

Calixarene Assemblies

by W. Śliwa

*Institute of Chemistry and Environmental Protection, Pedagogical University,
al. Armii Krajowej 13/15, 42-201 Częstochowa, Poland*

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Selected examples of calixarene dimers and oligomers are presented, along with calixarene assemblies with other molecules, including those containing fullerene units.

Key words: biscalixarenes, calixcrowns, calixfullerenes, complexing properties, conformation

INTRODUCTION

Calixarenes are macrocycles receiving a growing attention in recent years. They are a topic of numerous reviews [1–4] and original papers [5–7]. These compounds are readily accessible by condensation of phenols with aldehydes in the presence of alkali catalysts in high boiling glycol ether solvents [8]. Calixarenes are of importance in supramolecular chemistry and in the designing of fascinating molecular architectures. Numerous assemblies of calixarenes are known; these compounds may be linked with carbohydrates [9,10], amino acids [11], crown ethers [12,13], porphyrins [14] and fullerenes [15]; also host-guest systems containing calixarene units are known [16–20].

We describe here selected examples of calixarene dimers and oligomers, followed by calixarene assemblies with other molecules. The present review is a continuation of our publications concerning calixarenes [21–23] and heteracalixarenes [24–26]*. References are cited mainly of works that appeared during the years 1998–2000.

CALIXARENE DIMERS

Among works on calixarene assemblies [27–30] many reports deal with calixarenes of the dimeric type [31–37], often forming self-assembled capsules [38–43].

Calix[4]arenes, due to their rigid structure, may be used as a constraint in modification of cyclopeptides; they reduce the conformational freedom of cyclopeptides and provide additional binding sites, this property being interesting in molecular recognition.

*The name of heteracalixarenes was given to calixarenes having in their bridges N, O or S atoms; heterocalixarenes, e.g. calixpyrroles or calixpyridines contain heterocycles instead of phenolic units [4].

In the study of calixarenes containing peptide or amino acid units [11,44], lower-rim linked calix[4]arene-bearing cyclopeptide **1** and its dimer **2** have been synthesized by treatment of calix[4]arene **3** with L-cystine dimethyl ester dihydrochloride [45].

The properties of molecular recognition of the compound **1** have been tested using phosphomonoester. In these experiments **1** has proven to be more efficient receptor for phosphomonoester than calixarenes **4a,b**. It was shown that introduction of rigid calix[4]arene molecule as a constraint to the backbone of cyclic peptides improves their molecular recognition abilities (Scheme 1).

Biscalixarenes are interesting as ditopic receptors in host-guest chemistry. The 5,5'-biscalix[4]arenes are examples of double calixarenes with direct *para-para* linkage [46]. The alkylation of the compound **5** with propyl iodide and *para-t*-butylbenzyl bromide in the presence of K_2CO_3 , NaH and Cs_2CO_3 has been investigated [47]. These regio- and stereoselective reactions proceed in different way depending on the base used. The reaction of **5** with propyl iodide in the presence of K_2CO_3 results in tetraalkylated double cone derivatives **6–8**. The reaction of **5** with propyl iodide in the presence of NaH leads to octapropyl double cone derivative **9** and cone-partial cone atropoisomers **10–12**. It should be pointed out that compounds **10–12** are biscalix[4]arenes having two subunits linked in different conformations (Scheme 2).

Besides the above species, also larger double calixarenes are known, examples being 5,5'-biscalix[6]arene **13** and 5,5'-biscalix[8]arene **14** [48].

In order to obtain **13**, the calix[6]arene **15** was treated with benzoyl chloride to give pentabenzoylcalix[6]arene **16** which was submitted to oxidative coupling with $FeCl_3 \cdot 6H_2O$ affording decabenzoyl-5,5'-biscalix[6]arene. This compound was converted by hydrolysis into **13**.

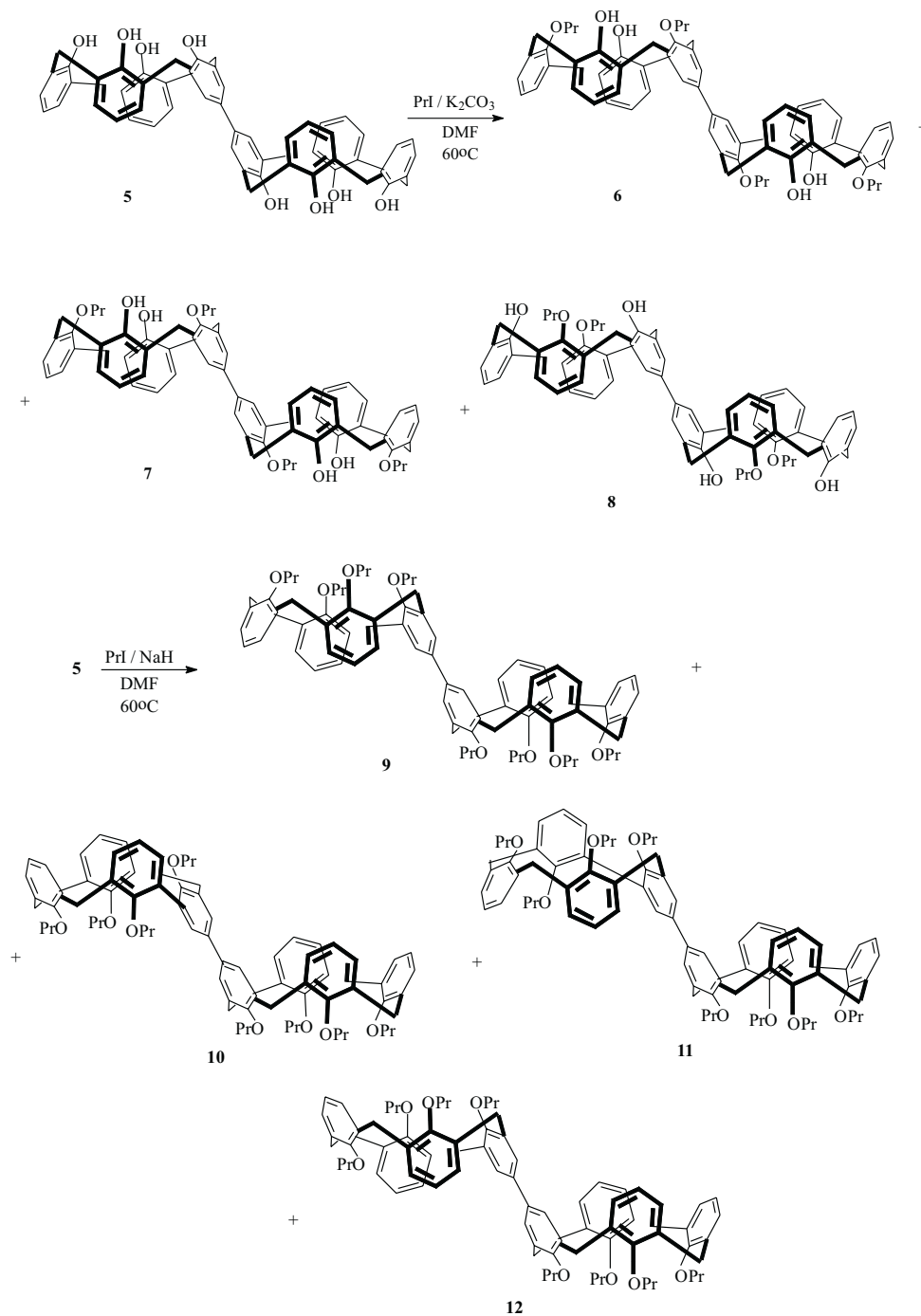
For the synthesis of **14**, the reaction of the calixarene **17** with *p*-bromobenzoyl chloride was performed and the resulting product **18**, after the removal of one *t*-butyl group by treatment with $AlCl_3$ gave **19**. The oxidative coupling of **19** with the use of $FeCl_3$, followed by alkaline hydrolysis afforded **14** (Scheme 3).

It was observed that calixarene dimers of the type **20** covalently linked at lower rims spontaneously self-organize into polymeric liquid crystals and then into micrometer-scale fibrous assemblies [49–51] (Scheme 4).

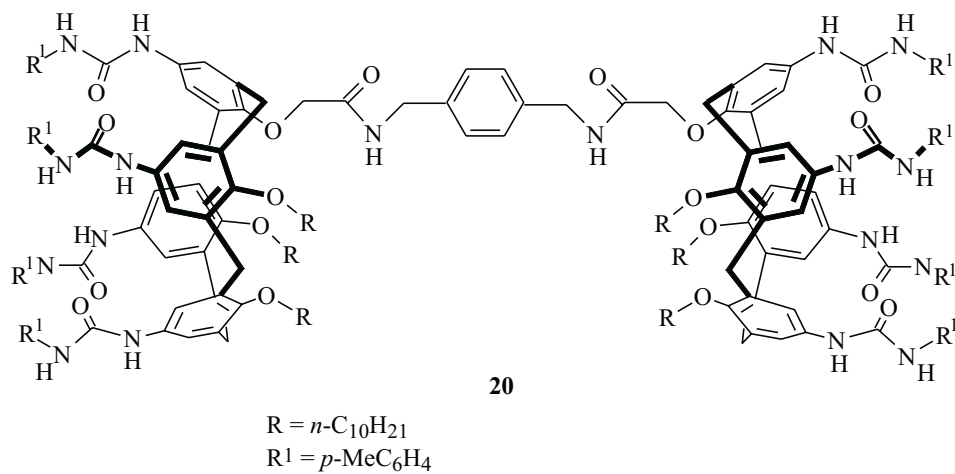
To doubly linked dimeric calixarenes belongs **21** [52], and an example of 1,3,5,7 four-point capped calix[8]arene is **22** [53,54] consisting of two calixarene moieties, synthesized in the reaction of calixarenes **17** and **23** in the presence of CsF under high dilution conditions (Scheme 5).

Calixbarreland **24** is a cage type compound tetrabridged through the lower rims [55]. Its synthesis begins with the reaction of **25** and 5,5'-bis(bromomethyl)-2,2'-bipyridine **26** resulting in semibarreland **27** which with the second molecule of **26** gives **24** (Scheme 6).

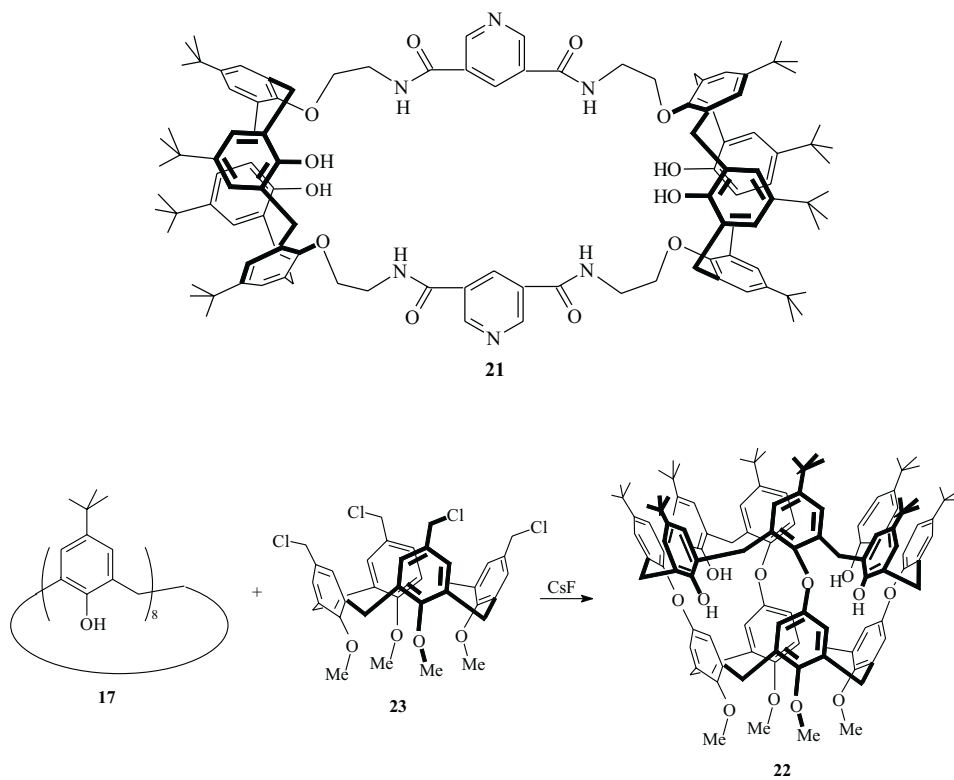
Scheme 2



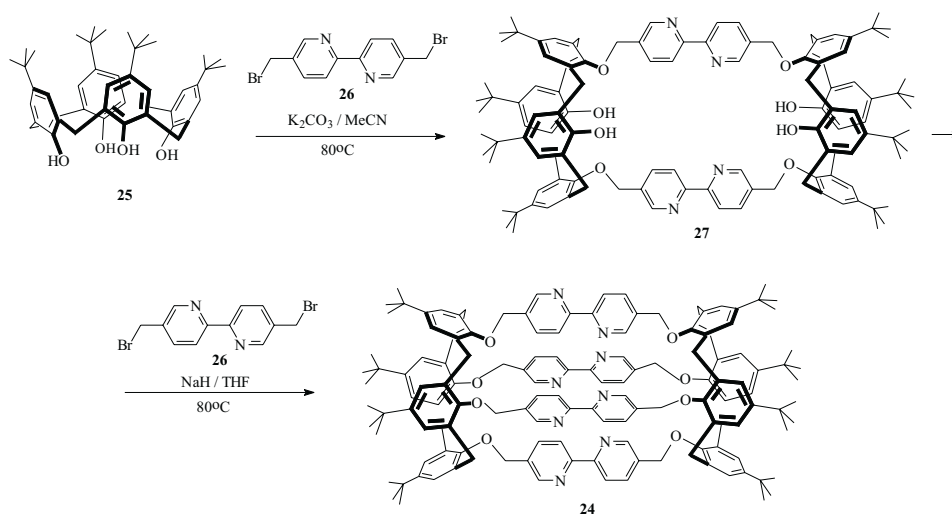
Scheme 4



Scheme 5



Scheme 6



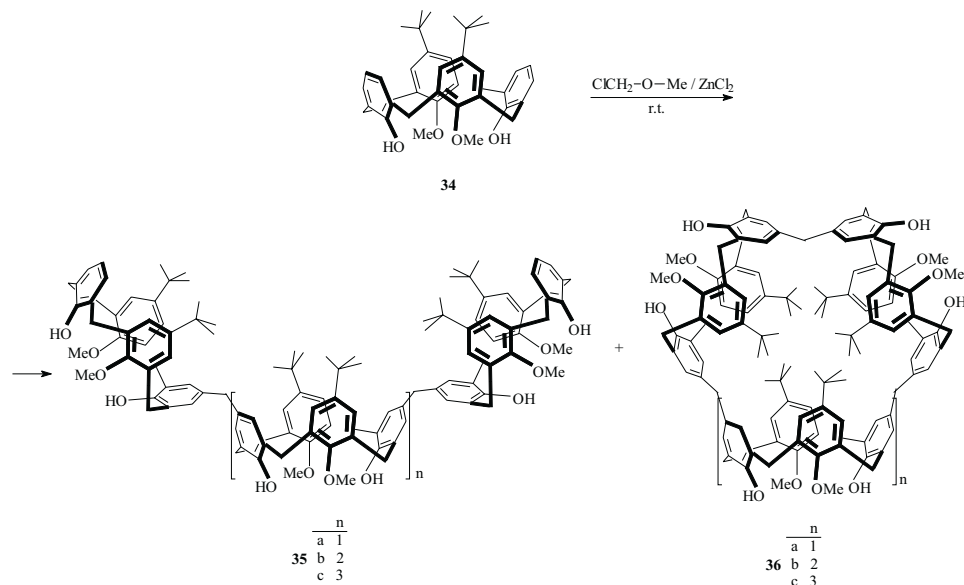
CALIXARENE OLIGOMERS

Annelated double and triple calixarenes **28** and **29**, respectively, are known. The two calix[4]arene moieties in **28** can only interconvert between cone, partial cone and 1,2-alternate conformations; the topomerization, *i.e.* the complete conformational inversion is impossible. In **29** the lateral moieties have a cone conformation and the middle one is fixed in the 1,2-alternate conformation [56].

The condensation of *exo*-calix[4]arene **30** with bisbromomethylated dimer of *p*-nitrophenol **31** affords the triple calixarene **32**. Single crystals of calcium salt of **32** [$\{[Ca \cdot (DMSO)_4 \cdot (H_2O)_2]^{2+} (4DMSO)\} (32 - 2H)^{2-} 2DMSO$] were obtained from DMSO-water containing $Ca(HCO_3)_2$ and their X-ray analysis was made. Due to the 1,2-alternate conformation of the middle unit in **32**, the molecular cone cavities are situated in opposite directions [56,57]. Taking into account their two cavities, triple calixarenes are interesting in the construction of supramolecular systems; it should be pointed out that the nitro groups present in **32** can be reduced to give amino derivatives able to further modifications.

It was found that calix[*n*]arenes **33** form nanotube-like structures [58]. These species have been obtained by the condensation – polymerization of appropriate calixarenes in toluene under reflux, in the presence of a metal salt, *e.g.* sodium bismuthate (Scheme 7).

Scheme 8



Bis-, tris- and hexakis-calix[4]arenes **37a–c**, **38** and **39**, respectively, have been synthesized by following procedures using monohydroxycalixarene **40** as starting material [60] (Scheme 9).

CALIXARENE ASSEMBLIES WITH OTHER MOLECULES

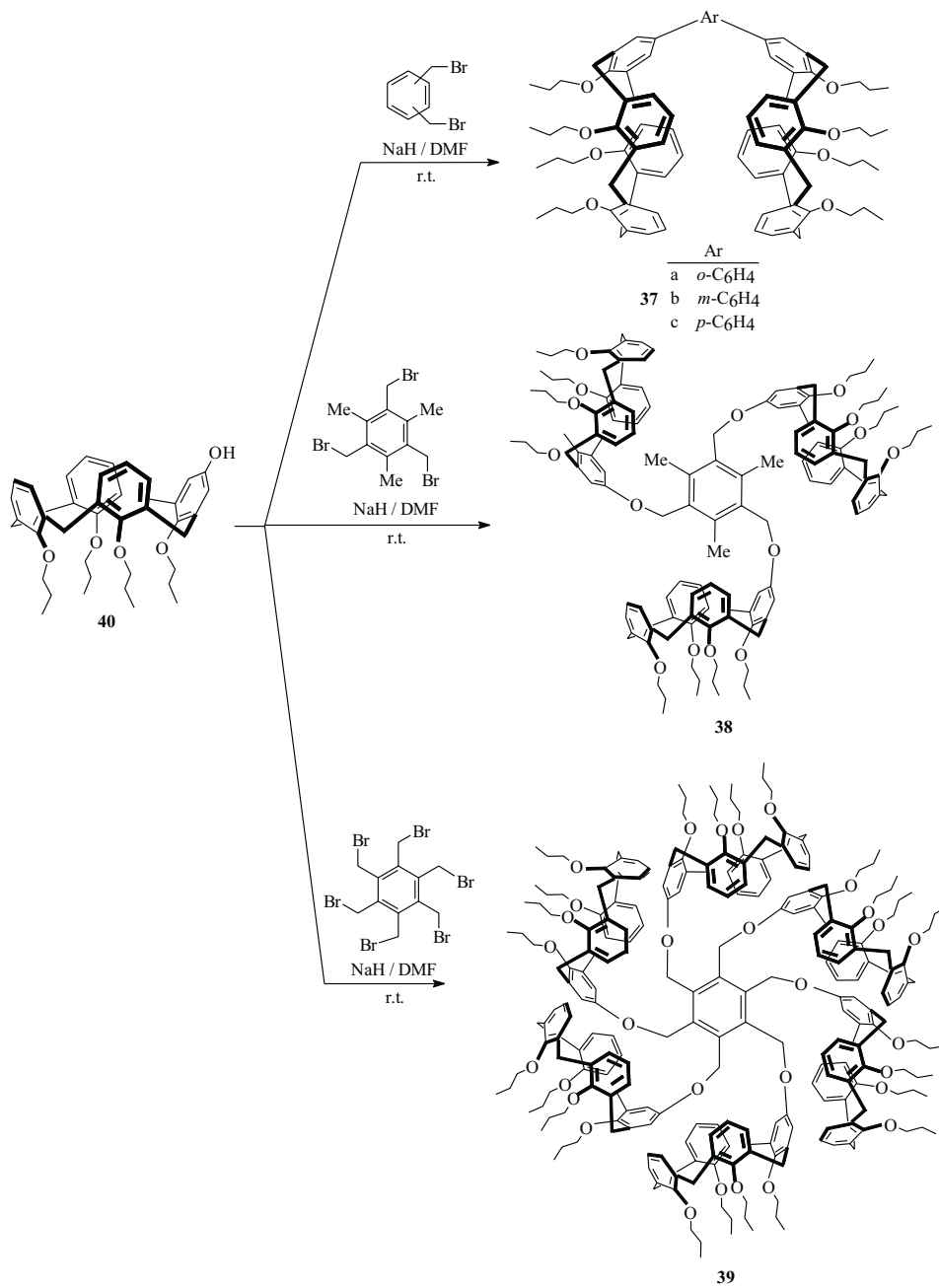
Numerous calixarenes linked with crowns [61,62] or azacrowns [63–65] are known. The reaction of the calixcrown **41** with arylene-modified pentaethylene-glycol ditosylates leads to calix[4]bis-crowns-6 **42** and **43** [66] (Scheme 10).

In the search for molecular machines, the compound **44** has been synthesized by condensation of the calix[4]arene derivative **45** with naphtho polyether diol **46** [67]. As a by-product the compound **47** was formed (Scheme 11).

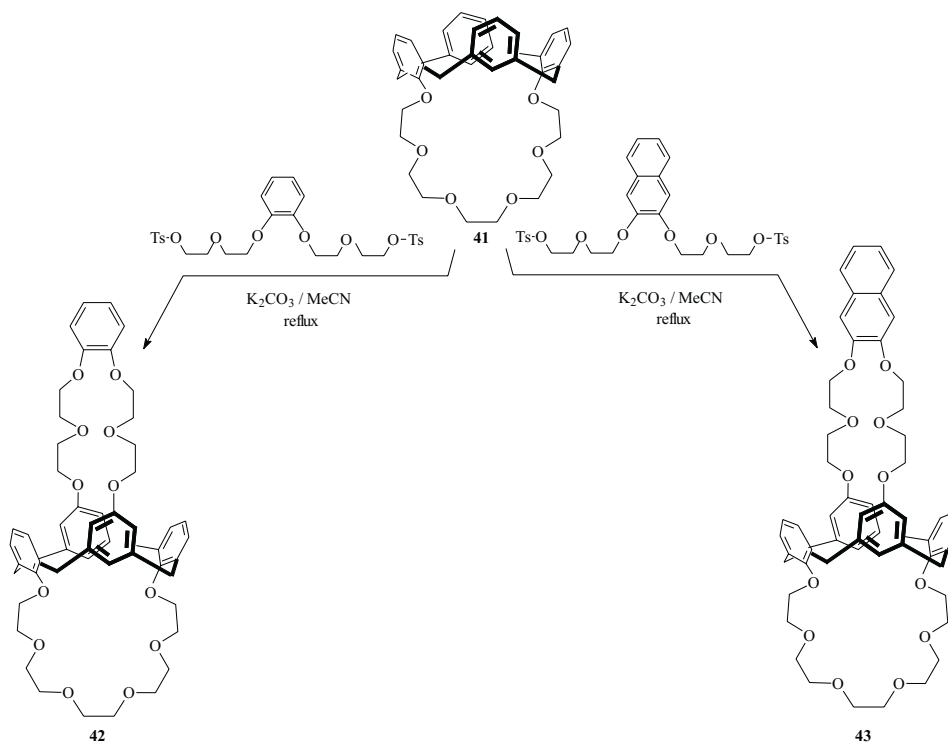
Examples of [2]catenanes containing calix[4]arene moieties are **48** and **49** synthesized as follows [68] (Scheme 12).

In the study of porphyrin-based calixarenes [69,70], compounds **50** have been synthesized from calix[4]arene monoaldehyde **51** and aryldipyrrolylmethanes **52**, obtained by condensation of *para*-substituted benzaldehydes **53** with pyrrole. The reaction of **51** and **52** was performed using $\text{BF}_3 \cdot \text{Et}_2\text{O}$ as catalyst; the subsequent treatment with DDQ gave **50** [71] (Scheme 13).

Scheme 9



Scheme 10

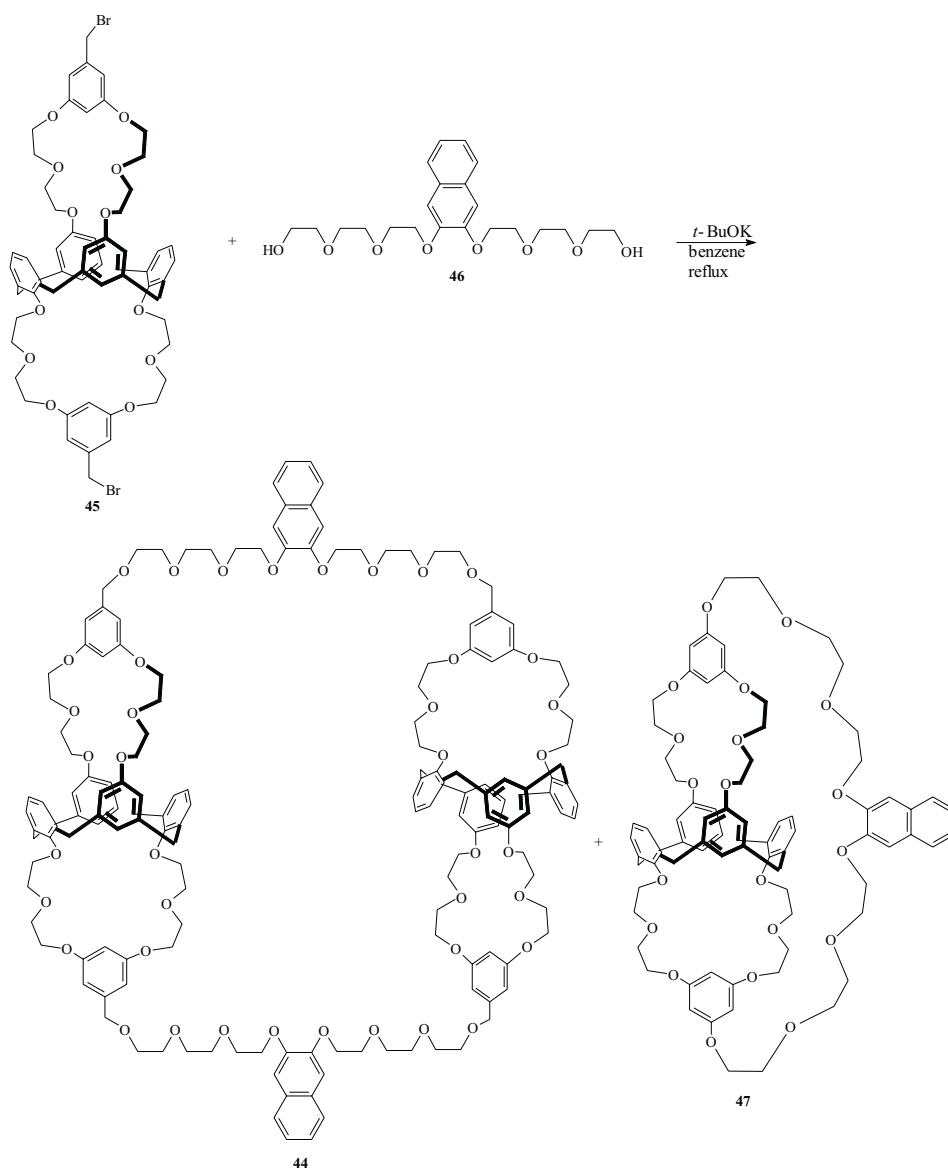


Calixfullerenes **54** and **55** have been synthesized [72]. In **54** the C₆₀ unit is covalently linked with a cone calix[4]arene, and in **55** with a 1,3-alternate calix[4]arene. In the case of **54** it was observed the formation of exohedral C₆₀-metal complexes with Li⁺, Na⁺ and Ag⁺, this fact being indicated by observation that the absorption spectrum of **54** is affected by addition of these metal ions. Synthetic approaches to **54** and **55** are shown below (Scheme 14).

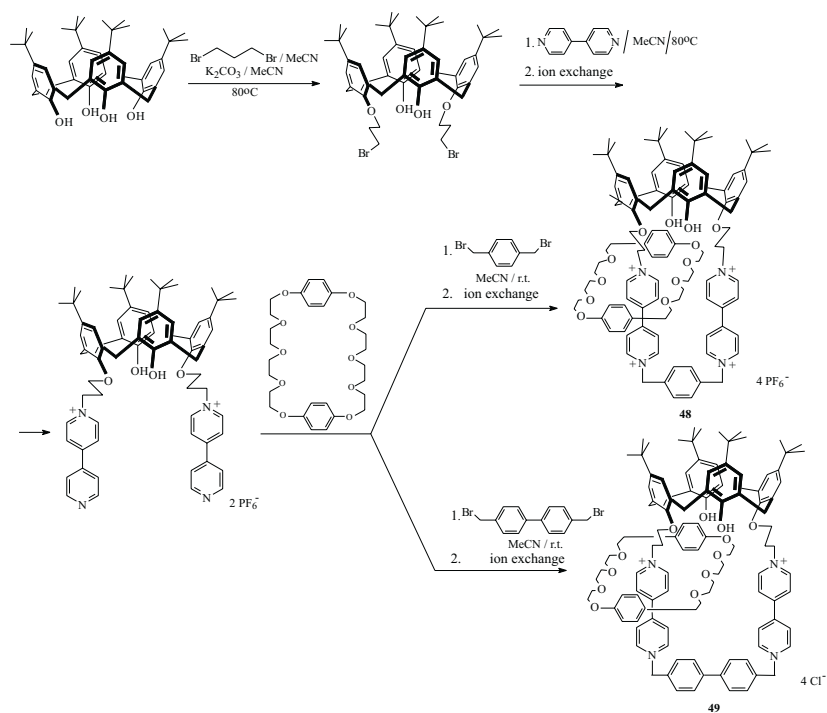
Compound **56** containing calixarene and fullerene moieties coupled *via* a spiro carbon atom has been synthesized by treatment of calixarene **25** with pentaerythritol tetra(monochloroacetate) **57** and the subsequent reaction of the resulting **58** with sodium azide. The formed bisazide **59** reacts with C₆₀ to give **56** [73] (Scheme 15).

The compound **60** belongs to calixfullerenes. The cavity of calix[8]arene **17** is complementary with the volume of C₆₀, and the spacer linking calixarene and fullerene is flexible enough to allow an equilibrium in solution between **60** and compound in which C₆₀ is encapsulated into calixarene moiety. The synthesis of **60** is shown below [54,74] (Scheme 16).

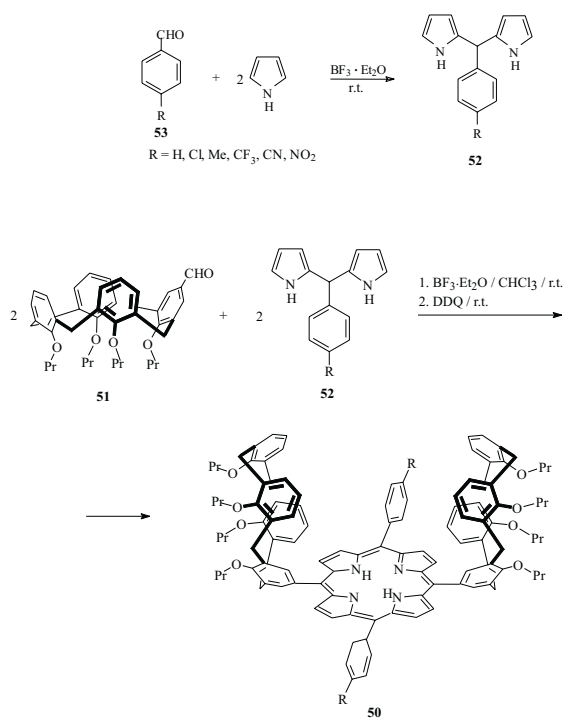
Scheme 11



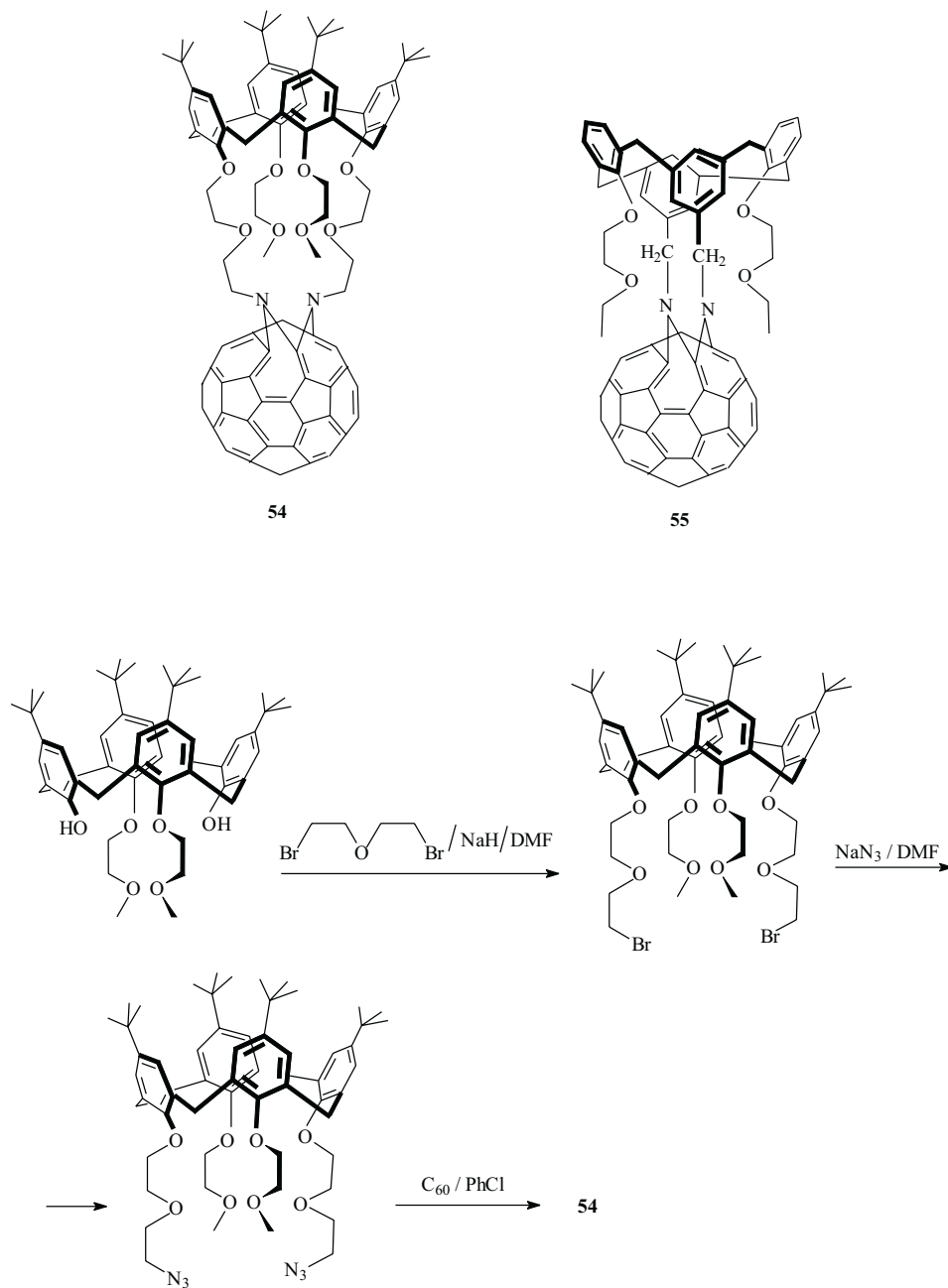
Scheme 12



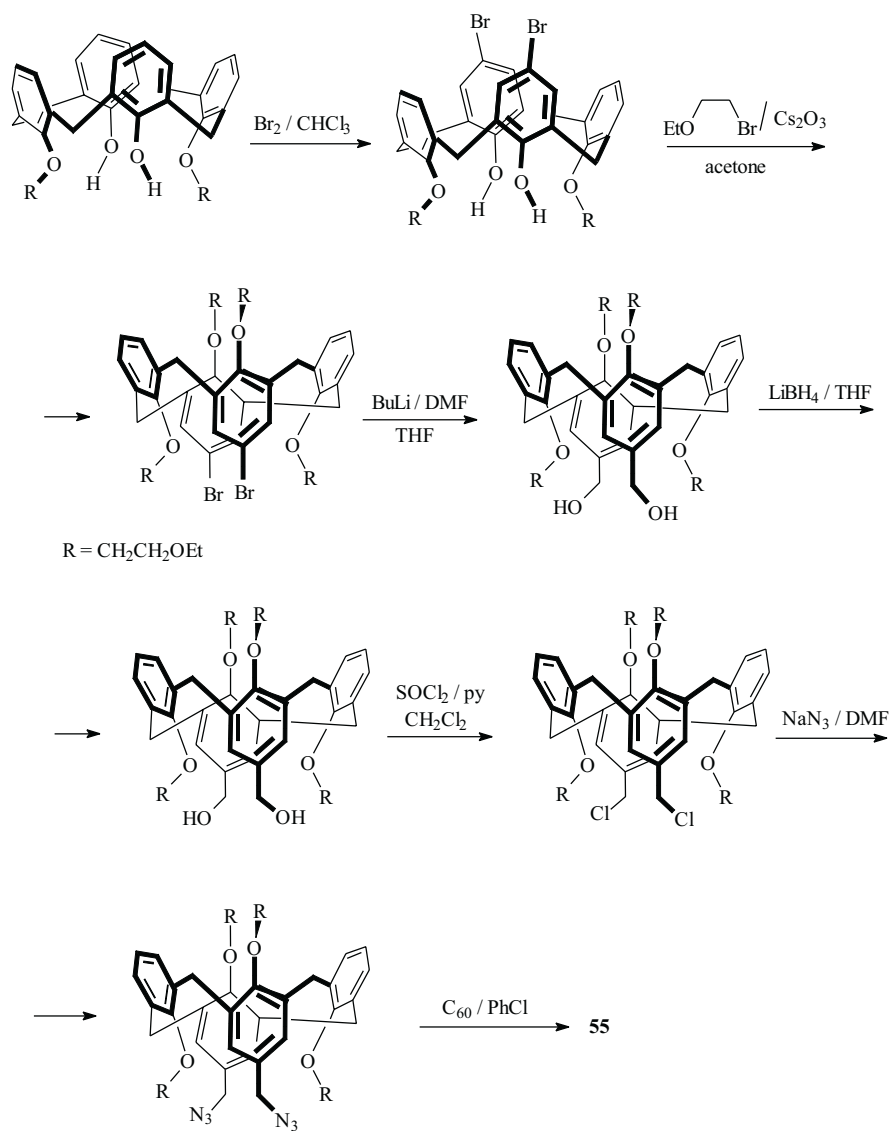
Scheme 13



Scheme 14

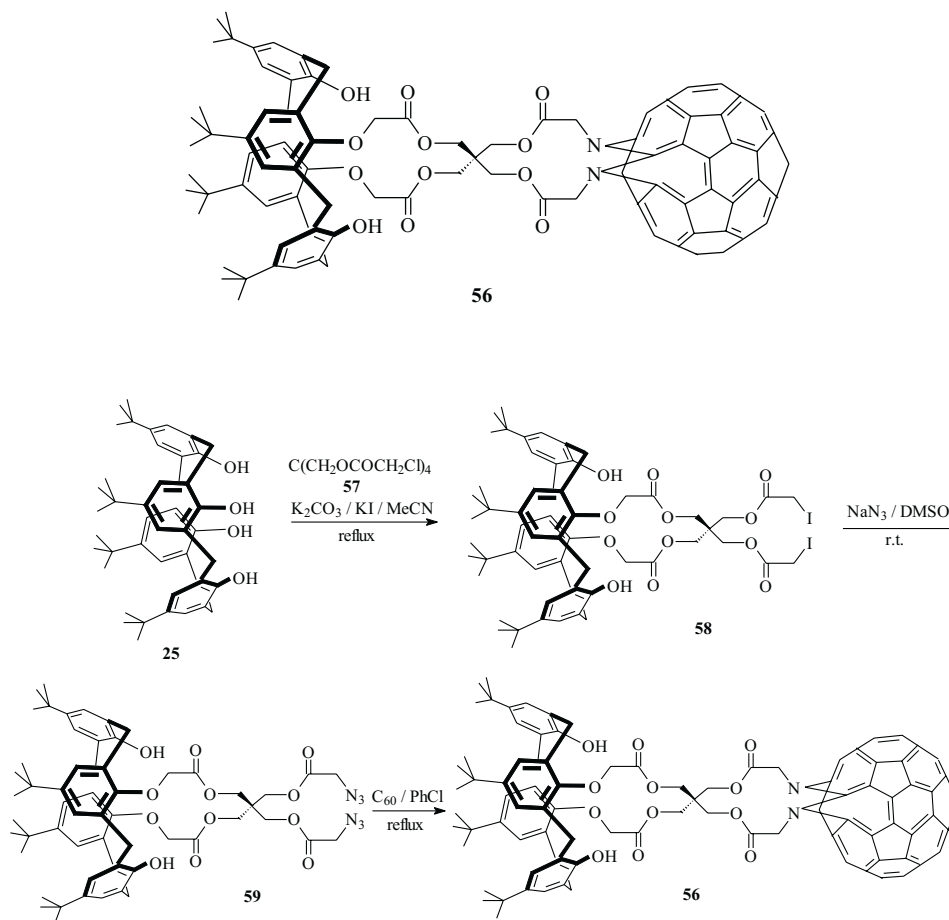


Scheme 14 (continuation)



In the study of Zn(II) porphyrin and fullerene assemblies, interesting as redox couple to mimic the photosynthesis, it was established that the electron transfer efficiency between Zn(II) porphyrin group (a fluorophore) and C_{60} group (a quencher) depends on the distance between them.

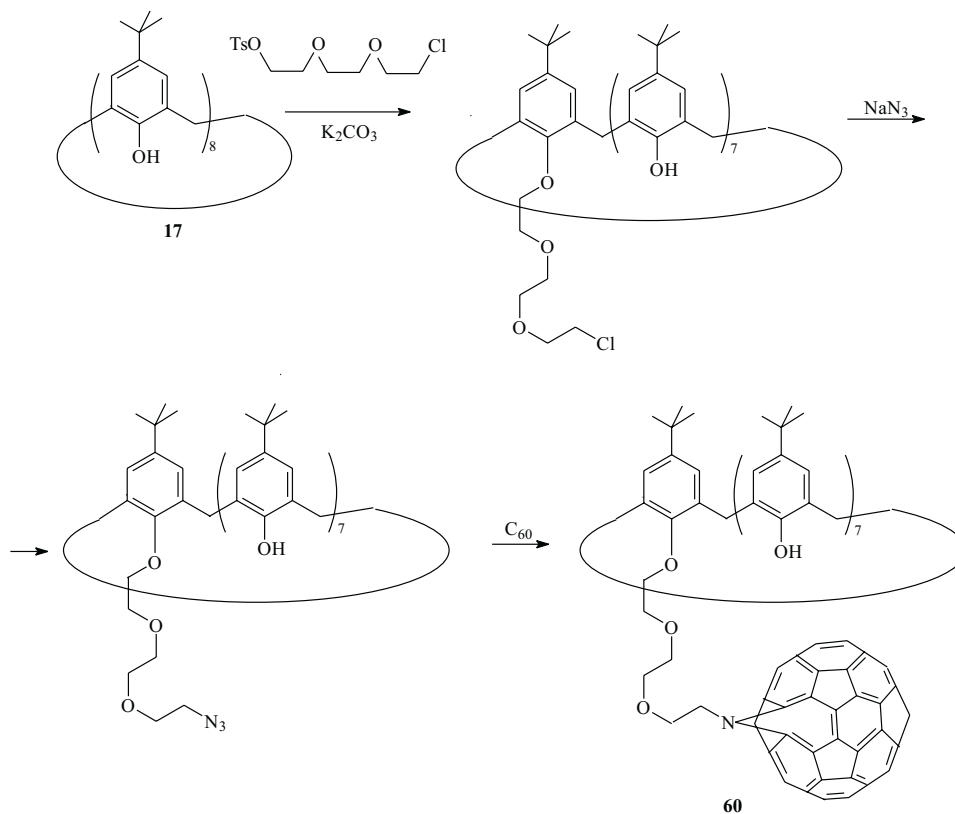
Scheme 15



Calixarenes are here suitable as linkers because they can change their conformations in response to added alkali metal ions, in this way an on-off-switched electron-transfer system may be obtained, in which the electron transfer can be controlled by added metal ions. Compounds **61** and **62** may serve here as examples [75].

In calix[4]arene derivative **61** carbonyl groups are directed outwards, but in the presence of Na^+ they adopt an inward position suitable for binding of this ion. In calix[6]arene derivative **62** the introduction of Cs^+ ion results in the conformational change from 1,2,3-alternate to cone, connected with the shortening of the distance between fluorophore and the quencher and in the consequence the higher electron transfer efficiency (Scheme 17).

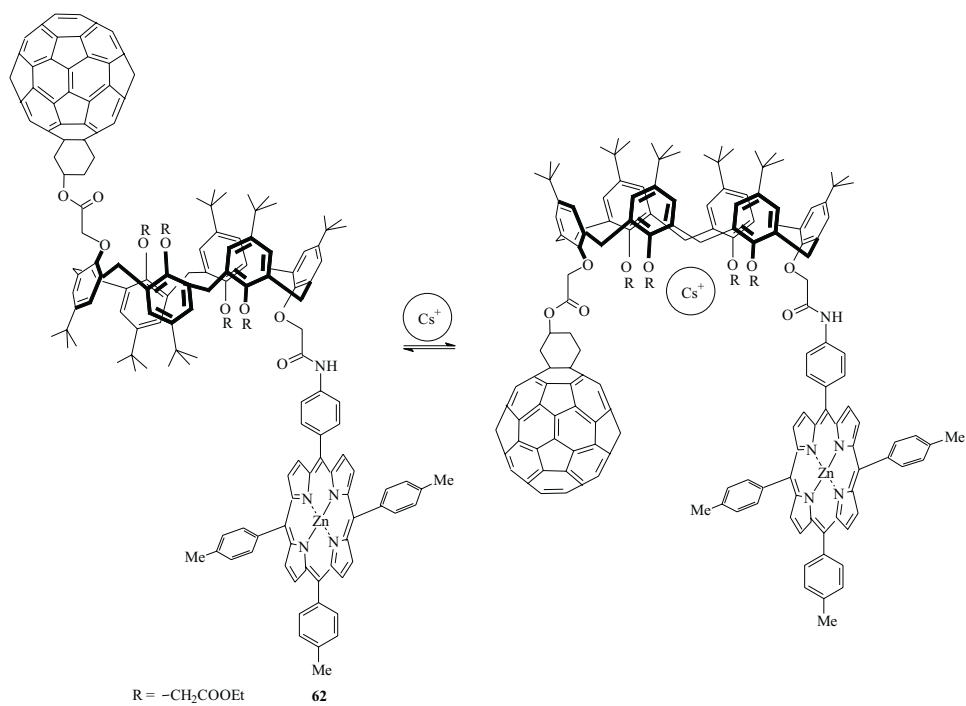
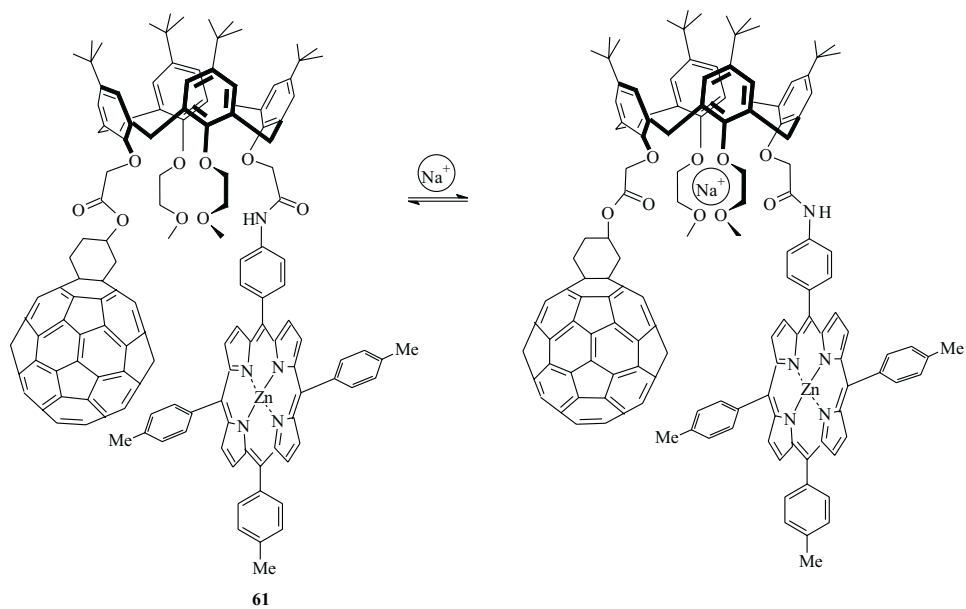
Scheme 16



CONCLUSIONS

In the first part of this review calixarene dimers and oligomers have been described, and in the second one assemblies consisting of calixarene units and other compounds were presented. The former species are useful as receptors of smaller molecules or ions; they may exist as capsules suitable for inclusion of guests. The compounds belonging to the second group are of interest for their complexation properties and for their often unusual shape. Especially promising are calixarenes useful in the extraction of lanthanides and actinides [76–78] and able to bind selectively cesium over alkali metal ions, these processes being of a great importance in nuclear waste management [79,80].

Scheme 17



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