

Calix[4]amidocrown Molecular Sensors for Fluoride and Arsenate Detection

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Abstract—Calixarenes are highly efficient chelating macrocyclic class of supramolecular compounds. The utilization of their derivatives for the detection and removal of toxic ions from water is well reported. Thus, a calix[4]arene based anion sensor i.e. calix[4]amidocrown was synthesized for the detection of toxic fluoride and arsenate ions in water. The detection limits and sensitivity of this sensor towards these two anions was better than earlier reported methods. Several spectroscopic techniques were employed to support such observations.

Keywords—Supramolecules, Calix[4]amidocrown, Molecular Sensors, Fluoride and Arsenate Detection

I. INTRODUCTION

Clean water is vital to all functions of civilization and its availability is increasingly threatened by human activities.¹ Apart from natural toxins from earth crust, ground water is usually contaminated by unsafe disposal of industrial effluents in rivers, seas and earth.² Therefore, the toxicity of water increases further with arsenic, fluoride, phosphates and heavy metals. Among these, first two are the most common toxicity causing ions. Fluoride and arsenic contamination in the environment has harmful effects on plants and animals including humans.³ Although, fluoride ion helps in preventing dental caries, and treatment of osteoporosis. Excess of fluoride can be toxic and may lead to neurotoxicity^{3b} and fluorosis.^{3d} Continuous intake of arsenic is linked with a broad variety of neurologic, cardiovascular, dermatologic, and carcinogenic effects.^{3a,3c} These cosmopolitan eco-toxins inversely affect millions of people every year across the world, especially the 3rd world poor population. Various part of India badly affected with fluoride and Arsenic toxicity in drinking water. Thus, there is a need of time to develop low cost and efficient methods for the detection and removal of such toxins from drinking and waste water. In this regard, several efforts have been made to develop an efficient and selective route for arsenic and fluoride sensing and removal.^{3,4}

Calixarenes are highly efficient chelating macrocyclic class of supramolecular compounds, which serve as templates to access new types of ion/molecular sensors and extracting agents.⁵ The aromatic core and phenolic -OH groups of calixarenes have the capability to be functionalized with numerous metal and non-metal ligating moieties. There are hardly any efficient scalable methods that can selectively

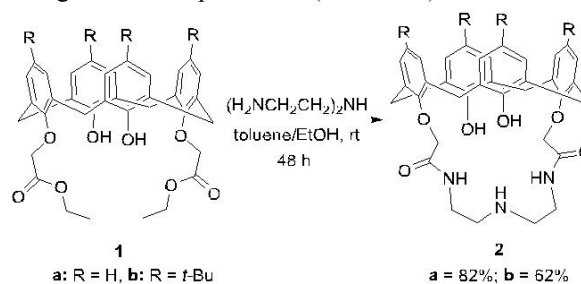
modify the calixarene core to perform the desired application.⁶ Calixarenes containing amide groups⁷ at their hydrophilic part provide possibilities of hydrogen bonding with guest anions or molecules and electrostatic forces in a way similar to peptides and proteins. In this series, calix[4]amidocrown derivatives have been prepared^{7b,7c,7f} and their cation sensing behaviour has been studied.^{7c}

With consideration to known methodologies and urge of exploring the ion sensing behaviour of calixarene based molecules, herein, we report a rapid, low cost, accurate and simple analytical method for the determination of fluoride and arsenic(III) at sub-milligram level. The key molecule that detects these anionic toxicants is “28H-4,18-(Methano[1,3] benzenomethano)-23,27-metheno-6H,22H-dibenzo[n,w][1,13,4,7,10]dioxatriazacyclotetracosine-7,15(8H,16H)-dione,9,10,11,12,13,14-hexahydro-29,32-dihydroxy” or shortly

Calix[4]amidocrown. The fluoride ion could be detected directly and investigated using UV-Vis spectroscopy. Whereas, acidic potassium iodate is used as co-reagent for arsenic detection and estimated by released iodine, generated by oxidation of As(III) after encapsulation in Calix[4]amidocrown, responsible for this oxidation. The detection limit and sensitivity is better than the existing spectrophotometric methods reported.

II. RESULT AND DISCUSSION

Synthesis of calix[4]amidocrowns were performed following a literature procedure (Scheme 1).^{7f}



Scheme 1. Preparation of Calix[4]amidocrown

In order to justify 1:1 binding stoichiometry and qualitative sensing capability for ions, the absorption spectra of both the ligands with different ions were recorded (Fig. 1).

The change in λ_{\max} values was observed for both ligands during interaction with arsenate and fluoride ions. Thus, the solution of ligand A and B (1.0×10^{-3} M) in DCM were added to water containing various concentrations of arsenate and fluoride, and shaken thoroughly. After shaking, organic and aqueous layers were separated and subjected to UV-visible titrations. In the UV visible spectra of ligands with arsenate ion, rhodamine was used to explain the host guest interaction in a way of absorbance variability, and observed at 556 nm, as

arsenate alone does not show any strong UV-visible peaks. An enhancement of rhodamine peak was observed in DCM layer after shaking it with arsenate containing water. Thus, with increasing concentration of ions, UV-visible enhancement was observed in DCM layer, whereas reduction in absorbance peaks was identified in aqueous layer. The above result suggested the transfer of fluoride and arsenate ions from water to DCM.

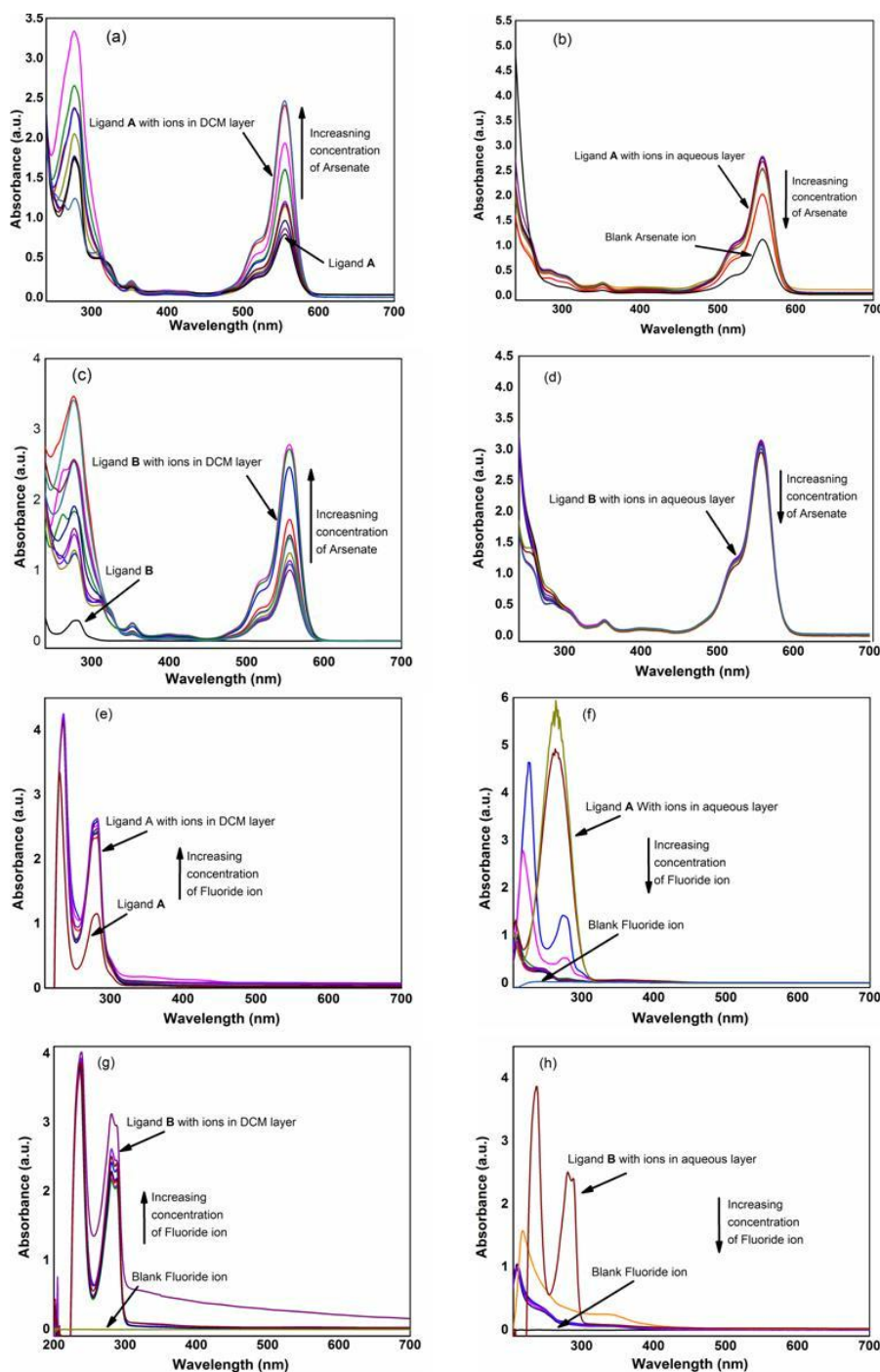


Fig. 1. UV-visible spectra of (a-b) Ligand A with arsenate: DCM and aqueous layer; (c-d) Ligand B with arsenate: DCM and aqueous layer; (e-f) Ligand A with fluoride: DCM and aqueous layer; (g-h) Ligand B with fluoride: DCM and aqueous layer

Benesi Hildebrand plots were prepared to determine the stoichiometry in these Guest-Host complexes.⁸ Figure 2 shows Benesi Hildebrand plot for both ligands in DCM and aqueous environment in absorption spectroscopy. In these cases, absorbance values of free guest (ions) were compared with complexes thus formed. It was observed that the absorbance value of the complex is higher than that of the free guest, which might be due to the intermolecular hydrogen bonding between guest anions and hydroxyl group of the ligands. The association constant was determined by spectroscopic method, using Benesi Hildebrand equation:

$$\frac{1}{I - I_0} = \frac{1}{[CB[6]]K_a\alpha} + \frac{1}{\alpha} \quad (1)$$

Where *I* and *I*₀ represent intensity of spectrum in presence and absence of ligands, respectively, and *α* is constant. *K*_a is the association or binding constant for ligand-ion molecular association as 1:1 guest-host complexes.

A plot of 1/*I*-*I*₀ versus 1/[Ionic Concentration] resulted in a straight line, which reflected the formation of 1:1 inclusion complexes of arsenate and fluoride ions with both ligands (Fig. 2). The values of binding constant are calculated from the slope and the intercept of the plot. The binding constant values for both ions are significantly changed, which revealed different types of inclusion associated with ligands. The association constant values are shown in Table 1. A significant interaction was observed during the interaction of fluoride with ligand A.

NMR spectra were recorded to understand the interactions of fluoride and arsenate ions with calix[4]amidocrown ligands **2**. Due to the solubility reasons, the binding of arsenate ion with ligands was studied in DMSO-d₆ using sodium arsenate, and the spectra of fluoride with ligands were recorded in a mixture of CD₃CN and CDCl₃ (3:1 v/v) by taking a solution of tetrabutylammonium fluoride (TBAF) as a fluoride source. The interaction of arsenate and fluoride with ligands could be emphasized on the basis of changes observed in amide and phenolic -OH group peaks were observed in all cases (Fig. 3-6). However, fluoride addition in Ligand A and B resulted in significant changes in other peaks as well (Fig. 5-6).

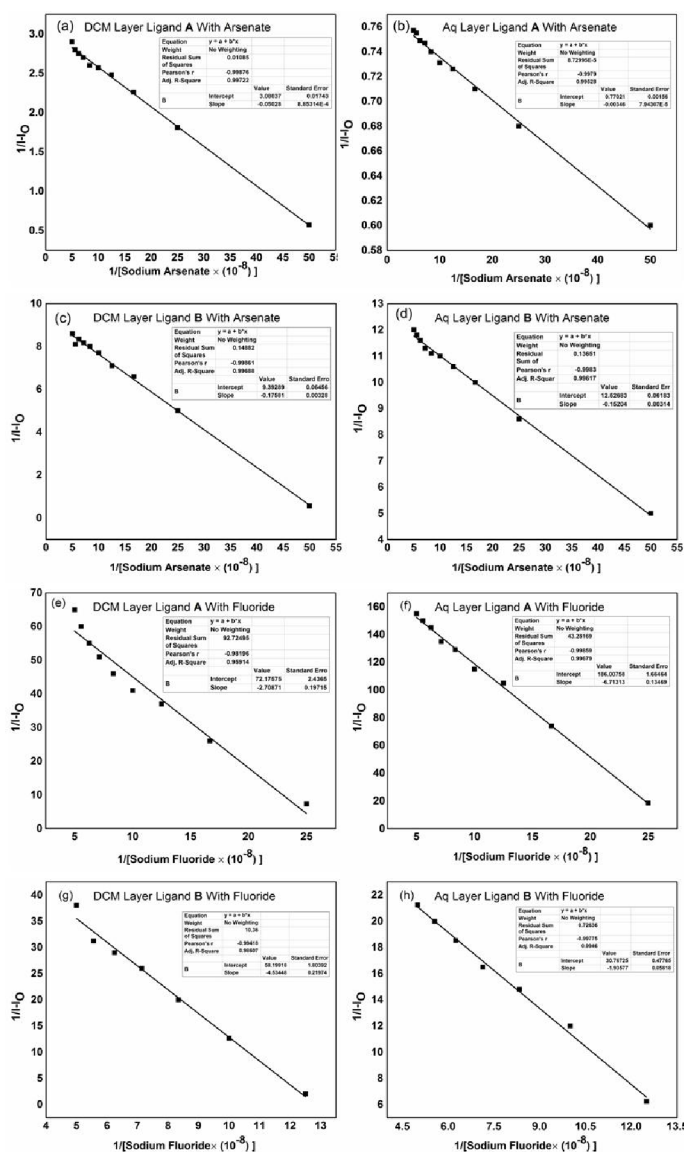


Fig. 2. Benesi Hildebrand plots of (a-b) Ligand A with arsenate: DCM and aqueous layer; (c-d) Ligand B with arsenate: DCM and aqueous layer; (e-f) Ligand A with fluoride: DCM and aqueous layer; (g-h) Ligand B with fluoride: DCM and aqueous layer

Table 1. Benesi Hildebrand plot data from UV-visible spectroscopy

Desired Values	Ligand A-arsenate		Ligand A-fluoride		Ligand B-arsenate		Ligand B-fluoride	
	DCM	Aqueous	DCM	Aqueous	DCM	Aqueous	DCM	Aqueous
<i>K</i> _a (10 ⁸)	61.6	222.6	26.66	27.71	53.43	82.4	12.82	15.86
Adj R Square	0.997	0.995	0.959	0.996	0.997	0.996	0.998	0.994
Wavelength Used	556	556	347	347	556	556	347	347

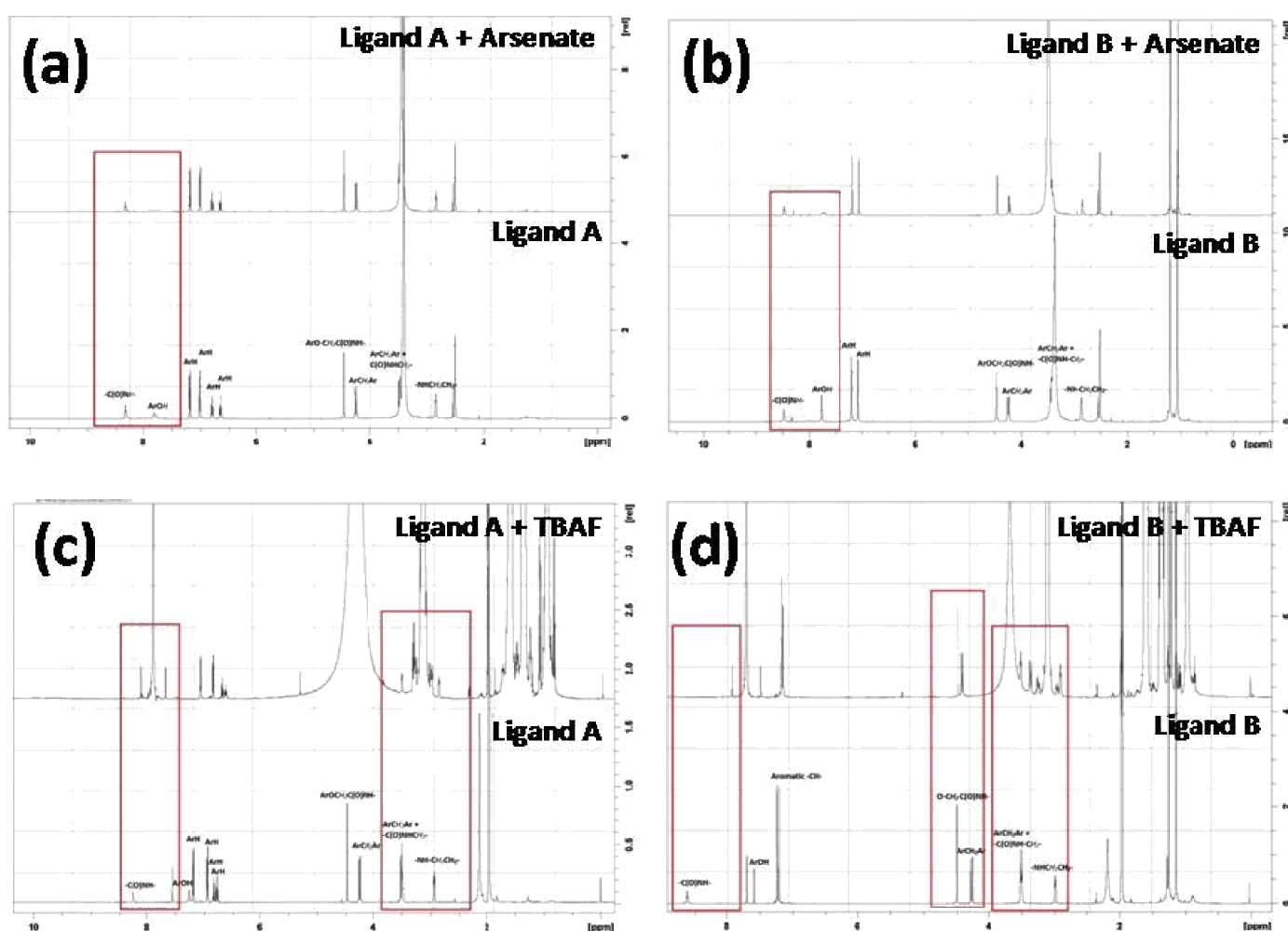


Fig. 3. ^1H NMR data of (a) Ligand A before and after the addition of sodium arsenate in DMSO- d_6 (b) Ligand B before and after the addition of sodium arsenate in DMSO- d_6 (c) Ligand A before and after the addition of TBAF in $\text{CD}_3\text{CN}-\text{CDCl}_3$ (3:1 v/v) (d) Ligand B before and after the addition of TBAF in $\text{CD}_3\text{CN}-\text{CDCl}_3$ (3:1 v/v)

A comparative analysis of UV-vis and NMR data suggested a stronger binding of both calix[4]amidocrown ligands with fluoride ion. However, a possible interaction between the amide $-\text{NH}$ and phenolic $-\text{OH}$ groups resulted in the detection of these ions.

III. CONCLUSION

In summary, we have explored the sensing behavior of calix[4]amidocrown ligands for the detection of fluoride and arsenate ligands. The interaction behavior and its mechanism were supported by UV-vis and NMR analyses.

IV. EXPERIMENTAL SECTION

UV-Vis measurements were carried on Varian Cary 4000 in the range of 200-800 nm. Nuclear magnetic resonance spectra were recorded on a Bruker 500 spectrometer operating at 500 MHz in DMSO- d_6 for arsenate detection and in $\text{CD}_3\text{CN}-$

CDCl_3 mixture (3:1) for fluoride detection. Compound **1a-b** were prepared as reported earlier.⁹

General Procedure: Calix[4]amidocrowns **2** were synthesized from **1**, following a literature procedure.^{7f} Calix[4]arene **1** (1 mmol) and bis(2-aminoethyl)amine (3 mmol) were taken in a mixture of ethanol (10 mL) and toluene (10 mL), and stirred at room temperature for 48 h. After completion of the reaction, resulting solution was concentrated under vacuum. The crude thus obtained was suspended in methanol/water, filtered and recrystallized to obtain **2** in good to high yields. Melting point, NMR and IR data were taken and compared with known literature data.^{7f}

2a: yield 82%, mp: 263-264 °C (*n*-BuOH) (lit mp 264-265 °C)^{7f}; **2b:** yield 62%, mp 182-183 °C (EtOH) (lit mp 183-185 °C)^{7f}

Sample preparation for UV-Vis measurements: Ligand A and B were separately dissolved in DCM. Sodium fluoride 10 ppm and sodium arsenate 50 ppb aqueous solutions were prepared. Variable amounts of arsenate and fluoride (from 0-10 mL) were dissolved in 10 mL DCM solution and marked up to 20

mL. After 1.5 h shaking, organic and aqueous layers were separated and subjected to UV-visible analysis for fluoride. However, 0.05% rhodamine (1ml), 2% KIO₃ solution (1 mL) and 0.4M HCl (0.5mL) were dissolved in case of arsenate, which required further layer separation before analyzing under UV-visible spectroscopy.

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