Homocalixarenes

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Received June 16, 1998

Introduction

Since the calixarenes were fully characterized as homologous cyclic compounds in the work of Gutsche et al., their usability as host and sensor substances has been a matter of intensive investigations.[1] In particular, the selective complexation of cations by calixarenes has been the topic of a comprehensive review article.[2] The still increasing interest in calixarenes as hosts for organic guests is shown by a number of current publications.[3] Calixarenes (**I**, cf. Figure 1) are the condensation products between often para-substituted phenols and formaldehyde.[1] Although they belong to the group of [1$_n$]metacyclophanes, the calixarene nomenclature (from the Greek expression "calix" = vase) invented by Gutsche is usually applied because of its higher succinctness.

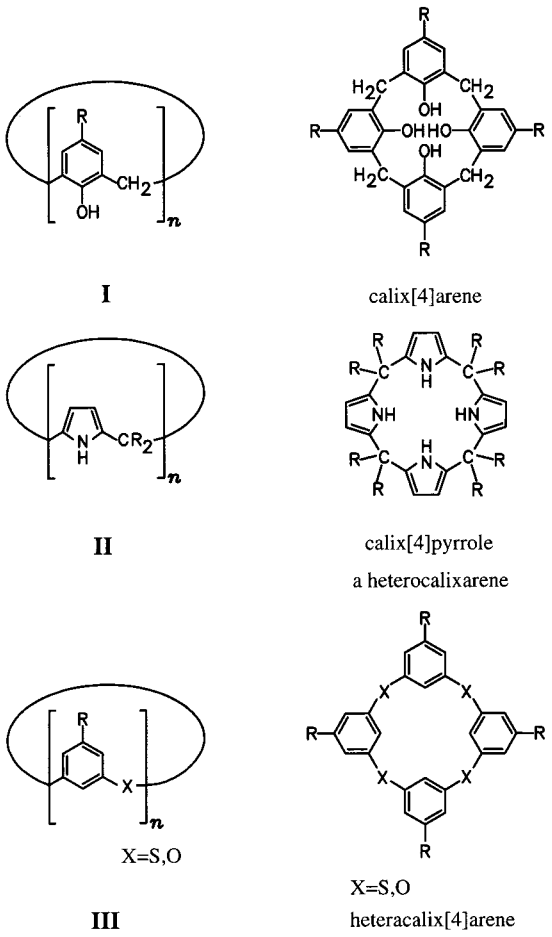

FIGURE 1. General formulas of calixarenes, calixpyrroles, and heterocalixarenes in comparison.

Characteristic in calixarene chemistry, especially in the calix[4]arene series, is the formation of several stable conformers, described by the geometrical arrangement of the benzene subunits as cone, partial cone, and alternate conformations.[1] The existence of stable conformers influences the host/guest behavior of calixarene derivatives. A negative effect of the conformational flexibility on the ion selectivity of membrane-integrated ion sensors has been reported.[4] Today, several methods for rigidification of the calixarene skeleton to avoid conformational interconversions have been established. A well-known example represents a synthetic calix[4]arene ionophore, which is fixed in a 1,3-alternate conformation by a crown-5-bridge. It shows a higher K^+/Na^+ selectivity than the naturally occurring valinomycin.[5]

In any case, the occurrence of conformers which probably cannot include guest molecules requires additional separation and purification steps. Therefore, we decided 10 years ago to synthesize a host system based on a conformationally more flexible carbocyclic scaffold similar to calixarenes. Our efforts resulted in the prepara-

Stefan Ibach was born in Germany in 1968. He received his degree in chemistry from Bonn University in 1996 and Ph.D. in 1998, working in Fritz Vögtle's group on ionselective supramolecular structures, particularly on the formation of *all*-bishomocalixarenes and macrobicyclic ligands.

Volker Prautzsch was born in Germany in 1967 and studied Chemistry at Bonn University from 1988 to 1996. He received his Ph.D. in 1998 working in the research group of Fritz Vögtle on the synthesis of macrocyclic extreme ligands, such as functionalized *all*-homocalixarenes, calixarenes, and dendrimers.

Fritz Vögtle, born in 1939 in South Germany, received his Ph.D. for research with H. A. Staab in Heidelberg on the valence isomerization of double Schiff bases. After his habilitation he was professor in Würzburg. In 1975 he accepted a position as full professor and director of the Kekulé-Institut für Organische Chemie und Biochemie in Bonn. Awards obtained include a "literature prize" for his book *Supramolekulare Chemie* (translated to English, Japanese, Chinese) and the Lise Meitner−Alexander von Humboldt Prize. He is interested in the field of supramolecular chemistry and molecular recognition (homocalixarenes) and has pioneered multibridged compounds with large intramolecular cavities, dendrimers, strained helical molecules, and catenanes and rotaxanes.

Christine Chartroux was born in France in 1972. She received her degree from the European High School Institute of Chemistry of Strasbourg (France) in 1995. She is currently working on her Ph.D. in K. Gloe's group at the Institute of Inorganic Chemistry of TU Dresden, working on the complexation properties of supramolecular ligand systems.

Karsten Gloe was born in Germany in 1947. He received his degree in chemistry in 1969 and Ph.D. in 1972, both from TU Dresden. After 20 years of research in the Institute of Solid State Physics and Materials Research in Dresden, he joined the Institute of Inorganic Chemistry of TU Dresden in 1992, becoming Professor of Coordination Chemistry. His current research interests are concerned with design and investigation of supramolecular ligand systems, development and application of selective complexation reactions for solvent extraction processes, thermodynamics, and modeling of complexation equilibria.

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10.1021/ar970231j CCC: $18.00
Published on Web 05/29/1999

tion of the "*all*-homocalixarenes", representing large macrocycles which can take nearly planar conformations in contrast to calixarenes. Additionally, from the beginning of our work, we took into account the possibility of integrating heteroaromatic subunits (e.g., pyridine rings) in our host system, which had been a synthetic problem in calixarene chemistry for a long time. Only recently, several groups succeeded in the synthesis of "heterocalixarenes", which will be discussed in detail in the second section of this Account. This short review deals mainly with the chemistry of homocalixarenes, homocalixpyridines, and structurally related compounds, including the latest results about their behavior as phase-transfer ligands for metal ions. We would like to emphasize the superiority of homocalixarenes compared to calixarenes with respect to special applications such as extracting agents. In this research field, the platinum group metals will especially attract more interest in the future, because of the ecological problems caused by platinum and palladium, which are commonly used in automobile catalytic converters.[6] The long-term phytotoxic potential of these metals has not been settled so far and is, therefore, the topic of current investigations.[7]

Structure Relationships and Nomenclature

Calixarene-Related Compounds. Substitution of the phenol moieties in the calixarene skeleton leads to several closely related compound groups. One topical example includes totally and partially saturated calixarene analogues containing cyclohexanol rings.[8] Substitution of phenolic units by heterocyclic ones leads to the large group of heterocalixarenes, in which the calix[*n*]pyrroles (**II**) are of particular importance. First synthesized nearly as early as the calixarenes themselves, they were, in their unsubstituted form, almost exclusively used as porphyrin precursors (porphyrinogens).[9] The meso-substituted calixpyrroles have attracted much less attention so far, because they cannot be converted to useful porphyrin precursors. However, a recent publication shows that, after consecutive insertion of dichlorocarbene in calix[4]pyrroles, calix[4]pyridines could be obtained, representing one of the youngest members of the calixarene family.[10] Furthermore, the observation of anion selectivities led to the recently published use of calixpyrroles, immobilized on silica gel, as column material for the efficient separation of anions as well as anionic natural products.[11] A few years ago, reports about furano calixarenes[12] and thiopheno calixarenes[13] as well as calixindoles[14] were also published. Currently, interesting examples of the heterocalixarene family are those containing uracil moieties[15] and benzimidazol-2-one groups, respectively.[16] The latter are able to form complexes with two different solvent molecules at the same time, which are bound subsequently in a kind of cascade inclusion reaction.

Similarly, the methylene bridges of the calixarene structure can be substituted by heteroatoms, leading to "heteracalixarenes" (**III**) according to the cyclophane nomenclature.[17] Among these, the compounds bearing

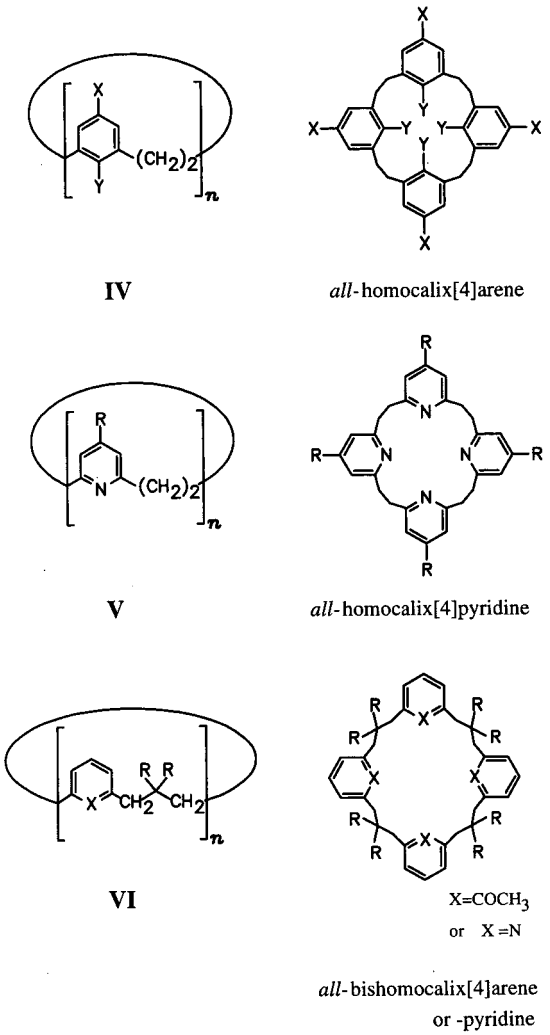


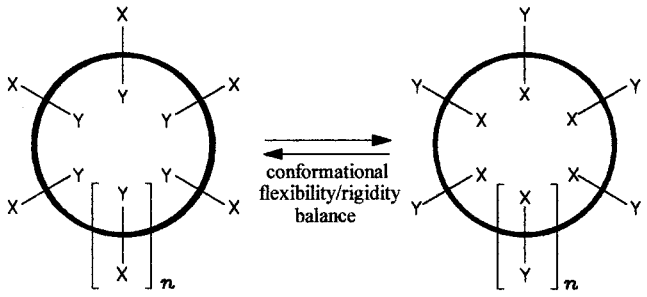
FIGURE 2. General structure of *all*-homocalixarenes, -pyridines, and *all*-bishomocalixarenes.

sulfur bridges are of greater interest, as described in the literature cited.[18] Recently, the first calixarene analogues have been reported, in which both structural elements (bridges and aromatic subunits) contain heteroatoms. These silacalix[*n*]phospharenes represent a new type of macrocycle because of their strong π-acceptor properties and are envisioned to be useful for the stabilization of negative oxidation states and for reductive catalyses.[19]

Homocalixarenes and Related Compounds. In contrast to the calixarenes, *all*-homocalixarenes (**IV**) are based on a [2_n]metacyclophane scaffold (cf. Figure 2); i.e., the methylene bridges are symmetrically expanded to ethylenic ones, resulting in an increased cavity size as well as a higher flexibility of the macrocyclic ring.

Additionally, a great variety of aromatic subunits and their substitution patterns, respectively, is given. For instance, *all*-homocalixpyridines (**V**) are much easier to obtain than pyridine analogues of the calixarenes, which will be explained in detail in the Synthesis section. Instead of the expressions "upper rim" and "lower rim" used in calixarene chemistry to define the substituent positions in homocalixarene chemistry, "intraannular" and "extraannular", respectively, are used (cf. Scheme 1).

Scheme 1. Turnover between Extraannular and Intraannular Substituents in Homocalixarenes



Furthermore, the enlargement of the aliphatic bridges to C3 chains leads to the so-called *all*-bishomocalixarenes (**VI**, X = $COCH_3$) and -pyridines (**VI**, X = N).

Why *all*-Homocalixarenes? A Versatile and Convenient Host Concept

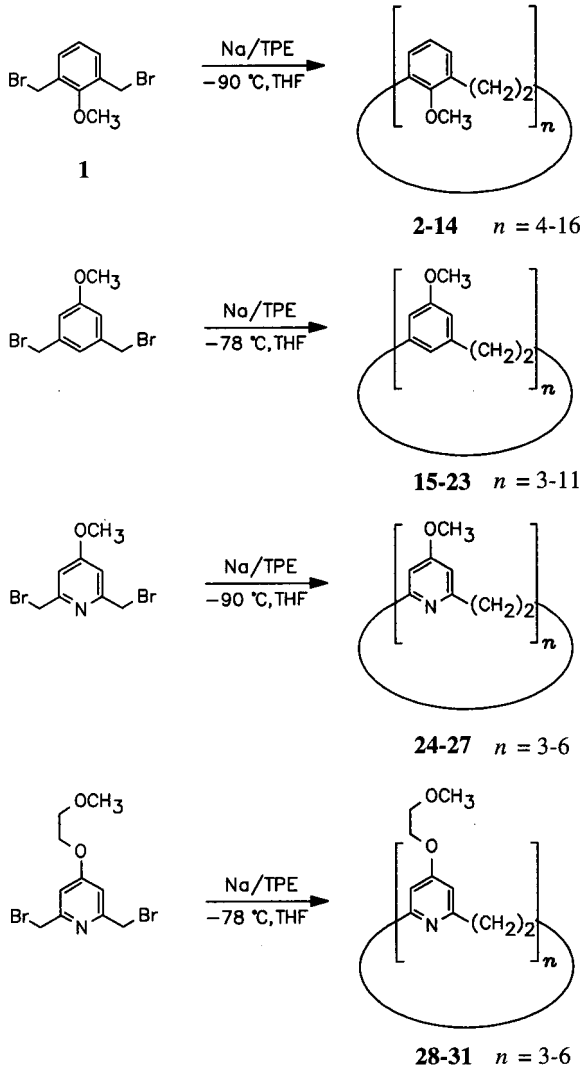
Because of their molecular structure, *all*-homocalixarenes fit in a concept of tailor-made host compounds for ionic and neutral molecular guests. They are accessible in different ring sizes with direct correlation to the size of the cavity. The fine-tuning of the guest selectivity is further influenced by a broad variety of functionalized substituents and, therefore, possible host/guest interactions, for example, π-donor/acceptor, acid−base interaction (endoacidic or endobasic cavity, cf. Scheme 1), HSAB principle, hydrogen bridges, and charge effects. The conformational flexibility of the macrocyclic ring allows a cooperative binding of guests by several substituents and types of interaction, respectively. Besides, the carbocyclic scaffold guarantees a high chemical and thermal stability and a good solubility in organic solvents. The lipophilicity can further be raised by placing appropiate substituents in extraannular positions or in the hydrocarbon bridges. These substituents may also be used as anchor groups for the immobilization of the host molecules (e.g., for use as ion sensors).

Synthesis

Whereas some calixarenes are already commercially available, the *all*-homocalixarene skeleton has to be synthesized from suitable monomeric molecular building blocks. Compared to calixarene chemistry, this method is disadvantageous, in particular because of the lower product yields (see below). On the other hand, the need to begin with monomeric cyclization precursors gives the opportunity to directly introduce functionalities other than phenol rings into the macrocyclic scaffold.

From the great variety of synthetic pathways to metacyclophanes, the Müller Röscheisen cyclization has been found to be a simple and convenient way to obtain homologuous cyclic products in one step.[20] This method is a variation of the Wurtz coupling, which is carried out at −70 to −90 °C using powdered sodium and tetraphenylethene (TPE) as a catalyst. It leads to the formation of the intra- and extraannular substituted *all*-homocalixarenes[21] **2**−**23** and *all*-homocalixpyridines[22,23] **24**−**31** (cf. Scheme 2).

Scheme 2. Synthesis of *all*-Homocalixarenes and -pyridines



Usually the isolation of pure *all*-homocalixarenes requires the chromatographic separation of the crude product. Unsubstituted *all*-homocalixpyridines have also been synthesized by this route (not shown). The substituent position clearly influences the homologues obtained: the presence of intraannular methoxy groups shifts the product distribution to larger ring sizes (cf. Figure 3). In general, *all*-homocalixarenes are still obtained in smaller yields than the calixarenes, which can be easily synthesized in yields of more than 50%. Although the vast synthetic experience with calixarenes has to be taken into consideration, we have to admit that *all*-homocalixarene syntheses are still to be optimized.

In this connection, the extensive work by Tsuge and Yamato et al. on symmetrical and asymmetrical homocalixarenes and their host/guest behavior should be mentioned.[24] They recently reported the synthesis of substituted [3.1.1]metacyclophanes and derivatives of tetrahydroxy[3.1.3.1]metacyclophane. These enlarged calixarenes, being not as flexible as *all*-homocalixarenes, still show conformational isomerism examined by NMR stud-

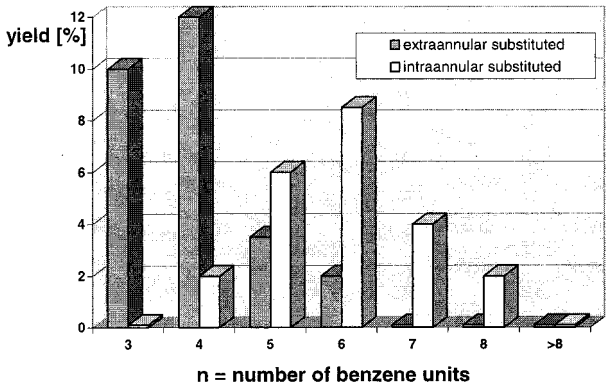
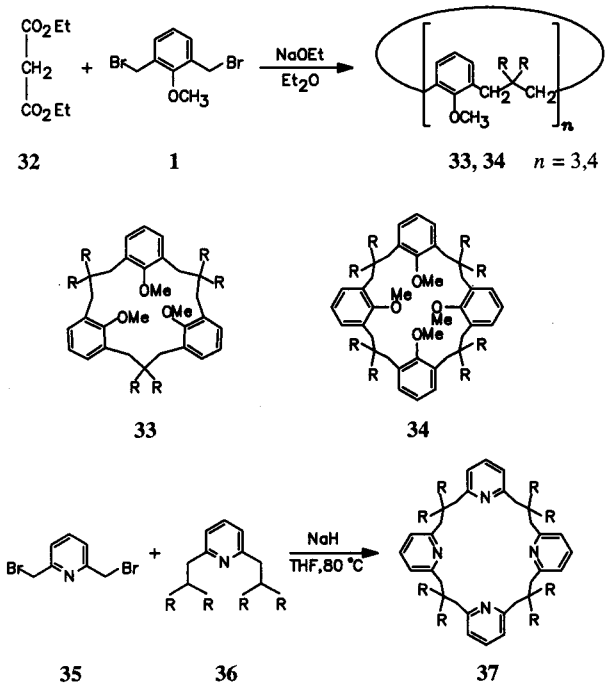


FIGURE 3. Yield dependence of homocalixarenes (**2**−**23**) on substitution pattern.

Scheme 3. Synthesis of *all*-Bishomocalixarenes and -pyridines



ies. Furthermore, a *partial cone* [3.1.1]metacycophanetriamide derivative shows a strong ability to complex Na^+ ions.[25]

Another classical synthetic method to form C−C-bonds is the malonic ester condensation.[26] A similar reaction pathway, using deprotonated diethyl malonate as a nucleophile, presents a convenient method for obtaining *all*-bishomocalixarenes (**VI**, Figure 2). It was already used by us in the early 1970s to build up [3_n]metacyclophane systems with diethyl malonate and bis-bromomethylarenes as cyclization components.[27] Other groups reported on similar systems without ethyl ester groups obtained by a stepwise reaction pathway.[28] Recently, our synthetic efforts have led to the formation of the *all*-bishomocalixarenes (**33**, **34**) and the *all*-bishomocalixpyridine (**37**) by applying the malonic ester condensation (cf. Scheme 3).[29] This method, however, has further synthetic potential: by the reaction of **36** with **38** under basic conditions, the bicyclic ligand **39** is obtained (cf. Scheme 4), which represents a new type of ligand, since

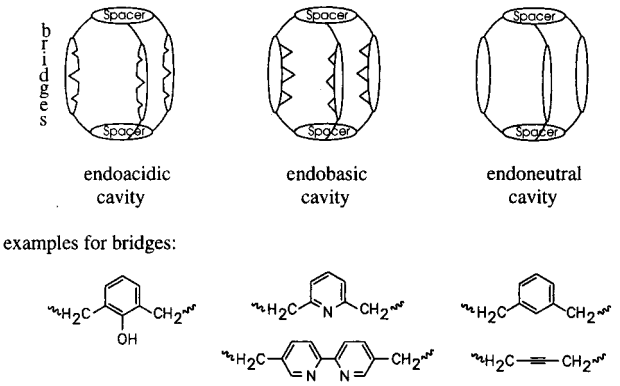
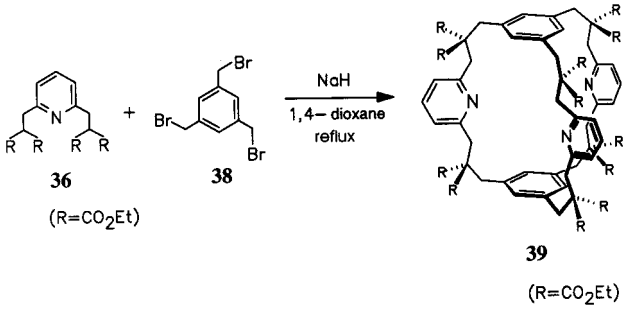


FIGURE 4. Endofunctionalized cage ligands, schematically.

Scheme 4. Synthesis of Bicyclic Cage Ligand 39



for the first time such a convergent orientation of three pyridine donors could be achieved.[30] Provided kinetically fast complexation and decomplexation processes occur, bicyclic ligands often offer a better steric fit of donor sites. Therefore, guests usually are bound more strongly than by monocyclic or open-chain ligands.[31]

The convergent orientation results in a remarkable complexation behavior and efficient phase-transfer properties of **39**, which will be discussed below. According to the one-step cyclization principle outlined in Scheme 4, similar cage molecules with different functionalities pointing into the intramolecular cavity (endo orientation) can be synthezised. By using suitable spacers and building blocks bearing functional groups, endoacidic and neutral cage ligands are also obtainable. Figure 4 schematically illustrates endobasic, endoacidic, and endoneutral cage ligands by cartoons symbolizing their electron donor/acceptor properties and gives some examples of functional groups.

A disadvantage of this synthesis is the rather low yield of only 4%, but this value is consistent with the literature for cyclizations of five components in one step.[31,32] Besides, the low yield is partially compensated for by the easily accessible and inexpensive reaction precursors. A synthetic strategy in several reaction steps and the presence of the cesium bases could probably also improve the overall yield.

Refunctionalization of *all*-Homocalixarenes

The first step in refunctionalization of *all*-homocalixarenes is cleavage of the intraannular ether groups, resulting in oligophenolic *all*-homocalixarenes, which represent hosts

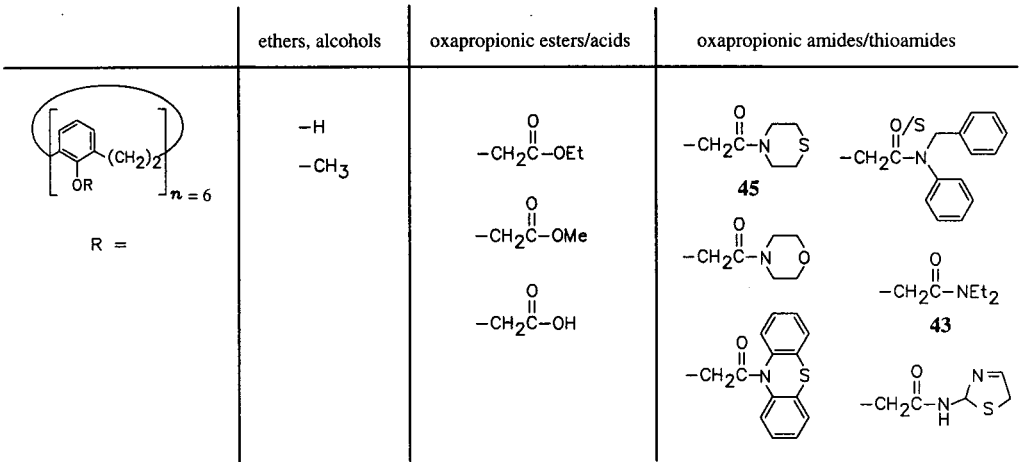
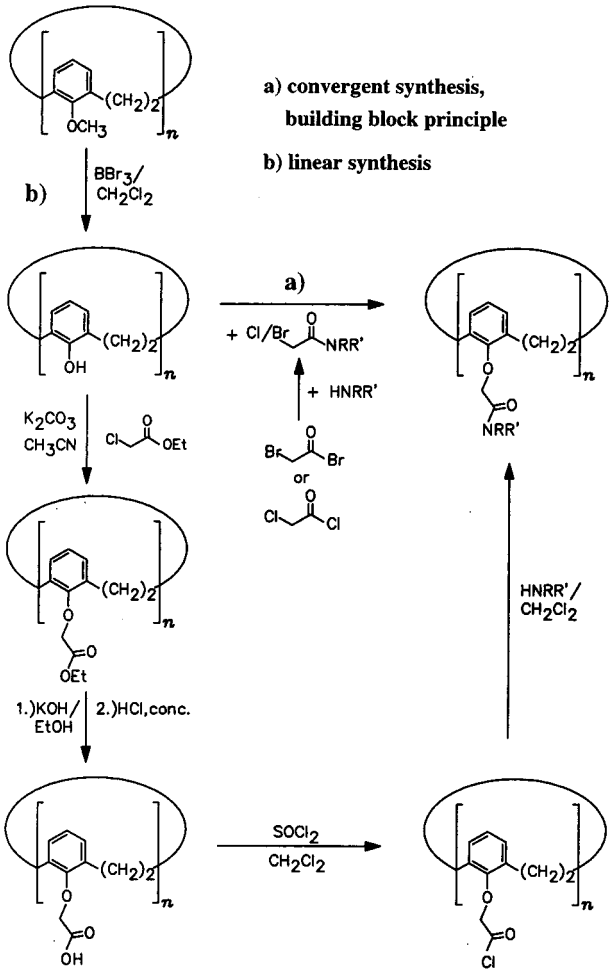


FIGURE 5. List of derivatives obtained in the *all*-homocalix[6]arene series.

Scheme 5. Refunctionalization of *all*-Homocalixarenes



with endoacidic cavities. Subsequent modifications of the ligands are carried out according to Scheme 5. Figure 5 gives an overview of intraannular functionalities integrated in the homocalixarene scaffold. In recent years, we directed our attention mainly to heterocycles containing nitrogen and sulfur atoms to tune the guest selectivities to noble metal ions such as palladium and silver.

Therefore, the amide-substituted homocalixarenes were considered as the most promising derivatives. In this case, the functionalization of *all*-homocalixarenes can be carried out either by a convergent synthetic strategy or according to a linear stepwise reaction pathway (cf. Scheme 5).

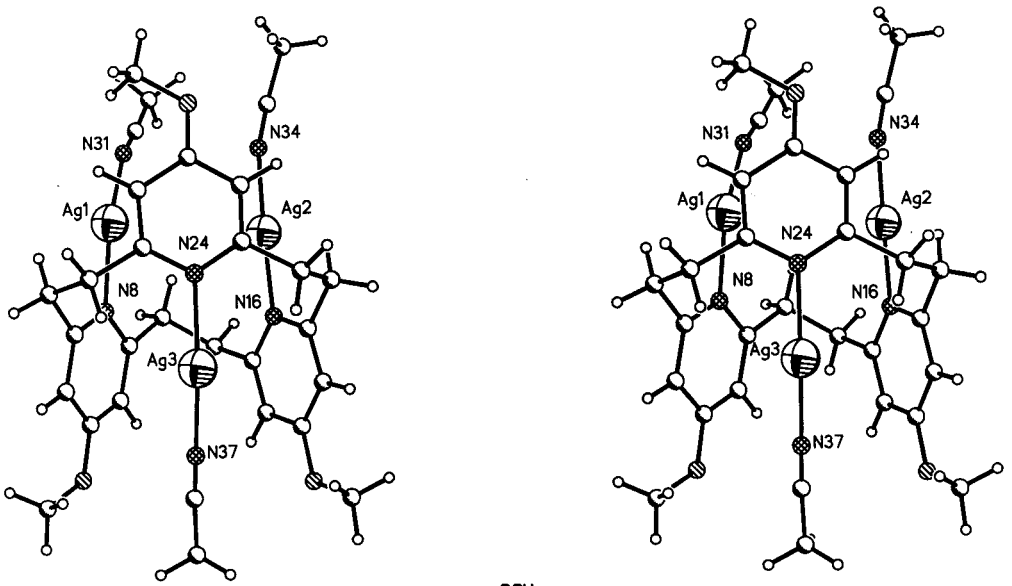
The convergent strategy of introducing new functionalities turned out to be more convenient, as it offers the application of a building block principle. Thus, it is not necessary to prepare and isolate homocalixarene ethylesters, carboxylic acids, and carboxylic acid chlorides as product intermediates. Therefore, a variety of alkylating agents have been prepared and brought to reaction with free oligophenolic homocalixarenes in a one-pot process. In most cases, the convergent strategy leads to higher product yields than the linear pathway.[33]

The number and variety of functionalizations in extraannularly substituted *all*-homocalixarenes is not very extensive so far, because they did not reveal such interesting host properties as their intraannularly substituted homologues.[34] In the case of the extraannularly substituted *all*-homocalixpyridines **24**−**31**, however, the methoxy and ethylmethoxy groups cause an increased nitrogen donor activity. Additionally, for **28**−**31**, the lipophilicity of the ligands is higher than that for unsubstituted homocalixpyridines. Consequently, these compounds turned out to be effective in phase-transfer ion transport.

Host Properties of *all*-Homocalixarenes

To examine the structural characteristics and host properties of *all*-homocalixarenes, several complementary methods have been applied. First, the conformational flexibility desired was confirmed by NMR spectroscopic data, because the ^{1}H NMR spectra of *all*-homocalixarenes and -pyridines as well as *all*-bishomocalixarenes exhibit only one signal for the bridge methylene groups at room temperature.

X-ray crystallographic studies of *all*-homocalixarenes and -pyridines often revealed the inclusion of guest molecules in the crystal structure. For example, extraannular methoxy-substituted cyclic trimer **24** shows a partial cone conformation in the solid state. This conformation is preserved in a trinuclear silver complex isolated



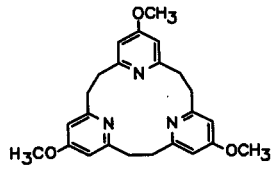


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FIGURE 6. X-ray crystallographic investigation of *all*-homocalixarenes and pyridines often revealed inclusion of guest molecules: tris-Ag(I) complex of **24**, stereoview.

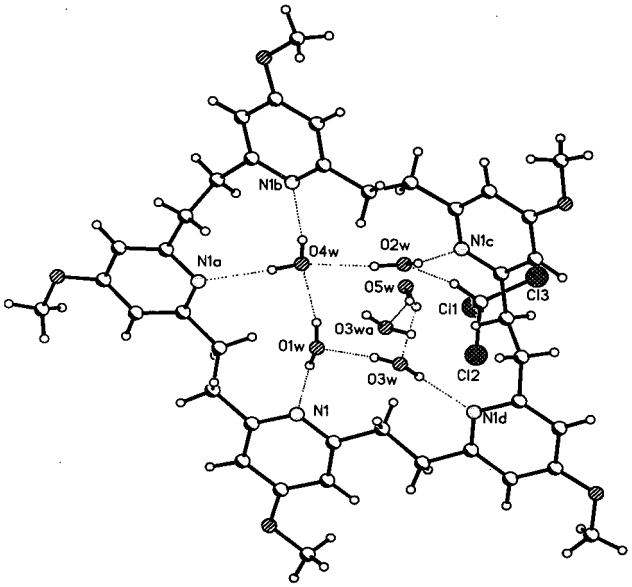
from a mixture of **24** and silver tetrafluoroborate in a dichloromethane/acetonitrile solution.[23] Each silver cation is linearly coordinated between one pyridine nitrogen and an acetonitrile molecule (cf. Figure 6)

With increasing ring size, *all*-homocalixpyridines become more planar. In contrast to **24**, the pentameric homologous homocalixpyridine **26** ($n = 5$) has a nearly planar structure. Inclusion of five water molecules and one trichloromethane molecule inside the cavity is confirmed. Four water molecules are connected to the pyridine nitrogens and to each other by a kind of hydrogen bond network (Figure 7.). The trichloromethane is connected to the 25-membered macrocycle by interaction in the form of hydrogen bridges to one of the complexed water molecules.[22] This planarity of the ring skeleton, which is not known for calixarenes with a similar ring size, is also demonstrated in the series of methoxy-substituted *all*-homocalixarenes. A single crystal of hexameric *all*-homocalixarene **4** ($n = 6$) has been revealed as an inclusion complex with cyclohexane.[21]

In the case of the bicyclic ligand **39**, the structure of the free ligand could be solved by single-crystal X-ray analysis.[30] Considering the steric situation, the ligand seems appropiate for complex formation, with metal ions preferring a linear coordination between two adjoining pyridine nitrogen atoms. This was confirmed by molecular modeling calculations of a 1:1 silver complex with **39** starting from a minimum energy conformation of the free ligand. The parameter set used was in accordance with X-ray structure data obtained. The calculation reveals only minor changes of the minimized conformation of the silver complex with **39** in comparison to the free ligand and additionally reasonable Ag−N bond distances, as shown in Figure 8.

As indicated before, our main method of surveying guest selectivities of *all*-homocalixarenes has been liquid−liquid extraction measurements in a two-phase system.[35] Aqueous solutions of suitable metal salts were extracted with $CHCl_3$ containing the macrocyclic ligand investigated in various concentrations. The determination of metal ion concentration by the radiotracer method in both layers after separation allows comparison of the extraction efficiency and conclusions about the complex stoichiometry.[36] These experiments have the highest relevancy with regard to the applicability of *all*-homocalixarenes for sensor processes or ion transport phenomena. The most important analytical results revealed so far will be pointed out here.

As expected, the pyridine-containing macrocycles **24**−**31** and bicyclic ligand **39** exhibit more affinity for late transition metals than for hard alkali or alkaline earth metals. These are generally discriminated against in ion-transfer experiments (cf. Figure 9a). In particular, the cyclic trimers **24**, **28** and unsubstituted homologue **40** (R = H) all show selectivity for Ag(I), Cu(II), and Hg(II) in nitrate-containing solution.[23] The substitution pattern of the pyridine units has an obvious influence on extraction efficiency and selectivity. Increasing the nitrogen donor strength and lipophilicity by electron density-donating substituents in the para position causes higher extractabilities, especially for Ag(I) and somewhat less for Cu(II) and Hg(II). The extractabilities for silver are about 2−3-



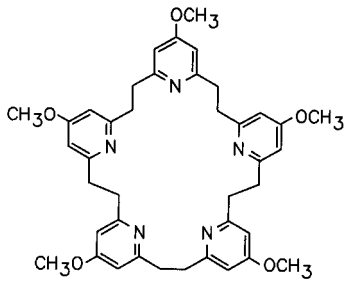


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FIGURE 7. Inclusion cluster of **26** with five water molecules and one $CHCl_3$.

fold that for mercury. Bicycle **39** shows higher selectivity for silver, as predicted by molecular modeling calculations. Other metal ions investigated are discriminated in a ratio of more than 200:1.[30]

Under different experimental conditions of type of counteranion and pH value, the extraction selectivity of *all*-homocalixarenes can be optimized for other cations, in particular ions of noble metals such as Pd(II) and Au(III).[23] The remarkable selectivity for these, as shown in Figure 9b, is interesting in view of their application as ionophores for effective separation of noble metals from heterogeneous systems such as effluents or mining debris.

Due to their versatility, *all*-homocalixarenes show the most varied extraction behavior dependent on the intraannular functionalities. Free oligophenolic *all*-homocalixarenes are selective extraction agents for alkaline earth metals while excluding alkali metals. Comparison between pentamer **42**, octamer **44**, and monomeric reference compound **41** (cf. Figure 10 a) reveals a direct correlation between the extraction strength and the number of free hydroxy groups. Nevertheless, in all cases, 1:1 complex stoichiometry is observed. This can only be explained by cooperative binding of one guest ion/molecule by all donor groups. Especially remarkable is the high selectivity of octamer **44** for Ba(II) compared with other alkaline earth metals. Even more selective for Ba(II) is the *all*-homocalix[6]arenehexadiethylamide derivative (**43**) in toluene solution (condition iii), extracting more than 47% of the metal into the organic phase.[21]

However, to be used for industrial applications, compounds **41**−**44** are still too soluble in aqueous solution. With increased lipophilicity, e.g., by inserting *tert*-butyl substituents in the extraannular position, even higher extraction rates of oligohydroxy *all*-homocalixarenes should be reached, because less host substance will remain in the aqueous phase.

As outlined in Figure 5, we have succeeded in the synthesis of various *all*-homocalixarenes with weak donor sites affixed in the form of heterocyclic pendant arms containing sulfur and nitrogen atoms. We have examined the extraction behavior of hexathiomorpholino derivative **45** in comparison to the analogously substituted calix[6]arene **46** (cf. Figure 10b).[33] Both ligands can realize a tetracoordinated planar structure with Pd(II) and, therefore, effectively transfer it into the organic phase nearly quantitatively under the experimental conditions chosen.

However, only the *all*-homocalix[6]arene derivative also showed a remarkable selectivity for palladium in the extraction process, while discriminating against, e.g., Tl(I) and Zn(II). Surprisingly, neither ligand coordinates the thiophilic mercury. As expected, both compounds are also usable as effective phase-transfer extractants for silver ions. Nevertheless, separation between silver and palladium is possible due to their totally different complexation kinetics. While silver ions are bound quickly, it takes between 2 and 24 h until complexation equilibrium is

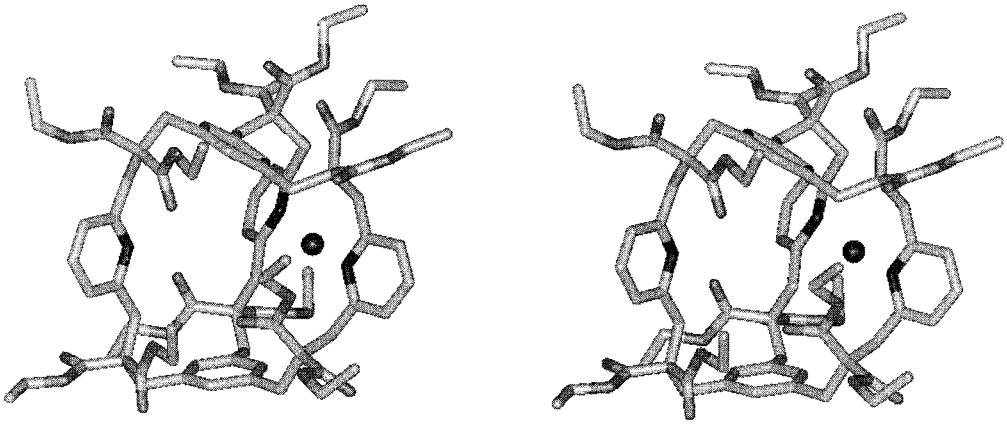

FIGURE 8. Calculated structure of the silver complex of **39**, ZINDO/1 method, stereoview.

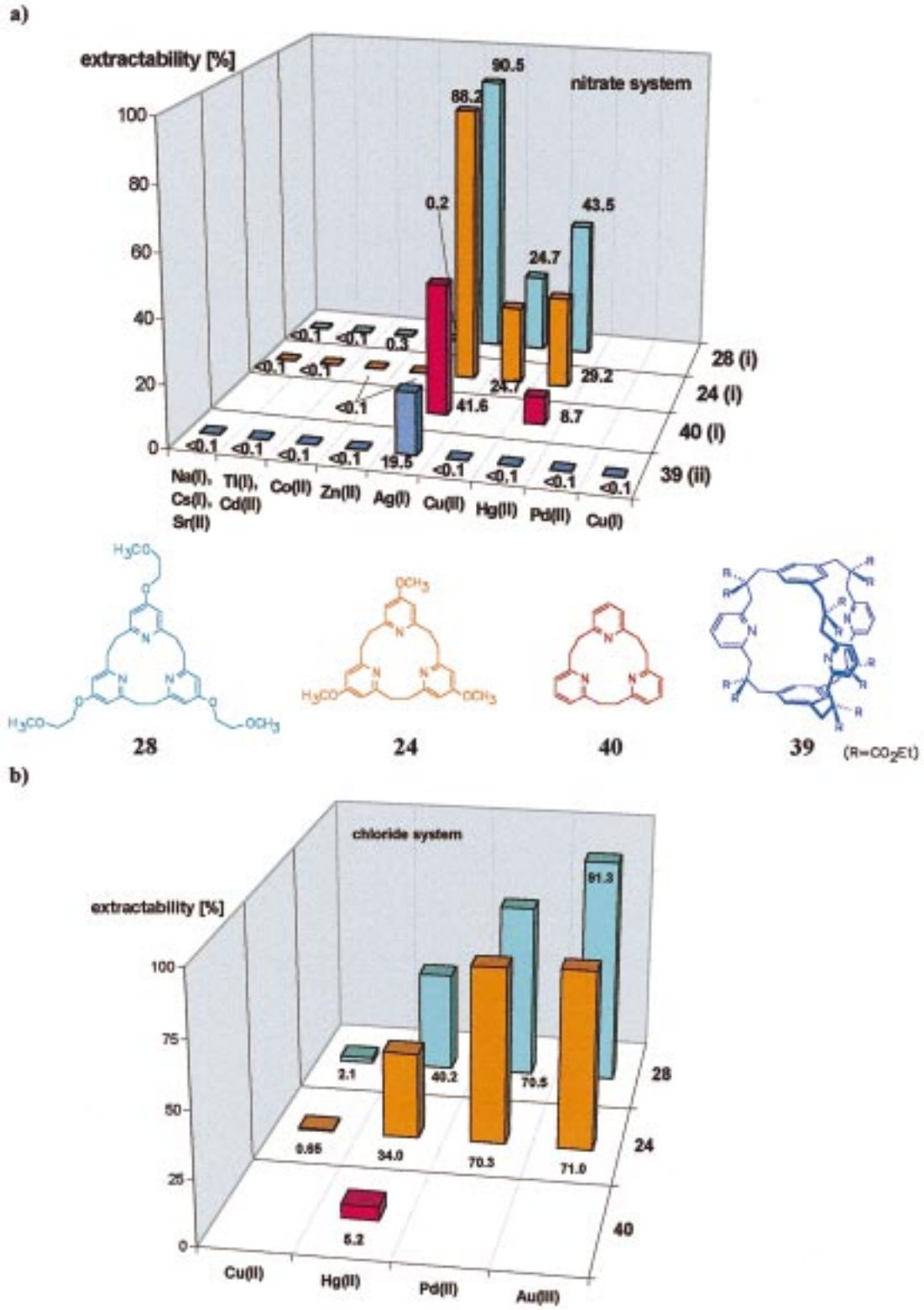

FIGURE 9. (a) Extraction properties of *all*-homocalixpyridines in comparison. Conditions: (i) $[M(NO_3)_n] = 1 \times 10^{-4}$ M, $[KNO_3] = 0.1$ M, pH = 6.3 (MES/NaOH buffer), [ligand] $= 1 \times 10^{-3}$ M in $CHCl_3$; (ii) $[M(NO_3)_n] = 1 \times 10^{-4}$ M, [picric acid] $= 1 \times 10^{-2}$ M, [ligand] $= 1 \times 10^{-3}$ M in $CHCl_3$; for Cu^{I}, copper nitrate (1×10^{-4} M)−hydroxylammonium sulfate (5×10^{-3} M)−KNO_3 (1×10^{-2} M), pH = 5.3 (MES/NaOH buffer). (b) Extraction properties of *all*-homocalixpyridines in comparison. Conditions: $[MCl_n] = 1 \times 10^{-4}$ M (M = Cu (II), Pd (II)), pH = 5.2 (NaOAc/HCl) buffer, $[HAuCl_4] = 1 \times 10^{-4}$ M, $[HNO_3] = 1 \times 10^{-2}$, [ligand] $= 1 \times 10^{-3}$ M in $CHCl_3$.

reached in the case of palladium.[37] The values presented were determined after 2 h shaking time. To determine the structure of the (ligand:metal = 1:1) species formed under extraction conditions, again molecular modeling methods have been chosen, since no crystalline material of **45** with $PdCl_2$ could be obtained. The calculated complex structure, as shown in Figure 11, indicates that the Pd(II) ion is coordinated by two thiomorpholine-containing pendant

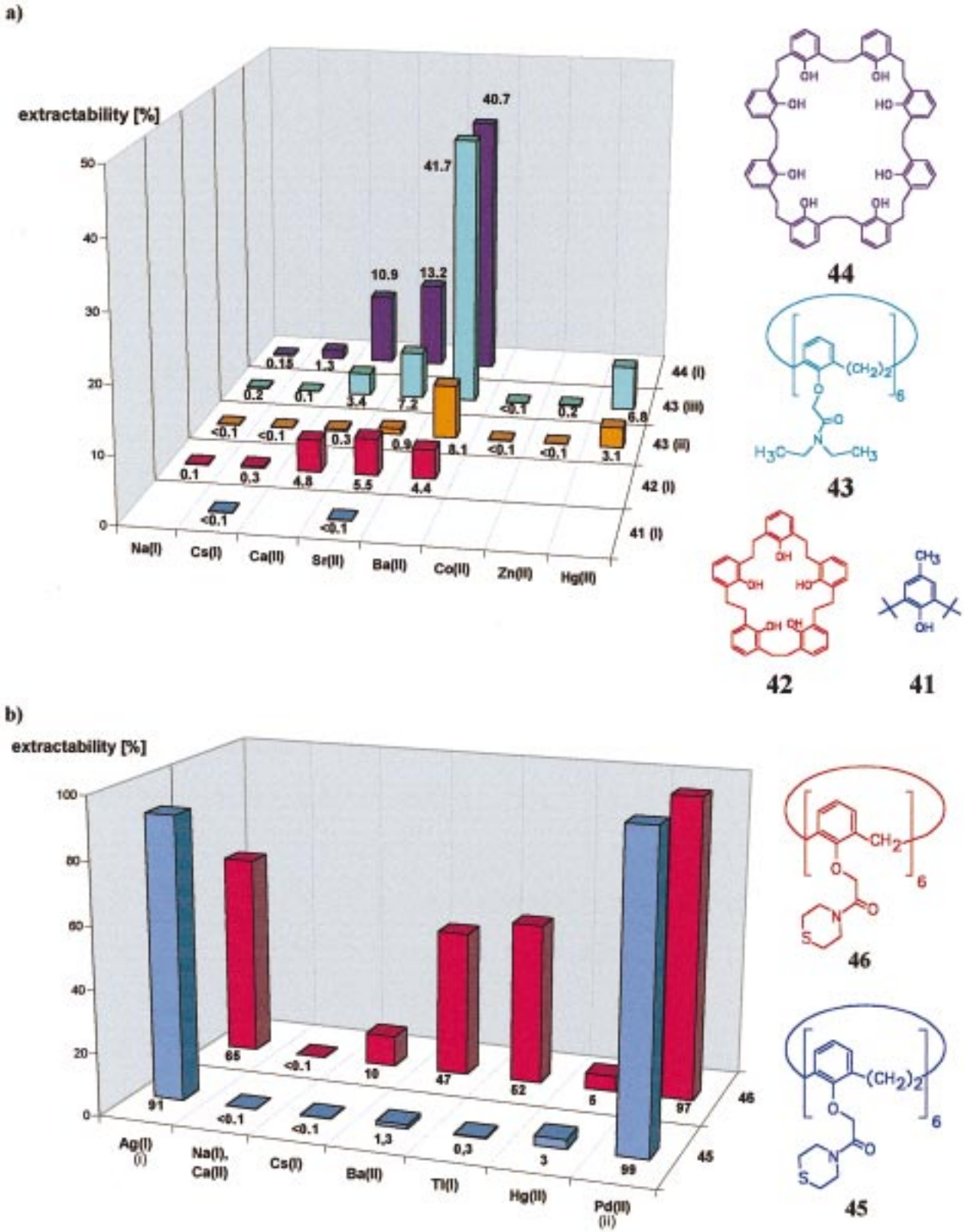

FIGURE 10. (a) Conditions: (i) $[M(NO_3)_n] = 1 \times 10^{-4}$ M, $[NaNO_3] = 0.1$ M in 0.1 M NaOH, [ligand] $= 5 \times 10^{-3}$ M in $CHCl_3$; (ii) $[M(NO_3)_n] = 1 \times 10^{-4}$ M, [picric acid] $= 5 \times 10^{-3}$ M, [ligand] $= 1 \times 10^{-3}$ M in $CHCl_3$; (iii) $[M(NO_3)_n] = 1 \times 10^{-4}$ M, [picric acid] $= 5 \times 10^{-3}$ M, [ligand] $= 1 \times 10^{-3}$ M in toluene. (b) Conditions: $[M(Cl)_n]$ or $[M(NO_3)_n] = 1 \times 10^{-4}$ M, pH = 5.2 (NaOAc/HCl buffer), [picric acid] $= 5 \times 10^{-3}$ M; (i) $[AgNO_3] = 1 \times 10^{-4}$ M, pH = 5.2 (NaOAc/HCl buffer), [picric acid] $= 5 \times 10^{-3}$ M, 30 min shaking time; (ii) $[PdCl_2] = 1 \times 10^{-4}$ M, pH = 5.2 (NaOAc/HCl buffer), 2 h shaking time, [ligand] $= 1 \times 10^{-3}$ M in $CHCl_3$.

arms between the sulfur atoms, while the planar coordination geometry is completed by two additional chloride anions. The remaining four pendant arms point toward the ligand periphery, allowing the macrocycle to take up

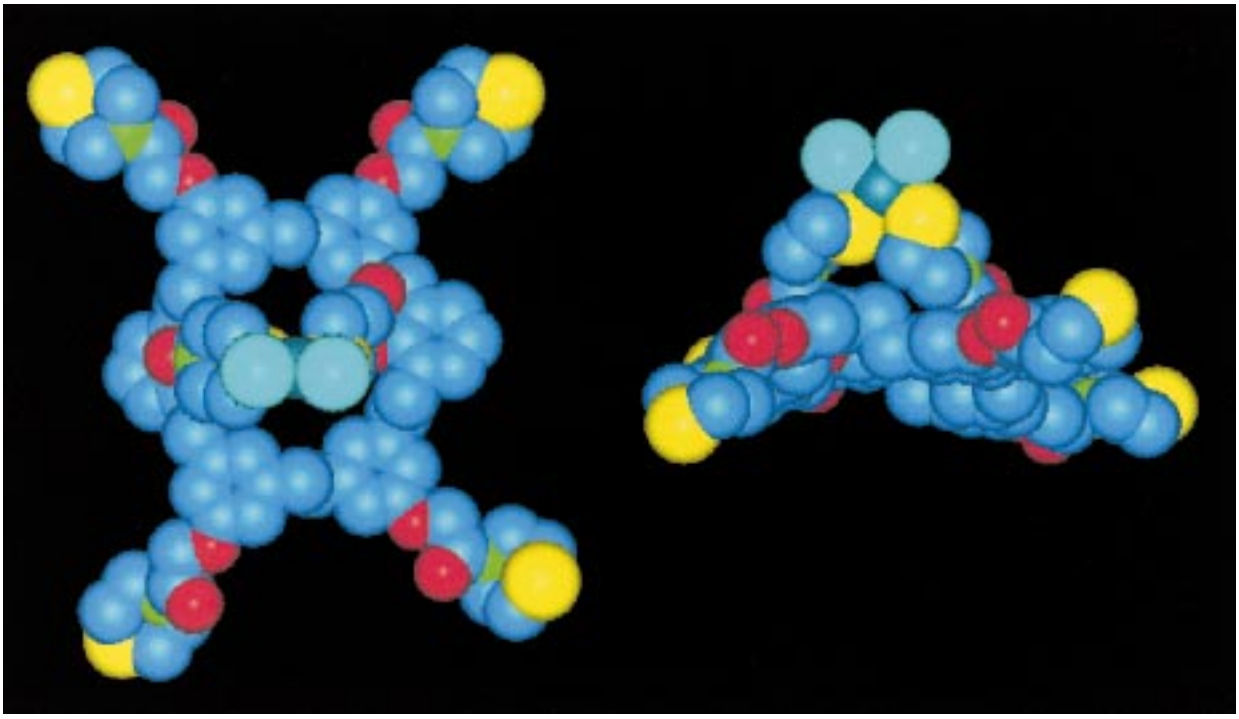

FIGURE 11. Calculated structure of palladium complex of **45**, ZINDO/1 method.

a nearly planar conformation. Probably these pendant arms, which are not involved in the guest complexation, are responsible for the solubilization of the complex by interaction with the solvent molecules.

Conclusions and Outlook

In conclusion, *all*-homocalixarenes represent an easy-to-obtain mono- or polycyclic host system with versatile molecular architecture. The comparison to oligomeric open-chain ligands in phase-transfer measurements has shown the superiority of cyclic systems in extraction efficiency.[23] *all*-Homocalixarenes offer access to a variety of different ligands either by refunctionalization with particularly functionalized pendant arms or by direct integration of donor sites into the cyclic skeleton (i.e., *all*-homocalixpyridines). The formation of unfavorable stable conformers in solution is prevented because of their increased flexibility compared to that of calixarenes. Additionally, the molecular building block principle can be extended to bicyclic host systems representing a three-dimensional preorganized ligand environment. Whereas the calixarenes already have the advantage of several decades of optimization, the extraction experiments using metal isotopes presented are just the beginning of an examination of the different host−guest selectivities of *all*-homocalixarenes and whether their complexing abilities can be fine-tuned for particular precious metal ions.[6,7] Our ultimate aim is to use tailor-made hosts of this kind for physiologically relevant molecules, e.g., amino acids, carbohydrates, and purine bases and, last but not least, for the selective binding of anions. To summarize, *all*-homocalixarenes combine the advantage of an easy and quick synthesis with high application potential and are, therefore, not only enlarged calixarenes but also a separate important family of host compounds.

Thanks are due to the Federal Ministry of Science and Technology, Bonn, Germany, and the DECHEMA e. V., Frankfurt a. M., Germany, for financial assistance (project "Organized Supramolecular Systems", OSS). We are also very grateful for a grant by the Deutsche Forschungs Gemeinschaft, DFG, concerning the work presented (Schwerpunktprojekt "Makrocyclische Extremliganden", VO 145/46 and GL 183/3). Thanks are also due to Prof. Dr. K. Rissanen, University of Jyväskylä, Finland, and Dr. M. Nieger, Institut für Anorganische Chemie der Universität Bonn, Germany, for carrying out X-ray crystallographic studies. The authors also wish to thank Dr. T. Rambusch-Krüger, Institut für Anorganische Chemie der TU Dresden, Germany, for carrying out molecular modeling calculations and B. Windisch for revising the manuscript.

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AR970231J