Tetrahedron 65 (2009) 7963–7968

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Synthesis of di-substituted calix[4]arene-based receptors for extraction of chromate and arsenate anions

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ARTICLE INFO

Article history:
Received 7 February 2009
Received in revised form 8 June 2009
Accepted 23 July 2009
Available online 29 July 2009

Keywords:
Calixarene
Arsenate anion
Chromate anion
Proton-switchable
Liquid–liquid extraction

ABSTRACT

The article describes the synthesis of a family of novel calix[4]arene ionophores, 25,27-bis-(2-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5a**), 25,27-bis-(3-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5b**) and two chromogenic calix[4]arenes, 5,17-dinitro-25,27-bis-(2-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5c**), 5,17-dinitro-25,27-bis-(3-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5d**) bearing pyridinium units. In the synthesis, the upper and lower rims of *p-tert*-butylcalix[4]arene were modified in order to acquire binding sites for the recognition of arsenate and dichromate anions. It has been observed that protonated alkylammonium forms of the ionophores showed high affinity toward dichromate and arsenate anions.

1. Introduction

Calixarenes are cyclic oligomers made of several phenolic units bounded with methylene bridges and are regarded as the third generation of host molecules because of their inclusion ability to cations, anions, and neutral molecules.[1–3] Calix[4]arenes can be easily functionalized both at the phenolic OH groups (lower rim) and, after partial removal of *tert*-butyl groups, at the *para* positions of the phenol rings (upper rim).[4,5] The vast majority of these modified calixarenes exist in the cone conformation in which there is a cavity suitable for reception of different ionic and neutral species.[6] Furthermore, the most significant feature of the chemistry of these molecules is their ability to bind selectively alkali and alkaline earth cations. Chromate and arsenate anions are important because of their high toxicity and because of their presence in soils and waters.[7,8] Arsenic is an omnipresent eco-toxin; the presence of arsenic in water is a serious threat for more than 100 million people in the world.[9] Humans are clearly sensitive to arsenic carcinogenesis; prolonged exposure to arsenic damages the central nervous system and results in diverse types of cancer in liver, lung, bladder, and skin.[10,11] Chromium and its compounds are widely used in plating, leather tanning, dye, cement, and photographic industries, producing large quantities of toxic pollutants.[12] Chromium can exist in several oxidation states, however, only the trivalent and hexavalent forms are environmentally important.[13] Chromium(III) has been reported to be biologically essential to mammals as it maintains effective glucose, lipid, and protein metabolisms. However, chromium(VI) can be toxic as it can diffuse as $Cr_2O_7^{2-}$ or $HCr_2O_7^-$ through cell membranes and oxidize biological molecules.[14] Therefore, treatment of wastewater containing Cr(VI) prior to discharge is essential. Solvent extraction is one of the most commonly used treatment methods and employs a selective complexant especially for ions in aqueous solution. Although there are numerous examples of molecules that act as hosts and complexants for cations, relatively fewer molecules have been reported as hosts for anions.[15–18] Thus, the development of efficient extractants for anions has received considerable attention in recent years.[19] Compared to the number of reports on the binding of anions with calixarenes, reports on the binding of oxyanions are still limited.[20–24] From this point of view calixarene receptors bearing pyridinium units are at the center of interest.[25,26]

In a previous study,[27] we reported a di-substituted calix[4]arene amide derivative bearing pyridinium units, which acted as a receptor for both dichromate anions and some selected cations, and observed that pyridinium units were effective binding sites for these ions. However, there are no articles showing the effect of substituents on upper rim of calixarenes in literature. Thus, in this study, we aimed to synthesized new calix[4]arene receptors bearing pyridinium units on their lower rim and nitro substituents instead of *tert*-butyl groups on their upper rim as mentioned in

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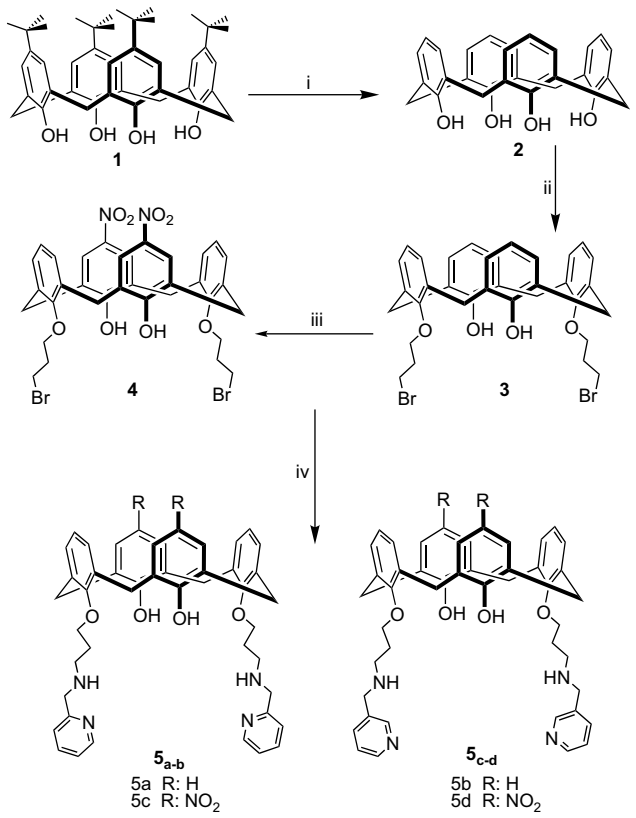
doi:10.1016/j.tet.2009.07.062

Scheme 1. Furthermore, their recognition abilities were investigated toward dichromate and arsenate anions by means of liquid–liquid phase extraction processes.



Scheme 1. Synthetic route of preparation of calix[4]arene derivatives. (i) $AlCl_3$, phenol, toluene, rt, 1 h; (ii) 1,3-dibromopropane, CH_3CN, reflux, 48 h; (iii) HNO_3 (70%), glacial AcOH, 0 °C, CH_2Cl_2, 2 h; (iv) 3-aminomethylpyridine and 2-aminomethylpyridine, THF, NaI, reflux, 72 h.

2. Results and discussion

2.1. Synthesis

As mentioned above, a set of new calix[4]arenes bearing pyridine units on their lower rim and nitro groups instead of *tert*-butyl groups on their upper rim were prepared. The binding properties of calix[4]arene derivatives were explored toward dichromate and arsenate anions. The synthesis of the new calix[4]arene derivatives is given in Scheme 1. For the synthesis of calix[4]arenes and dinitrocalix[4]arene based on pyridine units **5a**–**d**, the parent compounds (**1**–**3**) and noncyclic compound (**9**) were prepared according to published procedures.[5,28,29] All of the structures have been characterized through ^{1}H NMR, IR, and elemental analyses. Firstly, *p*-*tert*-butylcalix[4]arene was dealkylated according to literature procedure[28] and then functionalized with 1,3-dibromopropane in the presence of K_2CO_3 to obtain the dibromocalix[4]arene compound **3** by O-substitution on the lower rim of calix[4]arene in 1,3-(distal) position.[29] The treatment of dibromocalix[4]arene with HNO_3 and CH_3COOH in dichloromethane gave the corresponding dinitro-substituted product on upper rim of the dibromocalix[4]-arene compound **4**. In the following step, these compounds **3** and **4** were treated with 2-aminomethylpyridine or 3-aminomethylpyridine to synthesize corresponding dinitro-calix[4]arene and calix[4]arene bearing pyridinium units **5a**–**d** in the presence of a catalytic amount of NaI in THF. ^{1}H NMR data showed that compounds **5a**–**d** are in the cone conformation. A typical AX pattern was observed for the methylene bridge $ArCH_2Ar$ protons at 3.49 ppm and 4.22 ppm (J=13 Hz) for **5a**, 3.45 ppm and 4.20 ppm (J=13.1 Hz) for **5c** in the ^{1}H NMR. The high field doublets at 3.49 ppm for **5a**, and 3.45 ppm for **5c** were assigned to the equatorial protons of methylene groups, whereas the low field signals at 4.22 ppm for **5a**, and 4.20 ppm for **5c** were assigned to the axial protons in the ^{1}H NMR. However, some of the methylene protons were overlapped in the case of **5b** and **5d**. Furthermore, the pyridinium units on lower rim of calixarenes are characterized by the presence of singlet peaks at 3.82, 4.10, 4.02, 4.12 ppm ($NHCH_2Ar$) for **5a**–**d**, respectively. Overlapping peaks in the range of 3.56–3.50 ppm (NH and $ArCH_2Ar$) for **5b** and **5d** and 2.44–2.30 ppm ($OCH_2CH_2CH_2$ and NH) for **5a** and **5c** were also observed. All other data were in agreement with the proposed structures of **5a**–**d**.

2.2. Two-phase solvent extractions

2.2.1. Arsenate anion. For a molecule to be effective as a host, it is necessary that its structural features are compatible with those of the guest anions. The arsenate ($H_2AsO_4^-$/$HAsO_4^{2-}$) ions are dianions where the periphery of the anions has oxide moieties. These oxides are potential sites for hydrogen bonding to the host molecule. A preliminary evaluation of the extraction efficiencies of **5a**–**d** has been carried out by solvent extraction of arsenate ions from water into dichloromethane at different pH values. The results are summarized in Table 1 and Figure 1.

Table 1
Percentage extraction of arsenate ion by extractants **5a** and **5b** at different pH values[a,b]

Compounds	pH			
	3.5	4.5	5.5	7.0
5a	32±1	50±1	22±1	2±1
5b	5±1	24±1	10±1	3±1

[a] Averages and standard deviations calculated for data obtained from three independent extraction experiments.
[b] Aqueous phase, [sodium arsenate]=1×10^{-5} M; organic phase, [ligand]=1×10^{-3} M at 25 °C, for 1 h.

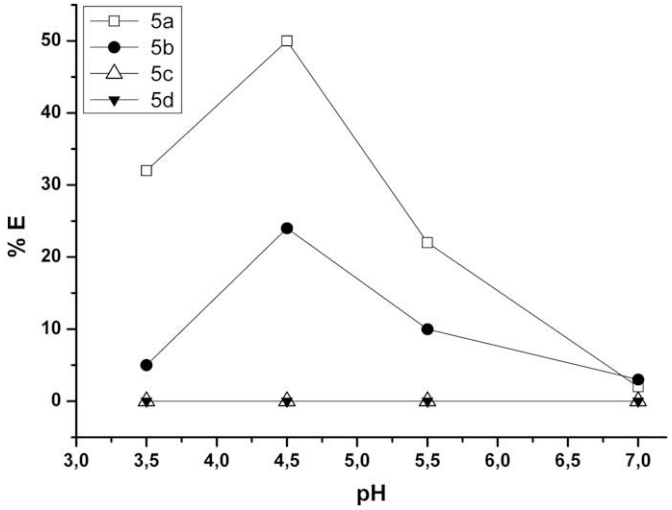
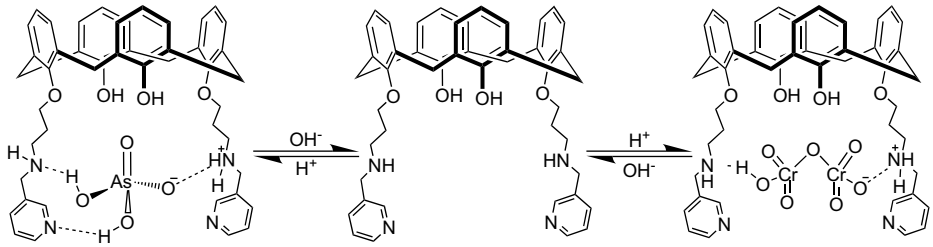


Figure 1. Plots of extraction (E %) versus pH following the two-phase solvent extraction of arsenate with compounds **5a**–**d**.

From the extraction data, **5a** was found to be an effective extractant for the phase transfer of arsenate anions at pH 4.5. From Table 1 and Figure 1 it is clear that maximum extraction 50% for **5a** and 20% **5b** occur at pH 4.5, which shows that best interaction between the ligand **5a** and the arsenate ions occurs at this pH. This



Scheme 2. The suggested complexation phenomena of arsenate and dichromate ion with **5b**.

interaction is attributed to the hydrogen bonding and electrostatic interaction between amino groups and the oxygens of arsenate ions.[30] The arsenate anion was not extracted by dinitro-calix[4] arene **5c** and **5d** at pH 3.5–7.0 because of the solubilizing properties of nitro-calix[4]arene in water.[31] Among these compounds, calixarene derivatives **5a** and **5b** gave the best efficiency for the extraction of arsenate ions in pH 4.5 medium. The proposed interaction for the attraction between the arsenate and the ligand **5a** is shown in Scheme 2. As(V) speciation is affected by the solution pH through the following equilibrium:[32]

$$H_3AsO_4 \leftrightarrow H_2AsO_4^- + H^+ \qquad pK_{a1} = 2.3 \tag{1}$$

$$H_2AsO_4^- \leftrightarrow HAsO_4^{2-} + H^+ \qquad pK_{a2} = 6.8 \tag{2}$$

$$HAsO_4^{2-} \leftrightarrow AsO_4^{3-} + H^+ \qquad pK_{a2} = 11.6 \tag{3}$$

From Eqs. 1–3, the As(V) species occurs mainly in the form of $H_2AsO_4^-$ in the pH range between 3 and 6, while a divalent anion $H_2AsO_4^{2-}$ dominates at higher pH values (such as between pH 8 and 11). The monoanion ($H_2AsO_4^-$) will have a smaller free energy of hydration than does the dianionic form $HAsO_4^{2-}$. As a result, there is a smaller loss in hydration energy as $H_2AsO_4^-$ is transferred from the aqueous phase into the dichloromethane phase. An additional advantage of $H_2AsO_4^-$ over $HAsO_4^{2-}$ is that for the former only one sodium ion needs to be coextracted to maintain charge balance, whereas for $HAsO_4^{2-}$ two sodium ions are extracted, with additional loss of hydration energy.[32]

2.2.2. Dichromate anion. The dichromate ions ($Cr_2O_7^{2-}/HCr_2O_7^-$) are anions where the periphery of the anion has oxide moieties. It is known that calix[4]arenes with a nitrogen functionality such as pyridine, amino, and imino on their lower rim are efficient extractants for oxoanions.[22–25] We have performed some preliminary evaluations to investigate binding efficiencies of the extractants **5a** and **5b** for $Na_2Cr_2O_7$ by using solvent extraction. The results showed that $Na_2Cr_2O_7$ could be extracted from aqueous solution into dichloromethane at different pH values. The results are summarized in Table 2 and Figure 2. An aqueous solution of $Na_2Cr_2O_7$ shows no extraction into an organic phase in the absence of the extractant.

The extraction data (Fig. 2) showed that the extractants **5a** and **5b** are more effective for the extraction of dichromate anions at low pH. The percentage of dichromate ions extracted was 67% for **5a** and 72% for **5b** when the pH of the aqueous solution was 1.5 and they attained minimum level of 4% for **5a** and 10% for **5b** when the pH of the aqueous solution was increased to 4.5. Calix[4]arene derivatives **5a** and **5b** provide suitable binding sites for dichromate anions at low pH due to containing protonable pyridyl and amine moieties. Therefore, an anion-switchable complex is formed in the two-phase extraction system (Scheme 2) because of the proton transfer to the nitrogen atom of the alkyl chain in **5a** and **5b**.

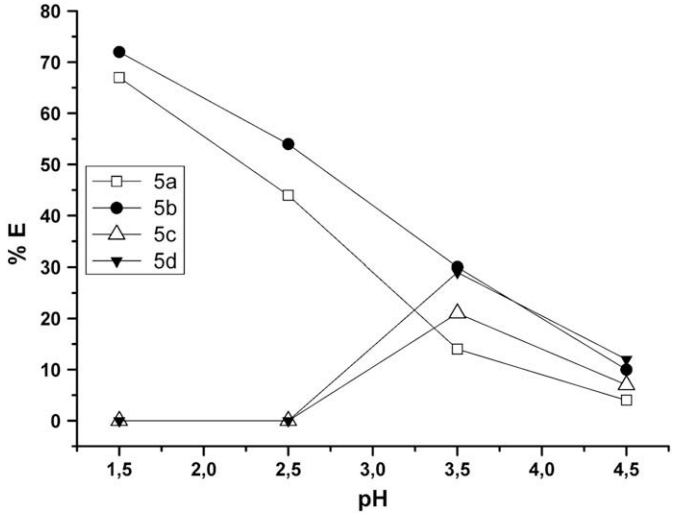


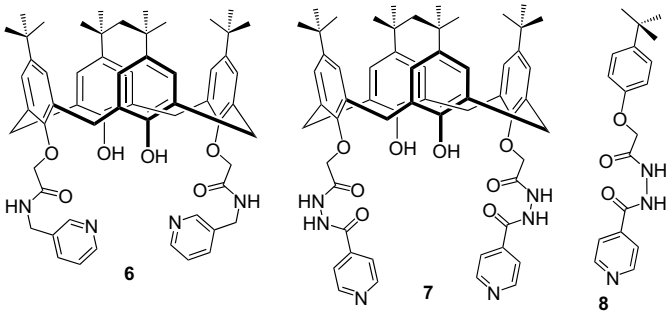
Figure 2. Plots of extraction (E %) versus pH following the two-phase solvent extraction of dichromate with compounds **5a–d**.

Table 2
Percentage extraction of dichromate by extractants **5a** and **5b** at different pH values[a,b]

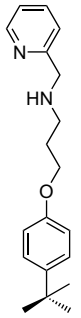
Compounds	pH			
	1.5	2.5	3.5	4.5
5a	67±1	44±2	14±1	4±1
5b	72±1	54±1	30±1	10±1
6[c]	24.8	11.5	10.3	<1.0

[a] Averages and standard deviations calculated for data obtained from three independent extraction experiments.
[b] Aqueous phase, [metal dichromate]=1×10^{-4} M; organic phase, [ligand]=1×10^{-3} M at 25 °C, for 1 h.
[c] Ref. 27.

In order to establish an effective role of the macrocyclic scaffold of calixarenes (**5a** and **5b**) in the anion binding, noncyclic monomeric analog (**9**) (Scheme 4) was synthesized. Because of the soluble properties of monomeric analog (**9**) in water at low pH, $HCr_2O_7^-$ anion was not extracted at low pH by the compound. In our previous study,[23,27] to understand the chelating effect of both pyridine fragments in the anion binding, noncyclic monomeric analog (**8**) of macrocyclic ligands (**7**) (Scheme 3) was used. It was observed that dichromate anion was only extracted in trace amounts. Based on the



Scheme 3. Previously synthesized ligands **6**, **7**, and noncyclic analog **8**.[23,27]



9

Scheme 4. Noncyclic analog of new ligands **9**.

results, it has been concluded that calix[4]arene unit plays an important role in confirming the cooperative participation of the functional groups. From the extraction data in Table 2, calix[4]arene bearing amide-pyridinium units **6** (Scheme 3) exhibited lower extractability (24.8%) than the calix[4]arene derivative bearing amine-pyridinium units (**5a** and **5b**). This reflects the fact that calix[4]arene amine binding sites more strongly complex with dichromate in low pH medium. The pK_a of protonated nitrogen of secondary amine groups is around 10–11, the protonated form of calix[4]arene derivatives (**5a** and **5b**) is expected to be present in significant concentration in aqueous solution (generally the pK_a of protonated pyridine is around 5.25).[33] However, it was also observed that the replacement of *tert*-butyl groups in calix[4]arene by nitro groups affects the extraction ability. $HCr_2O_7^-$ ions were not extracted by the dinitro-calix[4]arenes **5c** and **5d** due to their solubilization in water.[31] Among these compounds, calixarene derivatives **5a** and **5b** therefore present the best efficiency for the extraction of $HCr_2O_7^-$/$Cr_2O_7^{2-}$ ions in a low pH medium. An anion-switchable complex is formed in the two-phase extraction system. Upon addition of NaOH to the aqueous layer, the deprotonated calixarene in CH_2Cl_2 is no longer an effective host molecule for $Cr_2O_7^{2-}$ and the dianion then migrates back into the aqueous layer in a reversible process as shown in Scheme 2. This situation results from the proton transfer to the nitrogen atom of the alkyl chain in compounds **5a** and **5b**. In aqueous solutions having a lower pH the dichromate will be primarily in its protonated form $HCr_2O_7^-$. This monoanion will have a smaller free energy of hydration compared to dianionic form $Cr_2O_7^{2-}$. As a result, there is a smaller loss in hydration energy as $HCr_2O_7^-$ is transferred from the aqueous phase into the dichloromethane phase. An additional advantage of $HCr_2O_7^-$ over $Cr_2O_7^{2-}$ is that for the former, only one sodium ion needs to be coextracted to maintain charge balance, whereas for $Cr_2O_7^{2-}$ two sodium ions are extracted, with additional loss of hydration energy.[34] All data have been analyzed using the classical slope analysis method.[23] Assuming that the extraction of an anion A^{n-} by the receptor LH^{n+} is according to following equilibrium:

$$n\left(\mathrm{LH}^{n+}\right)_{\mathrm{org}}+n\mathrm{A}_{\mathrm{aq}}^{n-} \leftrightharpoons \left[\left(\mathrm{LH}^{n+}\right)_n,\mathrm{A}_n^{n-}\right]_{\mathrm{org}} \quad (4)$$

The extraction constant K_{ex} is then defined by:

$$K_{\mathrm{ex}}=\frac{\left[\left(\left(\mathrm{LH}^{n+}\right)_n,\mathrm{A}_n^{n-}\right)\right]_{\mathrm{org}}}{\left[\mathrm{A}^{n-}\right]_{\mathrm{aq}}^{n}\left[\mathrm{LH}^{n+}\right]_{\mathrm{org}}^{n}} \quad (5)$$

Eq. 5 can be re-written as:

$$\log D_{\mathrm{A}}=\log K_{\mathrm{ex}}+n\log\left[\mathrm{LH}^{n+}\right]_{\mathrm{org}} \quad (6)$$

where D_A is defined as the ratio of the analytical concentration of the anion A^{n-} in both phases:

$$D_{\mathrm{A}}=[A]_{\mathrm{org}}/[A]_{\mathrm{aq}}$$

Consequently, a plot of log D_A versus log [L] leads to a straight line with a slope that allows for the determination of the stoichiometry of the extracted species, where [L] is defined as the analytical concentration of the ligand in the organic phase. Figure 3 exhibits the extraction into dichloromethane at different concentrations of **5a** and **5b** with dichromate, respectively. A linear relationship between log D_A versus log [L] is observed with the slope of the line for extraction of dichromate anion by ligands **5a** and **5b** is approximately equal to 1 (for ligands **5a** and **5b** at pH 1.5, respectively), suggesting that these ligands **5a** and **5b** form 1:1 complexes with the dichromate anion. However, it is well known that under more acidic conditions $Na_2Cr_2O_7$ is converted into $H_2Cr_2O_7$ and after ionization in an aqueous solution it exists in the $HCr_2O_7^-$/$Cr_2O_7^{2-}$ form. At more strongly acidic conditions $HCr_2O_7^-$ and $Cr_2O_7^{2-}$ dimers become the dominant Cr^{6+} form and pK_{a1} and pK_{a2} values of these equations are 0.74 and 6.49, respectively. It is clear that the ligands **5a** and **5b** form complexes mostly with $HCr_2O_7^-$ ions. This has allowed us to consider that this simultaneous extraction of 1:1 complexes occurs according to the following equilibria:

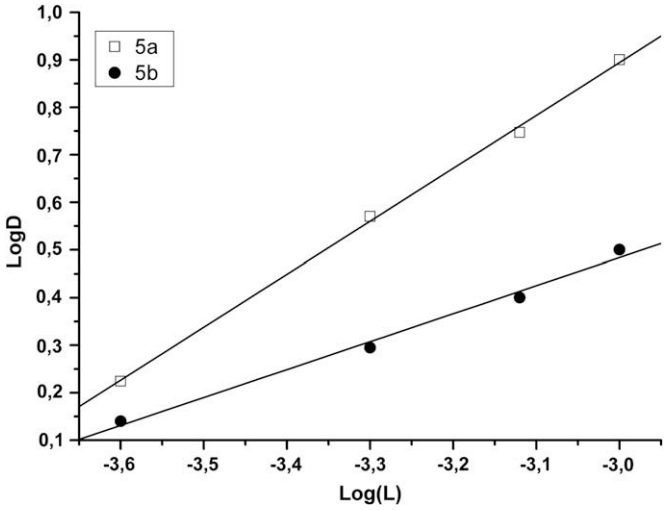


Figure 3. log D versus log [L] for the extraction of dichromate and its anions by the ligands **5a** and **5b** from an aqueous phase into dichloromethane at 25 °C and pH 1.5.

$$\left(\mathrm{LH}^{+}\right)_{\mathrm{org}}+\mathrm{HCr_2O_{7aq}^-} \overset{K_{\mathrm{ex}}}{\leftrightharpoons} \left(\mathrm{LH}^{+},\mathrm{HCr_2O_7^-}\right)_{\mathrm{org}} \quad (7)$$

According to these assumptions, the extraction constant has been calculated from the experimental data with similar K_{ex} values using Eq. 6. Calculations of these constant values lead to log K_{ex}=2.24±0.2 for **5a** and log K_{ex}=4.23±0.2 for **5b**. Figure 4 shows UV–vis spectra of **5c** and **5d** in dichloromethane.

While compounds **5c–d** could not be used in the recognition studies of dichromate anions because of the increased solubility of compounds **5c–d** in water at low pH, examination of the spectra showed broad absorption bands at 331 and 332 nm suggesting that compounds **5c** and **5d** could potentially be used as a sensor for anions.

3. Conclusion

In conclusion, the synthesis and ion extraction abilities of calix[4]arene and dinitro-calix[4]arene based on pyridinium units receptors **5a–d** were studied. The spectroscopic data indicated that the new compounds are in the cone conformation. The dichromate

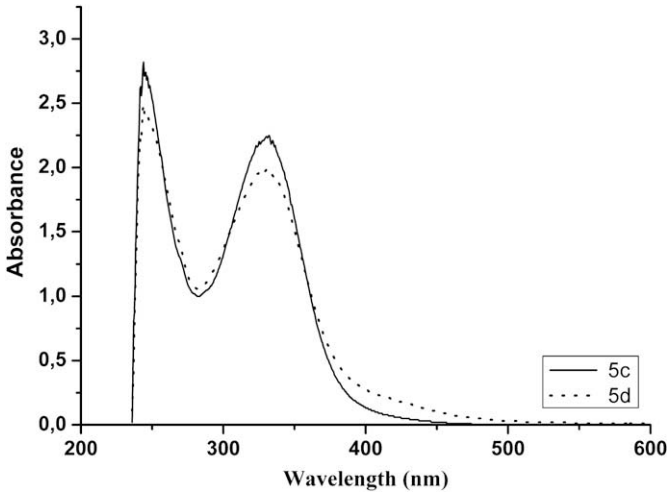


Figure 4. The UV–vis spectrum of compounds **5c** and **5d**.

and arsenate anion studies showed that compounds **5a** and **5b** were effective extractants for $HCr_2O_7^-$ and $H_2AsO_4^-$ anions. The variety of hydrogen bonding sites that occur in these calix[4]arene derivatives may be of considerable importance for the future design of novel calix[4]arene-based receptors, carriers, or supramolecular structures. The calix[4]arene and dinitro-calix[4]arene based on pyridinium units receptors could be proved to find remarkable applications in the design of chemical sensors, in anion-binding processes, especially phase-transfer catalyses and solid-state sensors.

4. Experimental

4.1. General

All of the reagents used in this study were obtained from Merck or Fluka and used without further purification. Dry THF was distilled from the ketyl prepared from sodium and benzophenone. Acetonitrile was dried from calcium hydride and stored under N_2 over molecular sieves (4 Å). CH_2Cl_2 was distilled from $CaCl_2$·MeOH over Mg and stored over molecular sieves. Anions were used as their sodium salts. Thin layer chromatography (TLC) was performed using silica gel on glass TLC plates (silica gel H, type 60, Merck). Generally solvents were dried by storing them over molecular sieves (Aldrich; 4 Å, 8–12 mesh). All aqueous solutions were prepared with deionized water that had been passed through a Millipore Milli-Q Plus water purification system. Melting points were determined on a Gallenkamp apparatus. ^{1}H NMR spectra were obtained using a Varian 400 MHz spectrometer operating at 400 MHz. IR spectra were recorded on a Perkin–Elmer 1605 FTIR spectrometer as KBr pellets. UV–visible spectra were obtained on Jenway 6105 and Shimadzu 160 A UV–visible recording spectrophotometers. Atomic absorption spectra were obtained on ContrAA 300 (Analytikjeno). Elemental analyses were performed using a Leco CHNS-932 analyzer. An Orion 410A+ pH meter was used for the pH measurements.

4.2. Synthesis

5,11,17,23-Tetra-*tert*-butyl-25,26,27,28-tetrahydroxycalix[4]arene (**1**), 25,26,27,28-tetrahydroxycalix[4]arene (**2**), and 25,27-bis-(bromopropoxy)-26,28-dihydroxycalix[4]arene compounds (**3**) were synthesized according to literature procedures.[5,28,29] Compound **4** was synthesized through a modified literature procedure.[35] The dinitro-calix[4]arene (**4**) and final products (**5a**–**d**) were synthesized according to the following procedures:

*4.2.1. 5,17-Dinitro-25,27-bis-(bromopropoxy)-26,28-dihydroxycalix[4]arene (**4**).* 25,27-Bis-(bromopropoxy)-26,28-dihydroxycalix[4]arene (**3**) (3.3 mmol) and acetic acid (118 mmol) in 60 mL CH_2Cl_2 was added to solution of 65% HNO_3 (168 mmol) at 0 °C in ice bath, and then stirred for half an hour. Then, water (50 mL) was added. The organic layer was separated and washed with water (3×50 mL), dried under sodium sulfate, filtered, and evaporated under reduced pressure. The crude product was recrystallized from CH_2Cl_2 and MeOH. Yield 55%, pale yellow solid, mp 323–325 °C with decomposition. ^{1}H NMR ($CDCl_3$): δ 9.07 (s, 2H, OH), 8.05 (s, 4H, ArH), 7.0 (d, 2H, J=7 Hz, ArH), 6.9 (t, 2H, J=8 Hz, ArH), 4.30–4.27 (d, 4H, J=13.5 Hz, $ArCH_2Ar$), 4.20–4.18 (t, J=5 Hz, 4H, OCH_2), 3.96 (t, 4H, J=7 Hz, CH_2Br), 3.57–3.54 (d, 4H, J=14 Hz, $ArCH_2Ar$), 2.59–2.56 (t, J=6 Hz, 4H, $CH_2CH_2CH_2$); IR (ν) 2900, 2860 (C–H), 1600 (CN), 1555, 1525, 1480 (C=C), 810 (C–Br). Anal. Calcd $C_{34}H_{32}Br_2N_2O_8$. C, 53.99; H, 4.26; N, 3.70%. Found: C, 53.93; H, 4.31; N, 3.73%.

4.2.2. General procedure for the synthesis of ligands. 25,27-Bis-(bromopropoxy)-26,28-dihydroxycalix[4]arene (**3**) and 5,17-dinitro-25,27-bis-(bromopropoxy)-26,28-dihydroxycalix[4]arene compounds (**4**) (0.6 mmol) were refluxed in THF (30 mL) in the presence of catalytic amount of NaI for 1 h. To this mixture, excess of suitable pyridine compounds 3-aminomethylpyridine and 2-aminomethylpyridine (1.4 mmol) were added dropwise and then refluxed for 72 h. After filtration, the solution was evaporated to dryness. The residue was washed with water. Then, the product was recrystallized from CH_2Cl_2 and MeOH.

*4.2.3. 25,27-Bis-(2-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5a**).* Yield 35%, dark yellow solid, mp 111–112 °C with decomposition. ^{1}H NMR ($CDCl_3$): δ 8.65 (d, J=8.0 Hz, 2H, Py-H), 8.30 (t, J=7.9 Hz, 2H, Py-H), 8.02 (t, 2H, J=7.9 Hz, Py-H), 7.35 (d, 2H, J=7.7 Hz, Py-H), 7.25 (s, 2H, OH), 7.05 (d, J=8 Hz, 4H, ArH), 6.96 (d, J=8.1 Hz, 4H, ArH), 6.79–6.75 (m, 4H, ArH), 4.22–4.20 (d, 4H, J=13.1 Hz, $ArCH_2Ar$), 4.15 (t, J=5 Hz, 4H, OCH_2), 4.02 (s, 4H, $NHCH_2Ar$), 3.49–3.46 (d, 4H, J=13 Hz, $ArCH_2Ar$), 3.38–3.36 (t, J=8 Hz, 4H, $NHCH_2$), 2.30 (br m, 6H, $OCH_2CH_2CH_2$ and NH); IR (ν) 3185 (NH), 2900, 2875 (C–H), 1610 (CN), 1555, 1510, 1485 (C=C). Anal. Calcd $C_{46}H_{48}N_4O_4$. C, 76.64; H, 6.70; N, 7.77%. Found: C, 76.65; H, 6.73; N, 7.73%.

*4.2.4. 25,27-Bis-(3-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5b**).* Yield 38%, pale yellow solid, mp 138–140 °C with decomposition. ^{1}H NMR ($CDCl_3$): δ 8.69 (br s, 2H, Py-H), 8.60 (d, 2H, Py-H), 8.27 (t, J=6.5 Hz, 2H, Py-H), 7.95 (d, J=7.9 Hz, 2H, Py-H), 7.40 (s, 2H, OH), 7.21–7.19 (d, J=8 Hz, 4H, ArH), 6.96–6.94 (d, J=7.9 Hz, 4H, ArH), 6.80 (m, 4H, ArH), 4.27–4.20 (overlapped, 8H, OCH_2 and $ArCH_2Ar$), 4.13 (br s, 4H, $NHCH_2Ar$), 3.55–3.50 (overlapped, 6H, NH and $ArCH_2Ar$), 3.12–3.08 (t, 4H, J=7.5 Hz, $NHCH_2$), 2.30–2.26 (m, 4H, $CH_2CH_2CH_2$ and NH); IR (ν) 3185 (NH), 2900, 2875 (C–H), 1610 (CN), 1555, 1510, 1485 (C=C). Anal. Calcd $C_{46}H_{48}N_4O_4$. C, 76.64; H, 6.70; N, 7.77%. Found: C, 76.55; H, 6.77; N, 7.80%.

*4.2.5. 5,17-Dinitro-25,27-bis-(2-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5c**).* Yield 40%, dark yellow solid, mp 180–182 °C with decomposition. ^{1}H NMR ($CDCl_3$): δ 8.70 (d, J=7.9 Hz, 2H, Py-H), 8.35 (t, J=7.9 Hz, 2H, Py-H), 8.00 (t, 2H, J=8.1 Hz, Py-H), 7.38 (d, 2H, J=7.7 Hz, Py-H), 7.22 (s, 2H, OH), 7.12 (d, J=7.9 Hz, 4H, ArH), 6.95 (d, J=8.0 Hz, 4H, ArH), 6.81 (m, 4H, ArH), 4.20–4.18 (d, 4H, J=13.1 Hz, $ArCH_2Ar$), 4.15–4.13 (t, J=5 Hz, 4H, OCH_2), 3.82 (s, 4H, $NHCH_2Ar$), 3.45–3.42 (d, 4H, J=13 Hz, $ArCH_2Ar$), 3.35–3.32 (t, J=8.1 Hz, 4H, $NHCH_2$), 2.44–2.40 (m, 6H, $CH_2CH_2CH_2$ and NH); IR (ν) 3200 (NH), 2910, 2875 (C–H), 1625 (CN), 1555, 1500

(C=C). Anal. Calcd $C_{46}H_{46}N_6O_8$. C, 68.13; H, 5.72; N, 10.36%. Found: C, 68.03; H, 5.68; N, 10.31%.

*4.2.6. 5,17-Dinitro-25,27-bis-(3-aminomethylpyridine-propoxy)-26,28-dihydroxycalix[4]arene (**5d**).* Yield 44%, pale yellow solid, mp 180–182 °C with decomposition. ^{1}H NMR ($CDCl_3$): δ 8.70 (br s, 2H, Py-H), 8.55 (d, 2H, Py-H), 8.20 (t, J=6.5 Hz, 2H, Py-H), 8.0 (d, J=7.9 Hz, 2H, Py-H), 7.55 (s, 2H, OH), 7.16–7.14 (d, J=8 Hz, 4H, ArH), 6.96–6.94 (d, J=8 Hz, 4H, ArH), 6.84 (m, 4H, ArH), 4.30–4.25 (overlapped, 8H, OCH_2 and $ArCH_2Ar$), 4.1 (br s, 4H, $NHCH_2Ar$), 3.56–3.51 (overlapped, 6H, NH and $ArCH_2Ar$), 3.15–3.12 (t, 4H, J=7.5 Hz, $NHCH_2$), 2.32–2.25 (m, 4H, $CH_2CH_2CH_2$); IR (ν) 3190 (NH), 2910, 2800 (C–H), 1610 (CN), 1510, 1500, 1485 (C=C). Anal. Calcd $C_{46}H_{46}N_6O_8$. C, 68.13; H, 5.72; N, 10.36%. Found: C, 68.17; H, 5.64; N, 10.40%.

4.3. Liquid–liquid extraction studies

The dichromate anion and arsenate extraction experiments of calix[4]arene derivatives bearing pyridine units **5a–d** were studied by liquid–liquid extraction experiments following Pedersen's procedure.[36] Into a vial was pipetted an aqueous solution (10 mL) containing $Na_2Cr_2O_7$ or $Na_2HAsO_4{\cdot}7H_2O$ solution at a concentration of 1×10^{-4} M (1×10^{-5} for $Na_2HAsO_4{\cdot}7H_2O$), a few drops of 0.01 M KOH/HCl solution in order to obtain the desired pH at equilibrium and 10 mL of 1×10^{-3} M calixarene ligand in CH_2Cl_2. The mixture was shaken vigorously in a stoppered glass tube with a mechanical shaker for 2 min and then magnetically stirred in a thermostated water bath at 25 °C for 1 h, and finally left standing for an additional 30 min. The concentration of dichromate ion remaining in the aqueous phase was then determined spectrophotometrically as described previously.[37] The concentration of arsenate ion remaining in the aqueous phase was also determined by atomic absorption spectrometer. Blank experiments showed that no dichromate and arsenate extraction occurred in the absence of calix[4]arene. The percent extraction (E%) was calculated using the following expression:

$$\text{Extraction}\% = (A_0 - A/A_0)\times 100$$

where A_0 and A are the initial and final concentrations of the dichromate and arsenate ion before and after the extraction, respectively.

Acknowledgements

The authors gratefully would like to thank The Scientific and Technological Research Council of Turkey (TUBITAK Grant No. 107T873) and S.U. Research Foundation (BAP) for financial support.

References and notes

1. Demirtas, H. N.; Bozkurt, S.; Durmaz, M.; Yilmaz, M.; Sirit, A. *Tetrahedron: Asymmetry* **2008**, *19*, 2020–2025.
2. Memon, S.; Roundhill, D. M.; Yilmaz, M. *Collect. Czech. Chem. Commun.* **2004**, *69*, 1231–1250.
3. Demirtas, H. N.; Bozkurt, S.; Durmaz, M.; Yilmaz, M.; Sirit, A. *Tetrahedron* **2009**, *65*, 3014–3018.
4. Gutche, C. D. *Calixarenes, Revisited*; The Royal Society of Chemistry: Cambridge, 1998; Vicens, J.; Boehmer, V. *Calixarenes: A Versatile Class of Macrocyclic Compounds*; Kluwer Academic: Boston, 1991.
5. Van Loon, J. D.; Arduini, A.; Coppi, L.; Verboom, W.; Pochini, A.; Ungaro, R.; Harkema, S.; Reinhoudt, D. N. *J. Org. Chem.* **1990**, *55*, 5639–5646.
6. Morzherin, Y.; Rudkevich, D. M.; Verboom, W.; Reinhoudt, D. N. *J. Org. Chem.* **1993**, *58*, 7602–7605.
7. Stearns, D. M.; Kennedy, L. J.; Courtney, K. D.; Giangrande, P. H.; Phieffer, L. S.; Wetterhahn, K. E. *Biochemistry* **1995**, *34*, 910–919.
8. Wittbrodt, P. R.; Palmer, C. D. *Environ. Sci. Technol.* **1995**, *29*, 255–263.
9. Tyrovola, K.; Peroulaki, E.; Nikolaideis, N. *Eur. J. Soil Biol.* **2007**, *43*, 356–367.
10. Hall, A. H. *Toxicol. Lett.* **2002**, *128*, 69–72.
11. Valenzuela, O.; Germolec, D.; Borja-Aburto, V.; Contreras-Ruiz, J.; Garcia-Vargas, G.; Delrazo, L. *Toxicol. Appl. Pharmacol.* **2007**, *222*, 264–270.
12. Raji, C.; Anirudhan, T. S. *Water Res.* **1998**, *32*, 3772–3780.
13. Goyal, N.; Jain, S. C.; Banerjee, U. C. *Adv. Environ. Res.* **2003**, *7*, 311–319.
14. Krishna, P. G.; Gladis, J. M.; Rambabu, U.; Rao, T. P.; Naidu, G. R. K. *Talanta* **2004**, *63*, 541–546.
15. Busch, D. H. *Chem. Rev.* **1993**, *93*, 847–860.
16. Lindoy, L. F. *The Chemistry of Macrocyclic Ligand Complexes*; Cambridge University Press: Cambridge, 1989.
17. Gokel, G. Crown Ethers and Cryptands. In *Monographs in Supramolecular Chemistry*; Stoddart, J. F., Ed.; Royal Society of Chemistry: London, 1991.
18. Van Veggel, F. C. J. M.; Verboom, W.; Reinhoudt, D. N. *Chem. Rev.* **1994**, *94*, 279–299.
19. Hamdi, A.; Nam, K. C.; Ryu, B. J.; Kim, J. S.; Vicens, J. *Tetrahedron Lett.* **2004**, *45*, 4689–4692.
20. Akceylan, E.; Yilmaz, M.; Bartsch, R. A. *J. Macromol. Sci., Pure Appl. Chem.* **2006**, *43*, 477–486.
21. Memon, S.; Tabakci, M.; Roundhill, D. M.; Yilmaz, M. *React. Funct. Polym.* **2006**, *66*, 1342–1349.
22. Yilmaz, A.; Memon, S.; Yilmaz, M. *Tetrahedron* **2002**, *58*, 7735–7740.
23. Tabakci, M.; Memon, S.; Yilmaz, M.; Roundhill, D. M. *J. Inclusion Phenom. Macrocycl. Chem.* **2003**, *45*, 265–270.
24. Bayrakci, M.; Ertul, S.; Sahin, O.; Yilmaz, M. *J. Inclusion Phenom. Macrocycl. Chem.* **2009**, *63*, 241–247.
25. Tabakci, M.; Memon, S.; Yilmaz, M. *Tetrahedron* **2007**, *63*, 6861–6865.
26. Creaven, B. S.; Gernon, T. L.; McGinley, J.; Moore, A.-M.; Toftlund, H. *Tetrahedron* **2006**, *62*, 9066–9071.
27. Yilmaz, A.; Tabakci, B.; Akceylan, E.; Yilmaz, M. *Tetrahedron* **2007**, *63*, 5000–5005.
28. (a) Gutsche, C. D.; Iqbal, M.; Stewart, D. *J. Org. Chem.* **1986**, *51*, 742–745; (b) Gutsche, C. D.; Dhawan, B.; No, K. H.; Muthukrishnan, R. *J. Am. Chem. Soc.* **1981**, *103*, 3782–3792.
29. Bozkurt, S.; Durmaz, M.; Yilmaz, M.; Sirit, A. *Tetrahedron: Asymmetry* **2008**, *19*, 618–623.
30. Memon, S.; Akceylan, E.; Sap, B.; Tabakci, M.; Roundhill, D. M.; Yilmaz, M. *J. Polym. Environ.* **2003**, *11*, 67–74.
31. Hamilton, K. Synthesis, Characterization, and Application of Water-Soluble Chiral Calix[4]arene Derivatives in Spectroscopy and Capillary Electrokinetic Chromatography. Ph.D. Thesis, Louisiana State University, 2003.
32. Yusof, A. M.; Malek, N. A. N. N. *J. Hazard. Mater.* **2009**, *162*, 1019–1024.
33. Perrin, D. D.; Dempsey, B.; Serjeant, E. P. *pK_a Prediction for Organic Acids and Bases*; Chapman and Hall: London, 1981.
34. Memon, S.; Yilmaz, A.; Roundhill, D. M.; Yilmaz, M. *J. Macromol. Sci., Part A* **2004**, *41*, 433–447.
35. Kelderman, E.; Derhaeg, L.; Heesink, G. J. T.; Verboom, W.; Engbersen, J. F. J.; van Hulst, N. F.; Persoons, A.; Reinhoudt, D. N. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1075–1077.
36. Pedersen, C. J. *Fed. Proc. Fed. Am. Soc. Exp. Biol.* **1968**, *27*, 1305–1309.
37. Deligöz, H.; Yilmaz, M. *Solvent Extr. Ion Exch.* **1995**, *13*, 19–26.