete change of spectrum as that of **3**-Zn^{2+} complex. On contrast no spectral changes were observed upon the titration of K^+ ions into **3**-Zn^{2+} complex (see ESI S19†). This means **3**-Zn^{2+} complex act as a gateway which regulates the binding of K^+ ions to crown ether moiety of **3**. From these experiments, it may be concluded that **3**-Zn^{2+} complex formation triggers the K^+ ion de-complexation and

'switch off" the recognizing ability of crown ether ring attributed to the negative allosteric behaviour between Zn^{2+} and K^+ ions (**Figure 4**).

Further receptor **3**/**5** can be used for analytical purposes to determine the zinc ion content in drugs. Zinc ion is needed for several metabolic processes and its deficiency can cause several abnormalities like hair loss, weight loss, loss of appetite, skin problems, hypogonadism and many genetic disorders. As the zinc supplements are taken to make up its deficiency and we can determine the zinc ion content in those supplements. Hence we have carried out the fluorescence titration of compound **3**/**5** with the drug named 'zinconia' (zinc acetate tablets), zinc nitrate and zinc chloride and here we found that the gradual addition of these salts leads to the enhancement in blue fluorescence emission at 445 nm (see ESI S30-S33†). Thus our probe **3**/**5** can serve as analytical tool for determining zinc ion content in drugs as well.

Recently, there has been few a reports about the use of metal ensembles for the sensing of different anionic species in aqueous medium due to the strong interaction between water and anions.[19] The hydrogen bonding interactions or electrostatic interactions involved in the anion recognition by receptor are not strong enough to have high affinity in aqueous medium. However the use of d- block elements with one or more vacant coordination sites can be used as receptors for the recognition of anions since these have coordinative interactions which are stronger than that of electrostatic interactions and hence can compete with the anion solvation.[20] Also polytopic ligands can be employed to preorganize two or more metal centres in space which can give them definite binding geometry and further this increases the affinity and selectivity for anion recognition.[21] For example, in literature only a few of the reports on Zn^{2+}-ensemble are known for the sensing of phosphate ions which work well in aqueous medium.[22] Dihydrogenphosphate ions are among the biologically important anions since they are involved in the biological processes like energy transduction, genetic information storage, protein regulation, signal processing and membrane transport. These are also involved in eutrophication of rivers which is due to excess use of agricultural fertilizers and are found in antiviral and chemotherapeutic drugs.[23] Thus keeping in view the significance of dihydrogenphosphate anions, we were interested to use thiacalix[4]arene based **3**-Zn^{2+} ensemble for sensing different types of anions which can work well in mixed aqueous media and for this we studied the behavior of **3**-Zn^{2+} ensemble with different types of anions by UV-vis and fluorescence spectroscopy. The change in fluorescence emission of **3**-Zn^{2+} complex upon addition of dihydrogenphosphate ions is shown in figure 3. The addition of $H_2PO_4^-$ (0-60/0-40 equiv) to the solution of **3**/**5**-Zn^{2+} complex results the decrease in fluorescence emission at 445 nm (see ESI S34†). This decrease in the emission intensity is ascribed to the formation of Zn^{2+}-phosphate complex and thus, Zn^{2+} is no longer available to stimulate emission intensity favoring the emission quenching at 445 nm. Further to observe whether the binding behavior of **3**-

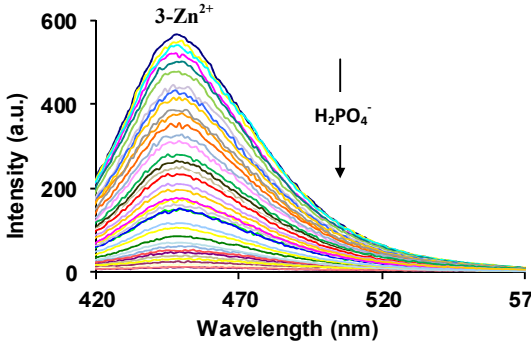


Figure 3. Fluorescence emission spectra of **3** (10 μM) upon addition of $H_2PO_4^-$ (0-60 equiv) to the **3**-Zn^{2+} complex in CH_3CN/H_2O (8:2, v/v) buffered with HEPES, pH = 7.0; λ_{ex} = 380 nm.

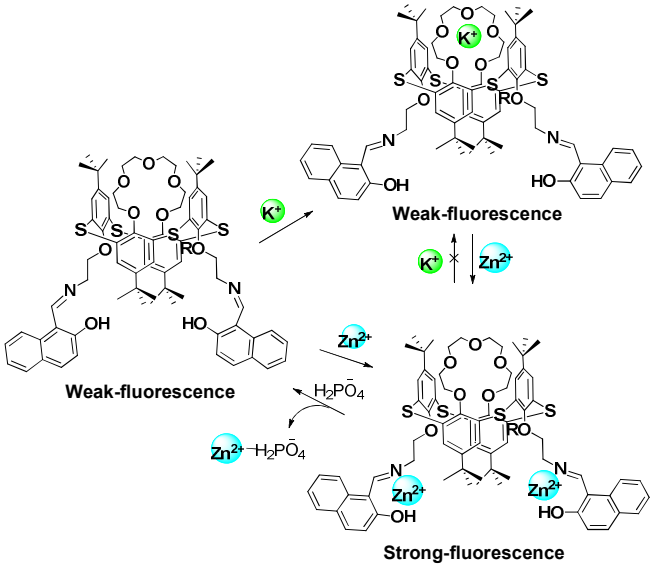


Figure 4. Schematic representation of ion exchange between metal ions and $H_2PO_4^-$ induced fluorescence turn-off.

Zn^{2+} complex is reversible, we have again added 240 equiv. of Zn^{2+} ions to the above solution which leads to the enhancement in fluorescence emission intensity at 445 nm (see ESI S35†). The addition of 60 equiv. of $H_2PO_4^-$ ions into the solution of **3** did not show any change in fluorescence emission intensity and then further addition of 89 equiv. of Zn^{2+} ions leads to the fluorescence enhancement at 445 nm. Since the addition of Zn^{2+} ions into **3**+$H_2PO_4^-$ solution has capability to bind with $H_2PO_4^-$ as well as receptor and that is why now fluorescence is increased but with less emission intensity as compare to the titration of Zn^{2+} with receptor **3** (see ESI S36†). No change in fluorescence emission was observed upon addition of other inorganic anions such as F^-, Cl^-, Br^-, I^-, OAc^-, CN^-, NO_3^-, $H_2PO_4^-$, $HP_2O_7^{3-}$, PO_4^{3-}, AMP, ADP and ATP to the solution of **3**/**5**-Zn^{2+} complex (see ESI S37-S40†). Thus **3**/**5**-Zn^{2+} complex can serve as a chemo-sensing system for the detection of $H_2PO_4^-$ ions based on the displacement approach.

Recently, the development of sequential logic devices where chemically encoded information is converted into fluorescent signals has become an emerging research area.[24] Therefore depending upon the two different chemical inputs (Zn^{2+} and $H_2PO_4^-$) and fluorescence signal of compound **3** as output, a sequential logic circuit is constructed. The two chemical inputs of Zn^{2+} and $H_2PO_4^-$ are designated as In Z and In P, respectively. The threshold value of the fluorescence intensity is taken as 150 at the output (445 nm). Fluorescence intensity higher than the threshold value is assigned as "1" and lower than that value is assigned as "0" defines the "On" and "Off" states, respectively. By using the different combinations of two chemical inputs, the truth table (**Table 1, Figure 5**) is drawn for the output at 445 nm and the sequential logic circuit of the output fluorescence emission, representing the set/reset element, corresponds to the memory device (**Figure 5A**). The

Table 1.

Sr. No.	In P	In Z	Output 445 nm
1	0	0	0
2	0	1	1
3	1	0	0
4	1 (1st)	1 (2nd)	1
5	1 (2nd)	1 (1st)	0

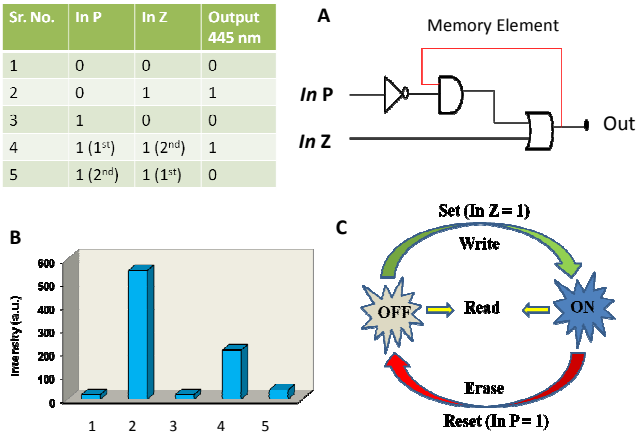


Figure 5. Table 1 is the Truth Table for sequential logic circuit A, where '0'= Off and '1' = On signals. (A) Sequential logic circuit displaying memory unit with two inputs (In P and In Z) and one output (445 nm); (B) Fluorescence emission spectra of **3** at different chemical inputs with respect to serial numbers of table 1. Fluorescence intensities higher than threshold value (150) specified at 445 nm are assigned as "1" and intensities lower than threshold value are assigned as "0". (C) Schematic representation of the reversible logic operations for memory element possessing "write-read-erase-read" functions.

output at 445 nm is read as "1" for the fluorescence intensities higher than threshold value and is "0" for intensities lower than threshold value (**Figure 5B**). The reversible and reconfigurable sequences of the set/reset logic operations explain the memory feature with "write-read-erase-read" functions through the output signal at 445 nm (**Figure 5C**). The set input (In Z = 1) results in the "turn-on" fluorescence at 445 nm. This reads the encoded information as "written" and the logic operation is saved as "Output = 1". The fluorescence gets turned off at 445 nm by the reset input (In P = 1) which "erased" the stored encoded information and the logic operation is saved as "Output = 0". Since the combinational logic is not enough to construct memory devices makes the development of such sequential logic circuits as important.

Experimental

General information

All reagents were purchased from Aldrich and were used without further purification. The experiments were carried out in a mixture of acetonitrile and HEPES buffer (8:2, v/v; pH 7.0). The UV-vis spectra were recorded on a SHIMADZU UV-2450 spectrophotometer with a quartz cuvette (path length of 1 cm). The cell holder was thermostated at 25°C. The fluorescence spectra were recorded with a SHIMADZU 5301 PC spectrofluorimeter. The ^1H and ^{13}C spectra were recorded on a JEOL-FT NMR-AL 300 MHz spectrophotometer using $CDCl_3/CD_3CN$ as the solvent, Bruker-AVANCE-II FT NMR-AL 500 MHz spectrophotometer using $CDCl_3$ as the solvent and tetramethylsilane as the internal standard. The data is reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet, br = broad singlet), coupling constants *J* (Hz).

UV-vis and fluorescence titrations

UV-vis and fluorescence titrations were performed with 10.0 μM solution of the ligands in CH_3CN/H_2O (8:2, v/v). Typically, aliquots of freshly prepared $M(ClO_4)_n$ (M = Pb^{2+}, Hg^{2+}, Cu^{2+}, Co^{2+}, Ni^{2+}, K^+, Na^+, Li^+, Fe^{2+}, Fe^{3+}, Ag^+, Zn^{2+}, Cd^{2+} and Al^{3+} ; n = 1, 2 or 3), tetrabutylammonium salts of anions ($H_2PO_4^-$, F^-, Cl^-, Br^-, I^-, OAc^-, CN^-, NO_3^-, $HP_2O_7^{3-}$, PO_4^{3-}) and various biologically relevant phosphate anions such as AMP, ADP and ATP (10^{-1} M to 10^{-3} M) were added to 3 ml solution of ligand to record the UV-vis and fluorescence spectra.

Synthesis of compounds 3, 5 and 7:

To a solution of **1** (0.100 g, 0.103 mmol) and **4** (0.100 g, 0.112 mmol) in 1:1 mixture of dichloromethane and ethanol (10 ml) was added **2**[25] (0.036 g, 0.207 mmol) and (0.039 g, 0.224 mmol) respectively, at room temperature. The resulting mixture was refluxed for 24 h. After the completion of the reaction, solvent was evaporated and the residue left was crystallized from $CHCl_3/C_2H_5OH$ to give pure compounds **3** and **5** respectively. Compound **6**[26] was added to a solution of **1** in 1:1 mixture of dichloromethane and ethanol (10 ml) at room temperature and was refluxed for 24 h. The solvent was evaporated after the completion of reaction and the residue was recrystallized from $CHCl_3/C_2H_5OH$ to give pure compound **7**.

Compound **3**: (Yield 73%); m.p. 225 °C; ^1H NMR ($CDCl_3/CD_3CN$, 300 MHz): δ = 1.32 [s, 18 H, $C(CH_3)_3$], 1.34 [s, 18 H, $C(CH_3)_3$], 3.01[t, *J* = 9.0 Hz, 4 H, NCH_2], 3.13 [t, *J* = 7.5 Hz, 4 H, OCH_2], 3.39 [br, 4 H, OCH_2], 3.60 [br, 4H, OCH_2], 3.93 [t, *J* = 7.5 Hz, 4 H, OCH_2], 4.16 [t, *J* = 7.5 Hz, 4 H, OCH_2], 6.92 [d, *J* = 9.0 Hz, 2 H, ArH], 7.21 [t, *J* = 7.5 Hz, 2 H, ArH], 7.33 [t, *J* = 7.5 Hz, 2 H, ArH], 7.38 [s, 4 H, ArH], 7.48[s, 4 H, ArH], 7.62 [d, *J* = 6.0 Hz, 2 H, ArH], 7.69 [d, *J* = 9.0 Hz, 2 H, ArH], 7.81[d, *J* = 6.0 Hz, 2 H, ArH], 8.78 [s, 2H, HC=N] and 14.47 [s, 2H, OH] ppm. ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 31.68, 34.70, 53.51, 65.99, 66.51, 70.50, 71.73, 73.85, 107.82, 118.46, 123.38, 126.88, 127.44, 128.16, 128.45, 129.59, 136.79, 147.09, 147.45, 155.61, 156.93, 159.52 and

172.19 ppm. ESI-MS m/z 1295.49 $(M+Na)^+$. Analysis calcd for $C_{74}H_{84}N_2O_9S_4$: C 69.78, H 6.65, N 2.20. Found C 69.46, H 6.34, N 2.06.

Compound **5**: (Yield 76%); m.p. 240 °C; ^{1}H NMR ($CDCl_3/CD_3CN$, 300 MHz): δ = 0.65 [t, *J* = 7.5 Hz, 6 H, CH_3], 1.23 [s, 18 H, $C(CH_3)_3$], 1.32 [s, 18 H, $C(CH_3)_3$], 1.98 [m, 4 H, CH_2], 3.32 [t, *J* = 7.5 Hz, 4 H, OCH_2], 3.83 [t, *J* = 7.5 Hz, 4 H, OCH_2], 4.22 [t, *J* = 7.5 Hz, 4 H, OCH_2], 6.9 [d, *J* = 9.0 Hz, 2 H, ArH], 7.22 [t, *J* = 7.5 Hz, 2 H, ArH], 7.34 [t, *J* = 10.5 Hz, 2 H, ArH], 7.42 [s, 4 H, ArH], 7.5[s, 4 H, ArH], 7.62 [d, *J* = 9.0 Hz, 2 H, ArH], 7.7 [d, *J* = 12.0 Hz, 2 H, ArH], 7.86 [d, *J* = 6.0 Hz, 2 H, ArH], 8.84 [s, 2 H, HC=N] and 14.46 [s, 2 H, OH] ppm. ^{13}C NMR ($CDCl_3$, 75 MHz) δ = 10.30, 22.33, 31.40, 34.52, 53.62, 66.82, 70.58, 107.74, 118.45, 123.35, 123.64, 127.07, 128.05, 128.22, 128.42, 128.81, 129.61, 133.62, 136.87, 146.50, 156.13, 157.63, 159.73 and 172.77 ppm. ESI-MS m/z 1199.49 $(M+1)^+$. Analysis calcd for $C_{72}H_{82}N_2O_6S_4$: C 72.08, H 6.89, N 2.34. Found C 71.83, H 6.76, N 2.05.

Compound **7**: (Yield 77%); m.p. 180 °C; ^{1}H NMR ($CDCl_3$, 500 MHz): δ = 1.30 [s, 18 H, $C(CH_3)_3$], 1.37 [s, 18 H, $C(CH_3)_3$], 3.07[t, *J* = 5.0 Hz, 4 H, NCH_2], 3.20 [t, *J* = 10 Hz, 4 H, OCH_2], 3.40 [br, 4 H, OCH_2], 3.62 [br, 4H, OCH_2], 3.67 [s, 6H, OCH_3], 3.99 [t, *J* = 15 Hz, 4 H, OCH_2], 4.25 [t, *J* = 10 Hz, 4 H, OCH_2], 7.15 [d, *J* = 10 Hz, 2 H, ArH], 7.34 [t, *J* = 7.5 Hz, 4 H, ArH], 7.39 [s, 4 H, ArH], 7.46 [t, *J* = 7.5 Hz, 2 H, ArH], 7.51[s, 4 H, ArH], 7.73 [d, *J* = 7.5 Hz, 2 H, ArH], 7.83 [d, *J* = 5.0 Hz, 2 H, ArH], 8.96 [s, 2H, HC=N] ppm. ^{13}C NMR ($CDCl_3$, 125 MHz) δ = 29.73, 31.37, 34.44, 56.06, 60.56, 65.60, 67.23, 70.32, 71.40, 73.56, 112.30, 117.10, 123.89, 125.99, 127.35, 127.73, 127.89, 128.06, 129.01, 131.85, 132.38, 146.31, 155.74, 156.55, 158.02 and 159.90 ppm. ESI-MS m/z 699.293 $(M+Na^+ + K^+ + 2H_2O)$. Analysis calcd for $C_{76}H_{88}N_2O_9S_4$: C 70.12, H 6.81, N 2.15. Found C 69.87, H 6.74, N 2.04.

Conclusions

In conclusion, we designed and synthesized thiacalix[5]crown of 1,3-alternate conformation based receptor **3** which shows "turn-on" fluorescence with Zn^{2+} ions. **3**-Zn^{2+} complex formation triggers the decomplexation of K^+ ions from crown-5 ring and thus a negative allosteric behaviour has been observed between Zn^{2+} and K^+ ions with high selectivity and fluorescence amplification. Further probe **3**/**5** can serve as analytical tool for determining zinc ion content in drugs. Also **3**/**5**-Zn^{2+} system can be used as a chemosensor for the "turn-off" detection of $H_2PO_4^-$ ions. In addition, the fluorescence signal obtained for **3**-Zn^{2+} complex is used to mimic the function of logical memory devices.

Acknowledgements

We are thankful to CSIR and UGC, New Delhi for financial support. S.I.R is thankful to UGC for senior research fellowship and Guru Nanak Dev University for laboratory facilities.

Notes and references

Department of Chemistry, UGC Sponsored Centre for Advance Studies-1, Guru Nanak Dev University, Amritsar, Punjab, India. E-mail: mksharmaa@yahoo.co.in; Fax: + 91 (0) 183 2258802 9 ext. 3205

Electronic Supplementary Information (ESI) available: [^{1}H NMR, ^{13}C NMR, IR spectra, mass spectra, UV-vis and fluorescence spectra]. See DOI: 10.1039/b000000x/

1 (*a*) B. Valeur and I. Leray, *Coord. Chem. Rev.,* 2000, **205**, 3; (*b*) Chemosensors of Ions and Molecular Recognitions; J. P. Desvergne and A. W. Czarnik; Eds.; *NATO ASI Series, Kluwer Academic:* Dordrecht, 1997; (c) J. S. Kim and D. T. Quang, *Chem. Rev.* 2007, **107**, 3780.

2 (*a*) J. M. Berg and Y. Shi, *Science,* 1996, **271**, 1081; (*b*) X. Xie and T. G. Smart, *Nature,* 1991, **349**, 521; (*c*) C. J. Frederickson, J.-Y. Koh and A. I. Bush, *Nat. Rev. Neurosci.,* 2005, **6**, 449.

3 W. J. Bettger and B. L. O' Dell, *J. Nutr. Biochem.,* 1993, **4**, 194.

4 (*a*) A. I. Bush, *Curr. Opin. Chem. Biol.*, 2000, **4**, 184; (*b*) M. P. Cuajungco and G. J. Lees, *Neurbiol. Dis.*, 1997, **4**, 137.

5 (*a*) P. J. Fraker and L. E. King, *Annu. Rev. Nutr.,* 2004, **24**, 277; (*b*) C. F. Walker and R. E. Black, *Annu. Rev. Neurosci.,* 2004, **24**, 255; (*c*) D. W. Choi and J. Y. Koh, *Annu. Rev. Neurosci.,* 1998, **21**, 347; (*d*) J. H. Weiss, S. L. Sensi and J. Y. Koh, *Trends Pharmacol. Sci.,* 2000, **21**, 395.

6 S. L. Galasso and R. H. Dyck, *Mol. Med.,* 2007, **13**, 380.

7 (*a*) L. C. Costello, Y. Liu, J. Zou and R. B. Franklin, *J. Biol. Chem.,* 1999, **274**, 17499; (*b*) S. M. Henshall, D. E. H. Afar, K. K. Rasiah, L. G. Horvath, K. Gish, I. Caras, V. Ramakrishnan, M. Wong, U. Jeffry and J. G. Kench, *Oncogene,* 2003, **22**, 6005.

8 (*a*) D. Schildkraut, P. dao, J. Twist A. Davis and K. Robillard, *Environ. Toxicol. Chem.,* 1998, **17**, 642; (*b*) A. Ceresa, A. Radu, S. Peper, E. Bakker and E. Pretsch, *Anal. Chem.,* 2002, **74**, 4027; (*c*) K. Kimura, S. Yajima, K. Tatsumi, M. Yokoyama and M. Oue, *Anal. Chem.,* 2000, **72**, 5290; (*d*) S. Chung, W. Kim, S. B. Park, I. Yoon, S. S. Lee and D. D. Sung, *Chem. Commun.,* 1997, 965; (*e*) R. Martinez-Manez and F. Sancenon, *Chem. Rev.,* 2003, **103**, 4449.

9 F. Sun, G. Zhang, D. Zhang, L. Xue and Hua Jiang, *Org. Lett.,* 2011, **13**, 6378.

10 (*a*) M. Kumar, R. Kumar and V. Bhalla, *Chem. Commun.,* 2009, 7384; (*b*) M. Kumar, N. Kumar and V. Bhalla, P. R. Sharma and Y. Qurishi, *Chem. Commun.,* 2012, **48**, 4719.

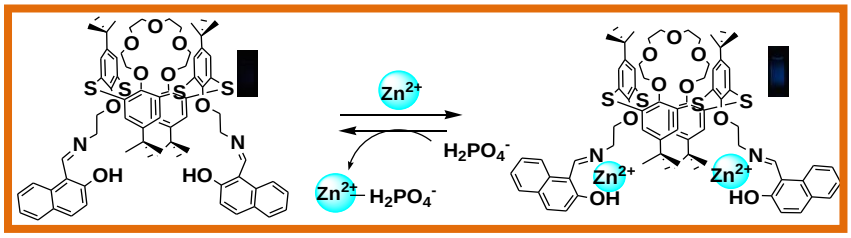
11 (*a*) M. Kumar, N. Kumar and V. Bhalla, *Dalton Trans.,* 2011, **40**, 5170; (*b*) M. Kumar, N. Kumar and V. Bhalla, *Dalton Trans.,* 2012, **41**, 10189; (*c*) M. Kumar, A. Dhir and V. Bhalla, *Eur. J. Org. Chem.*, 2009, 4534; (*d*) M. Kumar, N. Kumar and V. Bhalla, *Dalton Trans.,* 2013, **42**, 981; (*e*) M. Kumar, A. Dhir and V. Bhalla, *Dalton Trans.,* 2010, **139**, 10122.

12 S. Lee, J. H. Lee, T. Pradhan, C. S. Lim, B. R. Cho, S. Bhuniya, S. Kim, J. S. Kim, *Sens. Actuators, B* 2011, **160**, 1489.

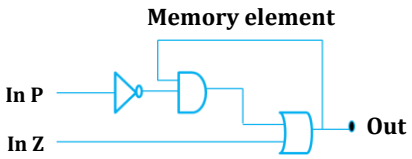
13 (*a*) J. Wang, W. Chen, X. Liu, C. Wesdemiotis and Y. Pang, *J. Mater. Chem. B,* 2014, **2**, 3349; (*b*) J. F. Zhang, S. Kim, J. H. Han, S-J Lee, T. Pradhan, Q. Y. Cao, S. J. Lee, C. Kang and J. S. Kim, *Org. Lett.,* 2011, **13**, 5294; (*c*) J. Wang, X. Liu and Y. Pang, *J. Mater. Chem. B,* 2014, **2**, 6634; (*d*) L. Tang, Y. Li, H. Zhang, Z. Guo and J. Qian, *Tetrahedron Lett.* 2009, **50**, 6844; (*e*) T. Sakamoto, A. Ojida and I. Hamachi, *Chem. Commun.,* 2009, 141.

14 X. –l Ni, X. Zeng, C. Redshaw and T. Yamato, *J. Org. Chem.* 2011, **76**, 5696.
15 (*a*) P. T. Chou, J. H Liao, C. Y. Wei, C. Y. Yang, W. S. Yu and Y. H. Chou, *J. Am. Chem. Soc.,* 2000, **122**, 986; (*b*) A. Kyrychenko, J. Herbich, M. Izydorzak, F. Wu, R. P. Thummel and J. Waluk, *J. Am. Chem. Soc.,* 1990, **112**, 11179.
16 H. Wang, L. Xue and H. Jiang, *Org. Lett.,* 2011, **13**, 3844.
17 S. Goswami, S. Das, K. Aich, D. Sarkar, T.K. Mondal, C. K. Quah and H.-K. Fun, *Dalton Trans.,* 2013, **42**, 15113.
18 (*a*) S. K. Kim, S. H. Lee, J. Y. Lee, J. Y. Lee, R. A. Bartsch and J. S. Kim, *J. Am. Chem. Soc.* 2004, **126**, 16499; (*b*) R. Kumar, Y. O. Lee, V. Bhalla, M. Kumar and J. S. Kim, *Chem. Soc. Rev.,* 2014, **43**, 4824.
19 S. Kubik, *Chem. Soc. Rev.,* 2010, **39**, 3648.
20 L. Fabbrizzi, M. Licchelli, G. Rabaioli and A. Taglietti, *Coord. Chem. Rev.,* 2000, **205**, 85.
21 V. Amendola, M.Bonizzoni, D. Esteban-Gomez, L. Fabbrizzi, M. Licchelli, F. Sancenon and A. Taglietti, *Coord. Chem. Rev.,* 2006, **250**, 1451.
22 (*a*) C. S. He, W. Zhu, Y. Xu, Y. Zhong, J. Zhou and X. Qian, *J. Mater. Chem.,* 2010, **20**, 10755; (*b*) S. Khatua, S. H. Choi, J. Lee, K. Kim, Y. Do and D. G. Churchill, *Inorg. Chem.,* 2009, **48**, 2993.
23 X. Shang, H. Wu, S. Jia, J. Han, Y. Liu, Z. Yin, X. Qin, J. Zhang and X. Xu, *J. Chil. Chem. Soc.,* 2013, **58**, 3.
24 (*a*) M. Kumar, N. Kumar and V. Bhalla, *Chem. Commun.,* 2013, **49**, 877; (*b*) N. Sharma, S. I. Reja, V. Bhalla and M. Kumar, *Dalton Trans.,* 2014, **43**, 15929.
25 K. Reimer and F. Tiemann, *Ber.,* 1876, **9**, 824.
26 G. Zengin and J. W. Huffman, *Synthesis*, 2004, 1932.

Graphical Abstract



Sr. No.	In P	In Z	Output 445 nm
1	0	0	0
2	0	1	1
3	1	0	0
4	1 (1st)	1 (2nd)	1
5	1 (2nd)	1 (1st)	0



A thiacalix[5]crown based di-topic receptor **3** possessing two types of binding sites viz crown-5 ring and imino moieties has been synthesized which undergoes fluorescence enhancement in the presence of Zn^{2+} ions. The selective binding of Zn^{2+} to compound **3** does not allow the K^+ ions to bind with crown-5 ring and thus a negative allosteric behaviour has been observed between Zn^{2+}/K^+ ions. In addition, **3**-Zn^{2+} complex can be used for the detection of $H_2PO_4^-$ ions with fluorescence "turn-off" response. Further based on the fluorescence response, a two input and one output sequential logic circuit has been constructed.