

ANALYTICAL POTENTIALITIES OF CALIX-CROWN ETHERS

K.R.Sharma and Y.K.Agrawal*

*Chemistry Department, School of Sciences, Gujarat University
Ahmedabad-380 051,
Gujarat, India.*

ABSTRACT

A review on the different calix-crown ethers and their analytical potentialities is reported. It consists of the synthesis of calix-crown ethers, calix(aza)-crown ethers, thia calix-crown ethers, calix bis(crowns) and double calix(crowns) ethers, chiral calix-crown ethers and chelating poly calix-crown ethers. Their applications in the metal complexation, metal extraction, metal transportation, molecular switches and in ion sensing devices are discussed.

Key Words: Calix-crown ethers, Calix (aza) crown ethers, Thia calix-crown ethers, Calixarenes, Crown ethers, Complexation.

1. INTRODUCTION

During the last decade, there has been a growing interest in the study of calix[n]arenes /1,2/, owing to their unique molecular structure and simple one-pot preparation. Indeed, calix[n]arenes have been proved to be very important building blocks in supramolecular chemistry /3/. The easy chemical transformability of this molecule, together with its “tunable”

* To whom correspondence should be addressed at:

Institute of Pharmacy, Nirma University of Science and Technology
Sarkhej-Gandhinagar Highway, Ahmedabad 382-481, India.

E-mail – drykagrawal@yahoo.com

structure make calix[n]arene an attractive candidate for molecular design strategies and has led to an increasing number of examples in the literature. In particular, the calix[4]arenes /4,5/ are the best developed family as a molecular scaffold for the synthesis of more elaborate molecules, supramolecular assemblies /6/, sensors /7/ and receptors /8/, following crown-ethers and cyclodextrins. Calixarenes and their derivatives are enjoying a burgeoning role in host-guest and supramolecular chemistry /6/. Calix[4]arene and their derivatives provide a versatile platform of well-defined shape for the construction of sophisticated and functional structures. For example, calix[4]arene moieties have been incorporated in to multiple systems, connected to porphyrins /4/, crown ethers /5/, fullerenes /9/ and cyclodextrins as well as catenanes /10/ etc. These derivatives have been used in several fields such as sensor technology /7/, extraction /11/, membrane transport /6/ and chromatography /12/. Introduction of substituents on the phenolic –OH groups of the calix[n]arenes produces derivatives with different shapes and conformational mobilities depending upon the nature and the number of the substituents. Several tetra- and disubstituted calix[n]arenes have been synthesized, some of which are now well-established as selective receptors for metal ions. There are examples in which two calixarenes are joined by a single bridge, the singly bridged calixcrowns[poly(oxyethylene) bridged], calixspherands(m-teranisyl bridged) as well as double or triple calixarenes with metallocene (ferrocene) bridges /13/.

2. CALIX-CROWN ETHERS

Calix[n]crown ether compounds are macrocycles, characterized by possessing two kinds of receptor elements composed of the subunits of calix[n]arene and crown ether, joined via the phenolic oxygens of calix component. The interest in this class of compounds as hosts has mainly arisen in order to improve the binding ability as well as the selectivity to a particular guest species such as organic molecules /14/, cations or anions /15/ by the synergic effects of the two receptor elements arranged in a three-dimensional array. Calix[n]crowns, in which the calix[n]arene is functionalized at the distal phenolic oxygens with a poly(oxy-ethylene) chains, have usually been utilized as the molecular scaffold. In this context, the calix skeleton comprised of *p*-alkyl phenols connected at the O,O'-

positions with the polyether linkages is very intriguing because of the improved metal binding ability of the calix[n]arene molecular frame-work and thus due to the presence of the glycolic chains in their frame-work, calix-crown compounds have been continuously used as complexing agents for alkali, alkaline earth and ammonium cations and the selectivity of the complexation shown to depend upon the conformation (cone, partial cone, 1,2-alternate and 1,3-alternate) adopted by the rigidified calix unit. Among the variety of the calixarene derivatives synthesized, calix-crown compounds undoubtedly occupy a prominent role due to their complexing properties towards several cations often with very remarkable selectivity leading to several practical applications. This is attributed to the ion sensing properties of such compounds, which can be modulated by varying the conformation of the calix-platform, size of crown ether loop and length of the connecting spacer (polyether loop) viz. 1,3-dialkoxy-calix[4]arene crown-6 derivatives probably represent the most potent synthetic complexing agents for alkali metal ions /16-18/ (Fig. 1).

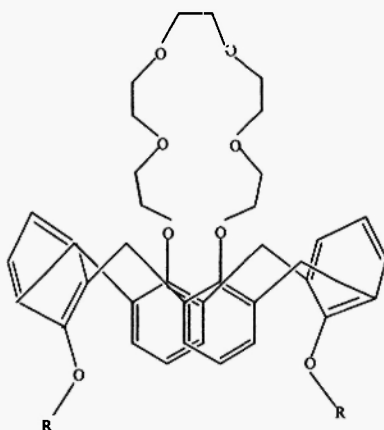


Fig. 1: 1,3-alternate calix[4]crown-6

They have been found to be selective for cesium ion due to the electrostatic force of attraction between cation and cavity of the crown ether and also with the two aromatic rings (cation/ π -interaction), when fixed in 1,3-alternate conformation /15,19/.

The importance of calix[4]arenes may be due to the readily convertible nature into a wide variety of derivatives at the lower rim of the calix by the

alkylation of the of the phenolic groups. This type of chemical modifications was first introduced by Gutsche /1,2/ as a part of his study of conformational change in calix[4]arene and since then, it has been used widely by several scientific groups to produce derivatives with pendent ether /20/, carboxylate /21/, ester /22/, amide /21/ and keto /21/ groups. The vast majority of these modified calixarenes exists in the cone conformation, in which the mutually *syn* pendent groups possess a considerable degree of pre-organizations and define the boundaries of a hydrophobic cavity, suitable for ion reception. Indeed, the most significant feature of the chemistry of these molecules is their ability to bind selective alkali, alkaline earth, ammonium and transition metal ions inside the cavity. Although less extensively studied, the chemically modified calix[5]-, calix[6]- and calix[8]crown ethers /23-25/ also possess receptor properties for selected inorganic and organic cations. It is well known that in calix[4]arene, the oxygen-through-the-annulus reaction is inhibited simply through the introduction of the substituents bulkier than the ethyl group onto the lower rim and calix[4]arene conformation thus can be immobilized, but the same attempt failed for the calix[n]arene ($n > 4$), even if the introduced substituents are bulkier e.g. cholesterol group/26/. The reason is, as Shinkai /27/ pointed out, that the calix[6]arene enjoys not only the oxygen-through-the-annulus rotation, but also the para-substituent-through-the-annulus rotation.

Expanding the field of so-called calix-crown compounds, a new trend has been developed, where the O- as a donor atom is replaced by –N /28/ or –S /29/ donor named as calix-aza and thia calix-crown ethers, respectively. The introduction of these compounds has made it possible to study the complexation abilities towards certain anions and transition metal ions /30/.

3. SYNTHESIS

The systematic reactions of the calix-crown can be shown as follows, by the reaction between calix[n]arenes with various ditosylates under weak alkaline medium. Depending upon the reaction conditions (nature of the base, structure of the ditosylates, stoichiometry of the reactants), products with the different topologies can be isolated.

The reactions of calix[n]arenes with different equivalents of various ditosylates (containing 2,3,4,5,6,7-oxygens) in the weak alkaline medium gives different calix-crown ethers (Fig. 2).

Synthesis of Calix-crown Ethers

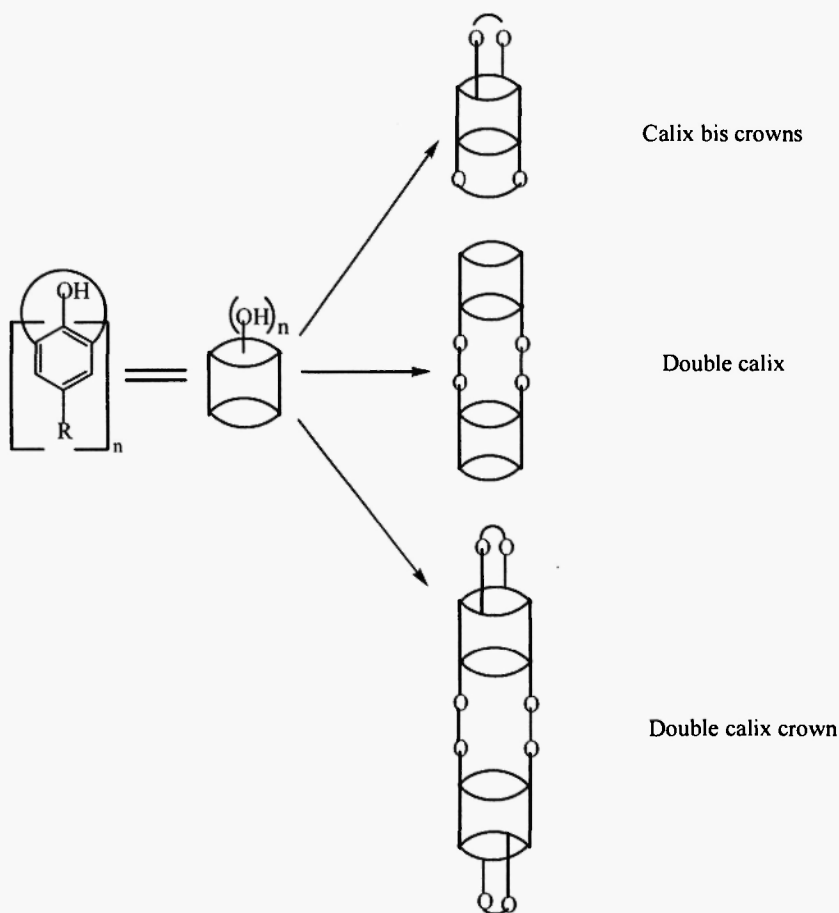


Fig. 2: Different Structures of Calix-crown

4. CALIX-CROWN ETHERS: METAL BINDING DYNAMICS

As calix-crown compounds possess preorganized structures and more rigid binding sites in comparison with calixarenes and crown ether, separately. They exhibit superior recognition ability toward alkali, alkaline earth metal, ammonium and transition metal ions due to the co-operative effects of the calixarene and crown ether moieties /15,28,29/. Mori *et al.* /31/

have reported that, structural features and the presence of the bulkier substituents also play a relevant role in determining the selectivity. In 1990, Reinhoudt *et al.* /21/ have reported the substituents at the remaining -OH groups of calix-crown for the first time. Study reveals that the introduction of four ester, keto, amide or mixed type binding sites on the phenolic -OH groups [lower rim] of the p-tert-butyl calix[4]arene fixes this macrocycle in "cone" conformation, giving a Na⁺-selective cation receptor (Fig. 3); on the other hand, the selective 1,3-dialkylation of the calix-crown followed by the polyether loop attached at two remaining -OH groups results in a K⁺-selective ionophore.

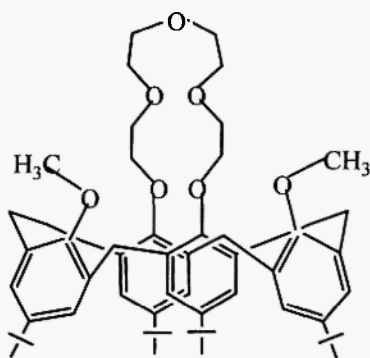


Fig. 3: Sodium Selective Cation Receptor

In recent years, with the increased use of nuclear power, more radioactive waste is generated, mostly from atomic power plants /32/. Therefore, techniques for disposing of radioactive wastes safely and in as little space as possible are found to be desirable without delay. In the disposal of such waste, of particular interest have been extractants, which are capable of selectively separating heat-generating nuclides such as cesium or strontium ions /33/. Thus, if the cesium ions contained in radio active waste are selectively separated, this could have a large effect on the disposal of radio active waste in terms of stability and energy, efficiently. In this regard, calix-crown ethers /1/ have attracted interest as cesium selective extractants. Reinhoudt *et al.* /34/ have reported that 1,3-dialkoxy calix[4]arene crown-6 derivatives were found to be exceptionally selective ionophores for cesium ions due to the complexation of cesium ion not only with crown ether moiety but also with the two rotated aromatic nuclei (cation- π -interaction), when fixed

in 1,3-alternate conformation. Kim *et al.* /35/ reported that the introduction of benzene rings in to the crown ether loop of calix[4]arene can improve the selectivity for Cs^+ ion due to the “flattening effect” /36/. For example, 1,3-alternate calix[4]arene bis(dibenzo crown)ethers, in which two benzo groups are attached on both upper and lower rim, revealed more selective complexation with Cs^+ ion over other alkali metal ions /35/. In the nuclear waste treatment plan, the separation of Cs^+ ion from the solutions containing alkali metal ions, especially from sodium, is a major goal and 1,3-alternate calix[4]crown-6s have proven to be the best extractants for Cs^+ ion in solvent extraction experiment /37-39/. It has been reported that Cs^+/Na^+ selectivities are enhanced when benzo groups are grafted on to the crown ether loop, due to a lower extraction of sodium, whatever the composition of the aqueous phase and to a higher extraction phase of Cs^+ in the presence of nitric acid /40,41/. Other macrocyclic extractants like 18-C-6, 21-C-7 and 24-C-8 are also experimentally studied for the removal of Cs^+ . The most efficient compounds are found in the 21-C-7 series with Cs^+/Na^+ selectivity but it is enhanced when the benzo derivatives are substituted /42/. Ungaro and coworkers /37/ have successfully removed the long-lived ^{137}Cs from an aqueous solution, which is in 1M HNO_3 and 4M NaNO_3 . They also reported that calix[4]arene crown-6s, when fixed in 1,3-alternate conformation, are extremely selective for the extraction of cesium over sodium from an aqueous phase containing metal nitrate.

With the aim of obtaining new ionophores for Rb^+ and Cs^+ , a series of new calix[4]arenes bridged with a longer crown ether chain have been synthesized by Mori *et al.* /31/ and used for the Cs^+ ion in supported liquid membranes. The thermodynamic and membrane transport data show that the most efficient and selective ligands are those fixed in 1,3-alternate conformation, which also allows interactions of the complexed Cs^+ -ion with the aromatic rings of two rotated nuclei, most interfering ions are K^+ , Rb^+ and NH_4^+ , since their size is close to that of cesium. They have also confirmed that not only the ring size but also the substituents play a relevant role in determining the selectivities of the cations. The same kind of study has been reported by Kim and coworkers /35/, who studied Cs^+ -selectivity over other cations such as Na^+ , K^+ and selectivity is reduced successively and this decreased selectivity is observed due to the enlargement of crown ether size from crown-6 to crown-8. Kim *et al.* /47/ have reported one of the most efficient Cs^+ ion selective extractants substituting dibenzo-18-crown-6 on calix[4]arene unit (Fig.4)

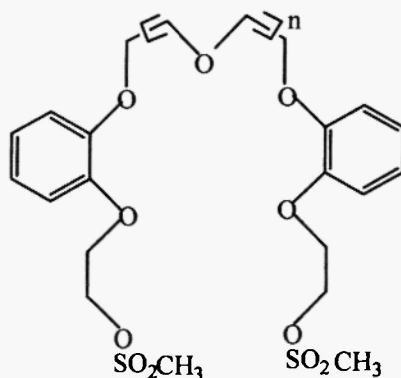


Fig. 4: Dibenzo 18-C-6 Substituted on alix[4]arene

Studies have shown that calix[4]arenes functionalized with DB-18-C-6 are efficient and selective extractants for Cs^+ -ion over other alkali cations. From supported liquid membranes, using these compounds permeation coefficients of the Cs^+ -ion were estimated to be 0.42 and 0.29 cm/h of two compounds. The selectivity of Cs^+ -ion was observed to increase with permeation time.

The synergic effects of the *p*-tert-butyl calix[4]arene crown ethers [DC18-C-6, DB18-C-6, B15-C-5] and *p*-tert-butyl calix[4]arene in DCM in the extraction of alkali metals have been reported by Asfari *et al.* /44/, concluding that the ion size affects the stability constants of the adducts, which reveals the strong interactions between the crown ether and the cation in the crown-calix systems. The analytical data have shown that the Cs^+ -15-C-5 system has a very low stability constant in comparison with the others. This revealed that bis(15-C-5) is unable to remove Cs^+ -ion from "Cs-calix-cup".

For the treatment of the alkaline nuclear wastes, Bruce and co-workers /45/ patented the extraction technique for Cs^+ from aqueous neutral and alkaline solutions containing Cs^+ and other complexing metal ions. An important application for this invention would be the treatment of alkaline nuclear tank wastes. Guillon *et al.* /46/ have synthesized calix[4]crown-6 conformers as potential selective cesium extractants for the selective extraction of Cs^+ from the radioactive nuclear wastes and they are found to show better selectivity for Cs^+ . Moyer *et al.* /47/ have reported the hybrid structure of calix[4]arene and crown ether in which, one or two crown-6

fragments bridge the phenolic positions of calix[4]arene in 1,3-alternate conformation exhibiting the facing pair of the aromatic ring of the calixarene in their conformation form two cavities that are each preorganized for the partial insertion of Cs^+ ion. These compounds are found to be efficient for 2:1 metal-ligand organic phase dissociation producing CsB^+ and NO_3^- ($\text{B}=\text{calix}$). Binding of the second Cs^+ -ion by the ligand is approximately two orders of magnitude weaker than binding of the first Cs^+ -ion.

Recently, Debostiani and coworkers /48/ have reported a new highly selective calix[4]crown-6 fluorescent cesium probe. It is known that calix[4]crown-6 in a 1,3-alternate conformation binds cesium with remarkable strength and selectivity. Significant efforts have also been made to use these compounds in the sensing, monitoring and remediation of ^{137}Cs , a fission product present in the general wastes during the reprocessing of irradiated nuclear fuels. The need for the sensitive cesium sensors has led to the study of calix[4]crown-6 ethers as fluorescent cesium probe.

Mahajan and coworkers /49/ have developed a Cesium Ion Selective Electrode (Cs-ISE) based on calix[4]crown ether-ester. The potentiometric response characteristics of Cs-ISE PVC membrane electrode deploying calix[4]crown ether-ester exhibit a good response for Cs^+ -ion over a wide concentration range of Cs^+ , while recently a new amino functionalized calix[4]arene bis- and mono-(benzo crown-6) for pH-switched CsNO_3 extraction has been reported by Gorbunova *et al.* /50/, where the Cs^+ extraction behaviour is observed under alkaline and acidic conditions and compared with of non-amine containing analogue. Prodi *et al.* /11/ have reported the photo physical study of 1,3-alternate calix[4]crowns and their metal complexes. This suggested that the cation / π -interactions play a major role in tuning the luminescence spectroscopy which is considered to be a suitable technique for the determination of host species and a possible tool to study cation / π -interactions. Wasikiewicz *et al.* /51/ have derived crown ethers from bicyclo calix[4]arenes as chromoionophores, in which opposite phenolic units are connected by a poly(oxyethylene) bridges at the narrow rim and 2,6-dimethyl-4-nitrophenol bridges at the side rim. The bicyclo calix[4]arene bridged crown ethers are able to recognize K^+ and Cs^+ , respectively. The first synthesis of a calix[4]disaleno crown ether as a sensor for ISEs has been reported by Xeng *et al.* /52/. The study involves the sensor ability of the compound towards different alkali metals. Yeol *et al.* /52a/ have synthesized calixcrown-6 compounds carrying a pair of phenyl azo moieties on the upper rim and two $-\text{OH}$ groups and two $-\text{OR}$ groups at the lower rim

were prepared, in both the cone and partial cone conformations. A UV/Visible spectral measurement showed a red shift upon the addition of Ca^{2+} to the calix-crown carrying two $-\text{OH}$ groups and a blue shift for the calix-crown carrying two OR groups. This is attributed to a blue shift, caused by electrostatic interaction between the oxygen atoms of $-\text{OR}$ and the metal ions as well as a red shift caused by the π -metal complexation between the rotated calix benzene and the metal ion were observed. Lu *et al.* /52b/ have reported the mesoporous organo silicas containing size-selective microporous from covalently bound calix[4]crown-6, which are selective for Cs^+ ion. In the study, the co-polymerization of the silylated calix-crown monomer with tetramethoxy silane in the presence of a structure-directing surfactant, cetyltrimethyl ammonium bromide (CTB) resulted in the formation of calix-crowns based on organo silicas showing good up take and high cesium selectivity by these novel materials from water even in the presence of high concentration of Na^+ -ion.

4.1. Calix(aza) Crowns

Calix(aza) crowns refer to the molecules combining calix[n]arene elements and aza crown units. They are constructed with NH -ethylene chains attached to the phenolic oxygens atoms of the calix *via* acetamido functions and chelating groups. The first calix(aza) crowns were prepared by the reaction of either calix dimethyl ester or calix-diacid chloride with the appropriate diamine $\text{NH}_2\text{-NH}_2$ and were shown to complex with divalent (Be^{2+} , Mg^{2+} , Ca^{2+} , Sr^{2+} and Ba^{2+}) and trivalent (Sc^{3+} , Y^{3+} , In^{3+} , Gd^{3+} and Bi^{3+}) metal ions /53/.

Regioselective alkylations of the two remaining phenolic $-\text{OH}$ and $-\text{NH}$ groups of 1,3-calix[4]arene(aza)-crowns afforded new derivatives with labile protons /54,55/, however, no complexation studies were reported. Related methylated calix[4]arene(aza)-crowns were obtained by bridging appropriate 1,3-dimethoxy-2,4-dimethyl ester calix derivatives. Only the fully methylated derivatives containing two $-\text{OCH}_3$ and one $-\text{NCH}_3$ were shown to complex Co^{2+} , Cu^{2+} and their picrate, while the related compounds presenting labile protons were observed to extract picric acid /56/. An alternative route to calix[4](aza)-crowns consisted preliminary amidation of *syn* 1,2- and 1,3-diethyl ester calix[4]arenes with various alkanolamines followed by chlorination of the terminal $-\text{OH}$ groups and double intramolecular ring closure leading to 1,2:3,4-calix[4]bis(aza)-crowns in cone conformation and

doubly bridged with aza crowns /57/. Recently, tetra ethyl ester calix[4]arene was treated with ethylene diamine to yield the corresponding 1,2:3,4-calix[4]bis(aza)-crowns in cone conformation /58/. Azo benzenes make-up an interesting class of compounds, that exhibits photo responsive properties. They have been incorporated into a number of supramolecular frame-works to produce ionophores for transports and photo switch able receptors. Considering this property of azo unit, Pipoosananakaten and coworkers /59/ have reported the *p*-tert-butyl calix[4]arene aza crown and their roles as switch able ionophores for Na^+/K^+ , mimicking the biological Na^+/K^+ pump. One of the calix(aza)crown ethers has been synthesized by Kim *et al.* /60/ in 1,3-alternate positions for the study of K^+ -ion complexation. In the study, it has been found that, the compound exhibits high K^+ -ion selectivity over other alkali ions as found out by two-phase extraction bulk liquid membrane. The factor, which plays an important role, is the hydrogen atom of the chromogenic moiety attached to -N that can assist the complexation by encapsulation of metal.

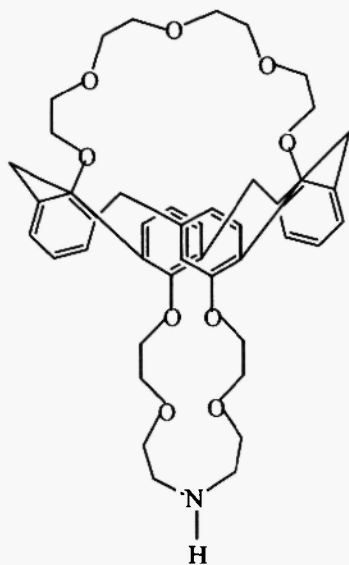


Fig. 5: Calix[4](Aza) Crown Ether Tube

Further, Kim and coworkers /61/ have reported a novel work on Ag^+ -ion oscillation through calix[4](aza)crown ether tube (Figs. 5, 6) in which silver ion oscillation through calix[4]crown-5 and of 1,3-alternate calix[4]-bis-aza-

crown-5 was investigated by temperature variable $^1\text{H-NMR}$. Further, the replacement of O-atom by N-methyl group in a crown loop leads calix[4]aza crowns acting as an artificial “molecular syringe” that Ag^+ -ion locates in the aza crown cavity at neutral pH but on protonation it moves to the other part through the calix tube because of significant repulsion between $-\text{NH}$ and Ag^+ -ion. Seung *et al.* [62] synthesized calix(aza) crown-5 in 1,3-alternate revealing that K^+ -ion selectivity is not only due to the size compatibility but also due to significant K^+/π -interaction between the two aromatic rings and the K^+ -ion. Study was confirmed by X-Ray analysis.

The complexation studies of $\text{K}^+ \text{-pic}^-$ and $\text{Cs}^+ \text{-pic}^-$ has been carried out by Vicens *et al.* [63] involving the novel synthesis of calix[4]arene cryptand crown-6 by passing through calix(aza) crown ether intermediate and ending with glycolic ditosylate chain.

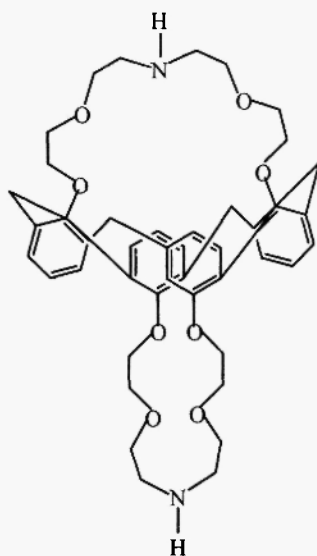


Fig. 6: 1,3-Alternate Calix[4](Aza) Crown

Complexes with NH_4^+ with calix(aza)-crowns have been reported by Kim *et al.* [64] by synthesizing 1,3- alternate calix[4](aza) crowns. Further, they have compared the results with 1,3-calix[4]bis crown-5 and results suggest the better binding by the replacement of the central O-atom by $-\text{NH}$ group. Thus, it has been confirmed that modified $-\text{NH}$ -crown-5 displays a better binding behaviour that crown-5 does for NH_4^+ ion. It means that it has been

found better than ether loop containing O-as a donor atom. This is due to the attachment of crown ether loop containing N-as a donor to the lower rim of calix, which has increased the complexation ability toward NH_4^+ ion.

Other than common alkali and alkaline earth metal ions, calix(aza)-crown ethers are found to complex some transition metals and fewer anions. Related to this, Seung and coworkers /65/ have tried to encapsulate Cu^{2+} and Zn^{2+} ion with calix(aza)-crown with the assistance of pendent indo-aniline unit. $^1\text{H-NMR}$ and UV-Visible study confirms the encapsulation of these metals with calix(aza)-crown ethers with O-as a donor atom. Thus, this also supports the metal complexation of transition metal ions with calix(aza) crown ethers which is not quite probable with calix crown ethers. The anion complexation studies using calix(aza)-crown ethers have been a less extensively studied part of the calix-crown family. Tuntulani *et al.* /66/ have studied the supramolecular chemistry with transition metals and some anions and have found that compounds cannot form complexes with F^- , SO_4^{2-} .

In the case of basic anions such as CO_3^{2-} , PO_4^{3-} , AsO_2^- , HPO_4^{2-} and H_3PO_4^- , two phenomena – complexation and deprotonation – occurred, simultaneously. Calix-crown having –NH linkage shown that they can bind transition metal ions like Co^{2+} , Ni^{2+} and Cu^{2+} in 1:1 fashion. Seung and coworkers /67/ have synthesized a series of new calixarene-based fluoroionophores pyrene-armed calix[4](aza)-crowns. With this new calixarenes derivatives bearing a crown ether and aza crown ether as two binding sites, the metal ions like Ag^+ , K^+ , Cu^{2+} and Cs^+ were found to choose selectively between the ligating pockets. Further, interesting (“molecular taekowndo”) processes between $\text{Ag}^+\text{-K}^+$, $\text{K}^+\text{-Cu}^{2+}$ and $\text{Ag}^+\text{-Cs}^+$ pairs were easily monitored *via* fluorescence change. Sungeun *et al.* /67a/ have reported on the potassium ion-selective electrode based on 1,3-alternate calix[4]crown-5-azacrown-5 with different side arms. Selectivity coefficients indicated that interference from all common alkali, alkaline and transition metal ions was very small.

4.2. Thia Calix(crowns)

Thia calix(crowns) are macrocycles comprising phenolic units connected in the *ortho* positions by sulfur bridges instead of the methylene bridges of calixarenes. The first synthesis of *p*-tert-butyl thia calix[4]arene (Fig. 7), in which one to four methylene bridges were replaced by sulfur bridges, was published in 1997 /68/ and recent publications report on the synthesis of new

compounds on the thia(calixarenes) platforms, which is interesting because of the affinity of sulfur atoms for transition metals /69/. The size of the cavity is enlarged and the chemical reactivity (oxidation products) and chelating properties are modified upon the replacement of carbon by sulfur bridges /70/.

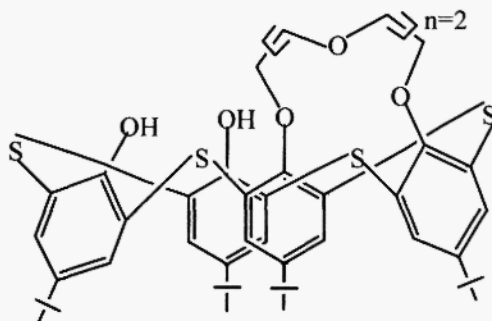


Fig. 7: 25,26-(thia) Calix[4]crown Ether

The thia calix[n]crowns, in which the calix skeleton is comprised of *p*-alkyl phenols connected at the O, O'-position with epithio linkages, are very intriguing because of the improved metal-binding ability of the thia calix[4]arene molecular frame-work /71-73/ by the ligation of the lone-pair electrons on the sulfur to metal cations /69,73,74-76/. Recently, Vicens and coworkers /77/ reported the first synthesis of 25,27,26,28-doubly bridged thia calix[4]bis(crown-n)s ($n=5,6$) for the investigation of their ability to extract Na^+ , Cs^+ ions. On the other hand, very little is known about the chemistry of 25,26-bridged calix[4]crowns /78-80/ and no examples were reported on 25,26-bridged thia calix crowns. This is mainly due to the scarcity of efficient methods for the proximal 25,26-O-positions. Considering the anticipated potassium metal-binding ability of the 25,26-thia calix[4]crown-class compounds by the co-operative complexation using the ligating sites comprised of the tridentate O-S-O and the crown ether moiety arranged in apparently suitable steric arrangement, Narumi *et al.* /81/ have synthesized 25,26-bridged thia calix[4]crowns for the first time by the use of 25,26-O-disiloxanediy-l-capped *p*-tert-butyl calix[4]arene.

Nowadays, calix-crown compounds with -N and -S as donor atom(s) have been reported continuously. Macrocycles containing O- as a donor atoms mainly complex alkali, alkaline and ammonium cations, whereas those

containing soft donor atoms such as -N, -S and -P can bind transition, rare and heavy metal ions. The importance that has been given to study the complexation of rare metals with macrocycles is mainly due to their applicability in biological environment processes. Most calixarenes with pendent ether, ester, ketone, carboxylic acids, amide or crown ether groups complex alkali and alkaline earth metal ions. Calixarenes can be better ligands for transition, rare earth and heavy metal ions and if derived by incorporating softer "N, S and / or P atom(s)" in to the lower rim. Schiff's base, thio-amide, thio-ether derivatives are able to extract Ag^+ , Pb^{2+} , Cu^{2+} and Hg^{2+} ions, but among such calixarene derivatives that have been reported, the selectivity for these transition metals was not very pronounced. So, in order to enhance the selectivity towards transition metals by controlling the cavity size of the calix[4]crown derivatives and also the rigidity of crown ether, the crown ether with such donor atoms have been reported.

From the literature, it has been found that complexation studies were also carried out with various metal ions like Na^+ , K^+ , Rb^+ , Cs^+ , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Zn^{2+} and Cu^{2+} . But the determination of the complex formation constants with these kinds of calix-crown compounds was not possible. Such behavior can indicate that no complexation takes place between calix-crown with Cu^{2+} , Ag^+ /82/.

4.3. Calix bis(crowns) and Double Calix(crowns)

Calixarenes have been used as three-dimensional building blocks for the construction of artificial molecular receptors capable of recognizing neutral molecules, cations and more recently anions. The design and synthesis of conformationally preorganized calix[n]crown ethers of different technology, such as 1,2-calix[4]crowns /83/, 1,3-calix[4]crowns /55/, 1,2-calix[4]bis crowns /84/, 1,3-calix[4]bis (crowns (Fig.8) /85/, double calixarenes /86/ and double 1,3-calix bis crowns /87/ have developed very rapidly, owing to their proclivity to bind alkali, alkaline earth and primary ammonium cations. The first 1,3-capping of calix[4]arene at the lower rim results in to the 1,3-calix[4]crowns, while the second capping enforces the calix-crown in to calix bis(crowns), double calix crowns or double calix bis(crowns) etc. Neu *et al* /88/ have studied the complexation abilities of calix bis(crowns) towards Cs^+ , K^+ and Rb^+ . The results show that calix[4]bis crowns prefer Cs^+ in complexation as well as in extraction. This selectivity is mainly attributed to the excellent size match between the cation and ether chain of the

polyether loop, attached to the calixarenes to wrap around the smaller Cs^+ , K^+ and Rb^+ ions. It is further improved by the introduction of aryl group to the crown units like BC_6B , BC_6N . Since, complexation level of Na^+ is reduced, but these compounds achieve excellent selectivity for K^+ and Rb^+ ions.

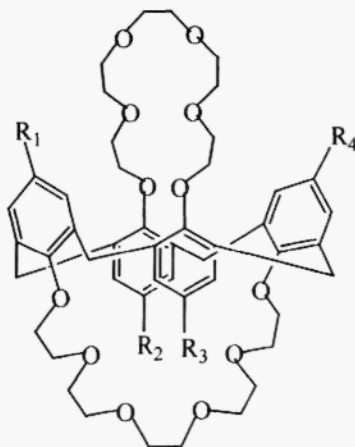


Fig. 8: 1,3-Calix[4]arene(bis)Crown-6

While Neu *et al.* /88/ have shown the enhanced selectivity of Cs^+ -ion by the attachment of aryl group to the calix-crown compounds, Kim and coworkers /89/ have also shown the complexation enhancing effects by the attachment of benzo unit to the polyether loop. They have also reported the selective sensing of Cs^+ -ion using newly synthesized calix[4]arene bis[dibenzo crown] ether. The compounds show the best selectivity for Cs^+ -ion using the single flux method through the bulk liquid membrane systems.

Harrowfield *et al.* /90/ have synthesized an unsymmetrical calix[4]bis crown-6 as a Cs^+ -selective carrier for the extraction of Cs^+ -ion from the nuclear wastes. One different calix-crown has been reported by synthesizing a double calix-crown known as a spiro bis calix[4]crown. The binding properties of Li^+ , Na^+ , K^+ , NH_4^+ , $(\text{CH}_3)_2\text{-NH}_3^+$, $(\text{CH}_3\text{CH}_2)\text{-NH}_2^+$ and $\text{CH}_3\text{CH}_2\text{CH}_2\text{NH}_3^+$ have been studied. It has been revealed that the compound is highly preorganized for binding these ions /91/.

Recently, Talanov *et al.* /92/ have reported the synthesis of calix[4]arene bis(dibenzo crown-6) ethers with one proton ionizable group and analytical results suggest that the compound exhibits high Cs^+ -extraction efficiency and selectivity. The selectivity for Cs^+/Na^+ , Cs^+/K^+ has been found to be very

much higher than their analogues.

While studying the role of upper rim substituents towards the complexation behaviors, Dozol *et al.* /93/ have reported the synthesis and complexation properties of nitro derivatives of 1,3-calix[4]arene bis(crown-6). The compounds exhibit six oxygen donor atoms and were shown to be a potential extractant for the selective removal of Cs⁺ from radioactive nuclear wastes.

Molecular dynamics (MD) simulation studies showed that the introduction of -NO₂ group does not significantly modify the behaviour of the calix-crown towards alkali and alkaline but the exceptional selectivity was maintained even after the -NO₂ group was introduced to the crown-calix compound, but, as the number of -NO₂ group decreases, the extraction power decreases. For the first time, in the field of calix-crown family, a water soluble *p*-sulfonated 1,2,3,4-calix[4]arene bis(crowns) has been reported by Mathieu *et al.* /94/, showing a pronounced selectivity of Cs⁺/ Na⁺, while Guilton *et al.* [95] have studied the extraction experiments with the newly synthesized 25,27-bis(alkoxy)calix[4]arene-crown-6 conformers. Results suggest that 1,3-alternate conformers were found to be the most potent for Cs⁺-extraction. Lamaire *et al.* /95a/ have recently studied the cesium-selective sodium separation by nanofiltration complexation with water-soluble calix[4]arene-bis(benzocrown-6), concluding that the ligands show more or less affinity for the larger cation depending on the nature and the position of the substituents grafted on the benzo-ether chain only.

Recently, Kim *et al.* /85/ have reported the complexation chemistry of double and multi-1,2-alternate calix-crowns. This has been investigated through X-Ray crystallography, two-phase extraction and ¹H-NMR measurements.

4.4. Chiral Calix-crown Compounds

Chiral recognition and discrimination is one of the main goals in areas like host-guest chemistry or biochemistry or simply in analytical chemistry. These phenomena play essential roles in biological systems, where the life functions are primarily regulated by the selective recognition processes. Among them, chiral recognition, in which a chiral host molecule selectively binds one of the enantiomers, is of high interest for supramolecular chemists, who have devoted much effort to the design, synthesis and investigation of synthetic chiral receptors /96,97/. Such host molecules not only provide a

controlled means for studying the fundamentals of non-covalent interactions in nature, but also open new routes for developing novel enantioselective sensors, catalysts, selectors and other molecular devices /98/. Di-1,1'-binaphtho(22-crown-6) was reported for the first time by Cram *et al.* /99/ and shown to exhibit remarkable chiral discrimination between the enantiomers of organic ammonium salts, since the receptor possessing a C_{2v} axis of symmetry provides a chiral cavity due to the steric effects between the naphthalene rings.

Since calix-crown compounds are suitable and widely used as host molecules or building blocks for the construction of supramolecules /100/, a number of supramolecules combining crown ethers and calixarenes have been reported and applied in analytical and separation chemistry /101/. But chiral calix-crowns are rarely found in the literature.

Arnecke *et al.* /102/ have reported the inherently chiral derivative calix[5]crowns, Pappalardo *et al.* /103/ reported inherently chiral calix[4]crown ethers and Geraci *et al.* /104/ reported calix[8]crown ether. Later, on Neu *et al.* /105/ have reported synthesis, optical resolution and complexation properties of inherently chiral mono alkylated *p*-tert-butyl-(1,2)-calix[4]crown ethers. Study involves the enantiomeric resolution by direct HPLC separation, using chiral stationary phases. A screening of the complexing abilities of pyridine-(1,2)-calix[4]crown ethers showed a low extraction level of alkali, alkaline earth metal and heavy metal picrates, while Ag^+ -ion was found to be extracted at 25%. In 1990 Caccamese *et al.* /106/ reported the enantioselective HPLC resolution of inherently chiral α -picolyloxy-*p*-butyl calix[5]crown ethers. The enantioselective resolution of recemates has been achieved by direct HPLC separation using enantioselective stationary phase. Results show that the enantiomers of these compounds exhibit one of the largest separation factor (α) so far reported for inherently chiral calixarenes. Recently, Bitter *et al.* /107/ reported the synthesis of chiral 1,3-calix[4](crown-6) ethers as potential mediators for asymmetric recognition processes. UV-Visible spectrophotometric measurements of the 2,4-dinitrophenylazo chromogenic molecules, which indicated noticeable chiral discrimination associated with correlation towards primary amine enantiomers.

4.5. Chelating Poly Calix-crown

In addition to the Calix-crown family, a new member has been introduced

by Memon *et al.* /108-110/, who synthesized polymeric calix[4]crown-4 and further applied to solid-liquid and liquid-liquid extraction of alkali, alkaline earth and transition metals. From the results, it was deduced that the precursor 5-(5,7,11,23-tetra-tert-butyl-25-hydroxy-27-methoxy calix[4]arene crown-4) is selective for Hg^{2+} -ion. In another synthesis of 1,3-dialkylated *p*-tert-butyl calix[4] telomeres, they have reported that the monomers are selective for Hg^{2+} , Cu^{2+} , Pb^{2+} , Hg^{2+} and Ag^+ . Recently, Li *et al.* /111/ have reported the sol-gel technique to prepare calix[6]crown containing organosilicon resins and their adsorption properties towards the metal ions including 1°-amines and cesium. The study involves the adsorption capacity of the resin towards alkali metal ions (Li^+ , Na^+ and K^+) transition metal ions (Ni^{2+} , Co^{2+} , Cu^{2+}) and heavy metal ions (Pb^{2+} , Hg^{2+} , Ag^+) and thermodynamic parameters of the resins towards Hg^{2+} was deduced.

4.6. Miscellaneous Studies Carried Out Using Calix-crown Ethers

The work done on alkali and alkaline metal ions gives an overview of the complexation abilities of the so-called crown-calix compounds. But some efforts have also been made to study the complexing abilities and selectivities towards some different metal ions other than alkali and alkaline metal ions making them applicable to the various fields of sciences. Kurita *et al.* have /112/ reported a Pt-complex with calix[4]dithia-crown-6. This Pt-complex catalyzed hydroxylation of olefins with $(\text{EtO})_3\text{SiH}$. Ungaro and coworkers /113/ have carried out an analytical study with a new class of calix[4]crown ethers with one of two pyridines appended to the polyether chains and studied the luminescence properties of Eu^{3+} and Tb^{3+} . A novel dinuclear gold(I) calix[4]crown acetylide complex $[\text{Au}(\text{PPh}_3)]_2\text{L}$ has been reported by Yam *et al.* /114/ showing a high K^+/Na^+ selectivity over other alkali cations. Dodi /115/ has reported the calix[4]crown displaying an exceptional selectivity towards cesium, using high performance liquid chromatography with UV detection. They have also determined the conditions of separation between calixarene and its solvent by using the absorption chromatographic mode. Kim *et al.* /116/ have reported a new fluorogenic bezothiazolyl ionphore based upon calix[4]crown-5 ether for co-determination in aqueous media. In the study, pronounced selective fluorophoric behaviour toward Na^+ , K^+ , Mg^{2+} has also been determined. Grofcsik and coworkers /117/ have studied the photochromism of a spiropyran derivative of 1,3-calix[4]crown-5. In the kinetics of thermal decay of the merocyanine form of the calix-crown

spiropyran molecule shows a bi-exponential character in both solvents, while the decay is much slower in ethanol than in acetonitrile. The effects of the crown ether unit and Na^+ binding towards anion binding ability have been studied by Tongraung *et al.* /118/ with the calix[4]arenes containing urea and crown / urea moieties. The compound formed complexes with Cl^- , Br^- , NO_3^- and H_2PO_4^- to a different extent. Upon the addition of Na^+ , the binding ability H_2PO_4^- is increased due to ion-pair enhancement.

5. CONCLUSION

The review of the literature reveals that calix-crown ether is the fastest growing area of the experimental chemists. Chemists usually prefer the imitation of nature, which constructs the large and complex systems with high degree of efficiency.

As one of the vehicles, calix-crown ethers have proved to be very useful for the study of hydrogen bonding and electrostatic interactions as well as cation / π -interactions that occur when ions are complexed by these hosts.

The principal significance of these compounds has thus far mostly been in ion sensing and recognition. Cesium cation has been a particular target owing to its presence in radioactive wastes. Additionally, crown ether-based calixarenes have been designed for their use as ionophores, including alkali, transition, heavy and lanthanides as well as alkyl ammonium ions.

REFERENCES

1. C.D. Gutsche *Calixarenes*; Edited by Z.Asfari Kluwer Academic Publisher, Dordrecht, Netherland, (2001).
2. S. Shinkai, *Tetrahedron*, 1993, **49**, 8933. V. Bohmer, *Angew Chem. Int. Ed. Engl.*, 1995, **34**, 713.
3. P. Lhotak, S. Shinkai, *J. Synth. Org. Chem. Jpn.*, 1995, **53**, 963.
4. D. M. Rudkevich, W. Verboom, D. N. Reinhuodt, *J. Org. Chem.*, 1995, **60**, 6585.
5. N. Reynier, J. -F. Dozol, M. Saadioui, Z. Asfari, J. Vicens, *Tetrahedron Lett.*, 1998, **39**, 6461.
6. *Comprehensive Supramolecular Chemistry*; J. L. Atwood, J. E. Davies, D. D. Macnicol, F. Vogte, Eds; Pergomon, Oxford, U. K.

- 1996, 11 vols. J.M. Lehn, *Supramolecular Chemistry; Concepts and Perspectives*; VCH:Weinheim, 1995.
7. P. Buhlman, E. Pretsch, E. Bakker, *Chem. Rev.* 1998, **98**, 1593. D. Diamond, M. A. Mckervey, *Chem. Soc. Rev.*, 1996, 15.
 8. R. Ungaro, A. Arduini, A. Casnati, A. Pochini, F. Ugozzoli, *Pure and Appl. Chem.*, 1996, **68**, 1213. A. F. D. de Namor, R. M. Cleverley, M. L. Zapate-Ormacha, *Chem. Rev.* 1998, **98**, 2495.
 9. M. Kawaguchi, A. Ikeda, S. Shinakai, *J. Chem. Soc. Perkin Trans.* 1998, 179.
 10. Z. -T. Li, X. -L. Xang, X. -D. Lian, Y. -H. Yu, Y. Xia, C. -X. Zhao, Z. Chen, Z. -P. Lin, H. Chen, *J. Org. Chem.*, 2000, **65**, 5136.
 11. L. Prodi, F. Bullotta, M. Montalti, N. Zaccheroni, A. Casnati, F. Sansone, R. Ungaro; *New J. Chem.*, 2000, **24**, 155.
 12. J. D. Glennone, E. Horne, K. Hall, D. Cocker, A. Kuhn, S. J. Harris, M. Amckervey, *J. Chromatogr. A*, 1996, **731**, 47.
 13. M. Kumar, G. Hundal, V. Bhalla, M. M. Singh, *J. Inclusion Phenom. Macrocyclic Chem.* 2000, **36**, 461.
 14. F. A. Neu, S. Caccemese, S. Guabngswasdi, S. Pappalardo, M. F. Parisi, A. Patinga, G. Principato, *J. Org. Chem.*, 1997, **62**, 804.
 15. J. S. Kim, J. H. Pang, J. Y. Yu, W. K. Lee, J. H. Suh, J. K. Kim, M. H. Cho, E. T. Kim, D. Y. Rao, *J. Chem. Soc. Perkin. Trans. 2.*, 1999, 837.
 16. R. A. Sacheleben, A. Urvoas, J. C. Bryan, T. J. Haverlock, B. P. Hayer, B. A. Moyer, *Solvent Extr. Ion Exch.* 1999, **17**, 1445.
 17. R. A. Sacheleben, A. Urvoas, J. C. Bryan, T. J. Haverlock, B. P. Hayer, B. A. Moyer; *Chem. Comm.*, 1999, **17**, 1751.
 18. V. Lamare, J. -F. Dozol, F. Ugozzoli, A. Casnati, R. Ungaro, *Eyr. J. Org. Chem.* 1998, **8**, 1559.
 19. J. -S. Kim, R. Veki, T. Ishizuka, T. Shimotashiro, S. Maeda, *Talanta.*, 1999, **48**, 705.
 20. G. Ferguson, G. F. Gallagher, A. J. Laugh, A. Notti, S. Pappalardo, M. -F. Parisi, *J. Org. Chem.*, 1999, **64**, 5876.
 21. E. Ghidini, F. Ugozzoli, R. Ungaro, A. -El Fadi, D. N. Reinduodt, *J. Am. Chem. Soc.*, 1990, **112**, 6979.
 22. M. Kumar, G. Hundal, V. Bhalla, Madhu, M. Singh, *J. Incl. Phenom. Mol, Recog. Macrocyclic Chem.*, 2000, **36**, 461.
 23. S. Caccamese, A. Nottti, S. Pappalardo, M. F. Parisi, G. Principato, *J. Incl. Phenom. Mol, Recog. Macrocyclic Chem.*, 2000, **36**, 67.

24. Y. Chen, Y. Chen, *Tetrahecron Lett.*, 2000, **41**,9079.
25. C. Geraci, M. Piatteli, P. Neri, *Tetrahedron Lett.*, 1996, **37**, 3899.
26. S. Kanamthareddy, C. D. Gutsche, *J. Org. Chem.*, 1994, **59**, 3871.
27. H. Otsuka, K. Araki, T. Sakaki, K. Nakshima, S. Shinkai, *Tetrahedron Lett.*, 1993, **34**, 7272.
28. K. N. Koh, K. Araki, S. Shiankai, Z. Asafari, J. Vicens, *Tetrahedron Lett.*, 1995, **36**, 6095.
29. V. Lamare, J. -F. Dozol, P. Thuery, M. Nierlich, Z. Asafari, J. Vicens, *J. Chem. Perkin Trans. 2.*, 2001, 1920.
30. T. Tuntulani, P. Thovornylltikarn, S. Proompradub, M. Jaibeen, V. Ruagpornisuti, . N. Chaichit, Z. Asfari, J. Vicens, *Tetrahedron.*, 2002, **58**, 1027.
31. C. Bocchi, M. Careri, A. Casnati, G. Mori, *Anal. Chem.*, 1995, **67**, 4234.
32. *Radioactive Waste Management and Disposal* Ed. L. Cecille, Elsevier Science, London, New York, 1991.
33. C. Hill, J. F. Dozol, V. Lamare, H. Rouquette, S. Eymard, B. Tournois, J. Vicens, Z. Asfari, c. Bressot, R. Ungaro, A. Casnati, *Incl. Phenom. Mol,Recog. Macrocyclic Chem.* 1994, **19**,399.
34. A. Casnati, A. Pochini, R. Ungaro, F. Ugozzoli, F. Arnaud, S. Fanni, M. -J. Schwing, R. J. M. Eghberink, F. de Jong, D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1995, **117**, 2767.
35. J. -S. Kim, J. -H. Pang, J. -Y. Yu, W. -K. Lee, J. -H. Suh, J. -K. Kim. M. -H. Cho, E. -T. Kim, D. -Y. Ra, *J. Chem. Perkin Trans. 2*, 1999, 837.
36. J. -S. Kim, T. -H. Suh, J. -K. Kim, M. -H. Cho, *J. Chem. Perkin Trans. 1* 1998, 2307.
37. R. Ungaro, A. Casnati, F. Ugozzoli, A. Pochini, J. -F. Dozol, C. Hill, H. Rouquette, *Angew. Chem. Int. Ed. Engl.*, 1994, **33**, 1506.
38. Z. Asfari, C. Bressot, J. Vicens, C. Hill, J. -F. Dozol, H. Rouquette; S. Eymard, V. Lamare, B. Tournois, *Anal. Chem.*, 1995, **67**, 3133.
39. T. J. Haverlock, P. V. Bonnsen, R. A. Sachleben, B. A. Moyer, *Radiochim Acta.*, 1997, **76**, 103.
40. J. -F. Dozol, V. Lamare, N. Simon, R. Ungaro, A. Casnati in *Calixarene Molecules for Separations*, ed. G. Lumetta, R. D. Rogers, A. S. Gopalan, ACS Symposium Series. 757, Ch. 2, Am. Chem. Soc. Washington DC 2000, p. 12.
41. V. Lamare, J.-F. Dozol, S. Fuangswasdi, F.A Neu, P. Theury, M.

- Neirlich, Z. Asfari, J. Vicens, *J. Chem. Perkin Trans. 2*, 1999, 271.
42. V. Lamare, D. Haubertin, J. Golebiowski, J. -F. Dozol, *J. Chem. Perkin Trans. 2* 2001, 121.
43. J. -S. Kim, A. Ohki, R. Veki, J. Ishizuka, T. Shimatashiro, S. Maeda, *Talanta*. 1999, **18**, 705.
44. J. Natatou, M. Burgard, Z. Asfari, J. Vicens, *J. Incl. Phenom. Mol,Recog. Macrocyclic Chem.* 1995, **22**, 107.
45. B. A. Moyer PCI Int. Appl. WO 9912, 878[Cl, CO7 (43/00) 18 Mar 1993, US Appl. 57, 974. 5 Sep 1997, 53 pp].
46. J. Guillon, J. -F. Leger, P. Sonnet, C. Jarry, M. Robba, *J. Org. Chem.*, 2000, **65**, 8283.
47. T. J. Haverlock, P. V. Bonnsen, R. A. Sachleben, B. A. Moyer; *J. Incl. Phenom. Mol,Recog. Macrocyclic Chem.* 2000, **36**, 21.
48. R. Debostiani, V. Lamare, J. -F. Dozol, P. Thuery, M. Nierlich, Z. Asafari, J. Vicens; *J. Chem. Perkin Trans. 2.*, 2001, 823.
49. R. K. Mahajan, M. Kumar, V. Sharma, J. Kuar, *Talanta*, 2002, **58**, 445.
50. M. G. Gorbunova, P. V. Bunnsen, N. L. Engle, E. Bazalaiare, L. H. Delmau, BA. Moyer; *Tetrahedron Lett.* **44**, 5397 (2003).
51. W. Wasikiewicz, M. Slaski, G. Rockiki, V. Gohmer, C. Schmidt, E. Paulus, *New J. Chem.*, 2001, **25**, 581.
52. X. Xeng, X. Han, L. Chen, K. Li, F. Xu, X. He, Z. -Z. Zhang, *Tetrahedron Lett.* 2002, **43**,131.
- 52a. K.-J. Yeol, K.-G. Kim, C. Ryul, S. Ho, L. -J. Hae, J. Seung, *J. Org. Chem.* 2003, **68**, 1933.
- 52b. V. Lu, J. B. Lambert, *J. Mater. Chem.*, 2004, 14.
53. R. Oszewski, T. W. Stevens, W. Verboom, D. N. Reingoudt; *Recl. Trav. Chim Pays- Ras.*, 1991, **110**, 294.
54. V. Bohmer, G. Ferguson, J. F. Gallagher, A. J. Laugh, M. A. Mckervey, E. Madigan, M. B. Moran, G. J. Williams, *J. Chem. Perkin Trans. 2.* 1993, 1521.
55. J. Bitter, A. Brun, G. Toth, B. Balazs, L. Toke, *Tetrahedron*, 1997, **53**, 9799.
56. J. Ouslati, R. Abidi, P. Thuery, M. Nierlich, J. Harrowfield, J. Vicens, *Tetrahedron*. 2000, **56**, 551.
57. J. Bitter, A. Brun, G. Toth, B. Balazs, G. Horvath, L. Toke, *Tetrahedron*. 1998, **54**, 3857.
58. Y. Wu, X. Shen, C. Duan, Y. Liu, Z. Xu, J. Bitter, A. Brun, G. Toth,

- B. Balazs, L. Toke; *Tetrahedron.*, 1999, **55**, 5749.
59. B. Pipoosananakaton, M. Sukwattanasinit, N. Jaiaboon, N. Chaichi, T. Tuntulani; *Tetrahedron Lett.*, 2000, **41**, 9095.
60. J. S. Kim, O. J. Shon, J. Won Ko, M. H. Cho, J. Vicens, *J. Org. Chem.* 2000, **65**, 2368.
61. J. S. Kim, S. -H. Yang, J. A. -Rim, J. -Y. Kim, J. Vicens, S. Shinkai, *Tetrahedron Lett.* 2001, **42**, 8047.
62. K. -J. Seung, O. -J. Shon, J. -K. Lee, S. -H. Lee, J. -Y. Kim, *J. Org. Chem.* 2002, **67**, 1372.
63. B. Pulpoka, Z. Asfari, J. Vicens, *Tetrahedron Lett.*, 1996, **37**, 6315.
64. J. -S. Kim, W. -K. Lee, K. Nu, Z. Asfari, J. Vicens, *Tetrahedron Lett.*, 2000, **41**, 3345.
65. K. -J. Seung, O. J. Shon, N. Y. Seung, J. Y. Kim, M. J. Kim, *J. Org. Chem.*, 2002, **67**, 6514.
66. T. Tuntulani, P. Thavornnyutikarn, S. Poompradub, N. Jaiboon, V. Ruangpornvisuti, N. Chaichit, Z. Asfari, J. Vicens, *Tetrahedron*, 2002, **58**, 10277.
67. K. -J. Seung, S. Lee, R. J. Ah, K. S. Kyoung, Y. Young, *J. Org. Chem.* 2002, **61**, 709.
- (67a). K. Sungeun, K. Hasuck, K. Ho, L. Seoung, K. -S. Kuk, J. Seung, *Talanta*, (2003).
68. T. Sone, Y. Ohba, K. Moriya, H. Kumada, K. Ito, *Tetrahedron.*, 1997, **53**, 10689.
69. N. Iki, N. Morohashi, F. Narumi, S. Miyano, *Bull. Chem. Soc. Jpn.*, 1998, **71**, 1597.
70. N. Iki, H. Kumagi, N. Morohashi, K. Ijima, M. Hasegawa, S. Miyanari, S. Miyano; *Tetrahedron. Lett.*, 1998, **99**, 7559.
71. H. Kumagi, M. Hasegawa, S. Miyano, Y. Sugawa, Ysato, T. Mori, S. Yuba, H. Kamiyama, S. Miyano, *Tetrahedron. Lett.*, 1997, **38**, 3971.
72. N. Iki, C. Kabuto, T. Fukushima, H. Kamagi, H. Takeya, S. Miyanari, T. Miyashi, S. Miyano, *Tetrahedron.*, 2000, **56**, 1437.
73. N. Iki, S. Miyano, *J. Inclusion Phenom. Macrocyclic Chem.* 2001, **41**, 99.
74. B. Norohashi, N. Iki, A. Sugawara, S. Miyano, *Tetrahedron.*, 2001, **57**, 5557.
75. A. Bilyk, A. K. Hall, J. M. Harrowfield, M. Whusseini, B. W. Skelton, A. H. White, *Inorg. Chem.*, 2001, **40**, 672.
76. A. Bilyk, A. K. Hall, J. M. Harrowfield, M. Whusseini, B. W. Skelton,

- A. H. White, *Inorg. Chem.*, 2000, **39**, 823.
77. L. Lamare, J. -F. Dozol, P. Thuery, M. Nerlich, Z. Asfari, J. Vicens, *J. Chem. Soc., Perkin Trans. 2*, 2001, 1920.
78. H. Yamamoto, T. Sasaki, S. Shinkai, *Chem. Lett.*, 1994, 469.
79. A. Arduini, W. M. McGreger, D. Paganuzzi, A. Pochini, A. Secci, F. Ugozzoli, R. Ungaro, *J. Chem. Soc., Perkin Trans. 2*, 1996, 839.
80. A. Arduini, L. Domiano, A. Pochini, A. Secci, R. Ungaro, F. Ugozzoli, O. Struck, W. Verboom, D. N. Reinhoudt, *Tetrahedron*, 2002, **53**, 3767.
81. F. Narumi, N. Matsumara, N. Morohashi, H. Hakemaya, S. Miyano; *J. Chem. Soc. Perkin Trans. 2* 2002, 1843.
82. M. Asharam, *J. Chem. Soc. Perkin Trans. 2*, 2002, **10**, 1662.
83. H. Yamamoto, T. Sakaki, S. Shinkai, *Chem Lett.*, 1994, 469.
84. C. Bressot, J. P. Astier, Z. Asfari, J. Esteinne, J. Pepe, J. Vicens, *J. Inclusion Phenom.* 1994, **19**, 291.
85. S. -K. Kim, J. Vicens, K. -M. Park, S. -S. Lee, J-S. Kim, *Tetrahedron Lett.*, 2003, **44**, 993.
86. Z. Asfari, J. Weiss, S. Pappalardo, J. Vicens, *J. Pure Appl. Chem.*, 1999, **68**, 585.
87. Z. Asfari, R. Abidi, F. Sarnaud, J. Vicens, *J. Inclusion Phenom.*, 1992, **13**, 163.
88. F. A. Neu, Z. Asfari, B. Souley, J. Vicens, *New J. Chem.* 1996, **20**, 453.
89. J. S. Kim, Y. J. Yu, J. -H. Pang, J. -K. Kim, Y. -J. Lee, W. -O. Kune, *J. Chem. Soc., Perkin Trans. 1*, **1998**, 1307.
90. Z. Asfari, X. Nicolli, J. -F. Dozol, A. Duhart, J. M. Harrowfield, B. W. Skeltor, A. H. While, *J. Inclusion Phenom. Macrocyclic Chem.*, 1999, **33**, 251.
91. J. Li, Z. Zhong, Y. Chen, X. Lu, *Tetrahedron Lett.*, 2002, **43**, 1629.
92. V. Talanov, G. Talanov, G. Gorbonova, A. Bartsch, *Tetrahedron Lett.* 2002, **43**, 1629.
93. H. Dozol, Z. Asfari, J. Vicens, P. Theury, M. Nierlich, J. -F. Dozol, *Tetrahedron*, 2001, **42**, 8285
94. A. Matheiu, Z. Asfari, P. Thuery, M. Nierlich, S. Faure, J. Vicens, *J. Inclusion Phenom. Mol. Recogn. Macrocyclic Chem*, 2001, **40**, 173.
95. J. Guillon, P. Sounel, J. M. Malvi, S. Massip, J. Gosse, J. M. Leger, R. Lapouyade, J. Rochette, J. -P. Monty, C. Jarry, *Supramol. Chem.*, 2002, **14**, 437.

- 95a. S. P. Rostaing, F. Chitry, J. -A. Spitz, A. Sorin, A. -F. Reuilon, M. Lamaire, *Tetrahedron*, **59**, 2003, 1031.
96. B. chankvetadze, G. Endesz, G. Blaschke, *Chem. Rev.*, **1996**, **25**, 141.
97. C. Easton, S. F. Lincosin, *Chem. Soc. Rev.*, 1996, **25**, 163.
98. J. M. Lehn, *Supramolecular Chemistry*; VCH; Weinheim, 1995.
99. B. E. Kyba, R. L. Sousa, M. G. Seigel, D. J. Cram, *J. Am. Chem. Soc.*, 1973, **95**, 2692.
100. R. Ludwig, *Frensenius, Anal. Chem.*, **2000**, 103.
101. V. Bohmer, *Angew. Chem. Int. Ed. Engl.*, 1995, **34**, 713.
102. R. Arnecke, V. Bohmer, G. Ferguson, S. Pappalardo, *Tetrahedron Lett.*, 1996, **37**, 1497.
103. S. Pappalardo, M. -F. Parisi, *Tetrahedron Lett.*, 1996, **37**, 1493.
104. C. Geraci, M. Piattelli, P. Neri, *Tetrahedron Lett.*, 1996, **37**, 1621.
105. F. -A. Neu, S. Caccamese, S. Fuangswasdi, S. Pappalardo, M. -F. Parisi, A. Patringa, G. Principato, *Tetrahedron Lett.*, 2000, **41**, 1530.
106. S. Caccamese, A. Notti, S. Pappalardo, M. -F. Parisi, G. Principato, *Tetrahedron.*, 1999, **55**, 5505.
107. I. Bitter, E. Koszegi, A. Grun, R. P. Bako, K. Pal, A. Grofesik, M. Kubinyi, B. Blazs, G. Toth, *Tetrahedron Asymmetry.*, 2003, **14**, 1025
108. S. Memon, M. Yilmez, *React. Funct. Polym.* 2000, **44**, 227.
109. S. Memon, M. Yilmez, A. Yilmez, *J. Macromol. Sci. Part A. Pure Appl. Chem.* 2000, **37**, 865.
110. S. Memon, G. Vysal, M. Yilmez, *React. Funct. Polym.*, 2001, **47**, 165.
111. H. Li, Y. Chen, *React. Funct. Polym.*, 2003, **55**, 171.
112. F. Kurita, S. Fukushima, M. Fujimaki, Y. Matsuzawa, F. Kube, K. Ishimara, *J. Mater. Chem.*, 1998, **8**, 397.
113. C. Fisher, G. Sarti, A. Canati, R. Ungaro, *Chem. Eur. J.*, 2002, **6**, 1026.
114. V. W. -W. Yam, K. -L. Cheung, L. -H. Yuan, K. M. Chung, K. -K. Cheung, *Chem. Commun*, **2000**, 1513.
115. A. Dodi, *Analisis*, 2000, **28**, 23.
116. Y. -Hee Kim, N. -R. Cha, S. -K. Chang, *Tetrahedron Lett.*, 2002, **43**, 3883.
117. A. Grofesik, P. Baranyki, I. Bitter, A. Grun, E. Kovzegi, M. Kubinyi, K. Pal, T. Bidoczy, *J. Molecular Structure.*, 2002, **614**, 69.
118. P. Tongraung, N. Chantarasiri, T. Tuntulani, *Tetrahedron Lett.*, 2003, **44**, 29.