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平成11年12月博士（理学）申請

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1999

Shigehisa Akine

Contents

Abbreviations

aq.	aqueous
Ar	aryl
br	broad (in NMR spectral data)
Bu	butyl
d	day
d	doublet (in NMR spectral data)
δ	chemical shift of NMR signal in ppm
DMF	*N,N*-dimethylformamide
eq.	equivalent
Et	ethyl
FAB	fast atom bombardment
h	hour
HRMS	high-resolution mass spectrometry
IR	infrared
J	coupling constant in Hz (in NMR spectral data)
m	multiplet (in NMR spectral data)
m	meta
Me	methyl
min	minute
mp	melting point
NMR	nuclear magnetic resonance
o	ortho
p	para
Ph	phenyl
Pr	propyl
R	an organic group
r.t.	room temperature
s	second
s	singlet (in NMR spectral data)
t	triplet (in NMR spectral data)
tert	tertiary
THF	tetrahydrofuran
TLC	thin layer chromatography
UV/vis	ultraviolet and visible

Chapter 1

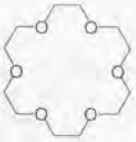
General Introduction

1.1. The chemistry of macrocyclic molecules

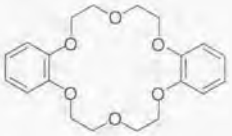
The chemistry of macrocyclic compounds has made a great progress ever since the discovery of crown ethers by Pedersen in 1967.[1] It became aware in very early stage that the nano-scale cavity of this type of molecules has the possibility of capturing other chemical species. Up to now, a number of this class of compounds including crown ethers,[2] cryptands,[2] calixarenes,[3] and cyclophanes[4] have been synthesized and their ability to form inclusion complexes has been revealed.

12-crown-4

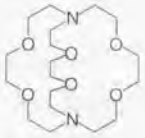
15-crown-5



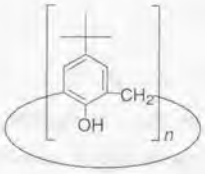
18-crown-6



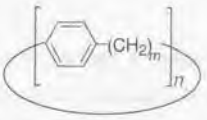
dibenzo-18-crown-6



cryptand



p-tert-butylcalix[*n*]arenes

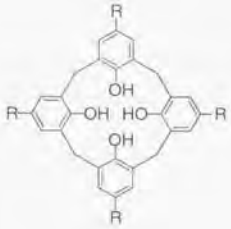


[m_n]paracyclophane

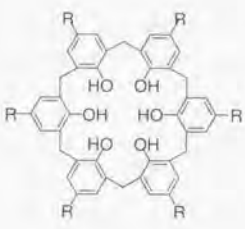
Complexation, the phenomenon that one molecule binds to another molecule by non-covalent interaction, has been a major area of interest and importance. This is partly because such a phenomenon, referred to as "host-guest interaction", is relevant to the receptor-substrate interaction in the enzymatic chemistry. Macrocyclic molecules have played an important role in the study of the host-guest chemistry based on a variety of non-covalent interactions such as hydrogen bonding or coordination to the transition metal centers. Nowadays, increasing attention is being paid not only to the host-guest chemistry but also to the construction of molecules with multi-functions based on the macrocyclic frameworks.[5,6]

1.2. Historical background of calixarenes

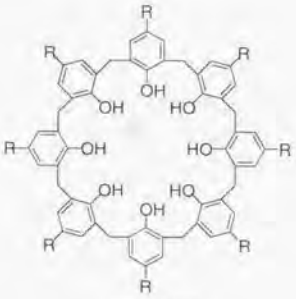
Calixarenes were at first discovered from "resinous tar"[7], cyclic, polymeric product obtained from the reactions of phenol and formaldehyde,[8] and they are now one of the most widely studied macrocyclic molecules. Calixarenes are cyclic compounds made up of benzene rings connected by methylene bridges in *meta*- positions.[1]



calix[4]arene



calix[6]arene

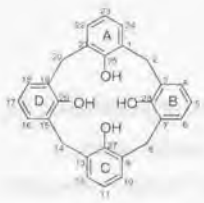


calix[8]arene

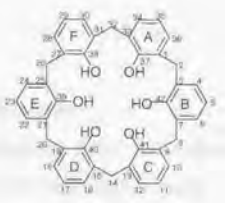
Calixarenes have high ability for the inclusion of other chemical species, especially alkali and alkaline earth metals, although this is not an advantage which only calixarenes have. One of the merits for using calixarenes is their facile synthetic procedure on a scale of 100 g, established by Gutsche in 1980s. *p-tert*-Butylcalix[4]arene (**1**), *p-tert*-butylcalix[6]arene (**2**), or

---

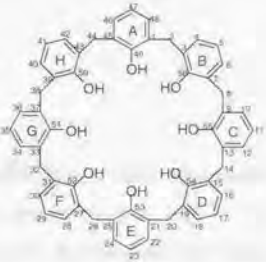
[1] The original calixarene nomenclature implicitly included the OH groups as part of the structure being named, and the nomenclature is used in this thesis. However, it is now general that the term "calixarene" is applied only to the basic structures devoid of substituents, as illustrated below.



calix[4]arene-25,26,27,28-tetrol



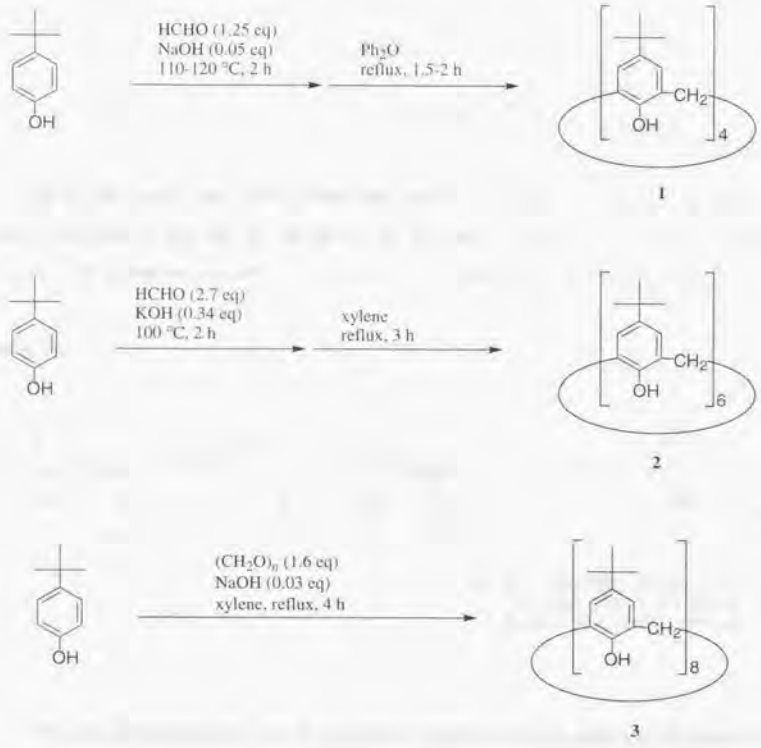
calix[6]arene-37,38,39,40,41,42-hexol



calix[8]arene-49,50,51,52,53,54,55,56-octol

p-tert-butylcalix[8]arene (**3**) can be selectively obtained using different conditions from an inexpensive starting material, *p-tert*-butylphenol (Scheme 1-1).[9] These facile procedures have given opportunities to participate in the macrocyclic chemistry or the host-guest chemistry to a number of chemists all over the world.

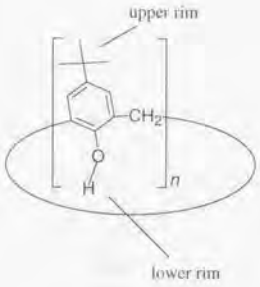
Scheme 1-1



1.3. Functionalization of calixarenes

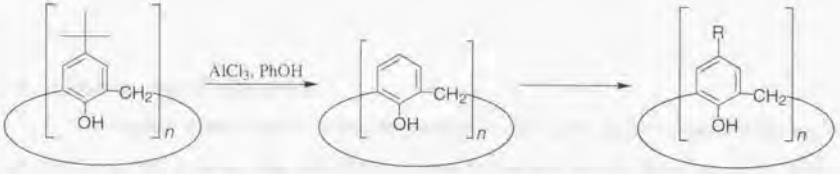
Another merit of calixarenes is the facile chemical modification of their frameworks. Calixarenes derived from *p-tert*-butylphenols have hydroxyl groups on one side of the macrocyclic ring (referred to as "lower rim") and *tert*-butyl groups on the other side (as "upper rim")[5] (Scheme 1-2).

Scheme 1-2



Both the "upper rim" and "lower rim" can be modified using simple procedures.[3] Various functional groups can be introduced on the upper rim by the procedures of de-*tert*-butylation with aluminum chloride[10] followed by electrophilic substitution (Scheme 1-3).

Scheme 1-3

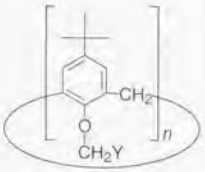


R = Br, I, NO_2, NH_2, CH_2NR_2, N_2Ar, CN, CO_2H, CH_2CO_2H, CH_2OH, CH_2SH, SO_3H, CHO, $COCH_3$, COPh *etc.*

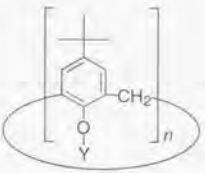
Various substituents can also be introduced into the hydroxyl groups at the lower rim by simple etherification or esterification. A number of calixarenes bearing substituents at the lower rim have been reported so far (Scheme 1-4) and their complexing ability toward various cations has been investigated. Oxidation of the methylene bridge or hydrogenation of the aromatic rings have also been reported.[11]

Scheme 1-4

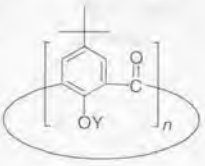
Y = C_6H_5
Y = 4-C_6H_4-*t*-Bu
Y = 4-C_6H_4Me
Y = 4-C_6H_4Br
Y = 4-$C_6H_4CF_3$
Y = 4-C_6H_4CN
Y = 4-$C_6H_4NO_2$
etc.

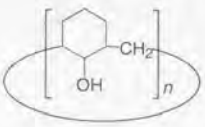


Y = CH=CH_2
Y = C≡CH
Y = CH_2CH_2OH
Y = 4-C_6H_4X
Y = CO_2R
Y = $CONR_2$
Y = CO_2H
etc.



Y = CH_2CH_2OH
Y = CH_2CH_2OR
Y = CH_2CH_2SR
Y = $CH_2CH_2SC(S)NEt_2$
Y = $CH_2CH_2OCH_2C(S)NMe_2$
Y = $CH_2C(S)NR'_2$
Y = $CH_2(CH_2OCH_2)_nCH_2OMe$
etc.





1.4. Conformation of calixarenes

Calixarenes usually have conformational mobility derived from the rotation of the single bonds between the aromatic rings and the methylene carbon atoms, leading to "*up*" and "*down*" conformations of each aromatic ring of calixarenes (Scheme 1-5).

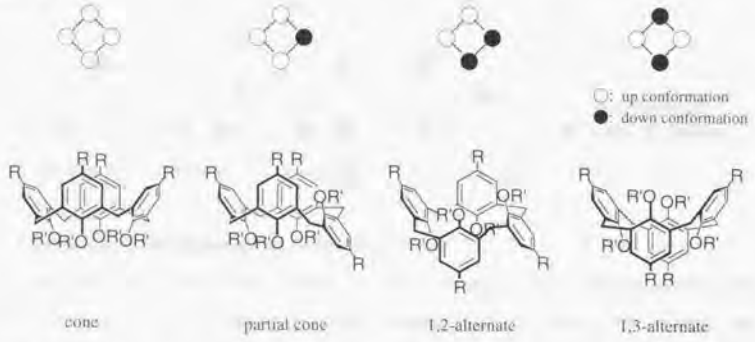
Scheme 1-5

up conformation *down* conformation

This mobility results in the formation of various conformations of calixarene molecules. For example, calix[4]arenes functionalized at their lower rim have four kinds of conformational

isomers,[12] which are now referred to as "cone", "partial cone", "1,2-alternate" and "1,3-alternate" (Scheme 1-6).[13] They are different from each other in the position of the phenolic hydroxyl groups with respect to the average plane of the macrocycle. Such variation in conformation is useful for construction of different types of molecular bases by using of the same framework.

Scheme 1-6



In the case of larger class of calixarenes, there are a large number of possible conformers. While calix[5]arenes can have only four "*up/down*" conformers, there are eight for calix[6]arenes and sixteen for calix[8]arene and so on. In order to denote these conformational isomers, a convenient notation has been introduced by Gutsche, which are summarized as shown below.[3,14]

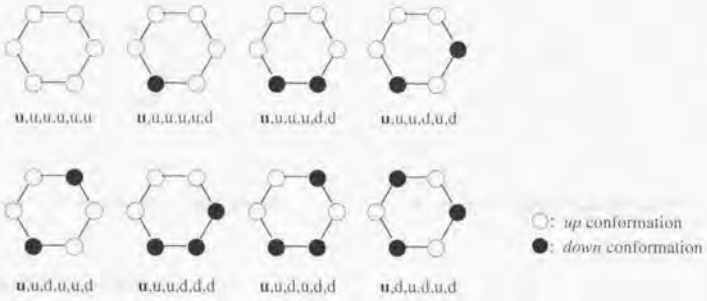
(A) The orientation of an aryl group of a calixarene macrocycle is designated as "*up*" or "*down*" relative to the average plane of the molecule, as determined by its methylene group using the descriptors "u" (*up*) and "d" (*down*).

(B) The aryl moiety carrying the highest priority substituent at any position other than the two attached to the bridging methylene groups is designated as the reference group. It is recommended that the reference group descriptor is bold faced and that it is listed first in the sequence.

According to this notation, the cone and 1,2,3-alternate conformations, which are frequently seen in the calix[6]arene chemistry, are described as (**u**,u,u,u,u,u) and (**u**,u,u,d,d,d),

respectively. Simple calix[6]arenes which have the same substituents on each of the aromatic rings have eight conformations due to the variation of "u" and "d" (scheme 1-7).

Scheme 1-7

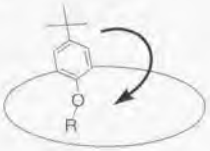


1.5. Conformational isomerism of calixarenes

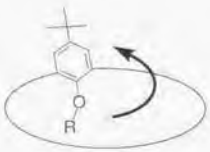
Variation of conformation makes calixarenes to suffer the conformational isomerism, which is sometimes troublesome in multiple functionalization. Calix[4]arenes have the four conformational isomers as discussed above. Although the calix[4]arenes bearing smaller groups (R' = Me, Et, CH_2CN) are reported to undergo conformational interconversion,[13,15] substituents bulkier than ethyl group (R' = *n*-Pr, *n*-Bu, $CH_2CH_2OCH_3$, CH_2COCH_3, COAr, *etc*) can restrict the conformational isomerization among these isomers.[13,16] Conformational interconversion of *p-tert*-butylcalix[5]arenes can be also suppressed by introduction of bulky substituents (R' = $COCH(CH_3)_2$, CH_2CO_2Et) at the lower rim.[17]

On the other hand, rigidification of the conformation of calix[6]arenes has been very difficult. For example, the conformation of *p-tert*-butylcalix[6]arenes, unlike those of *p-tert*-butylcalix[4]arenes and *p-tert*-butylcalix[5]arenes, cannot be fixed even by the introduction of very bulky groups such as cholesteryl and *p*-phenylbenzyl groups to the lower rim.[18] This fact indicates that the pathway of the isomerism of *p-tert*-butylcalix[4]arenes and *p-tert*-butylcalix[5]arenes is involved only with the "lower-rim-through-the-annulus pathway" whereas that of *p-tert*-butylcalix[6]arenes is involved also with the "upper-rim-through-the-annulus pathway" (scheme 1-8). Such conformational flexibility of calix[6]arenes has been one of the main obstacles to their use and the development of a new methodology to control their conformation has long been awaited.

Scheme 1-8



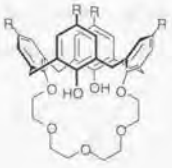
upper-rim-through-the-annulus pathway



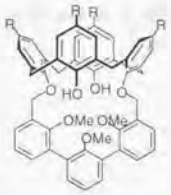
lower-rim-through-the-annulus pathway

1.6. Bridged calixarenes

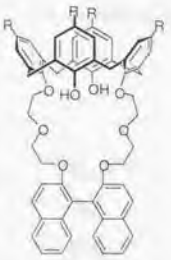
Calixarenes can also be modified with bifunctional reagents to afford bimacrocyclic compounds in one step. These additional cyclic system anchored from the parent calixarene framework can provide novel properties as reported in many papers. Calix[4]crowns **4**[19] and their alkylated derivatives are typical examples of this class of compounds. There have been also a number of reports on the calix[4]arenes bearing other type of bridge such as a terphenyl (**5**)[20] or a chiral crown ether unit (**6**).[21]



4



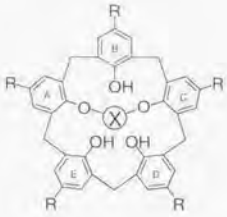
5

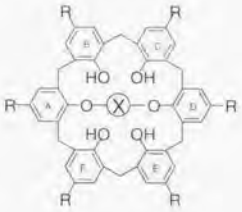


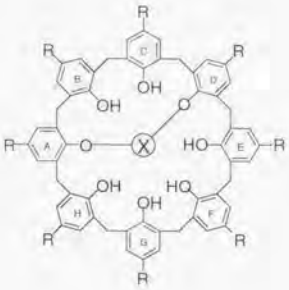
6

However, only a few examples of larger calixarenes bearing a crown ether unit have been reported, which is due to the difficulty of regio-selective bridging as well as the conformational mobility. Among them are included the A,C-bridged calix[5]arenes (**7**),[22] the A,D-bridged calix[6]arenes (**8**),[23] and the A,D-bridged calix[8]arenes (**9**)[24] with a

poly(ethylenoxy) unit.[2]





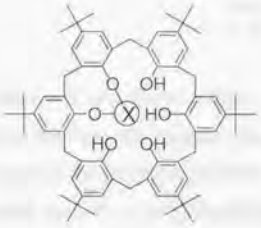


X = $CH_2(CH_2OCH_2)_nCH_2$

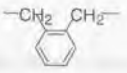
7 (n = 4-6) **8** (n = 4) **9** (n = 4)

On the other hand, bridging (or capping) of calixarenes with a more rigid bridge such as an aromatic ring is expected to lead to a bicyclic systems in rather high selectivity even if a larger class of calixarenes are used. Furthermore, bridging unit with a rigid unit is expected to reduce the conformational flexibility of a larger class of calixarenes.

The A,B-bridged calixarenes **10** and **11**[23,26] and A,C-bridged calix[6]arenes **12-14**[25,27] were synthesized by several groups. Shinkai and co-workers reported the successful optical resolution of **14** having inherent chirality, indicating that the ring inversion of the calix[6]arene macrocycle which would lead to the racemization is inhibited in this bridged compound on the "laboratory time scale".

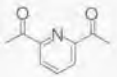


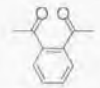
10: X =

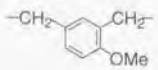


11: X =

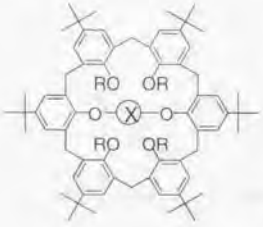
[2] Labeling of A, B, C, etc. is used to specify the aromatic rings to which the substituents are attached. Thus, the compounds **7**, **8**, and **9** can be designated as "A,C-" , "A,D-", and "A,D-bridged", respectively. See also footnote 1.

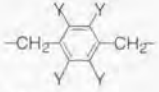
12: X =  R = H

13: X =  R = Me

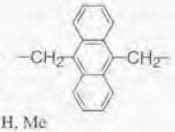
14: X =  R = Me

A number of calix[6]arenes **15**-**18** bridged by a xylylene unit in A,D-positions have also been reported. Calix[6]arenes **15** and **16**, bridged by a *p*-xylylene moiety and an anthracene unit, respectively, were synthesized.[14] Conformational behavior of **15** and **16** in solution was also studied in detail.

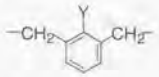


15: X = 

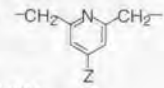
Y = H, Me
R = H, Me

16: X = 

Y = H, Me
R = H, Me

17: X = 

Y = H, Br, NO_2, SBu, SOBu, SOH, N_3
R = H, Me, Bn

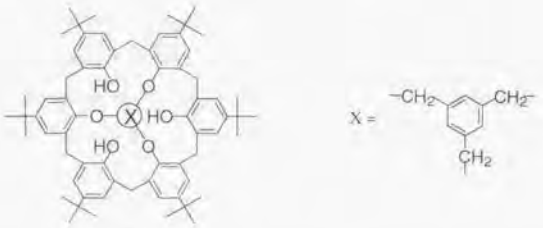
18: X = 

Z = H, OMe
R = H, Me

The synthesis of *m*-xylylene bridged calix[6]arenes **17** and **18** were also reported.[25,27,28] The author's group has been investigating the synthesis and application of **17**, whose framework was usefully employed for the stabilization of highly reactive species such as sulfenic acids (Y = SOH) and selenenic acids (Y = SeOH) embedded in the cavity.[28c,e] Lüning and co-worker also reported the synthesis and applications of concave reagents **18** based on pyridine-bridged calix[6]arene framework and showed their fascinating reactivities.[27]

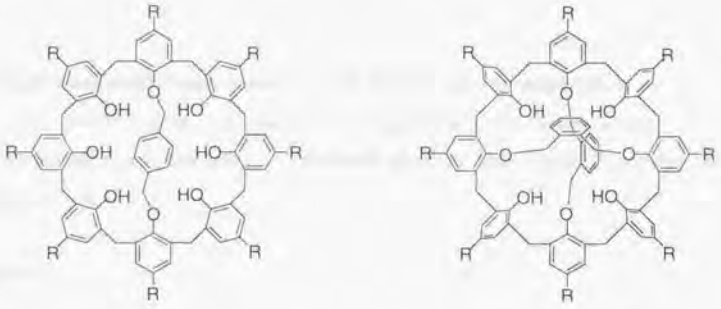
Besides these bridged calixarenes, a calix[6]arene capped with a rigid tripodal bridge (**19**) was also synthesized.[29] In the case of compound **19**, the conformation of the calix[6]arene

macrocycle is considered to be frozen on the NMR time scale.



19

Selective bridging of a macrocyclic system is also effective for the calix[8]arenes. Compounds **20** and **21**, which have one and two xylylene units, respectively, were synthesized.[30] Investigation of their structural features revealed that the conformational isomerization of the macrocycle is considerably restricted on the NMR time scale.

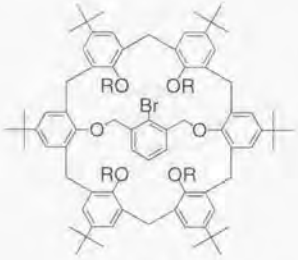


20 **21**

1.7. Conformational mobility of bridged calixarenes

As discussed above, bridged calix[6]arenes have higher conformational rigidity in comparison with other calix[6]arene derivatives without a bridge. They can also be utilized as a molecular platform with multi-functions if more than one substituent are introduced on the rigid macrocycle. However, the conformation of these bridged calix[6]arenes is not completely fixed with regard to non-bridgehead aromatic rings. The author's group has investigated that the

conformational mobility of *m*-xylylene bridged calix[6]arene **22** with four remaining hydroxy groups and its methylated derivative **23**.[28b] While the conformation of tetrahydroxy compound **22** was stabilized by a strong hydrogen bonding network, tetramethyl derivative **23** underwent flipping motion of non-bridgehead aromatic rings even at room temperature. It is necessary to restrict such kind of motion for the use of these molecules as a rigid molecular platform for further elaborate functionalization.

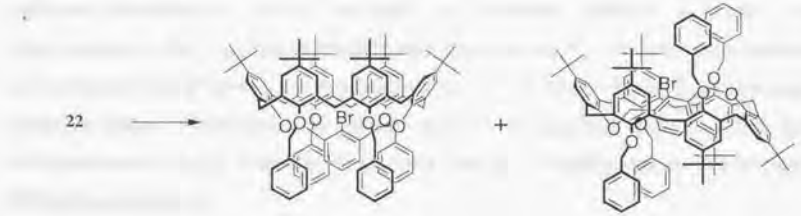


22: R = H
23: R = Me

1.8. Conformationally frozen isomers of calixarenes and their applications

The author's group has isolated two conformationally frozen isomers of bridged calix[6]arenes **24a** (cone) and **24b** (1,2,3-alternate) by introduction of benzyl groups to the lower rim (Scheme 1-9).[28d]

Scheme 1-9

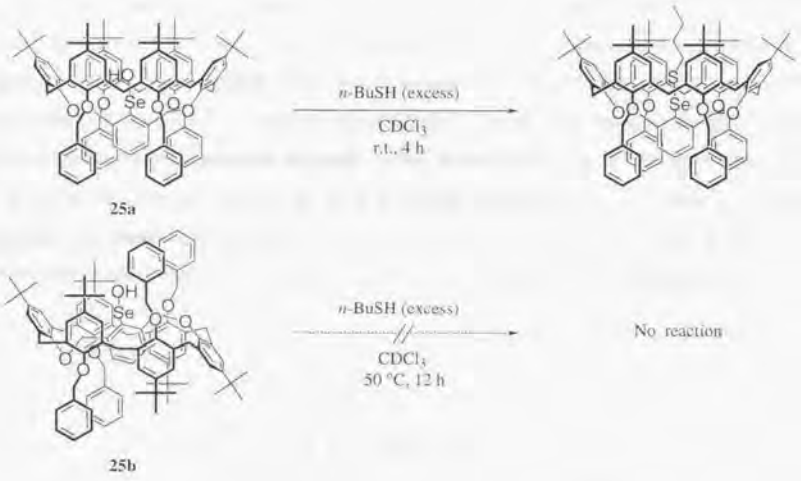


24a (cone) **24b** (1,2,3-alternate)

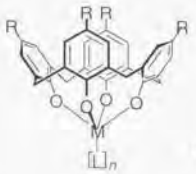
This fact indicates that the conformational mobility of bridged calix[6]arenes can also be

suppressed by simple substitution of their lower rim similarly to the cases of calix[4]arenes and calix[5]arenes. The completely different structures of isomers **24a** and **24b** are especially useful for the investigation of properties such as physical properties or reactivity related to the structural difference. Reactivities of the selenenic acids embedded in two conformationally frozen isomers **25a** and **25b** are reported to be different from each other (Scheme 1-10).[28e,f]

Scheme 1-10



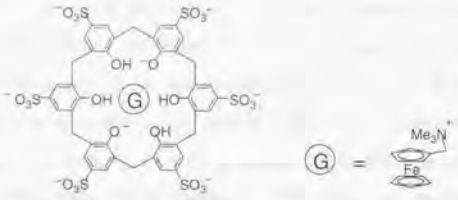
Moreover, the conformationally frozen bridged calix[6]arenes can be used as a molecular platform for further synthetic elaboration. Introduction of coordination sites to a calixarene framework can lead to a new type of multi-dentate ligands for the transition metals, and a number of their complexes such as **26** have been reported.[31] The conformational isomers of the bridged calix[6]arenes are also expected to act as a structurally well-defined ligand for transition metals. Furthermore, the bridged calix[6]arene framework bearing a central bridging unit could have a larger number of coordination sites than calix[4]arenes as well as other non-bridged calix[6]arenes.



M = Zr, Ti, Mo, W...

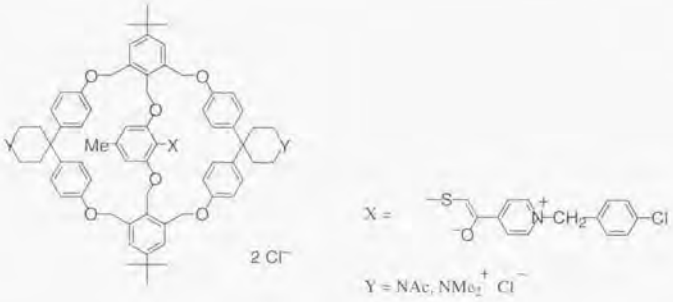
26

The cavity of the calixarenes has also been utilized as a reaction field for the incorporated species in it and the unique properties in nano-scale microenvironment have been reported. Such usage is especially effective in the case of the calix[6]arenes with a larger cavity as is seen in molecule **27**.[32] This type of complexes, however, were based on the non-covalent interactions and only the averaged properties of the complexed and dissociated guest species can be investigated. If a species to be studied is covalently anchored in the cavity with well-defined geometry, the behaviors of the species in a microenvironment in the cavity of the calix[6]arenes can be studied more definitely in relation with the structural features of the macrocycle.



27

In his master course, the author synthesized the bridged cyclophanes **28** bearing a chromophore in the cavity, which have a framework similar to that of the bridged calix[6]arenes, and investigated the micropolarity around the chromophore.[33] It is expected that the microenvironment in the cavity of the bridged calix[6]arenes also provides a unique reaction field for the functional group on the covalently anchored bridging unit.



28

1.9. The aim of this thesis

In this doctoral thesis, the author will describe the syntheses and structures of the conformationally frozen isomers of bridged calix[6]arenes as well as their applications. Investigation on the synthetic methods and structural features of the conformationally frozen isomers of the bridged calix[6]arenes will be explicated in Chapter 2, which provides the basic information for the use of the framework as a molecular platform for further synthetic elaboration and as a reaction field. These conformational isomers are expected to exhibit different physical properties, which will be discussed in Chapter 3 from the viewpoint of the aggregating properties of the water-soluble derivatives. The rigid framework based on the bridged calix[6]arenes is also utilized as a ligand for transition metals, which is expected to give structurally well-defined complexes more easily. Investigation on the synthesis of transition metal complexes using the calix[6]arene ligand will be described in Chapter 4. This rigid calix[6]arene macrocycle can be also utilized as a reaction field for the covalently anchored redox-active moiety. Electrochemical properties and the reactivities of the quinone-bridged calix[6]arenes will be described in Chapter 5.

Chapter 2

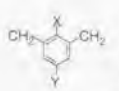
Syntheses and Structures of Conformationally Frozen Isomers of Bridged Calix[6]arenes

2.1. Introduction

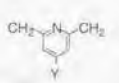
Synthesis of calix[6]arenes bearing a rigid aromatic bridge is one of the most promising method to construct structurally well-defined macrocyclic framework. One-step synthesis of the A,D-bridged calix[6]arenes with a *m*-xylylene unit (**2** and **3**)[25,27,28] or a *p*-xylylene unit (**4** and **5**)[14] have been reported by Shinkai, Gutsche, and Lüning as well as the author's group (Scheme 2-1). Some applications using this framework such as stabilization of highly reactive species[28c,e] or usage as concave reagents[27] have been reported.

Scheme 2-1

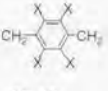
1

2 Z = 

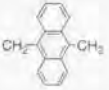
X = H, Y = H (**2A**)
X = Cl, Y = H
X = Br, Y = H (**2B**)
X = I, Y = H
X = S(*t*-Bu), Y = H
X = N_3, Y = H
X = CN, Y = H
X = CO_2Me, Y = H
X = NO_2, Y = H
X = H, Y = *t*-Bu
X = Br, Y = *t*-Bu

3 Z = 

Y = H
Y = OMe

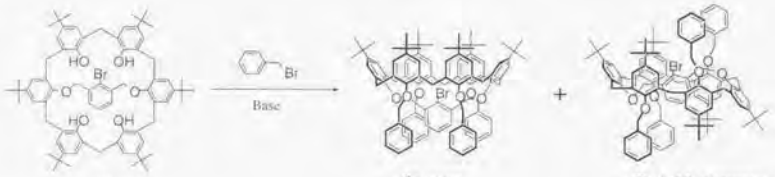
4 Z = 

X = H
X = Me

5 Z = 

Most of the structures of the reported calix[6]arenes bearing an aromatic bridging unit, however, have not been elucidated sufficiently, which is partly because some of the aromatic rings of their calixarene macrocycles undergo flipping motion in solution.[28f] The author's group has reported that the introduction of bulkier groups such as benzyl group to the lower-rim is effective for restriction of this motion, which affords two conformationally frozen isomers of a calix[6]arene (**6a** and **6b**, Scheme 2-2).[28d]

Scheme 2-2

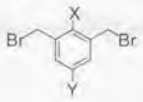


2B **6a** cone **6b** 1,2,3-alternate

In this chapter, the synthesis of the conformational isomers of the *m*-xylylene bridged calix[6]arenes are discussed as well as the selectivity of the formation of these isomers. Their structural features in the crystalline state are also delineated.

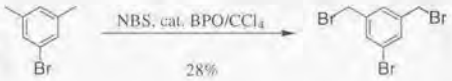
2.2. Construction of the bridged calix[6]arene framework

The bridged calix[6]arenes can be synthesized by coupling of the macrocyclic unit, *p*-*tert*-butylcalix[6]arene (**1**), and the bridging unit, 1,3-bis(bromomethyl)benzene derivatives **7**. The macrocyclic unit **1** was synthesized from 4-*tert*-butylphenol in one step procedure according to the literature.[19b] The bridging units **7B**[34] and **7I**[28f] were prepared according to the literature. Synthetic methods for the compounds **7C**,[35] **7E**,[36] **7F**,[37] and **7G**[38] were previously reported, but improved procedures were used as shown in Scheme 2-3. Compounds **7D** and **7H** were synthesized according to Scheme 2-3.

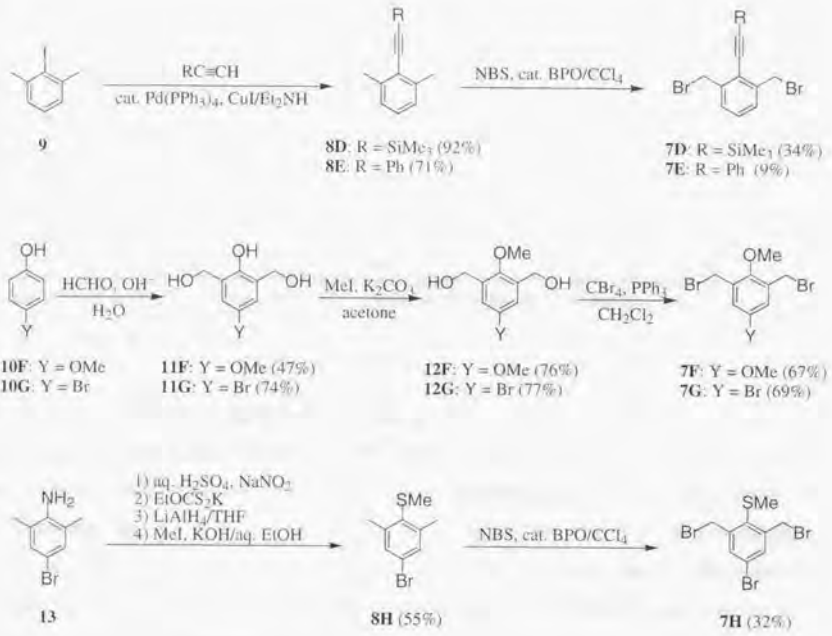


7A: X = H, Y = H
7B: X = Br, Y = H
7C: X = H, Y = Br
7D: X = C≡CSiMe$_3$, Y = H
7E: X = C≡CPh, Y = H
7F: X = OMe, Y = OMe
7G: X = OMe, Y = Br
7H: X = SMe, Y = Br
7I: X = Se(*n*-Bu), Y = H

Scheme 2-3



8C **7C**



9

8D: R = $SiMe_3$ (92%)
8E: R = Ph (71%)

7D: R = $SiMe_3$ (34%)
7E: R = Ph (9%)

10F: Y = OMe
10G: Y = Br

11F: Y = OMe (47%)
11G: Y = Br (74%)

12F: Y = OMe (76%)
12G: Y = Br (77%)

7F: Y = OMe (67%)
7G: Y = Br (69%)

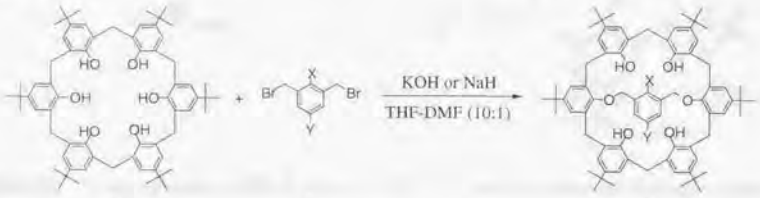
13

8H (55%)

7H (32%)

Bridging reactions of **1** were carried out according to the reported procedures[25a,28b,d,e] in the presence of NaH or KOH in THF-DMF (10:1) to afford the bicyclic products **2** in relatively high yields (Scheme 2-4). The results are shown in Table 2-1. In the reaction of **1** with **7D** (X = C≡CSiMe$_3$, Y = H), the trimethylsilyl group was removed under the reaction conditions to afford the bridged calix[6]arene **2J** (X = C≡CH, Y = H) with a terminal acetylene moiety.

Scheme 2-4



1 **7** **2**

Table 2-1. Results of the bridging reaction of *p-tert*-butylcalix[6]arenes.

7	X	Y	product	conditions	yield/%	ref
A	H	H	**2A**	I	68	[25a]
B	Br	H	**2B**	II	89	[28b,f]
C	H	Br	**2C**	I	91	
D	C≡CSiMe$_3$	H	**2J**[1)]	II	96	
E	C≡CPh	H	**2E**	II	76	
F	OMe	OMe	**2F**	II	88	
G	OMe	Br	**2G**	II	73	
H	SMe	Br	**2H**	II	68	
I	Se(*n*-Bu)	H	**2I**	II	80	[28e,f]

Conditions I: NaH, THF-DMF (10:1), reflux, 1 d. Conditions II: KOH, THF-DMF (10:1), rt, 1 d.

1) X = C≡CH, Y = H.

The structural features and dynamic behavior of the tetrahydroxy compounds **2** in solution have been reported in detail by the author's group[28b] and Lüning's group,[27c] but there has been no example of the determination of their crystal structures. The crystals of the bridged calix[6]arene **2B** (X = Br, Y = H) suitable for X-ray analysis were obtained from the chloroform solution, which was found to be liable to lose the solvent. The structure of **2B** is shown in Figure 2-1. The calixarene moiety adopts a "pinched cone" conformation, where the calixarene macrocycle is pinched at the C_A and C_B positions.

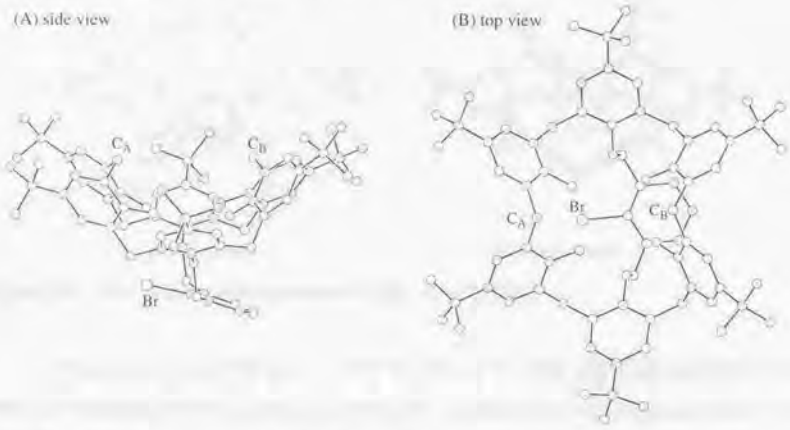


Figure 2-1. X-ray structure of **2B** (X = Br, Y = H). Disordered atoms and hydrogen atoms are omitted for clarity.

In the molecule of **2B**, there were observed the cyclic array of the hydrogen bonds between the OH groups and the ether oxygen atoms (2.68-2.82 Å), which is considered to stabilize the "pinched cone" conformation. It is of note that the bridging unit lies outside in such a way that it forms the bottom of the cone. The author's group previously reported that **2B** has a "pinched cone" conformation based on the NMR study and molecular mechanics calculations[28b] whereas Lüning's group proposed a "half-pinched/half-winged" conformation for **2B** (Figure 2-2)[27e]. The conformation of **2B** found in the crystalline state strongly supports their taking a "pinched cone" conformation also in solution.

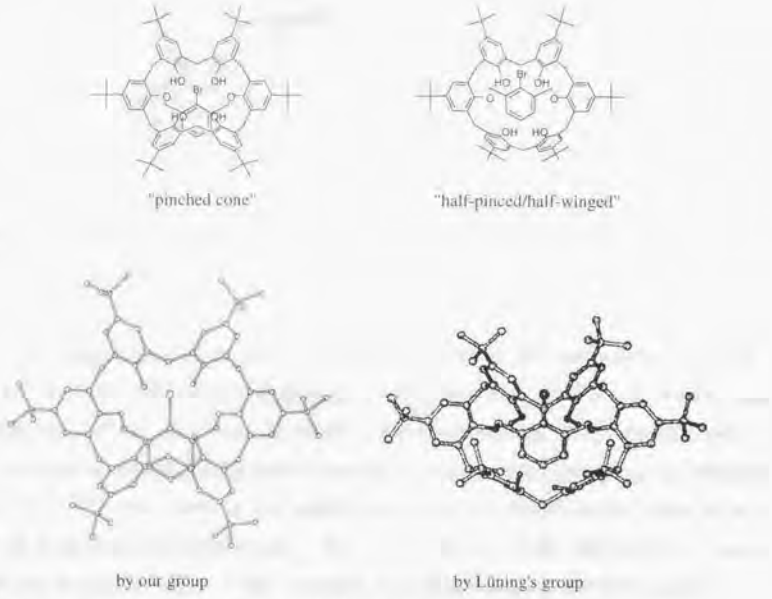


Figure 2-2. Two proposed conformations of **2B**. (ref [27e,28b])

Crystal structures of **2A** (X = Y = H), **2C** (X = H, Y = Br), and **2J** (X = C≡CH, Y = H) were also established by X-ray analyses, showing the "pinched cone" conformation similar to that of **2B** (Figure 2-3).

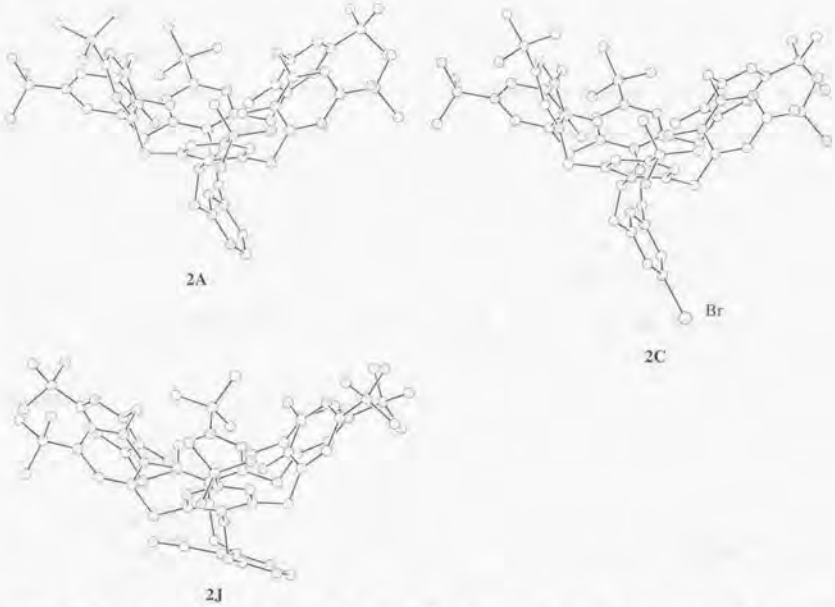


Figure 2-3. X-ray structures of **2A**, **2C**, and **2J**. Hydrogen atoms and disordered atoms are omitted for clarity.

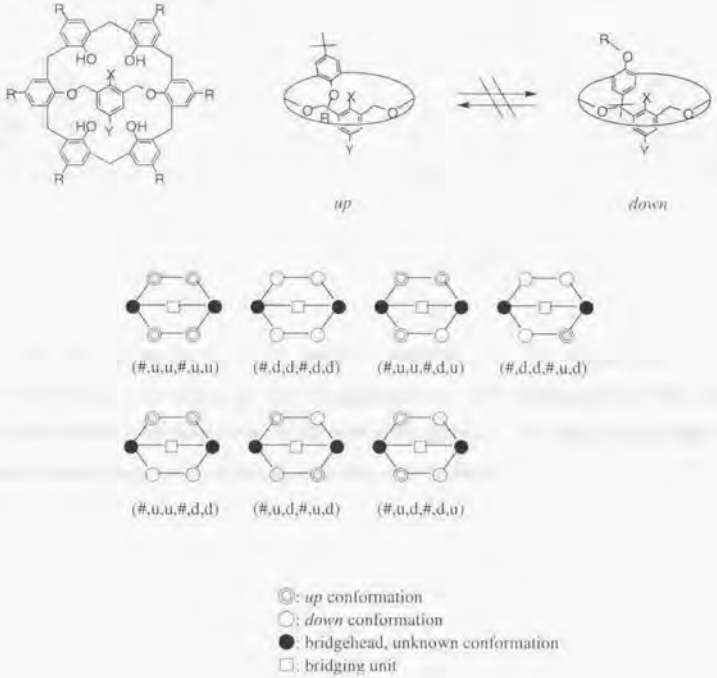
The bridging units of **2A** and **2C** locate, however, under the cone with an inclination of 60.5° (**2A**) and 60.4° (**2C**) to the average plane of the macrocycle, which is considerably larger value than those of **2B** (18.0°) and **2J** (19.6°). The previous study on the dynamic behavior showed that the tetrahydroxy compounds **2** undergo swinging motion in solution as depicted in Scheme 2-5.[27b,28b] The barrier of this motion was reported to depend on the bulkiness of the functional group X on the bridging unit. The larger inclination of **2A** and **2C** (X = H) can be explained by the smaller barrier of the swinging motion of the bridging unit of **2A** and **2C**.

Scheme 2-5

2.3. Possible isomers

Supposing that the arylmethylation of the bridged calix[6]arenes restricts the flipping motions of the four non-bridgehead aromatic rings of a calixarene macrocycle, formation of the seven conformational isomers is expected, which is derived from the difference of the orientation (*up* and *down*)[1] of these four aromatic rings (Scheme 2-6). In this discussion, the orientation of the bridgehead aromatic rings is assumed to be not restricted (described as a wildcard "#") because it is difficult to determine their orientation by the NMR data; for example, the (**u**,u,u,u,u,u) isomer and the (**d**,u,u,d,u,u) isomer show the same spectral symmetry.

Scheme 2-6

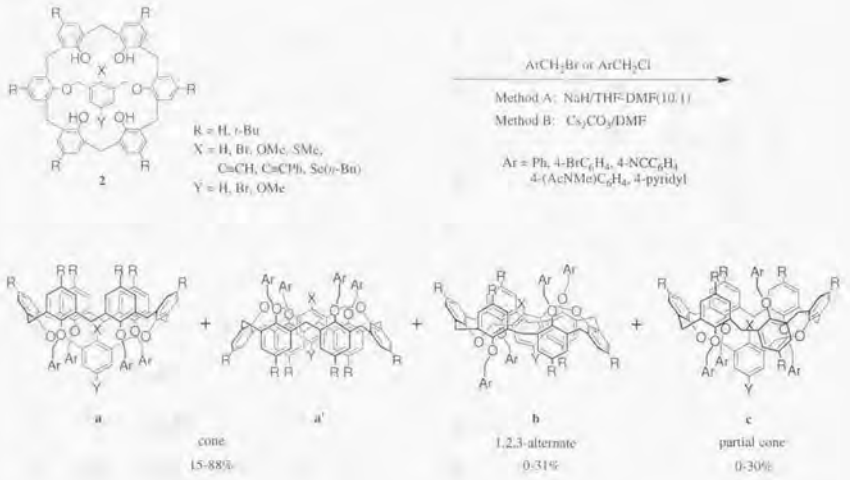


[1] The modified "*up*/*down*" nomenclature was used for the bridged calixarenes in this thesis in order to distinguish the different orientation (*up*/*down*) of aromatic rings as compared with that of bridging unit. The "*up*" is defined as the conformation where its upper rim orients the same direction as X group on the bridging unit does as depicted in Figure 2-6.

2.4. Arylmethylation of the bridged calix[6]arenes

Arylmethylation of the tetrahydroxy derivatives **2** was achieved by two methods: NaH, THF-DMF (10:1), reflux (method A) and Cs_2CO_3, DMF, 70 °C (method B). In these conditions, up to four conformational isomers (**a**, **a'**, **b**, and **c**) were obtained (Scheme 2-7).

Scheme 2-7



The ratios of the isomers of the tetrasubstituted products are summarized in Table 2-2. It was found that the cone isomer (**a** or **a'**) is predominantly formed irrespective of the conditions and the substituents on the calixarenes or the arylmethyl groups. The three isomers other than **a**, **a'**, **b**, and **c** among the possible seven isomers were not obtained.[2]

---

[2] Lüning *et al.* reported that the benzylation of pyridine-bridged calix[6]arene **3** (Y = H) afforded a tetrabenzylated compound with the conformation of flattened (**u**,u,d,u,u,d) conformation in 7% yield.[17c] Its structure was, however, not sufficiently elucidated.

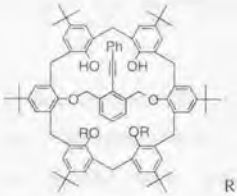
Table 2-2. Results of the arylmethylation of bridged calix[6]arenes.

							Base: NaH[1]			Base: Cs_2CO_3[2]		
entry	R	X	Y	S.M.	Ar	product	a	b	c	a	b	c
1	*t*-Bu	H	H	**2A**		**15**	63	1	6	89	0	0
2						**16**	39	2	16			
3						**17**	33	0	30	88	0	0
4	*t*-Bu	Br	H	**2B**		**6**	58	16	0	62	14	0
5						**18**	59	11	0	64	22	0
6						**19**	0	0	0	83	16	0
7						**20**	0	0	0	55	11	0
8	H	Br	H	**14**		**21**	35	31	8			
9						**22**				66	7	0
10	*t*-Bu	H	Br	**2C**		**23**	52	0	4	77	0	0
11	*t*-Bu	C≡CH	H	**2J**		**24**				70	0	0
12	*t*-Bu	C≡CPh	H	**2E**		**25**	15 (**a'**)	12	0	0	0	0
13	*t*-Bu	OMe	OMe	**2F**		**26**	27	10	3	87	0	0
14	*t*-Bu	OMe	Br	**2G**		**27**	35	7	7	93	0	0
15	*t*-Bu	SMe	Br	**2H**		**28**				48	0	0
16	*t*-Bu	Se(*n*-Bu)	H	**2I**		**29**	59 (**a'**)	4	0	92 (**a'**)	0	0

1) NaH/THF-DMF (10:1), reflux, 1-4 d. 2) Cs_2CO_3/DMF, 70 °C, 1-2 d.

Although both of the methods A and B gave almost the same results, there was still some differences in the total yield of the tetrasubstituted products as well as in the ratios of isomers between the conditions A and B for some kinds of the arylmethylating agent. The conditions B were effective when 4-(chloromethyl)pyridine hydrochloride or 4-cyanobenzyl bromide was used as the arylmethylating agent (entry 6 and 7). On the other hand, the conditions A were effective for the preparation of phenylethynyl derivative **25** (entry 12) while

disubstituted product **30** was obtained in 75% yield by using the conditions B. The ratios of isomers were slightly influenced also by the substituents on the bridging unit or the upper rim of the calixarene. Using the conditions A, the isomer **c** was obtained in 5-30% yields when **2A** was used (entry 1-3) whereas the isomer **b** was obtained in a relatively good yield (31%) when compound **14**, without *tert*-butyl groups at the upper rim, was used (entry 8 and 9).



R = CH_2Ph

30

It was also found that the bulkiness of the substituents on the bridging unit (X and Y) plays an important role in determining which of the isomers **a** and **a'** is formed. The reaction of the phenylethynyl derivative **2E** or *n*-butylseleno derivative **2I** with benzyl bromide afforded the cone isomer as a major product (entry 12 and 16), whose conformation was determined to be **a'**, not **a**, by X-ray analyses as well as the NMR studies. The factor which determines the conformation of the cone isomers (*i.e.* **a** and **a'**) will be discussed later.

2.5. Structural characterization

The structures of the conformational isomers can be determined by the symmetry of the ^{1}H NMR signals. The predicted patterns of the signals of the expected seven isomers are listed in Table 2-3. If turnstile-like rotation of the bridging unit is hindered, the pattern of the signals are classified into five patterns (Table 2-3, pattern I-V), while the rotation occurs, more symmetric patterns are expected (Table 2-3, pattern II', III', and IV').

Table 2-3. Patterns of ^{1}H NMR signals for the possible isomers of the bridged calixarenes.

Pattern	R (= *t*-Bu, H)	$ArCH_2Ar$	$ArOCH_2Ar$	corresponding isomer
I	s × 2 (4:2)	pair of d × 2 (4:2)	pair of d × 1 (4), s × 1 (2)	(#,u,u,#,u,u) and (#,d,d,#,d,d)
II	s × 3 (2:2:2)	pair of d × 3 (2:2:2)	pair of d × 3 (2:2:2)	(#,u,d,#,u,d)
III	s × 3 (2:2:2)	pair of d × 4 (2:2:1:1)	pair of d × 3 (2:2:2)	(#,u,u,#,d,d)
IV	s × 4 (2:2:1:1)	pair of d × 3 (2:2:2)	pair of d × 2 (2:2), s × 2 (1:1)	(#,u,d,#,d,u)
V	s × 6 (1:1:1:1:1:1)	pair of d × 6 (1:1:1:1:1:1)	pair of d × 6 (1:1:1:1:1:1)	(#,u,u,#,u,d) and (#,d,d,#,d,u)
II'	s × 2 (4:2)	pair of d × 1 (4), s × 1(2)	pair of d × 2 (4:2)	(#,u,d,#,u,d)
III'	s × 2 (4:2)	pair of d × 2 (4:2)	pair of d × 2 (4:2)	(#,u,u,#,d,d)
IV'	s × 2 (4:2)	pair of d × 1 (4), s × 1(2)	pair of d × 1 (4), s × 1 (2)	(#,u,d,#,d,u)

Figures in parentheses indicate the integral ratios of the signals.

According to Table 2-3, three isomers of the possible seven ones, that is, (#,u,d,#,u,d), (#,u,u,#,d,d), and (#,u,d,#,d,u) can be differentiated by the signal pattern and the rest four isomers are divided into two patterns: one is pattern I, which corresponds to (#,u,u,#,u,u) and (#,d,d,#,d,d), and the other pattern V, which corresponds to (#,u,u,#,u,d) and (#,d,d,#,d,u). The experimentally obtained arylmethylated compounds of the bridged calix[6]arenes showed four types of signal patterns, that is, patterns I, IV, IV', and V. The structures of the isomers which show patterns IV and IV' were determined to be the 1,2,3-alternate **b** (**u**,u,d,d,d,u) by X-ray analyses (*vide infra*). The structures of the isomers showing patterns I and V are difficult to establish based only on the NMR data because one cannot distinguish (#,u,u,#,u,u) from (#,d,d,#,d,d), both of which show pattern I, and (#,u,u,#,u,d) from (#,d,d,#,d,u), both of which show pattern V. By X-ray analyses, the compounds showing pattern I were found to take either of two cone conformations, **a** (**u**,u,u,u,u,u) and **a'** (**d**,d,d,d,d,d) depending on the bulkiness of the substituents (X and Y) on the bridging unit (*vide infra*).

The structure of one of the compounds showing pattern V was also established by X-ray analysis to be the partial cone isomer **c** (**u**,u,u,u,u,d). This conformation corresponds to the isomer (#,u,u,#,u,d) in Table 2-3 and not to the isomer (#,d,d,#,d,u). The structures were also corroborated by the ^{1}H NMR studies. The signals of the protons on the bridging unit of the isomer (#,d,d,#,d,u) are expected to be shifted to the high field (3.8-4.7 ppm) by analogy with the isomer **a'** (**d**,d,d,d,d,d). On the other hand, those of the isomer (#,u,u,#,u,d) are expected to be observed at the normal region (6.4-7.2 ppm) by analogy with the corresponding cone isomer **a** (**u**,u,u,u,u,u). From the observation of these signals at the normal region (6.6-7.0 ppm), the conformation of the obtained isomer showing pattern V is considered to be (#,u,u,#,u,d).

The substituent on the central bridging unit (X) is considerably enveloped by the calixarene framework especially in the case of the isomer **a**. For example, the ^{1}H NMR

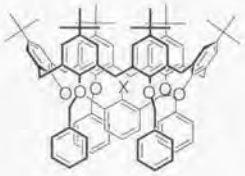
chemical shift of the methoxy group of the cone isomers **26a** and **27a** (X = OMe) was around 0.95 ppm, which indicates that the functional group at the X position is magnetically shielded to a great extent. On the other hand, such a strong upfield shift of the substituent X was not observed for the isomers **a'** and **b**. Instead, an upfield shift of the aromatic protons on the bridging unit was observed (δ = 3.5-4.8 ppm). The chemical shifts of the substituents of the bridging unit of several compounds are summarized in Table 2-4.

Table 2-4. Chemical shifts (δ) of the substituents on the bridging unit (X, Y)

compound	X					Y		aromatic
15a	H	5.61				H	7.00	7.06
6a	Br	–				H	6.68	7.09
23a	H	5.55				Br	–	7.28
24a	C≡CH	0.50				H	6.90	7.17
26a	OMe	0.95				OMe	3.36	6.68
27a	OMe	0.95				Br	–	7.40
28a	SMe	–0.25				Br	–	7.36
25a'	C≡CPh	7.65 (*o*-)	7.28 (*m*-)	7.28 (*p*-)		H	4.74	3.86
29a'	Se(*n*-Bu)	2.75 (1-)	1.35 (2-)	1.10 (3-)	0.77 (4-)	H	4.48	3.88
15b	H	4.66				H	6.08	5.30
6b	Br	–				H	6.11	3.55, 6.83
25b	C≡CPh	6.67 (*o*-)	7.11 (*m*-)	7.11 (*p*-)		H	6.25	3.53, 6.82
26b	OMe	2.14				OMe	3.05	4.14, 6.18
27b	OMe	2.21				Br	–	4.75, 6.75
15c	H	5.31				H	6.59	6.96, 6.97
23c	H	5.26				Br	–	6.71, 7.22
26c	OMe	1.36				OMe	3.37	6.39, 7.04
27c	OMe	1.40				Br	–	7.05, 7.75

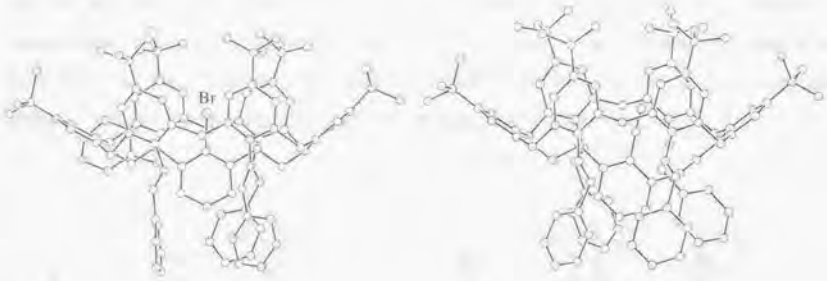
2.6. Conformation in the crystalline state

The crystal structures of the conformationally frozen bridged calix[6]arenes have been little known except for the cone isomer of bromide **6a**[28d] and selenenic acid **31a**[28e]. In this section, crystal structures of the isomers of arylmethylated bridged calix[6]arenes are delineated.



6a: X = Br
31a: X = SeOH

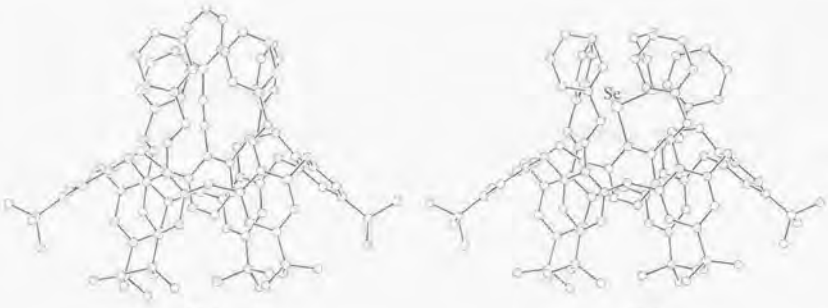
The structures of the isomer **a** of benzylated bridged calix[6]arenes, **6a** (X = Br)[28d] and **24a** (X = C≡CH), are shown in Figure 2-4. The calix[6]arene moiety adopts a cone conformation; all of the six benzene rings of the calix[6]arene moiety are directed upward and all the benzyl groups at the lower rims are directed downward. The substituent on the bridging unit is completely surrounded by six aromatic rings, which is consistent with the observation of the signal of the terminal acetylenic proton of **24a** at 0.50 ppm, high-field shifted by about 3 ppm from the normal region.



6a **24a**

Figure 2-4. X-ray structures of cone isomers **6a** and **24a**. Hydrogen atoms are omitted for clarity.

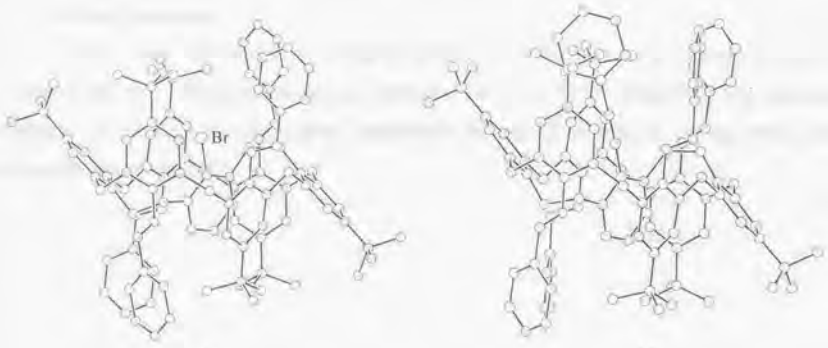
The structures of the isomer **a'** of the benzylated bridged calix[6]arenes **25** (X = C≡CPh) and **29** (X = Se-*n*-Bu) are shown in Figure 2-5. The calix[6]arene moiety adopts a cone conformation similarly to the isomer **a**, but the bridging unit is oriented to the opposite direction in comparison with the isomer **a**. In this isomer, the aromatic ring of the bridging unit is enveloped by the calixarene macrocycle, which is consistent with the high field shift of the ^{1}H NMR signals of the aromatic protons (3.8-4.7 ppm, Table 2-5).



25a' **29a'**

Figure 2-5. X-ray structures of cone isomers **25a'** and **29a'**. Hydrogen atoms are omitted for clarity.

The structure of the isomer **b** of benzylated calix[6]arenes **6** (X = Br) and **25** (X = C≡CPh) are shown in Figure 2-6. The calix[6]arene moiety adopts a 1,2,3-alternate conformation, where three adjacent benzene rings are directed upward and the other three downward. In the crystalline state, there is a pseudo inversion center in these molecules resulting from the disorder of the bridging unit, to form the crystallographic center of symmetry.



6b **25b**

Figure 2-6. X-ray structures of 1,2,3-alternate isomers **6b** and **25b**. Disordered atoms and hydrogen atoms are omitted for clarity.

The structure of the partial cone isomer **c** of benzylated calixarene **27** is shown in Figure 2-7. The calixarene moiety adopts a partial cone conformation, where one of the six benzene rings oriented downward and other five upward. In this case, the bridgehead benzene rings have "*up*" conformation, but one of them between the benzene rings of "*up*" and "*down*" leans outward. This is the first example of the crystallographic analysis of a calix[6]arene bearing a partial cone conformation.

Figure 2-7. X-ray structures of two independent molecules of **27c**. Hydrogen atoms are omitted for clarity.

2.7. Solvate formation

It was found that some of the bridged calix[6]arene derivatives contain a large number of solvent molecules. Halogenated solvent molecules are prone to be included in the crystals, especially in the case of tetrahydroxy compounds **2B** and **2J** as well as the pyridylmethyl derivative **15a** (Table 2-5).

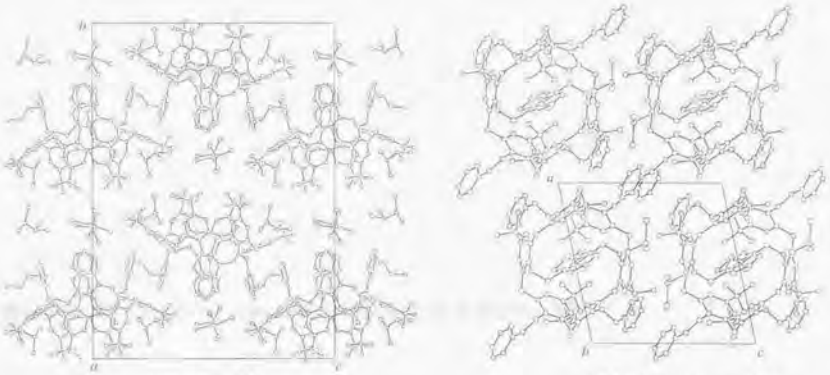
Table 2-5. Number of solvent molecules in the crystals.

compd.	conformation	solvent	ratio	cavity
2A	pinched cone	C_6H_6-MeCN	1:1:1	0
2B	pinched cone	$CHCl_3$	1:5	0
2C	pinched cone	C_6H_6-MeCN	1:1:1	0
2J	pinched cone	$CHCl_3$	1:5	0
6a	cone (**a**)	*p*-xylene	2:1	0
6b	1,2,3-alternate	–	–	–
20a	cone (**a**)	$C_2H_2Cl_4$	1:5	0
20b	1,2,3-alternate	$CHCl_3$	1:2	0
22a	cone (**a**)	THF	1:2	0
24a	cone (**a**)	–	–	–
25a'	cone (**a'**)	–	–	–
25b	1,2,3-alternate	C_6H_6	1:4	0
27c	partial cone	–	–	–
29a'	cone (**a'**)	–	–	–
32	(cone)	$CHCl_3$	1:2*	0
33	(cone)	$CHCl_3$	1:3	1
34	1,2,3-alternate	$CHCl_3$	1:2	0
35	cone (**a**)	C_6H_6	1:2	0

*Two chloroform molecules are located in the three sites.

It was also found that no solvent molecule is incorporated in the cavity of the calix[6]arene except for compound **33** bearing two (4-pyridyl)methyl groups in the diagonal positions (*vide infra*). This fact can be explained by the "self-inclusion"; the cavity is filled up by the bridging unit instead of the solvent molecules. Even if the substituent on the bridging unit is small enough to leave a vacant space in the cavity, one of the *tert*-butyl groups of the upper rim at the calix[6]arene collapses into the cavity to exclude the solvent molecules in many cases.

The packing diagrams of the crystal of isomers **20a** and **20b** are shown in Figure 2-8, looking down along the crystallographic *a* and *c* axes, respectively. It is of note that the calixarene molecules in the crystal of **20a** are completely surrounded by the solvent molecule, although the calixarenes are stacked along the *a* axis without the solvent molecules. On the other hand, the crystal of the 1,2,3-alternate isomer **20b** contains only two solvent molecules.



cone isomer **20a**
$C_{98}H_{109}BrN_4O_6{\cdot}5C_2H_2Cl_4$

1,2,3-alternate isomer **20b**
$C_{98}H_{109}BrN_4O_6{\cdot}2CHCl_3$

Figure 2-8. Packing diagrams of the two isomers of **20**.

2.8. Molecular mechanics calculations of the isomers

Figures 2-9 and 2-10 show the crystal structures of the two isomers of the pyridylmethyl derivative **20** (X = Br, Y = H). The ellipse made up of six benzene rings of cone isomer **20a** is somewhat larger than that of 1,2,3-alternate isomer **20b**, where the two non-bridged aromatic rings and the central benzene ring are almost parallel with the distance of about 3.5 Å.

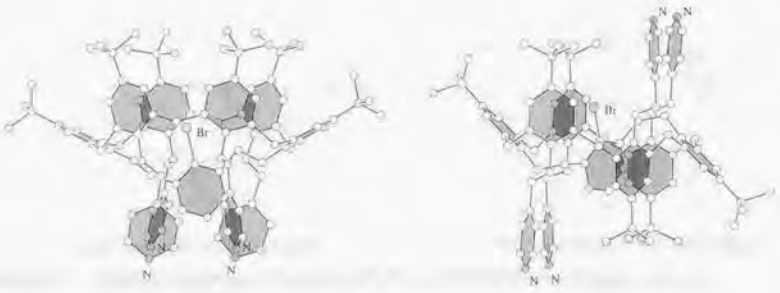


Figure 2-9. X-ray structures of isomers **20a** and **20b**.

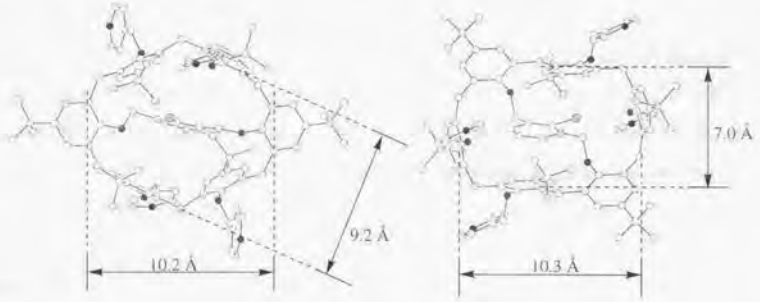
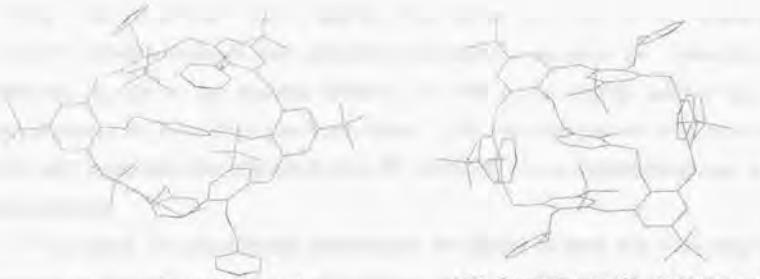


Figure 2-10. Top view of the molecular structures of **20a** and **20b**.

The molecular mechanics calculations of **20a** and **20b** were carried out using the molecular modeling system MacroModel V.6.5[39] with the MM3* force field. The lowest energy structures of both isomers were found to be essentially the same as their crystal structures in regard to the conformation of the calix[6]arene macrocycle and the bridging unit although there are small differences in the orientation of the 4-pyridylmethyl moieties (Figure 2-11). It was also found that the cone and the 1,2,3-alternate isomers have similar thermodynamic stability (337.33 vs 335.23 kJ mol^{-1}), indicating that the predominant formation of the cone isomer in the pyridylmethylation of **2** is due to the kinetic reasons.



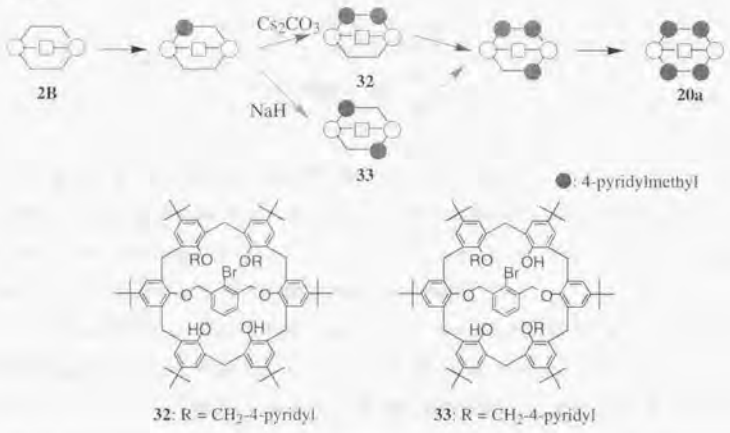
cone isomer **20a** (337.33 kJ/mol) 1,2,3-alternate isomer **20b** (335.23 kJ/mol

Figure 2-11. Energy-minimized structures of **20a** and **20b** (MM3*, GB/SA $CHCl_3$).

2.9. Intermediates

In order to understand the reason why the cone isomer is formed predominantly, the intermediates formed in these reactions were investigated using the reaction of **2B** with 4-(chloromethyl)pyridine as an example. Separation of the reaction mixture of **2B** and two equivalents of 4-(chloromethyl)pyridine hydrochloride using both of methods A and B gave some intermediary species (Scheme 2-9).

Scheme 2-9



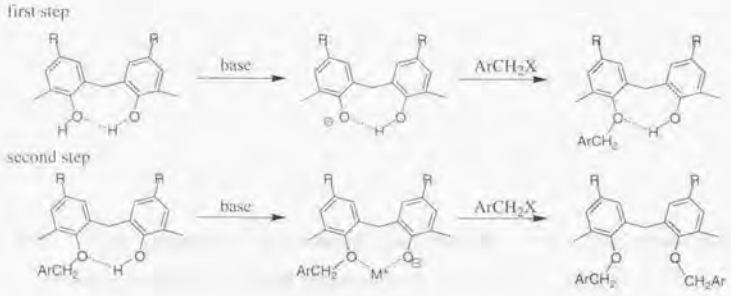
32: R = CH_2-4-pyridyl **33**: R = CH_2-4-pyridyl

When NaH was used as a base (conditions A), arylmethylation with two equivalents of 4-(chloromethyl)pyridine hydrochloride afforded a disubstituted derivative **33**, which has two pyridylmethyl groups in the diagonal positions, as well as the starting material and the tetrasubstituted products. On the other hand, when Cs_2CO_3 was employed as a base, the similar reaction gave a different disubstituted product **32**, which has two pyridylmethyl groups in the adjacent positions.

The reason why the different intermediates are formed in these two cases may have relationship to the hardness of the counter cations of bases. After the first alkylation, the interaction between the sodium cation and the remaining phenolate oxygen atom is so strong because of the hardness of the cation that the second alkylation on the same side of the bridge proceeds more slowly than that on the opposite side. On the other hand, interaction between a cesium cation and the remaining phenolate oxygen atom is weaker than the case of a sodium

cation, which results in the faster second alkylation on the same side (Scheme 2-10).

Scheme 2-10

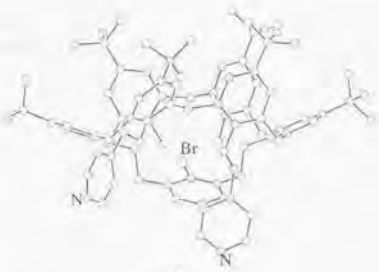


From the above analyses, the conformation of the tetrasubstituted product is considered to be determined in the second step. If the second arylmethyl group is introduced in the same orientation as the first one (*i.e. up* and *up*), the cone isomer is formed, and if the opposite direction (*i.e. up* and *down*), 1,2,3-alternate isomer is formed.

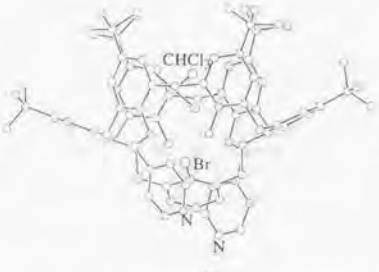
On considering the fact that the cone isomer was formed predominantly, the benzene rings of the calixarene framework are almost fixed in the same orientation during each step of the reaction. This can be explained in terms of the intramolecular hydrogen bonding or the chelation of metal cation between the oxygen atoms. The poor selectivity in the case of the reaction using NaH may result from two factors. One is that the slower reaction of the second step causes some conformational interconversion to the precursors of the isomers **b** and **c**. The other factor is that the reaction of the second step proceeds in the moiety separated by the bridging unit from the arylmethylated oxygen in the first step.

The structures of disubstituted products **32** and **33** were established by X-ray structural analyses (Figure 2-12). It was found that compound **32** exists in dimeric form[40] in the crystalline state (Figure 2-13); the two molecules were bound to each other by hydrogen bonds between the pyridine and the phenolic hydroxyl group (O-N: 2.81 Å) as well as the π - π stacking of the benzene rings of the central bridging unit (3.25 Å).

On the other hand, compound **33** exists in monomeric form in the crystalline state and the two hydroxy groups were involved in hydrogen bonding toward the adjacent ether oxygen atoms. It is of note that a chloroform molecule is incorporated in the large void cavity of **33**.



32



33

Figure 2-12. X-ray structures of disubstituted compounds **32** and **33**. Disordered atoms and solvent molecules are omitted except for that incorporated in the cavity of **33**.

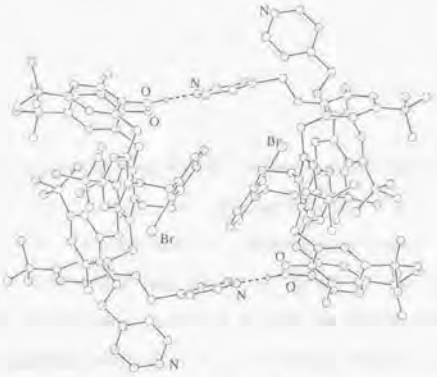
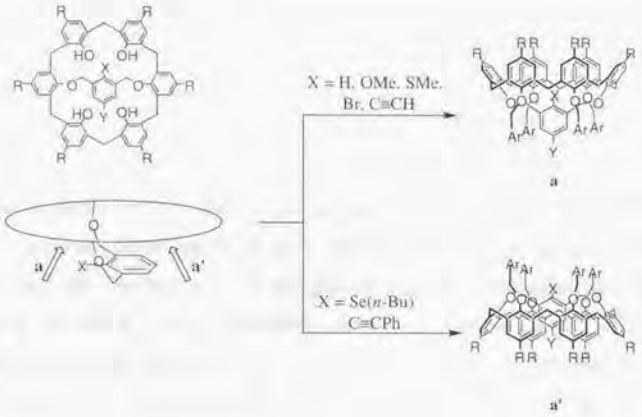


Figure 2-13. X-ray structure of **32** showing its dimeric form.

There are two kinds of cone isomers **a** and **a'** of the tetrasubstituted products. The bulkiness of the substituents on the bridging unit is considered as a factor determining which isomer is formed. The tetrahydroxy compounds **2** adopt the conformation with the bridging unit lying under the macrocycle irrespective of the bulkiness of the substituents X and Y, neither of which is directed into the cavity. When the group X is small, the X position of the bridging unit gets into the cavity during the arylmethylation reaction to form the isomer **a** whereas the aromatic ring of the bridging unit gets into the cavity instead of the X group (Scheme 2-11) when the group X is bulkier and Y is small.

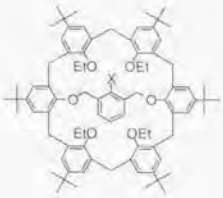
Scheme 2-11



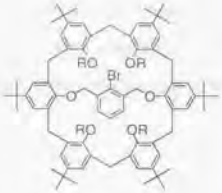
2.10. Conformational interconversion and the bulkiness of the lower rim substituents

In the author's group, it was previously demonstrated that the conformations of the benzylated bridged calix[6]arenes **6** are fixed at room temperature and even at 120 °C in 1,1,2,2-tetrachloroethane-d_2.[28d] This means that the benzyl groups at the lower rim have enough bulkiness to prevent the ring inversion (lower-rim through the annulus inversion). On the other hand, bulkiness of the upper-rim substituents is not necessary, which was established by the fact that the conformational interconversion did not occur when compounds **22a** and **22b** without *tert*-butyl groups at the upper rim were heated at 140 °C in toluene-d_8.

How large substituents at the lower rim are needed to freeze the conformation of the bridged calix[6]arenes? Methyl groups are not enough to restrict the conformation, as is clear from the ^{1}H NMR signals of **37**, which are broadened due to the conformational interconversion even at room temperature.[28b,f] The corresponding ethyl derivatives **34** (X = Br) and **35** (X = C≡CH) and allyl derivatives **36** were synthesized and their properties were investigated.

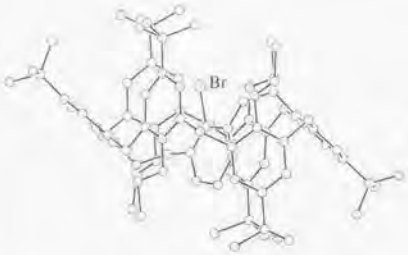


34: X = Br
35: X = C≡CH

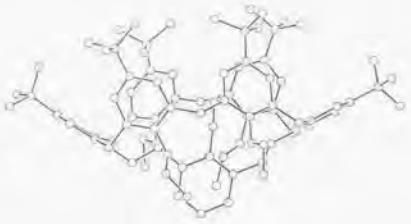


36: R = allyl
37: R = Me

The ^{1}H NMR spectra of ethyl derivatives **34** (X = Br) and **35** (X = C≡CH) showed well-resolved, sharp signals which can be assigned to both two isomers (cone and 1,2,3-alternate, 28/72 (**34**), 40/60 (**35**)), but they were not separable by silica gel chromatography unlike the case of benzylated analogs **6**. In the crystalline state, compound **34** adopts a 1,2,3-alternate conformation whereas **35** adopts a cone conformation, which was confirmed by the X-ray analyses (Figure 2-14). The ratio of the isomers (cone/1,2,3-alternate) of **34** was 28/72 even when the NMR spectrum was measured only 10 minutes after the crystals of the 1,2,3-alternate isomer were dissolved in $CDCl_3$. This fact indicates that the conformational interconversion occurs on the time scale slower than the NMR time scale (order of 1 second) but faster than the time scale of 10 minutes.



34

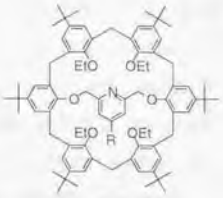


35

Figure 2-14. X-ray structures of **34** and **35**. Disordered atoms and the solvent molecules are omitted for clarity.

On the other hand, two isomers (cone and 1,2,3-alternate) of allyl derivative **36** were separated by silica gel chromatography. The isomers of **36**, however, underwent very slow

conformational interconversion at room temperature in $CDCl_3$ with a half-life time of about 2 weeks. This suggests that the thermally stable isomer can be synthesized by the reaction at a slightly elevated temperature and subsequent conversion of the allyl groups to bulkier groups.



38: R = H
39: R = OMe

Lüning's group has also reported that two conformers were observed for ethyl derivative **38** while **39** was isolated as a conformationally pure compound. They concluded that the lack of isomerism of **39** is ascribed to the OMe group on the bridging unit.[27e] It is obvious, however, that compound **39** only fell to a thermodynamically stable cone conformation among the possible conformers. The present study on conformational mobility of the compounds with alkyl groups of various sizes demonstrated that the substituents as bulky as benzyl groups at the lower rim are necessary to freeze the conformation of the bridged calix[6]arene derivatives.

Experimental

General. Melting points were determined on a Yanaco micro melting point apparatus. All melting points were uncorrected. THF was purified by distillation from sodium diphenylketyl under argon atmosphere before use. Dichloromethane and carbon tetrachloride were distilled from calcium hydride. Diethylamine was dried over KOH pellets before use. DMF (special grade) was purchased from Wako Pure Chemical Industries Ltd. and used without purification. Acetone and ethanol (technical grade) were used without purification. Column chromatography and preparative TLC were carried out with Wakogel C-200 and Merck Kieselgel 60PF254 Art. 7747, respectively. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker DRX-500, a JEOL JNM-A500, and a JEOL EX-AL270 spectrometers. ^{1}H and ^{13}C NMR chemical shifts were referenced to the resonances of tetramethylsilane. Assignments of NMR signals were based on 2D-COSY, HMQC, and HMBC spectra. Mass spectra were recorded on a JEOL SX-102 mass spectrometer. Elemental analyses were performed by the Microanalytical Laboratory of the Department of Chemistry, Faculty of Science, the University of Tokyo.

Materials. 5,11,17,23,29,35-Hexa-*tert*-butyl-37,38,39,40,41,42-hexahydroxycalix[6]arene (**1**),[9h] 2-bromo-1,3-bis(bromomethyl)benzene (**7B**),[34] 1,3-bis(bromomethyl)-2-(butylseleno)-benzene (**7I**),[28f] 2-iodo-1,3-dimethylbenzene (**9**),[41] and 37,38,40,41-tetrahydroxy-39,42-[2-bromo-1,3-phenylenebis(methylenoxy)]calix[6]arene (**14**)[28i] were prepared according to the literatures. 1,3-Bis(bromomethyl)benzene (**7A**), 1-bromo-3,5-dimethylbenzene (**8C**), 4-methoxyphenol (**10F**), 4-bromophenol (**10G**), 4-bromo-2,6-dimethylaniline (**13**), were purchased from Tokyo Chemical Industry Co., Ltd. Phenylacetylene is purchased from Aldrich. Ethynyltrimethylsilane is a gift from ShinEtsu Chemicals.

Preparation of 1-bromo-3,5-bis(bromomethyl)benzene (7C).[35] A mixture of 1-bromo-3,5-dimethylbenzene (**8C**) (3.4 mL, 25 mmol), *N*-bromosuccinimide (10.8 g, 61 mmol), and benzoyl peroxide (240 mg, 1 mmol) in carbon tetrachloride (20 mL) was refluxed for 10 h. After filtration of succinimide and the removal of the solvent, the residue was recrystallized from hexane to afford **7C** (2.40 g, 28%) as colorless crystals, mp 96-98 °C (lit.[35] mp 95-98 °C); ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.42 (s, 4H), 7.34 (t, J = 1.3 Hz, 1H), 7.47 (d, J = 1.3 Hz, 1H).

Preparation of (2,6-dimethylphenylethynyl)trimethylsilane (8D). To a solution of 2-iodo-1,3-dimethylbenzene (**9**)[41] (4.65 g, 20 mmol), copper(I) iodide (100 mg, 0.52 mmol), and ethynyltrimethylsilane (4.2 mL, 30 mmol) in diethylamine (25 mL) was added tetrakis-(triphenylphosphine)palladium (300 mg, 0.26 mmol) and the mixture was stirred at 50 °C for 24

h. After removal of the solvent and addition of water, the mixture was extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. Chromatography on silica gel (hexane) afforded the colorless liquid (3.72 g, 92%) with enough purity for the next reaction. **8D**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.26 (s, 9H), 2.42 (s, 6H), 7.01 (d, J = 7.5 Hz, 2H), 7.09 (t, J = 7.5 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 0.16 (q), 20.99 (q), 102.76 (s), 102.81 (s), 112.97 (s), 126.55 (d), 127.80 (d), 140.63 (s).

Preparation of [2,6-bis(bromomethyl)phenylethynyl]trimethylsilane (7D). A mixture of **8D** (1.0 g, 5.0 mmol), *N*-bromosuccinimide (3.13 g, 18 mmol), and benzoyl peroxide (100 mg, 0.4 mmol) in carbon tetrachloride (10 mL) was refluxed for 7 h. After filtration of succinimide and removal of the solvent, the residue was chromatographed on silica gel (hexane) to afford colorless crystals of **7D** (620 mg, 34%), mp 50-52 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.35 (s, 9H), 4.67 (s, 4H), 7.23 (t, J = 7.7 Hz, 1H), 7.34 (d, J = 7.7 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ –0.29 (q), 31.57 (t), 98.63 (s), 107.37 (s), 122.81 (s), 128.74 (d), 129.54 (d), 140.27 (s). Anal. Calcd for $C_{13}H_{16}Br_2Si$: C, 43.35; H, 4.48; Br, 44.37. Found: C, 43.16; H, 4.37; Br, 44.18.

Preparation of 1,3-dimethyl-2-(phenylethynyl)benzene (8E).[36] Compound **8E** was prepared from **9** (4.65 mL, 20 mmol) and phenylacetylene (2.6 mL, 24 mmol) in a manner similar to that of **8D** in 71% yield. **8E**: colorless liquid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.51 (s, 6H), 7.07 (d, J = 7.5 Hz, 2H), 7.12 (t, J = 7.5 Hz, 1H), 7.33-7.37 (m, 3H), 7.52-7.55 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.08 (q), 87.16 (s), 97.85 (s), 123.01 (s), 123.90 (s), 126.70 (d), 127.76 (d), 128.07 (d), 128.35 (d), 131.40 (d), 140.27 (s).

Preparation of 1,3-bis(bromomethyl)-2-(phenylethynyl)benzene (7E).[36] Compound **7E** was prepared from **8E** (2.78 g, 13.5 mmol) in a manner similar to that of **7D** in 9% yield. **7E**: colorless crystals, mp 137-139 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.75 (s, 4H), 7.30 (t, J = 7.7 Hz, 1H), 7.40-7.44 (m, 5H), 7.64-7.66 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 31.90 (t), 83.54 (s), 101.27 (s), 122.73 (s), 123.29 (s), 128.51 (d), 128.67 (d), 128.97 (d), 129.78 (d), 131.63 (d), 139.98 (s). Anal. Calcd for $C_{16}H_{12}Br_2$: C, 52.78; H, 3.32; Br, 43.89. Found: C, 52.75; H, 3.38; Br, 43.48.

Preparation of 2,6-bis(hydroxymethyl)-4-methoxyphenol (11F).[42] To a solution of *p*-methoxyphenol (**10F**, 12.4 g, 100 mmol) and sodium hydroxide (5.0 g, 12.5 mmol) in water (100 mL) was added a 37% formalin (40 mL) and the mixture was stirred at room temperature for 1 month. After neutralization with acetic acid, the mixture was extracted with ethyl acetate, dried over $MgSO_4$, and evaporated to dryness. The residue was washed with water and dried to give

11F (8.68 g, 47%) as colorless crystals, mp 125-127 °C (lit.[43] mp 127-128 °C); ^{1}H NMR (270 MHz, $CDCl_3$) δ 2.59 (brs, 2H), 3.75 (s, 3H), 4.77 (s, 4H), 6.63 (s, 2H), 7.64 (s, 1H); ^{13}C NMR (125 MHz, acetone-d_6) δ 55.73 (q), 62.08 (t), 112.24 (d), 128.77 (s), 148.01 (s), 153.65 (s).

Preparation of 1,3-bis(hydroxymethyl)-2,5-dimethoxybenzene (12F).[43] Compound **12F** was prepared from **11F** (4.62 g, 25 mmol) by the reported procedure in 76% method **12F**: colorless crystals, mp 106-108 °C (lit.[43] 106-108 °C); ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.04 (t, J = 6.0 Hz, 2H), 3.80 (s × 2, 6H), 4.72 (d, J = 6.0 Hz, 4H), 6.88 (s, 2H); ^{13}C NMR (125 MHz, acetone-d_6) δ 55.60 (q), 59.59 (t), 61.98 (q), 112.90 (d), 136.79 (s), 149.35 (s), 156.93 (s).

Preparation of 1,3-bis(bromomethyl)-2,5-dimethoxybenzene (7F).[37] To a solution of **12F** (994 mg, 5.0 mmol) and carbon tetrabromide (3.64 g, 11 mmol) in dichloromethane (25 mL) was added triphenylphosphine (2.89 g, 11 mmol) and the mixture was stirred for 1.5 h at room temperature. After addition of aq. $NaHCO_3$, the mixture was extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. Chromatography (silica gel, chloroform/hexane, 1:1) followed by recrystallization (hexane) afforded brominated compound **7F** (1.09 g, 67%) as colorless crystals, mp 100-101 °C (lit.[37] mp 90-92.5 °C); ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.79 (s, 3H), 3.96 (s, 3H), 4.52 (s, 4H), 6.89 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.54 (t), 55.63 (q), 62.31 (q), 117.06 (d), 132.56 (s), 150.10 (s), 155.88 (s).

Preparation of 4-bromo-2,6-bis(hydroxymethyl)phenol (11G).[35h] To a solution of *p*-bromophenol (**10G**, 12.5 g, 72 mmol) and KOH (4.6 g, 82 mmol) in water (12 mL) was added a 37% formalin (17 mL) and the mixture was stirred at room temperature for 2 weeks. The mixture was neutralized with hydrochloric acid, and the precipitation was collected and dried to give **11G** (12.4 g, 74%) as colorless crystals, mp 163-167 °C (lit.[35h] 164-168 °C); ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.36 (brt, 2H), 4.79 (d, J = 5.1 Hz, 4H), 7.22 (s, 2H), 8.07 (s, 1H) ; ^{13}C NMR (125 MHz, acetone-d_6) δ 61.32 (t), 111.62 (s), 129.20 (d), 130.44 (s), 153.41 (s).

Preparation of 5-bromo-1,3-bis(hydroxymethyl)-2-methoxybenzene (12G). To a suspension of **11G** (4.67 g, 20 mmol), K_2CO_3 (5.53 g, 40 mmol) in acetone (100 mL) was added iodomethane (4 mL, 62 mmol) and the mixture was stirred for 3 d at room temperature. After addition of water, the mixture was extracted with ethyl acetate, dried over $MgSO_4$, and evaporated to dryness. The residue was recrystallized from acetone/hexane to afford methylated product **12G** (3.83 g, 77%) as colorless crystals, mp 131-134 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.98 (brt, 2H), 3.83 (s, 3H), 4.72 (d, J = 4.9 Hz, 2H), 7.50 (s, 2H); ^{13}C NMR (125 MHz, acetone-d_6) δ 58.98 (t), 61.95 (q), 117.31 (s), 130.42 (d), 138.56 (s), 154.81 (s). Anal. Calcd for

$C_9H_{11}BrO_3$: C, 43.75; H, 4.49. Found: C, 44.25; H, 4.40.

Preparation of 5-bromo-1,3-bis(bromomethyl)-2-methoxybenzene (7G).[38] To a solution of **12G** (2.48 mg, 10.0 mmol) and carbon tetrabromide (6.66 g, 20 mmol) in dichloromethane (50 mL) was added triphenylphosphine (5.54 g, 21 mmol) and the mixture was stirred for 2 h at room temperature. After addition of aq. $NaHCO_3$, the mixture was extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. Chromatography (silica gel, chloroform/hexane, 1:1) followed by recrystallization (hexane) afforded the brominated compound **7F** (2.56 g, 69%) as colorless crystals, mp 85-87 °C (lit.[38] mp 82-83 °C); ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.00 (s, 3H), 4.48 (s, 4H), 7.49 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 62.35 (t), 117.21 (s), 133.97 (s), 134.74 (d), 155.58 (s).

Preparation of 4-bromo-2,6-dimethylphenyl methyl sulfide (8H). To a mixture of 4-bromo-2,6-dimethylaniline (**13**, 10 g, 50 mmol) and concentrated sulfuric acid (3 mL) in water (100 mL) was added an aqueous solution of sodium nitrite (3.7 g, 100 mmol). After stirring for 30 min at 0-5 °C, the mixture was added dropwise to a solution of potassium xanthate (14 g, 87 mmol) in water (50 mL) with vigorous stirring at 50 °C. After stirring for 2 h at 50 °C, the mixture was extracted with hexane, dried over $MgSO_4$, and evaporated to give a red oil. The oil was then dissolved in THF (50 mL) under argon, which was transferred into a suspension of lithium aluminum hydride (3.7 g, 100 mmol) in THF (50 mL) at 0 °C. After stirring for 30 min at room temperature, ethyl acetate was carefully added and the mixture was neutralized with 2 M aq. HCl. The mixture was extracted with hexane, dried over $MgSO_4$, and evaporated to give a crude product of 4-bromo-2,6-dimethylbenzenethiol. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.33 (s, 6H), 3.19 (s, 1H), 7.19 (s, 2H). The crude thiol was then dissolved in a solution of KOH (3.6 g, 64 mmol) in water (2 mL) and ethanol (100 mL), and to the mixture was added iodomethane (7.5 mL, 120 mmol) with stirring. After removal of the solvent and addition of water, the mixture was extracted with hexane, dried over $MgSO_4$, and evaporated to dryness. The residue was subjected to silica gel chromatography (hexane) to afford colorless liquid of **8H** (6.37 g, 55% from **13**) with enough purity for the next reaction. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.20 (s, 3H), 2.52 (s, 6H), 7.25 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 18.11 (q), 21.48 (q), 122.09 (s), 130.68 (d), 134.30 (s), 144.57 (s).

Preparation of 4-bromo-2,6-bis(bromomethyl)phenyl methyl sulfide (7H). A mixture of **8H** (2.31 g, 10 mmol), *N*-bromosuccinimide (5.41 g, 30 mmol), benzoyl peroxide (500 mg, 2 mmol) in carbon tetrachloride (25 mL) was refluxed for 6 h. After filtration of succinimide and

removal of the solvent, the residue was chromatographed on silica gel (hexane) to afford colorless crystals, which was recrystallized from hexane to give **7H** (1.25 g, 32%) as colorless crystals, mp 127-129 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.46 (s, 3H), 4.85 (s, 4H), 7.62 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 20.22 (q), 31.35 (t), 123.36 (s), 134.10 (d), 135.03 (s), 145.03 (s). Anal. Calcd for $C_9H_8Br_2S$: C, 27.79; H, 2.33; Br, 61.63; S, 8.24. Found: C, 27.75; H, 2.32; Br, 61.91; S, 8.09.

General procedure of the bridging reaction (for 2A and 2C). To a suspension of sodium hydride (60% in oil, 240 mg, 6 mmol) in THF (5 mL) was added a solution of *p-tert*-butylcalix[6]arene (**1**) (973 mg, 1.0 mmol) in THF (85 mL) and DMF (10 mL). After the mixture was stirred at room temperature for 2 h, a solution of dibromide **7** (1.0 mmol) in THF (10 mL) was added dropwise at room temperature, and the reaction mixture was refluxed for 24 h. After addition of water, the mixture was poured into 1 M aq. HCl, extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. Chromatographic separation on silica gel (hexane/chloroform, 1:1) followed by recrystallization (chloroform/methanol) afforded bridged calix[6]arene **2**.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,40-[1,3-phenylenebis(methylenoxy)]calix[6]arene-38,39,41,42-tetrol (2A):[25a] yield, 68%.

37,40-[5-Bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]-arene-38,39,41,42-tetrol (2C): yield, 91%; colorless crystals, mp 240 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.20 (s, 18H), 1.27 (s, 36H), 3.33 (d, J = 13.6 Hz, 2H), 3.50 (d, J = 13.4 Hz, 4H), 4.18 (d, J = 13.6 Hz, 2H), 4.27 (d, J = 13.4 Hz, 4H), 5.23 (s, 4H), 7.11 (s, 8H), 7.13 (s, 4H), 7.29 (s, 2H), 8.46 (s, 1H), 8.90 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 31.29 (q), 31.64 (q), 32.89 (t), 33.07 (t), 33.91 (s), 34.28 (s), 76.14 (t), 121.80 (s), 122.04 (d), 125.26 (d), 125.98 (d), 126.47 (d), 127.19 (s), 127.57 (s), 128.48 (d), 132.18 (s), 140.34 (s), 142.71 (s), 148.09 (s), 149.80 (s), 149.82 (s). Anal. Calcd for $C_{74}H_{89}BrO_6 \cdot 2H_2O$: C, 74.66; H, 7.87; Br, 6.71. Found: C, 74.88; H, 7.45; Br, 7.49.

General procedure of the bridging reaction (for 2B, 2E, 2F, 2G, 2H, and 2J). To a suspension of potassium hydroxide (85%, 330 mg, 5 mmol) and *p-tert*-butylcalix[6]arene (**1**) (245 mg, 0.25 mmol) in THF (100 mL) and DMF (10 mL), which was stirred at room temperature for 1 h, was added dibromide **7** (0.25 mmol) and the mixture was stirred at room temperature for 24 h. After removal of the solvent, the residue was treated with aq. NH_4Cl, extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. The residue was

purified by chromatography if necessary, and recrystallized from chloroform/methanol to afford bridged compound **2**.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]-arene -38,39,41,42-tetrol (2B):[28f] purified by recrystallization, yield, 89%.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,40-[2-ethynyl-1,3-phenylenebis(methylenoxy)]calix[6]-arene-38,39,41,42-tetrol (2J): purified by recrystallization, yield, 96%; colorless crystals, mp 245 °C (dec); ^{1}H NMR (270 MHz, $CDCl_3$, –20 °C) δ 1.19 (s, 18H), 1.23 (s, 18H), 1.28 (s, 18H), 3.21 (d, J = 13.7 Hz, 1H), 3.27 (d, J = 13.6 Hz, 1H), 3.47 (s, 1H), 3.52 (d, J = 13.0 Hz, 2H), 3.57 (d, J = 13.3 Hz, 2H), 3.98 (d, J = 13.7 Hz, 1H), 4.15 (d, J = 13.6 Hz, 1H), 4.18 (d, J = 13.0 Hz, 2H), 4.72 (d, J = 9.6 Hz, 2H), 4.80 (d, J = 13.3 Hz, 2H), 5.96 (d, J = 9.6 Hz, 2H), 7.01 (d, J = 2.3 Hz, 2H), 7.09 (s, 4H), 7.11-7.16 (m, 6H), 7.36 (t, J = 7.5 Hz, 1H), 7.53 (d, J = 7.5 Hz, 2H), 8.77 (s, 2H), 8.90 (s, 2H); ^{13}C NMR (68 MHz, $CDCl_3$, –20 °C) δ 31.20 (q), 31.56 (q ×2), 32.69 (t), 32.91 (t), 33.23 (t), 33.49 (t), 33.75 (s), 33.86 (s), 34.18 (s), 77.38 (t), 80 76 (d), 86.71 (s), 123.76 (s), 125.16 (d), 125.34 (d), 125.60 (d), 125.82 (d), 125.85 (d), 126.24 (d), 126.57 (s), 126.69 (s), 127.28 (s), 127.93 (s), 129.18 (d), 130.65 (d), 131.97 (s), 133.05 (s), 140.08 (s), 141.77 (s), 142.13 (s), 147.43 (s), 149.54 (s), 149.91 (s), 150.15 (s). Anal. Calcd for $C_{76}H_{90}O_6 \cdot H_2O$: C, 81.68; H, 8.30. Found: C, 81.39; H, 8.06.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,40-[2-phenylethynyl-1,3-phenylenebis(methylenoxy)]-calix[6]arene-38,39,41,42-tetrol (2E): purified by recrystallization, yield, 76%; colorless crystals, mp 259-262 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.17 (s, 18H), 1.25 (s, 18H), 1.26 (s, 18H), 3.22 (d, J = 13.7 Hz, 1H), 3.23 (d, J = 13.7 Hz, 1H), 3.31 (d, J = 13.4 Hz, 2H), 3.51 (d, J = 13.0 Hz, 2H), 3.98 (d, J = 13.7 Hz, 1H), 4.03 (d, J = 13.7 Hz, 1H), 4.28 (d, J = 13.0 Hz, 2H), 4.69 (d, J = 13.4 Hz, 2H), 4.74 (d, J = 9.5 Hz, 2H), 6.04 (d, J = 9.5 Hz, 2H), 6.52 (t, J = 7.6 Hz, 2H), 6.70 (d, J = 7.6 Hz, 2H), 6.82 (d, J = 2.3 Hz, 2H), 6.83 (t, J = 7.6 Hz, 1H), 7.018 (d, J = 2.4 Hz, 2H), 7.022 (d, J = 2.4 Hz, 2H), 7.07 (d, J = 2.3 Hz, 2H), 7.09 (d, J = 2.4 Hz, 2H), 7.13 (d, J = 2.4 Hz, 2H), 7.35 (t, J = 7.6 Hz, 1H), 7.58 (d, J = 7.6 Hz, 2H), 8.66 (s, 2H), 8.85 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 31.29 (q), 31.65 (q), 31.69 (q), 32.31 (t), 33.22 (t), 33.56 (t), 33.75 (t), 33.83 (s ×2), 34.22 (s), 77.58 (t), 86.39 (s), 97.42 (s), 121.89 (s), 124.94 (d), 125.25 (d), 125.41 (d), 125.94 (d), 125.97 (d), 126.21 (d), 126.79 (s), 127.09 (s), 127.15 (s), 127.18 (d), 127.59 (s), 127.74 (d), 128.82 (d), 131.06 (d), 131.34 (d), 132.20 (s), 133.33 (s), 139.56 (s), 141.91 (s), 142.20 (s), 147.63 (s), 149.99 (s), 150.19 (s), 150.37 (s). Anal. Calcd for $C_{82}H_{94}O_6 \cdot H_2O$: C, 82.51; H, 8.11. Found: C, 82.69; H, 8.04.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,40-[2,5-dimethoxy-1,3-phenylenebis(methylenoxy)]-calix[6]arene-38,39,41,42-tetrol (2F): purified by recrystallization, yield, 88%; colorless crystals, mp 212-215 °C; ^{1}H NMR (270 MHz, $CDCl_3$, –50 °C) δ 1.20 (s, 18H), 1.23 (s, 18H), 1.29 (s, 18H), 3.21 (d, J = 13.5 Hz, 1H), 3.31 (d, J = 13.8 Hz, 1H), 3.49 (d, J = 13.8 Hz, 2H), 3.63 (d, J = 12.8 Hz, 2H), 3.83 (s, 3H), 3.96 (s, 3H), 4.04 (d, J = 13.5 Hz, 1H), 4.15 (d, J = 13.0 Hz, 2H), 4.23 (d, J = 13.8 Hz, 1H), 4.58 (d, J = 10.0 Hz, 2H), 4.65 (d, J = 12.8 Hz, 2H), 5.83 (d, J = 10.0 Hz, 2H), 6.91 (s, 2H), 7.03 (brd, 2H), 7.08 (brd, 2H), 7.12 (brd, 2H), 7.14 (brd, 2H), 7.15 (brd, 2H), 7.20 (brd 2H), 8.99 (s, 2H), 9.06 (s, 2H); ^{13}C NMR (68 MHz, $CDCl_3$, –50 °C) δ 31.15 (q), 31.49 (q × 2), 32.66 (t), 32.83 (t), 33.09 (t), 33.19 (t), 33.69 (s), 33.81 (s), 34.14 (s), 55.29 (q), 60.97 (q), 75.36 (t), 116.61 (d), 125.10 (d), 125.22 (d), 125.54 (d), 125.64 (d), 125.73 (d), 126.16 (d), 126.64 (s), 126.69 (s), 127.16 (s), 127.45 (s), 131.34 (s), 131.83 (s), 132.84 (s), 141.58 (s), 141.95 (s), 147.14 (s), 149.71 (s), 149.84 (s), 150.14 (s), 153.11 (s), 154.49 (s). Anal. Calcd for $C_{76}H_{98}O_8 \cdot H_2O$: C, 79.13; H, 8.39. Found: C, 79.42; H, 8.25.

37,40-[5-Bromo-2-methoxy-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-calix[6]arene-38,39,41,42-tetrol (2G): purified by recrystallization, yield, 73%; colorless crystals, mp 222-224 °C; ^{1}H NMR (270 MHz, $CDCl_3$, –50 °C) δ 1.20 (s, 18H), 1.23 (s, 18H), 1.29 (s, 18H), 3.22 (d, J = 13.8 Hz, 1H), 3.32 (d, J = 13.3 Hz, 1H), 3.52 (d, J = 13.2 Hz, 2H), 3.63 (d, J = 12.8 Hz, 2H), 4.02 (s, 3H), 4.04 (d, J = 13.8 Hz, 1H), 4.06 (d, J = 13.2 Hz, 1H), 4.22 (d, J = 13.3 Hz, 2H), 4.59 (d, J = 10.4 Hz, 2H), 4.61 (d, J = 12.8 Hz, 2H), 5.81 (d, J = 10.4 Hz, 2H), 7.04 (brd, 2H), 7.09 (brd, 2H), 7.13 (brd, 2H), 7.15 (brd ×2, 4H), 7.20 (brd, 2H), 7.53 (s, 2H), 8.93 (s, 2H), 9.00 (s, 2H); ^{13}C NMR (68 MHz, $CDCl_3$, –50 °C) δ 31.15 (q), 31.49 (q ×2), 32.69 (t), 32.75 (t), 32.98 (t), 33.15 (t), 33.71 (s), 33.84 (s), 34.17 (s), 60.12 (q), 74.70 (t), 116.23 (s), 125.12 (d), 125.27 (d), 125.62 (d), 125.74 (d ×2), 126.26 (d), 126.53 (s), 126.67 (s), 126.98 (s), 127.39 (s), 131.80 (s), 132.67 (s), 132.71 (s), 134.59 (d), 141.75 (s), 142.07 (s), 147.38 (s), 149.53 (s), 149.71 (s), 150.03 (s), 158.192 (s). Anal. Calcd for $C_{75}H_{91}BrO_7$: C, 74.92; H, 7.80; Br, 6.65. Found: C, 74.93; H, 7.77; Br, 7.26.

37,40-[5-Bromo-2-methylthio-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene-38,39,41,42-tetrol (2H): purified by chromatography on silica gel (hexane/chloroform, 1:1) followed by recrystallization, yield, 68%; colorless crystals, mp 238 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.19 (s, 18H), 1.24 (s, 18H), 1.28 (s, 18H), 2.31 (s, 3H), 3.21 (d, J = 13.7 Hz, 1H), 3.27 (d, J = 13.6 Hz, 1H), 3.51 (d, J = 13.2 Hz, 2H), 3.54 (d, J = 13.4 Hz, 2H), 3.95 (d, J = 13.7 Hz, 1H), 4.06 (d, J = 13.6 Hz, 1H), 4.14 (d, J = 13.4 Hz, 2H), 4.63 (d, J

= 9.4 Hz, 2H), 4.94 (d, *J* = 13.2 Hz, 2H), 5.96 (d, *J* = 9.4 Hz, 2H), 7.01 (d, *J* = 2.2 Hz, 2H), 7.08 (d, *J* = 2.2 Hz, 2H), 7.10 (d, *J* = 2.2 Hz, 2H), 7.11 (d, *J* = 2.2 Hz, 2H), 7.13 (d, *J* = 2.2 Hz, 2H), 7.14 (d, *J* = 2.2 Hz, 2H), 7.71 (s, 2H), 8.69 (s, 2H), 8.70 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 22.12 (q), 31.29 (q), 31.65 (q), 31.67 (q), 32.90 (t), 33.12 (t), 33.56 (t), 33.60 (t), 33.86 (s), 33.91 (s), 34.27 (s), 77.31 (t), 122.89 (s), 125.28 (d), 125.43 (d), 125.75 (d), 126.01 (d), 126.08 (d), 126.33 (d), 126.82 (s), 127.13 (s), 127.59 (s), 127.77 (s), 132.33 (s), 133.38 (s), 134.94 (d), 139.69 (s), 142.09 (s), 142.39 (s), 142.65 (s), 143.85 (s), 147.68 (s), 147.94 (s), 149.35 (s). Anal. Calcd for $C_{75}H_{91}BrO_6S \cdot H_2O$: C, 73.93; H, 7.69; S, 2.63. Found: C, 73.65; H, 7.41; S, 2.99.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,40-[2-(butylseleno)-1,3-phenylenebis(methylenoxy)]-calix[6]arene-38,39,41,42-tetrol (2l):[280] purified by chromatography on silica gel (hexane/chloroform, 1:1) followed by recrystallization, yield, 80%.

General procedure of the arylmethylation (method A). To a suspension of NaH (60% in oil, 160 mg, 4.0 mmol) in THF (1 mL) was added a solution of bridged calixarene **2** (0.20 mmol) in THF (9 mL) and DMF (1 mL). After the mixture was stirred at room temperature for 1 h, arylmethyl halides (1.2-4.0 mmol) were added and the reaction mixture was refluxed for 2 d. After the addition of water, the mixture was poured into aq. NH_4Cl, extracted with chloroform, and dried over $MgSO_4$. After removal the solvent, the crude product was separated by preparative TLC.

General procedure of the arylmethylation (method B). To a suspension of bridged calix[6]arene **2** (0.20 mmol) and cesium carbonate (790 mg, 2.4 mmol) in DMF (20 mL) were added arylmethyl halides (1.2-4.0 mmol) and the reaction mixture was stirred at 70 °C for 1-2 d. After addition of aq. NH_4Cl, the mixture was extracted with chloroform, dried over $MgSO_4$ and the solvent was evaporated to dryness. The crude product was purified by recrystallization or separated by preparative TLC.

38,39,41,42-Tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butyl-37,40-[1,3-phenylenebis-(methylenoxy)]calix[6]arene (15). Method A: **a**, 63%; **b**, 1%; **c**, 5%. Method B: **a**, 89%.

15a: colorless crystals, mp 211-215 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 36H), 1.41 (s, 18H), 3.21 (d, *J* = 14.3 Hz, 2H), 3.34 (d, *J* = 15.4 Hz, 4H), 4.18 (s, 4H), 4.38 (d, *J* = 14.3 Hz, 2H), 4.42 (d, *J* = 15.4 Hz, 4H), 4.48 (d, *J* = 12.2 Hz, 4H), 4.57 (d, *J* = 12.2 Hz, 4H), 5.61 (s, 1H), 6.83 (d, *J* = 1.9 Hz, 4H), 6.96 (d, *J* = 1.9 Hz, 4H), 6.97 (d, *J* = 7.0 Hz, 8H), 7.00 (t, *J* = 6.9 Hz, 1H), 7.06 (d, *J* = 6.9 Hz, 2H), 7.07-7.14 (m, 12H), 7.28 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.65 (t), 30.51 (t), 31.30 (q), 31.67 (q), 34.06 (s), 34.25 (s), 71.74 (t), 74.75 (t), 121.13 (d), 122.82 (d),

124.40 (d), 125.13 (d), 126.76 (d), 126.95 (d), 127.18 (d), 127.80 (d), 127.92 (d), 132.59 (s), 133.04 (s), 133.38 (s), 137.94 (s), 138.20 (s), 145.31 (s), 145.90 (s), 152.04 (s), 152.93 (s). Anal. Calcd for $C_{102}H_{114}O_6 \cdot CHCl_3$: C, 79.54; H, 7.45. Found: C, 79.34, H, 7.52.

15b: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 50 °C) δ 0.93 (s, 36H), 1.29 (s, 18H), 3.35 (d, J = 15.6 Hz, 4H), 3.71 (s, 4H), 3.76 (s, 4H), 4.32 (d, J = 15.6 Hz, 4H), 4.66 (s, 1H), 4.78 (d, J = 11.0 Hz, 4H), 4.90 (d, J = 11.0 Hz, 4H), 5.30 (d, J = 7.3 Hz, 2H), 6.08 (t, J = 7.3 Hz, 1H), 6.54 (d, J = 2.1 Hz, 4H), 7.06 (d, J = 2.1 Hz, 4H), 7.09 (s, 4H), 7.34 (t, J = 7.2 Hz, 4H), 7.41 (t, J = 7.2 Hz, 8H), 7.58 (d, J = 7.2 Hz, 8H); ^{13}C NMR (125 MHz, $CDCl_3$, 50 °C) δ 29.87 (t), 31.36 (q), 31.63 (q), 34.01 (s), 34.12 (s), 34.62 (t), 74.34 (t), 74.66 (t), 124.52 (d), 126.56 (d), 127.09 (d), 127.42 (d), 127.49 (d), 127.52 (d), 127.83 (d), 128.15 (d), 128.57 (d), 132.50 (s), 132.57 (s), 132.65 (s), 134.37 (s), 138.17 (s), 141.67 (s), 145.40 (s), 152.88 (s), 153.53 (s). Anal. Calcd for $C_{102}H_{114}O_6$: C, 85.31; H, 8.00. Found: C, 85.25; H, 8.03.

15c: colorless crystals, mp 169-172 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.14 (s, 9H), 0.86 (s, 9H), 1.15 (s, 9H), 1.28 (s, 9H), 1.35 (s, 9H), 1.37 (s, 9H), 3.15 (d, J = 13.1 Hz, 1H), 3.18 (d, J = 14.2 Hz, 1H), 3.28 (d, J = 15.8 Hz, 1H), 3.55 (d, J = 17.4 Hz, 1H), 3.56 (d, J = 13.3 Hz, 1H), 3.67 (d, J = 12.5 Hz, 1H), 3.72 (d, J = 12.5 Hz, 1H), 3.87 (d, J = 13.3 Hz, 1H), 4.02 (d, J = 16.2 Hz, 1H), 4.06 (d, J = 16.2 Hz, 1H), 4.26 (d, J = 17.4 Hz, 1H), 4.34 (d, J = 13.1 Hz, 1H), 4.36 (d, J = 14.2 Hz, 1H), 4.41 (d, J = 12.3 Hz, 1H), 4.44 (d, J = 11.8 Hz, 1H), 4.49 (d, J = 11.8 Hz, 1H), 4.53 (d, J = 15.8 Hz, 1H), 4.54 (d, J = 12.2 Hz, 1H), 4.56 (d, J = 12.2 Hz, 1H), 4.58 (d, J = 12.3 Hz, 1H), 4.62 (d, J = 12.0 Hz, 1H), 4.73 (d, J = 11.5 Hz, 1H), 4.78 (d, J = 12.0 Hz, 1H), 5.19 (d, J = 11.5 Hz, 1H), 5.31 (s, 1H), 6.19 (d, J = 2.0 Hz, 1H), 6.59 (brt, J = 3.5 Hz, 1H), 6.83 (d, J = 1.7 Hz, 1H), 6.87-6.99 (m, 8H), 7.04-7.15 (m, 9H), 7.16-7.24 (m, 5H), 7.27-7.30 (m, 2H), 7.33-7.36 (m, 4H), 7.40-7.44 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.91 (t), 28.26 (t), 30.24 (t), 30.62 (q), 30.98 (q), 31.50 (q), 31.56 (q), 31.65 (q), 31.72 (q), 32.27 (t), 33.11 (t), 33.32 (s), 33.75 (s), 34.09 (s), 34.15 (s), 34.25 (s), 34.50 (s), 39.17 (t), 71.39 (t), 72.68 (t), 73.37 (t), 73.58 (t), 74.75 (t), 74.90 (t), 121.23 (d), 122.05 (d), 122.07 (d), 123.02 (d), 124.29 (d), 124.80 (d), 125.13 (d), 125.65 (d), 125.85 (d × 2), 126.54 (d), 126.75 (d), 126.78 (d), 126.92 (d), 127.00 (d), 127.05 (d), 127.19 (d), 127.28 (d), 127.36 (d), 127.40 (d), 127.55 (d), 127.77 (d), 127.81 (d), 127.89 (d), 127.97 (s), 128.10 (d), 128.15 (d), 128.34 (d), 129.18 (d), 131.35 (s), 131.71 (s), 132.09 (s), 132.92 (s), 133.00 (s), 133.07 (s), 133.39 (s), 133.45 (s), 133.67 (s), 134.28 (s), 134.45 (s), 137.08 (s), 137.77 (s), 138.19 (s), 138.28 (s), 138.42 (s), 138.46 (s), 145.22 (s), 145.28 (s), 145.42 (s), 145.74 (s), 146.15 (s), 146.18 (s), 151.69 (s), 152.34 (s), 152.40 (s), 152.48 (s), 153.20 (s), 145.57

(s). Anal. Calcd for $C_{102}H_{114}O_6$: C, 85.31; H, 8.00. Found: C, 85.29; H, 8.03.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,38,40,41-tetrakis[4-(*N*-methylacetamidobenzyloxy)]-39,42-[1,3-phenylenebis(methylenoxy)]calixarene (16). Method A: **a**, 39%; **b**, 2%; **c**, 16%.

16a: colorless crystals, mp 206-209 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 0.96 (s, 36H), 1.43 (s, 18H), 1.81 (s, 12H), 3.18 (d, J = 14.3 Hz, 2H), 3.20 (s, 12H), 3.32 (d, J = 15.4 Hz, 4H), 4.24 (s, 4H), 4.30 (d, J = 14.3 Hz, 2H), 4.42 (d, J = 15.4 Hz, 4H), 4.56 (d, J = 12.5 Hz, 4H), 4.62 (d, J = 12.5 Hz, 4H), 5.70 (s, 1H), 6.85 (d, J = 1.8 Hz, 4H), 6.94-6.96 (m, 12H), 7.02 (t, J = 7.5 Hz, 1H), 7.05 (d, J = 8.2 Hz, 8H), 7.11 (d, J = 7.5 Hz, 2H), 7.30 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$, 55 °C) δ 22.25 (q), 28.91 (t), 30.53 (t), 31.26 (q), 31.62 (q), 34.09 (s), 34.26 (s), 37.16 (q), 71.65 (t), 74.03 (t), 121.67 (d), 122.62 (d), 124.55 (d), 125.30 (d), 126.55 (d), 127.95 (d), 127.98 (d), 128.42 (d), 132.43 (s), 132.90 (s), 133.17 (s), 137.57 (s), 138.73 (s), 143.73 (s), 145.84 (s), 146.31 (s), 151.73 (s), 152.69 (s), 170.18 (s). Anal. Calcd for $C_{114}H_{134}N_4O_{10}\cdot 2H_2O$: C, 77.96; H, 7.92; N, 3.19. Found: C, 78.19; H, 7.64; N, 3.23.

16b: colorless crystals; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.96 (s, 36H), 1.30 (s, 18H), 1.93 (s, 12H), 3.31 (s, 12H), 3.37 (d, J = 15.3 Hz, 4H), 3.70 (s, 4H), 3.78 (s, 4H), 4.30 (d, J = 15.3 Hz, 4H), 4.67 (s, 1H), 4.83 (d, J = 11.0 Hz, 4H), 4.90 (d, J = 11.0 Hz, 4H), 5.32 (br, 2H), 6.13 (t, J = 7.5 Hz, 1H), 6.56 (d, J = 2.0 Hz, 4H), 7.06 (d, J = 2.0 Hz, 4H), 7.11 (s, 4H), 7.27 (d, J = 8.0 Hz, 8H), 7.65 (d, J = 8.0 Hz, 8H); HRMS (FAB$^+$) observed m/z 1720.0188, calcd for $C_{114}H_{134}N_4O_{10}$ 1720.0178.

16c: colorless solids; ^{1}H NMR (500 MHz, $CDCl_3$, 35 °C) δ 0.11 (s, 9H), 0.89 (s, 9H), 1.17 (s, 9H), 1.27 (s, 9H), 1.35 (s, 9H), 1.38 (s, 9H), 1.77 (s, 3H), 1.80 (s, 3H), 1.84 (s, 3H), 1.88 (s, 3H), 3.17 (d, J = 12.5 Hz, 1H), 3.17 (d, J, = 14.0 Hz, 1H), 3.18 (d, J = 15.9 Hz, 1H), 3.20 (s × 2, 6H), 3.22 (s, 3H), 3.26 (s, 3H), 3.58 (d, J = 16.9 Hz, 1H), 3.61 (d, J = 13.4 Hz, 1H), 3.66 (d, J = 12.8 Hz, 1H), 3.72 (d, J = 12.8 Hz, 1H), 3.91 (d, J = 13.4 Hz, 1H), 4.08 (s, 2H), 4.25 (d, J = 16.9 Hz, 1H), 4.26 (d, J = 12.5 Hz, 1H), 4.32 (d, J = 14.0 Hz, 1H), 4.44 (d, J = 15.9 Hz, 1H), 4.49 (d, J = 12.7 Hz, 1H), 4.52 (d, J = 15.4 Hz, 1H), 4.56 (d, J = 11.9 Hz, 1H), 4.57 (d, J = 15.4 Hz, 1H), 4.60 (d, J = 12.4 Hz, 1H), 4.61 (d, J = 11.9 Hz, 1H), 4.63 (d, J = 12.7 Hz, 1H), 4.73 (d, J = 11.6 Hz, 1H), 4.78 (d, J = 12.4 Hz, 1H), 5.20 (d, J = 11.6 Hz, 1H), 5.44 (s, 1H), 6.19 (d, J = 1.8 Hz, 1H), 6.63 (brd, J = 5.8 Hz, 2H), 6.88 (d, J = 1.7 Hz, 1H), 6.91-7.04 (m, 16H), 7.12 (d, J = 2.3 Hz, 1H), 7.14 (d, J = 2.1 Hz, 1H), 7.18 (d, J = 7.9 Hz, 2H), 7.19 (d, J = 7.8 Hz, 2H), 7.30 (d, J = 1.7 Hz, 1H), 7.35 (d, J = 2.3 Hz, 1H), 7.39 (d, J = 2.1 Hz, 1H), 7.40 (d, J = 2.1 Hz, 1H), 7.44 (d, J = 2.1 Hz, 1H), 7.49 (d, J = 7.8 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$, 35 °C) δ 22.32 (q × 3), 22.38 (q),

28.12 (t × 2), 30.15 (t), 30.63 (q), 31.02 (q), 31.44 (q), 31.56 (q), 31.59 (q), 31.64 (q), 32.29 (t), 33.17 (t), 33.30 (s), 33.78 (s), 34.10 (s), 34.17 (s), 34.26 (s), 34.54 (s), 37.04 (q), 37.13 (q × 3), 39.42 (t), 71.18 (t), 71.74 (t), 72.47 (t), 73.37 (t), 73.89 (t), 74.12 (t), 121.30 (d), 121.67 (d), 122.02 (d), 122.88 (d), 124.46 (d), 124.83 (d), 125.28 (d), 125.50 (d), 125.68 (d), 126.00 (d), 126.45 (d), 126.52 (d), 126.67 (d), 126.81 (d × 2), 127.08 (d), 127.14 (d), 127.84 (d), 128.16 (d), 128.25 (d), 128.38 (d), 128.57 (d × 2), 129.28 (d), 131.32 (s), 131.35 (s), 131.82 (s), 131.92 (s), 132.71 (s), 132.83 (s), 132.89 (s), 133.29 (s), 133.47 (s), 133.67 (s), 134.02 (s), 134.18 (s), 137.17 (s), 137.52 (s), 137.77 (s), 137.88 (s × 2), 138.68 (s), 143.54 (s), 143.60 (s), 143.67 (s), 143.97 (s), 145.65 (s), 145.73 (s × 2), 145.83 (s), 146.46 (s), 146.56 (s), 151.48 (s), 151.79 (s), 152.05 (s × 2), 152.94 (s), 154.32 (s), 170.24 (s), 170.34 (s), 170.45 (s × 2); HRMS (FAB$^+$) observed *m/z* 1720.0123, calcd for $C_{114}H_{135}N_4O_{10}$ 1720.0178.

37,38,40,41-Tetrakis(4-bromobenzyloxy)-5,11,17,23,29,35-hexa-*tert*-butyl-39,42-[1,3-phenylenebis(methylenoxy)]calix[6]arene (17). Method A: **a**, 33%; **c**, 30%. Method B: **a**, 88%.

17a: colorless crystals, mp 161-163 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 36H), 1.42 (s, 18H), 3.23 (d, J = 14.2 Hz, 2H), 3.38 (d, J = 15.3 Hz, 4H), 4.18 (s, 4H), 4.30 (d, J = 14.2 Hz, 2H), 4.38 (d, J = 12.5 Hz, 4H), 4.40 (d, J = 15.3 Hz, 4H), 4.51 (d, J = 12.5 Hz, 4H), 5.59 (s, 1H), 6.77 (d, J = 8.2 Hz, 8H), 6.83 (d, J = 1.4 Hz, 4H), 6.97 (d, J = 1.4 Hz, 4H), 7.09 (s, 3H), 7.19 (d, J = 8.2 Hz, 8H), 7.31 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.57 (t), 30.34 (t), 31.24 (q), 31.64 (q), 34.05 (s), 34.26 (s), 71.42 (t), 73.87 (t), 120.92 (d), 120.98 (s), 122.55 (d), 124.47 (d), 125.16 (d), 126.91 (d), 127.92 (d), 128.45 (d), 131.00 (d), 132.36 (s), 132.90 (s), 133.08 (s), 136.59 (s), 138.34 (s), 145.62 (s), 146.10 (s), 151.63 (s), 152.61 (s). Anal. Calcd for $C_{102}H_{110}Br_4O_6$: C, 69.94; H, 6.33; Br, 18.25. Found: C, 69.69; H, 6.35; Br, 18.18.

17c: colorless crystals, mp 162-166 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.12 (s, 9H), 0.92 (s, 9H), 1.17 (s, 9H), 1.29 (s, 9H), 1.37 (s, 9H), 1.38 (s, 9H), 3.22 (d, J = 13.1 Hz, 1H), 3.24 (d, J = 14.0 Hz, 1H), 3.31 (d, J = 16.1 Hz, 1H), 3.51 (d, J = 17.5 Hz, 1H), 3.58 (d, J = 13.4 Hz, 1H), 3.60 (d, J = 12.5 Hz, 1H), 3.65 (d, J = 12.5 Hz, 1H), 3.87 (d, J = 13.4 Hz, 1H), 4.05 (d, J = 16.8 Hz, 1H), 4.06 (d, J = 16.8 Hz, 1H), 4.17 (d, J = 17.5 Hz, 1H), 4.31 (d, J = 13.1 Hz, 1H), 4.33 (d, J = 14.0 Hz, 1H), 4.40 (d, J = 12.4 Hz, 1H), 4.48 (d, J = 16.1 Hz, 1H), 4.48 (d, J = 12.6 Hz, 1H), 4.49 (s, 2H), 4.54 (d, J = 12.4 Hz, 1H), 4.66 (d, J = 11.6 Hz, 1H), 4.68 (d, J = 12.6 Hz, 1H), 5.08 (d, J = 11.6 Hz, 1H), 5.37 (s, 1H), 6.15 (d, J = 2.0 Hz, 1H), 6.60 (d, J = 7.5 Hz, 1H), 6.66 (d, J = 8.3 Hz, 2H), 6.73 (d, J = 8.3 Hz, 2H), 6.81 (d, J = 2.0 Hz, 1H), 6.81 (d, J = 1.7 Hz, 1H), 6.95 (d, J = 7.5

Hz, 1H), 6.96 (d, J = 2.4 Hz, 1H), 6.99 (d, J = 8.2 Hz, 2H), 7.02 (t, J = 7.5 Hz, 1H), 7.04 (d, J = 2.4 Hz, 1H), 7.09 (d, J = 2.8 Hz, 1H), 7.09 (d, J = 2.2 Hz, 1H), 7.11 (d, J = 8.3 Hz, 2H), 7.16 (d, J = 8.3 Hz, 2H), 7.22 (d, J = 8.4 Hz, 2H), 7.31 (d, J = 1.7 Hz, 1H), 7.32 (d, J = 8.2 Hz, 1H), 7.36 (d, J = 2.8 Hz, 1H), 7.39 (d, J = 1.9 Hz, 1H), 7.42 (d, J = 2.2 Hz, 1H), 7.46 (d, J = 1.9 Hz, 1H), 7.48 (d, J = 8.4 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.89 (t), 28.02 (t), 30.09 (t), 30.58 (q), 31.04 (q), 31.47 (q), 31.54 (q), 31.63 (q), 31.70 (q), 32.45 (t), 33.17 (t), 33.29 (s), 33.81 (s), 34.11 (s), 34.19 (s), 34.27 (s), 34.57 (s), 39.37 (t), 71.20 (t), 71.82 (t), 72.50 (t), 73.35 (t), 73.83 (t), 74.02 (t), 120.79 (s), 121.05 (d), 121.14 (s), 121.17 (s), 121.32 (s), 121.87 (d), 121.98 (d), 123.01 (d), 124.52 (d), 124.84 (d), 125.25 (d), 125.59 (d), 125.81 (d), 125.97 (d), 126.80 (d), 126.88 (d), 127.15 (d), 127.90 (d), 128.22 (d), 128.52 (d), 128.53 (d), 128.83 (d), 128.90 (d), 129.39 (d), 130.90 (d), 131.05 (d), 131.24 (s), 131.32 (d), 131.37 (s), 131.51 (d), 131.81 (s), 131.95 (s), 132.69 (s), 132.83 (s), 132.69 (s), 132.83 (s), 132.97 (s), 133.35 (s), 133.44 (s), 133.66 (s), 134.03 (s), 134.26 (s), 136.45 (s), 136.87 (s), 137.06 (s), 137.17 (s), 137.38 (s), 138.49 (s), 145.69 (s), 145.72 (s × 2), 145.83 (s), 146.42 (s), 146.49 (s), 151.62 (s), 151.89 (s), 152.05 (s), 152.17 (s), 153.04 (s), 154.36 (s). Anal. Calcd for $C_{102}H_{110}Br_4O_6$: C, 69.94; H, 6.33; Br, 18.25. Found: C, 69.74; H, 6.27; Br, 18.25.

38,39,41,42-Tetrabenzyloxy-37,40-[2-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene (6).[28f] Method A: **a**, 58%; **b**, 16%. Method B: **a**, 62%; **b**, 14%.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetrakis[4-(*N*-methylacetamido)benzyloxy]calix[6]arene (18). Method A: **a**, 59%; **b**, 11%. Method B: **a**, 64%; **b**, 22%.

18a: colorless crystals, mp 259-262 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 1.04 (s, 36H), 1.45 (s, 18H), 1.84 (brs, 12H), 3.14 (d, J = 15.1 Hz, 2H), 3.22 (s, 12H), 3.30 (d, J = 15.3 Hz, 4H), 3.89 (s, 4H), 4.30 (d, J = 15.1 Hz, 2H), 4.48 (d, J = 12.1 Hz, 4H), 4.49 (d, J = 15.3 Hz, 4H), 4.51 (d, J = 12.1 Hz, 4H), 6.82 (t, J = 7.5 Hz, 1H), 6.84 (s, 4H), 7.01 (d, J = 8.2 Hz, 8H), 7.14 (d, J = 8.2 Hz, 8H), 7.18 (d, J = 7.5 Hz, 2H), 7.31 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$, 55 °C) δ 22.21 (q), 26.84 (t), 30.81 (t), 31.46 (q), 31.64 (q), 34.10 (s), 34.15 (s), 37.16 (q), 72.53 (t), 74.19 (t), 122.83 (s), 124.77 (d), 125.19 (d), 125.43 (d), 125.82 (d), 126.53 (d), 128.50 (d), 128.82 (d), 131.54 (s), 131.96 (s), 133.85 (s), 137.19 (s), 137.33 (s), 143.87 (s), 144.85 (s), 145.54 (s), 151.96 (s), 152.67 (s), 170.14 (s). Anal. Calcd for $C_{114}H_{133}BrN_4O_{10}{\cdot}H_2O$: C, 75.35; H, 7.49; N, 3.08; Br, 4.40. Found: C, 75.21; H, 7.31; N, 2.69; Br, 4.49.

18b; colorless crystals, mp > 300 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 0.99 (s, 36H), 1.29 (s, 9H), 1.31 (s, 9H), 1.93 (brs, 12H), 3.31 (d, J = 15.9 Hz, 2H), 3.31 (s, 12H), 3.39 (d, J = 15.7 Hz, 2H), 3.67 (dd, J = 1.6, 7.6 Hz, 1H), 3.77 (d, J = 12.5 Hz, 2H), 3.82 (d, J = 12.5 Hz, 2H), 4.00 (s, 2H), 4.08 (d, J = 15.9 Hz, 2H), 4.15 (s, 2H), 4.50 (d, J = 15.7 Hz, 2H), 4.83 (d, J = 11.3 Hz, 2H), 4.85 (d, J = 11.0 Hz, 2H), 4.87 (d, J = 11.3 Hz, 2H), 4.93 (d, J = 11.0 Hz, 2H), 6.15 (t, J = 7.6 Hz, 1H), 6.62 (br, 2H), 6.74 (d, J = 1.5 Hz, 2H), 6.84 (dd, J = 1.6, 7.6 Hz, 1H), 7.00 (d, J = 2.1 Hz, 2H), 7.12 (s, 4H), 7.13 (d, J = 1.5 Hz, 2H), 7.26 (d, J = 8.2 Hz, 4H), 7.27 (d, J = 8.2 Hz, 4H), 7.61 (d, J = 8.2 Hz, 4H), 7.68 (d, J = 8.2 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$, 55 °C) δ 22.41 (q), 22.43 (q), 29.05 (t), 29.51 (t), 31.39 (q), 31.46 (q), 31.58 (q), 31.61 (q), 34.10 (s), 34.11 (s), 34.19 (s × 2), 34.99 (t), 37.26 (q × 2), 71.32 (t), 73.39 (t), 73.47 (t), 74.38 (t), 124.17 (d), 125.13 (d), 125.35 (d), 126.72 (s), 127.19 (d), 127.24 (d), 127.32 (d), 127.63 (d), 128.01 (d), 128.14 (d), 129.04 (d), 129.84 (d), 130.67 (d), 131.35 (d), 131.79 (s), 132.11 (s × 2), 132.46 (s), 132.49 (s), 132.53 (s), 133.37 (s), 136.46 (s), 137.36 (s), 137.74 (s), 144.41 (s), 144.62 (s), 144.88 (s), 144.99 (s), 145.03 (s), 145.50 (s), 149.99 (s), 152.79 (s), 153.85 (s), 154.43 (s), 170.41 (s × 2). Anal. Calcd for $C_{114}H_{133}BrN_4O_{10}\cdot H_2O$: C, 75.35; H, 7.49; N, 3.08; Br, 4.40. Found: C, 75.40; H, 7.35; N, 3.15; Br, 4.40.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41, 42-tetrakis(4-cyanobenzyloxy)calix[6]arene (19). Method A: no tetrasubstituted product was obtained. Method B: **a**, 83%; **b**, 16%.

19a: colorless crystals, mp 211-213 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.03 (s, 36H), 1.45 (s, 18H), 3.20 (d, J = 15.0 Hz, 2H), 3.37 (d, J = 15.0 Hz, 4H), 3.87 (s, 4H), 4.19 (d, J = 15.0 Hz, 2H), 4.44 (d, J = 15.0 Hz, 4H), 4.48 (s, 8H), 6.83 (d, J = 1.7 Hz, 4H), 7.00 (t, J = 7.5 Hz, 1H), 7.05 (d, J = 8.1 Hz, 8H), 7.20 (d, J = 1.7 Hz, 4H), 7.27 (d, J = 7.5 Hz, 2H), 7.34 (s, 4H), 7.41 (d, J = 8.1 Hz, 8H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.59 (t), 30.56 (t), 31.43 (q), 31.66 (q), 34.14 (s), 34.22 (s), 72.20 (t), 73.71 (t), 111.21 (s), 118.52 (s), 122.52 (s), 124.90 (d), 125.20 (d), 125.40 (d), 125.98 (d), 127.22 (d), 128.61 (d), 131.18 (s), 131.78 (d), 131.78 (s), 133.75 (s), 137.37 (s), 142.60 (s), 145.00 (s), 145.83 (s), 151.59 (s), 152.38 (s). Anal. Calcd for $C_{106}H_{109}BrN_4O_6\cdot 2H_2O$: C, 77.12; H, 6.90 N, 3.39; Br, 4.84. Found: C, 77.47; H, 6.68; N, 3.44; Br, 4.66.

19b: colorless crystals, mp > 300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.98 (s, 36H), 1.28 (s, 9H), 1.31 (s, 9H), 3.27 (d, J = 15.3 Hz, 2H), 3.35 (d, J = 15.8 Hz, 2H), 3.62 (dd, J = 1.3, 7.5 Hz, 1H), 3.70 (d, J = 12.8 Hz, 2H), 3.74 (d, J = 12.8 Hz, 2H), 3.96 (s, 2H), 4.01 (d, J = 15.3 Hz, 2H), 4.12 (s, 2H), 4.43 (d, J = 15.8 Hz, 2H), 4.89 (s, 4H), 4.91 (d, J = 11.9 Hz, 2H), 4.96 (d, J = 11.9 Hz,

2H), 6.15 (t, J = 7.5 Hz, 1H), 6.60 (br, 2H), 6.74 (br, 2H), 6.86 (dd, J = 1.3, 7.5 Hz, 1H), 6.91 (d, J = 2.2 Hz, 2H), 7.01 (d, J = 2.3 Hz, 2H), 7.10 (s, 2H), 7.11 (s, 2H), 7.67 (d, J = 8.1 Hz, 4H), 7.74 (d, J = 8.3 Hz, 4H), 7.75 (d, J = 8.1 Hz, 4H), 7.75 (d, J = 8.3 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.83 (t), 29.29 (t), 31.24 (q), 31.27 (q), 31.53 (q), 31.57 (q), 34.07 (s × 2), 34.11 (s), 34.18 (s), 34.97 (t), 71.13 (t), 73.03 (t), 73.20 (t), 73.89 (t), 111.75 (s), 111.96 (s), 118.71 (s), 118.73 (s), 124.22 (d), 125.02 (d), 125.46 (d), 126.55 (s), 127.00 (d), 127.56 (d), 127.87 (d), 127.98 (d × 2), 128.69 (d), 130.62 (d), 131.26 (d), 131.46 (s), 131.84 (s), 131.96 (s), 132.14 (s), 132.22 (s), 132.35 (s), 132.47 (d), 132.54 (d), 133.21 (s), 136.33 (s), 142.83 (s), 143.23 (s), 144.94 (s), 145.08 (s), 145.29 (s), 145.84 (s), 149.65 (s), 152.36 (s), 153.34 (s), 154.12 (s). Anal. Calcd for $C_{106}H_{109}BrN_4O_6 \cdot 2H_2O$: C, 77.12; H, 6.90 N, 3.39; Br, 4.84. Found: C, 77.47; H, 6.77; N, 3.82; Br, 4.19.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41, 42-tetrakis(4-pyridylmethoxy)calix[6]arene (20). Method A: no tetrasubstituted product was obtained. Method B: **a**, 59%; **b**, 11%.

20a: colorless crystals, mp 233 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.04 (s, 36H), 1.45 (s, 18H), 3.27 (d, J = 15.0 Hz, 2H), 3.38 (d, J = 15.2 Hz, 4H), 3.93 (s, 4H), 4.25 (d, J = 15.0 Hz, 2H), 4.45 (d, J = 13.3 Hz, 4H), 4.47 (d, J = 15.2 Hz, 4H), 4.48 (d, J = 13.3 Hz, 4H), 6.84 (d, J = 1.6 Hz, 4H), 6.89 (d, J = 5.8 Hz, 8H), 7.08 (t, J = 7.5 Hz, 1H), 7.21 (d, J = 1.6 Hz, 4H), 7.34 (s, 4H), 7.34 (d, J = 7.5 Hz, 2H), 8.38 (d, J = 5.8 Hz, 8H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.56 (t), 30.55 (t), 31.43 (q), 31.65 (q), 34.12 (s), 34.18 (s), 72.16 (t), 72.94 (t), 121.20 (d), 122.58 (s), 124.88 (d), 125.52 (d), 125.68 (d), 125.94 (d), 128.59 (d), 131.23 (s), 131.68 (s), 133.77 (s), 137.26 (s), 144.82 (s), 145.76 (s), 146.14 (s), 149.49 (d), 151.60 (s), 152.39 (s); Anal. Calcd for $C_{98}H_{109}BrN_4O_6 \cdot H_2O$: C, 76.59; H, 7.28; N, 3.65; Br, 5.20. Found: C, 76.80; H, 7.32; N, 3.64; Br, 5.38.

20b: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.017 (s, 18H), 1.020 (s, 18H), 1.28 (s, 9H), 1.31 (s, 9H), 3.27 (d, J = 15.7 Hz, 2H), 3.35 (d, J = 15.7 Hz, 2H), 3.69 (dd, J = 7.6, 1.8 Hz, 1H), 3.72 (d, J = 12.8 Hz, 2H), 3.77 (d, J = 12.8 Hz, 2H), 4.01 (s, 2H), 4.04 (d, J = 15.7 Hz, 2H), 4.20 (s, 2H), 4.46 (d, J = 15.7 Hz, 2H), 4.85 (d, J = 12.7 Hz, 2H), 4.88 (d, J = 12.7 Hz, 2H), 4.91 (s, 4H), 6.22 (t, J = 7.6 Hz, 1H), 6.62 (br, 2H), 6.76 (brd, J = 2.4 Hz, 2H), 6.92 (dd, J = 7.6, 1.8 Hz, 1H), 6.97 (d, J = 2.4 Hz, 2H), 7.08 (d, J = 2.4 Hz, 2H), 7.10 (s, 2H), 7.11 (s, 2H), 7.49 (d, J = 5.6 Hz, 4H), 7.57 (d, J = 5.8 Hz, 4H), 8.69 (d, J = 5.6 Hz, 4H), 8.70 (d, J = 5.8 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.83 (t), 29.26 (t), 31.30 (q), 31.34 (q), 31.53 (q), 31.56 (q),

34.05 (s), 34.11 (s), 34.16 (s × 2), 34.90 (t), 71.13 (t), 72.26 (t), 73.10 (t), 73.25 (t), 121.88 (d), 122.49 (d), 124.27 (d), 125.06 (d), 125.52 (d), 126.51 (s), 127.02 (d), 127.53 (d), 127.88 (d), 127.94 (d), 130.67 (d), 131.19 (d), 131.50 (s), 131.87 (s), 131.94 (s), 132.16 (s), 132.19 (s), 132.35 (s), 133.24 (s), 136.37 (s), 144.81 (s), 144.98 (s), 145.38 (s), 145.91 (s), 146.37 (s), 146.77 (s), 149.73 (s), 150.07 (d), 150.17 (d), 152.38 (s), 153.38 (s), 154.20 (s). Anal. Calcd for $C_{98}H_{100}BrN_4O_6 \cdot 0.75CHCl_3$: C, 73.74; H, 6.88; N, 3.48; Br, 4.97; Cl, 4.96. Found: C, 73.96; H, 7.08; N, 3.47; Br, 4.89; Cl, 5.33.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-38,39,41,42-tetrakis[(*N*-methylacetamido)benzyloxy]calix[6]arene (21). Method A: **a**, 35%; **b**, 31%; **c**, 8%.

21a: colorless crystals, mp 296-302 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 1.84 (s, 12H), 3.18 (d, J = 15.0 Hz, 2H), 3.22 (s, 12H), 3.34 (d, J = 15.4 Hz, 4H), 4.36 (d, J = 15.0 Hz, 2H), 4.37 (s, 4H), 4.46 (d, J = 15.4 Hz, 4H), 4.51 (d, J = 12.2 Hz, 4H), 4.56 (d, J = 12.2 Hz, 4H), 6.74 (d, J = 7.6 Hz, 4H), 6.80 (t, J = 7.6 Hz, 4H), 6.94 (t, J = 7.6 Hz, 1H), 6.99 (d, J = 8.1 Hz, 8H), 7.07 (t, J = 7.3 Hz, 2H), 7.09 (d, J = 7.6 Hz, 4H), 7.12 (d, J = 8.1 Hz, 8H), 7.20 (d, J = 7.6 Hz, 2H), 7.25 (d, J = 7.3 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$, 55 °C) δ 22.28 (q), 27.23 (t), 31.07 (t), 37.20 (q), 72.37 (t), 74.10 (t), 122.34 (d), 123.93 (d), 124.94 (s), 125.03 (d), 126.68 (d), 126.96 (d), 127.90 (d), 128.68 (d), 129.01 (d), 131.62 (d), 131.91 (s), 132.52 (s), 134.60 (s), 137.07 (s), 137.63 (s), 144.02 (s), 154.13 (s), 155.11 (s), 170.12 (s). Anal. Calcd for $C_{90}H_{85}BrN_4O_{10} \cdot 0.25CHCl_3 \cdot 2H_2O$: C, 70.92; H, 5.89; N, 3.67; Br, 5.23; Cl, 1.74. Found: C, 71.26; H, 5.73; N, 3.73; Br, 5.23; Cl, 2.00.

21b: colorless crystals, mp 189-194 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 1.92 (s, 12H), 3.29 (d, J = 15.9 Hz, 2H), 3.30 (s, 12H), 3.35 (d, J = 15.9 Hz, 2H), 3.72 (d, J = 12.8 Hz, 2H), 3.74 (d, J = 12.8 Hz, 2H), 3.86 (dd, J = 7.6 Hz, 1.4 Hz, 1H), 3.99 (s, 2H), 4.10 (d, J = 15.9 Hz, 2H), 4.37 (s, 2H), 4.40 (d, J = 15.9 Hz, 2H), 4.85 (d, J = 12.1 Hz, 2H), 4.86 (d, J = 12.1 Hz, 2H), 4.96 (d, J = 11.9 Hz, 2H), 4.98 (d, J = 11.9 Hz, 2H), 6.20 (t, J = 7.6 Hz, 1H), 6.31 (d, J = 7.5 Hz, 2H), 6.53 (t, J = 7.5 Hz, 2H), 6.60 (d, J = 7.6 Hz, 2H), 6.71 (t, J = 7.6 Hz, 2H), 6.87 (dd, J = 7.6 Hz, 1.4 Hz, 1H), 6.94 (t, J = 7.5 Hz, 1H), 7.01 (t, J = 8.1 Hz, 1H), 7.04 (d, J = 7.5 Hz, 2H), 7.08 (d, J = 8.1 Hz, 2H), 7.08 (d, J = 7.5 Hz, 2H), 7.24 (d, J = 7.6 Hz, 2H), 7.25 (d, J = 7.9 Hz, 4H), 7.25 (d, J = 8.2 Hz, 4H), 7.53 (d, J = 7.9 Hz, 4H), 7.57 (d, J = 8.2 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$, 55 °C) δ 22.28 (q × 2), 29.55 (t), 29.65 (t), 33.03 (t), 37.12 (q × 2), 71.34 (t), 73.92 (t), 74.15 (t), 74.30 (t), 122.45 (d), 122.97 (d), 123.34 (d), 123.42 (d), 125.01 (d), 126.14 (s), 127.14 (d), 127.17 (d), 127.62 (d), 128.57 (d), 128.85 (d), 128.88 (d), 129.25 (d), 129.75 (d), 130.20 (d),

130.29 (d), 131.11 (d), 131.17 (d), 132.59 (s), 132.88 (s), 133.33 (s), 133.36 (s), 133.44 (s), 133.86 (s), 136.65 (s), 137.11 (s), 137.33 (s), 144.24 (s), 144.35 (s), 152.69 (s), 154.63 (s), 155.54 (s), 157.27 (s), 170.31 (s × 2). Anal. Calcd for $C_{90}H_{85}BrN_4O_{10}\cdot 2H_2O$: C, 72.13; H, 5.99; N, 3.74; Br, 5.33. Found: C, 72.25; H, 5.80; N, 3.85; Br, 5.39.

21c: colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$, 50 °C) δ 1.83(s, 6H), 1.91 (s, 6H), 3.18 (d, J = 14.0 Hz, 1H), 3.19 (d, J = 15.6 Hz, 1H), 3.227 (s, 3H), 3.234 (s, 3H), 3.281 (s, 3H), 3.288 (s, 3H), 3.37 (d, J = 16.0 Hz, 1H), 3.46 (d, J = 15.7 Hz, 1H), 3.64 (d, J = 15.9 Hz, 1H), 3.72 (d, J = 14.6 Hz, 1H), 3.73 (d, J = 14.6 Hz, 1H), 4.00 (d, J = 12.2 Hz, 1H), 4.05 (d, J = 12.2 Hz, 1H), 4.06 (d, J = 15.9 Hz, 1H), 4.20 (d, J = 11.8 Hz, 1H), 4.28 (d, J = 15.6 Hz, 1H), 4.35 (d, J = 11.8 Hz, 1H), 4.35 (d, J = 14.0 Hz, 1H), 4.40 (d, J = 16.0 Hz, 1H), 4.42 (d, J = 15.7 Hz, 1H), 4.45 (d, J = 12.0 Hz, 1H), 4.52 (d, J = 12.2 Hz, 1H), 4.52 (d, J = 11.3 Hz, 1H), 4.53 (d, J = 12.0 Hz, 1H), 4.55 (d, J = 11.9 Hz, 1H), 4.62 (d, J = 11.3 Hz, 1H), 4.64 (d, J = 12.2 Hz, 1H), 4.68 (d, J = 11.9 Hz, 1H), 6.34 (t, J = 7.5 Hz, 1H), 6.39 (d, J = 7.5 Hz, 1H), 6.52 (t, J = 7.5 Hz, 1H), 6.64 (d, J = 7.3 Hz, 1H), 6.66-6.70 (m, 2H), 6.82 (t, J = 7.3 Hz, 1H), 6.84-6.88 (m, 3H), 6.89 (d, J = 7.5 Hz, 1H), 6.96 (d, J = 7.0 Hz, 1H), 6.99-7.02 (m, 3H), 7.06-7.25 (m, 18H), 7.28 (d, J = 8.2 Hz, 2H), 7.41 (d, J = 7.9 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$, 50 °C) δ 22.30 (q), 22.37 (q), 28.29 (t), 30.80 (t), 31.32 (t), 31.85 (t), 32.90 (t), 35.73 (t), 37.19 (q), 72.95 (t), 73.72 (t), 74.30 (t), 74.34 (t), 74.90 (t), 75.07 (t), 122.30 (d), 122.62 (d), 123.29 (d), 123.73 (d), 125.33 (d), 125.85 (s), 126.74 (d), 126.89 (d × 2), 127.05 (d), 127.55 (d), 127.64 (d), 128.20 (d), 128.37 (d), 128.59 (d), 128.63 (d), 128.91 (d), 129.02 (d), 129.18 (d), 129.34 (d), 129.70 (d), 129.74 (d), 130.57 (d), 130.85 (d), 131.12 (s), 131.27 (d), 131.44 (d), 131.91 (d), 132.02 (d), 132.58 (s), 132.86 (s), 133.41 (s), 133.63 (s), 133.86 (s), 134.04 (s), 134.51 (s), 134.56 (s), 135.30 (s), 137.11 (s), 137.39 (s), 137.74 (s), 143.95 (s), 144.26 (s × 2), 144.36 (br, s × 3), 154.08 (s), 154.39 (s), 155.11 (s), 155.87 (s), 155.93 (s), 157.58 (s), 170.13 (s), 170.16 (s), 170.36 (s), 170.45 (s). Anal. Calcd for $C_{90}H_{85}BrN_4O_{10}\cdot 2H_2O$: C, 72.13; H, 5.99; N, 3.74; Br, 5.33. Found: C, 72.14; H, 5.83; N, 3.74; Br, 5.11.

37,40-[2-Bromo-1,3-phenylenebis(methylenoxy)]-38,39,41,42-tetrakis(4-pyridylmethoxy)-calix[6]arene (22). Method B: **a**, 66%; **b**: 7%.

22a: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.31 (d, J = 14.7 Hz, 2H), 3.43 (d, J = 15.4 Hz, 4H), 4.33 (d, J = 14.7 Hz, 2H), 4.41 (d, J = 13.4 Hz, 4H), 4.43 (s, 4H), 4.46 (d, J = 15.4 Hz, 4H), 4.51 (d, J = 13.4 Hz, 4H), 6.79 (d, J = 7.3 Hz, 4H), 6.85 (t, J = 7.3 Hz, 4H), 6.86 (d, J = 5.6 Hz, 8H), 7.09 (t, J = 7.5 Hz, 2H), 7.11 (t, J = 7.4 Hz, 1H), 7.15 (d, J = 7.3 Hz,

4H), 7.29 (d, J = 7.5 Hz, 4H), 7.35 (d, J = 7.4 Hz, 2H), 8.37 (d, J = 5.6 Hz, 8H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.76 (t), 30.73 (t), 71.98 (t), 72.75 (t), 121.06 (d), 122.35 (d), 124.19 (d), 124.45 (s), 125.62 (d), 126.92 (d), 128.08 (d), 129.98 (d), 131.50 (s), 131.70 (d), 132.24 (s), 134.51 (s), 137.56 (s), 145.98 (s), 149.60 (d), 153.75 (s), 154.74 (s). Anal. Calcd for $C_{74}H_{61}BrN_4O_6 \cdot H_2O$: C, 74.05; H, 5.29; N, 4.67; Br, 6.66. Found: C, 74.34; H, 5.42; N, 4.68; Br, 6.59.

22b: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.31 (d, J = 15.7 Hz, 2H), 3.37 (d, J = 15.8 Hz, 2H), 3.70 (d, J = 12.8 Hz, 2H), 3.72 (d, J = 12.8 Hz, 2H), 3.86 (dd, J = 7.6 Hz, 1.4 Hz, 1H), 4.02 (s, 2H), 4.08 (d, J = 15.7 Hz, 2H), 4.38 (d, J = 15.8 Hz, 2H), 4.41 (s, 2H), 4.83 (d, J = 13.2 Hz, 2H), 4.89 (d, J = 13.2 Hz, 2H), 4.93 (d, J = 13.1 Hz, 2H), 5.01 (d, J = 13.1 Hz, 2H), 6.27 (t, J = 7.6 Hz, 1H), 6.35 (d, J = 7.6 Hz, 2H), 6.59 (t, J = 7.6 Hz, 2H), 6.65 (d, J = 7.7 Hz, 2H), 6.78 (t, J = 7.7 Hz, 2H), 6.94 (dd, J = 7.6 Hz, 1.4 Hz, 1H), 6.95 (t, J = 7.5 Hz, 1H), 7.04 (t, J = 7.4 Hz, 1H), 7.05 (d, J = 7.5 Hz, 2H), 7.05 (d, J = 7.6 Hz, 2H), 7.11 (d, J = 7.4 Hz, 2H), 7.22 (d, J = 7.7 Hz, 2H), 7.44 (d, J = 5.4 Hz, 4H), 7.49 (d, J = 5.4 Hz, 4H), 8.69 (d, J = 5.4 Hz, 4H), 8.70 (d, J = 5.4 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 29.49 (t), 29.52 (t), 33.26 (t), 71.34 (t), 72.70 (t), 72.99 (t), 74.15 (t), 121.56 (d), 121.65 (d), 122.61 (d), 123.15 (d), 123.73 (d), 123.83 (d), 125.19 (d), 126.13 (s), 127.92 (d), 129.16 (d), 129.37 (d), 129.98 (d), 130.23 (d), 130.42 (d), 131.25 (d), 131.29 (d), 132.37 (s), 132.41 (s), 132.76 (s), 133.20 (s), 133.28 (s), 133.57 (s), 133.79 (s), 136.76 (s), 146.40 (s), 146.59 (s), 150.16 (d), 150.21 (d), 152.65 (s), 154.41 (s), 155.29 (s), 1257.23 (s). Anal. Calcd for $C_{74}H_{61}BrN_4O_6 \cdot 3H_2O$: C, 71.89; H, 5.46; N, 4.53; Br, 6.46. Found: C, 71.54; H, 5.14; N, 4.37; Br, 6.49.

38,39,41,42-Tetrabenzyoxy-37,40-[5-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29, 35-hexa-*tert*-butylcalix[6]arene (23). Method A: **a**, 52%; **c**, 4%. Method B: **a**, 77%.

23a: colorless crystals, mp 224-229 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.94 (s, 36H), 1.41 (s, 18H), 3.22 (d, J = 14.2 Hz, 2H), 3.31 (d, J = 15.4 Hz, 4H), 4.11 (s, 4H), 4.36 (d, J = 15.4 Hz, 4H), 4.39 (d, J= 14.2 Hz, 2H), 4.55 (d, J = 12.2 Hz, 4H), 4.59 (d, J = 12.2 Hz, 4H), 5.55 (s, 1H), 6.80 (d, J = 2.0 Hz, 4H), 6.97 (d, J = 2.0 Hz, 4H), 7.00-7.02 (m, 8H), 7.14-7.17 (m, 12H), 7.27 (s, 4H), 7.28 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.76 (t), 30.53 (t), 31.29 (q), 31.65 (q), 34.06 (s), 34.27 (s), 70.82 (t), 74.93 (t), 119.93 (d), 121.34 (s), 124.38 (d), 125.15 (d), 125.75 (d), 127.05 (d), 127.12 (d), 127.78 (d), 128.11 (d), 132.62 (s), 132.99 (s), 133.35 (s), 137.77 (s), 140.90 (s), 145.39 (s), 146.18 (s), 152.08 (s), 152.55 (s). Anal. Calcd for $C_{102}H_{113}BrO_6$: C, 78.99; H, 7.60. Found: C, 79.02; H, 7.32.

23c: colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.12 (s, 9H), 0.90 (s, 9H), 1.16 (s, 9H), 1.25 (s,

9H), 1.36 (s, 9H), 1.37 (s, 9H), 3.18 (d, J = 14.1 Hz, 1H), 3.19 (d, J = 13.3 Hz, 1H), 3.25 (d, J = 15.9 Hz, 1H), 3.46 (d, J = 13.8 Hz, 1H), 3.56 (d, J = 17.4 Hz, 1H), 3.64 (d, J = 12.4 Hz, 1H), 3.71 (d, J = 12.4 Hz, 1H), 3.85 (d, J = 13.8 Hz, 1H), 4.03 (s, 2H), 4.20 (d, J = 17.4 Hz, 1H), 4.31 (d, J = 14.1 Hz, 1H), 4.36 (d, J = 13.3 Hz, 1H), 4.38 (d, J = 12.7 Hz, 1H), 4.40 (d, J = 11.9 Hz, 1H), 4.44 (d, J = 12.7 Hz, 1H), 4.52 (d, J = 15.9 Hz, 1H), 4.54 (d, J = 12.0 Hz, 1H), 4.62 (d, J = 11.9 Hz, 1H), 4.62 (d, J = 12.0 Hz, 1H), 4.69 (d, J = 11.8 Hz, 1H), 4.72 (d, J = 11.6 Hz, 1H), 4.89 (d, J = 11.8 Hz, 1H), 5.23 (d, J = 11.6 Hz, 1H), 5.26 (s, 1H), 6.13 (d, J = 2.1 Hz, 1H), 6.71 (s, 1H), 6.84 (d, J = 1.9 Hz, 1H), 6.90-6.92 (m, 3H), 6.97-6.99 (m, 3H), 7.08 (d, J = 2.3 Hz, 1H), 7.09 (d, J = 2.4 Hz, 1H), 7.14-7.17 (m, 7H), 7.19-7.22 (m, 4H), 7.22 (s, 1H), 7.29 (d, J = 1.9 Hz, 1H), 7.31 (t, J = 7.4 Hz, 1H), 7.34 (d, J = 2.4 Hz, 1H), 7.35-7.39 (m, 4H), 7.41 (d, J = 2.3 Hz, 1H), 7.43 (d, J = 2.0 Hz, 1H), 7.48 (d, J = 7.3 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.97 (t), 28.08 (t), 30.16 (t), 30.60 (q), 30.98 (q), 31.51 (q × 2), 31.62 (q), 31.70 (q), 32.08 (t), 33.11 (t), 33.27 (s), 33.74 (s), 34.07 (s), 34.15 (s), 34.27 (s), 34.51 (s), 39.26 (t), 70.31 (t), 72.37 (t), 72.50 (t), 73.63 (t), 75.07 (t), 75.10 (t), 119.77 (d), 121.09 (s), 123.01 (d), 124.26 (d), 124.56 (d), 124.75 (d), 124.95 (d), 125.23 (d), 125.43 (d), 125.77 (d), 125.87 (d), 126.19 (d), 126.84 (d), 126.94 (d), 127.07 (d), 127.11 (d), 127.16 (d), 127.24 (d), 127.45 (d), 127.54 (d), 127.57 (d), 127.73 (d), 128.06 (d), 128.14 (d × 2), 128.22 (d), 128.44 (d), 129.18 (d), 131.34 (s), 131.66 (s), 131.94 (s), 132.01 (s), 132.74 (s), 132.93 (s), 133.15 (s), 133.39 (s), 133.45 (s), 133.63 (s), 134.41 (s), 134.49 (s), 137.60 (s), 137.98 (s), 138.27 (s), 138.28 (s), 139.59 (s), 141.14 (s), 145.30 (s), 145.35 (s), 145.64 (s), 145.82 (s), 146.49 (s), 146.56 (s), 151.67 (s), 152.07 (s), 152.50 (s), 152.68 (s × 2), 154 09 (s). Anal. Calcd for $C_{102}H_{113}BrO_6$: C, 80.87; H, 7.52; Br, 5.27. Found: C, 80.92; H, 7.46; Br, 5.40.

38,39,41,42-Tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butyl-37,40-[2-ethynyl-1,3-phenylenebis(methylenoxy)]calix[6]arene (24). Method B: **a**, 70%.

24a: colorless crystals, mp 187-191 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.50 (s, 1H), 1.04 (s, 36H), 1.40 (s, 18H), 3.22 (d, J = 14.5 Hz, 2H), 3.30 (d, J = 15.3 Hz, 4H), 4.37 (s, 4H), 4.43 (d, J = 12.0 Hz, 4H), 4.44 (d, J = 14.5 Hz, 2H), 4.46 (d, J = 15.3 Hz, 4H), 4.50 (d, J = 12.0 Hz, 4H), 6.74 (d, J = 1.9 Hz, 4H), 6.90 (t, J = 7.6 Hz, 1H), 7.02 (d, J = 7.2 Hz, 8H), 7.11 (t, J = 7.2 Hz, 8H), 7.16 (t, J = 7.2 Hz, 4H), 7.17 (d, J = 7.6 Hz, 2H), 7.19 (d, J = 1.9 Hz, 4H), 7.24 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.13 (t), 30.89 (t), 31.57 (q), 31.71 (q), 34.11 (s), 34.17 (s), 71.46 (t), 74.90 (t), 75.28 (s), 85.55 (d), 119.34 (s), 124.33 (d), 124.78 (d), 125.41 (d), 126.86 (d), 127.11 (d), 127.51 (d), 127.95 (d), 128.19 (d), 132.23 (s), 132.48 (s), 133.92 (s), 137.90 (s), 140.24 (s), 144.52 (s),

144.99 (s), 152.22 (s), 152.72 (s). Anal. Calcd for $C_{104}H_{114}O_6 \cdot 0.5H_2O$: C, 85.03; H, 7.89. Found: C, 84.91; H, 7.88.

38,39,41,42-Tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butyl-37,40-[2-phenylethynyl-1,3-phenylenebis(methylenoxy)]calix[6]arene (25). Method A: **a'**, 15%; **b**, 12%. Method B: disubstituted product **30**, 75%.

25a': colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.09 (s, 36H), 1.28 (s, 18H), 3.24 (d, J = 15.6 Hz, 4H), 3.27 (d, J = 12.8 Hz, 2H), 3.86 (d, J = 7.5 Hz, 2H), 4.40 (d, J = 15.6 Hz, 4H), 4.51 (s, 4H), 4.51 (d, J = 12.8 Hz, 2H), 4.74 (t, J = 7.5 Hz, 1H), 4.76 (d, J = 12.1 Hz, 4H), 4.87 (d, J = 12.1 Hz, 4H), 6.59 (d, J = 1.5 Hz, 4H), 6.98 (t, J = 7.3 Hz, 8H), 7.07 (s, 4H), 7.11 (t, J = 7.3 Hz, 4H), 7.27 (d, J = 1.5 Hz, 4H), 7.26-7.29 (m, 3H), 7.34 (d, J = 7.0 Hz, 8H), 7.65 (d, J = 7.0 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.33 (t), 29.83 (t), 31.42 (q), 31.64 (q), 34.09 (s×2), 73.28 (t), 75.52 (t), 87.44 (s), 98.59 (s), 124.71 (s), 124.83 (d), 124.86 (d), 125.05 (d), 127.09 (d), 127.21 (d), 127.31 (d), 127.42 (s), 127.64 (d×2), 127.95 (d), 128.14 (d), 132.50 (d), 133.21 (s), 133.40 (s×2), 136.59 (s), 137.94 (s), 144.20 (s), 144.86 (s), 152.71 (s), 153.14 (s). Anal. Calcd for $C_{110}H_{118}O_6 \cdot 0.5H_2O$: C, 85.51; H, 7.76. Found: C, 85.38; H, 7.73.

25b: colorless crystals, mp 166-171 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.56 (s, 18H), 0.98 (s, 18H), 1.27 (s, 9H), 1.39 (s, 9H), 3.30 (d, J = 15.4 Hz, 2H), 3.38 (d, J = 16.0 Hz, 2H), 3.53 (dd, J = 7.8, 1.3 Hz, 1H), 3.68 (d, J = 13.1 Hz, 2H), 3.76 (d, J = 13.1 Hz, 2H), 4.09 (s, 2H), 4.20 (s, 2H), 4.21 (d, J = 15.4 Hz, 2H), 4.43 (d, J = 16.0 Hz, 2H), 4.65 (d, J = 11.0 Hz, 2H), 4.80 (d, J = 11.2 Hz, 2H), 4.83 (d, J = 11.0 Hz, 2H), 4.90 (d, J = 11.2 Hz, 2H), 6.25 (t, J = 7.8 Hz, 1H), 6.48 (brs, 2H), 6.67 (dd, J = 7.9, 1.4 Hz, 2H), 6.82 (dd, J = 7.8, 1.3 Hz, 1H), 6.90 (d, J = 2.4 Hz, 2H), 6.98 (s×2, 4H), 7.05 (s, 2H), 7.08-7.13 (m, 3H), 7.26-7.33 (m, 6H), 7.32 (s, 2H), 7.36 (t, J = 7.4 Hz, 2H), 7.43 (t, J = 7.4 Hz, 4H), 7.48 (d, J = 6.7 Hz, 4H), 7.54 (d, J = 7.4 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.77 (t), 29.15 (t), 30.68 (q), 31.33 (q), 31.62 (q), 31.84 (q), 33.49 (s), 33.98 (s), 34.06 (s), 34.33 (s), 36.31 (t), 69.26 (t), 73.98 (t), 74.26 (t), 74.55 (t), 86.02 (s), 95.36 (s), 122.22 (s), 123.71 (d), 124.26 (s), 124.61 (d), 126.86 (d), 127.08 (d×2), 127.51 (d), 127.58 (d), 127.65 (d), 127.71 (d), 127.93 (d), 127.98 (d), 128.02 (d), 128.44 (d), 128.47 (d), 128.81 (d), 129.50 (d), 129.87 (d), 131.42 (s), 131.67 (s), 132.26 (d), 132.28 (s), 132.47 (s), 133.03 (s), 133.16 (s), 135.48 (s), 137.80 (s), 137.87 (s), 138.30 (s), 144.16 (s), 144.73 (s), 144.90 (s×2), 149.96 (s), 153.03 (s), 154.27 (s), 156.43 (s). Anal. Calcd for $C_{110}H_{118}O_6 \cdot H_2O$: C, 85.01; H, 7.78. Found: C, 84.80; H, 7.56.

30: colorless crystals, mp 192-197 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.97 (s, 18H), 1.26 (s, 18H),

1.29 (s, 18H), 3.03 (d, J = 13.4 Hz, 1H), 3.13 (d, J = 13.5 Hz, 2H), 3.29 (d, J = 12.9 Hz, 1H), 3.37 (d, J = 14.8 Hz, 2H), 3.88 (d, J = 13.4 Hz, 1H), 4.44 (d, J = 9.0 Hz, 2H), 4.52 (d, J = 13.5 Hz, 2H), 4.61 (d, J = 12.9 Hz, 1H), 4.63 (d, J = 14.8 Hz, 2H), 4.83 (d, J = 11.1 Hz, 2H), 4.89 (d, J = 11.1 Hz, 2H), 5.58 (d, J = 9.0 Hz, 2H), 6.26 (d, J = 1.9 Hz, 2H), 6.32 (d, J = 7.6 Hz, 2H), 6.44 (t, J = 7.6 Hz, 2H), 6.75 (d, J = 7.6 Hz, 1H), 6.75 (d, J = 2.2 Hz, 2H), 6.85 (t, J = 7.6 Hz, 1H), 7.03 (d, J = 2.2 Hz, 2H), 7.07 (d, J = 2.3 Hz, 2H), 7.13 (d, J = 1.9 Hz, 2H), 7.21 (d, J = 2.3 Hz, 2H), 7.42-7.46 (m, 8H), 7.50 (s, 2H), 7.60-7.63 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.97 (t), 31.30 (t), 31.34 (q), 31.48 (q), 31.48 (t), 31.73 (q), 32.66 (t), 33.80 (s), 33.95 (s), 34.22 (s), 76.18 (t), 76.65 (t), 87.16 (s), 95.75 (s), 122.20 (s), 123.28 (d), 123.57 (s), 125.14 (d), 125.24 (d), 125.68 (d), 125.77 (d), 127.06 (d), 127.24 (d), 127.39 (s), 127.66 (s), 128.01 (d), 128.12 (d), 128.46 (d), 128.54 (d), 129.16 (d), 131.16 (d), 131.96 (s), 132.07 (s), 132.13 (d), 133.21 (s), 133.68 (s), 138.12 (s), 138.41 (s), 141.60 (s), 144.96 (s), 146.63 (s), 150.30 (s), 152.13 (s), 152.42 (s). Anal. Calcd for $C_{96}H_{108}O_6 \cdot H_2O$: C, 83.93; H, 7.92. Found: C, 84.16; H, 7.84.

38,39,41,42-Tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butyl-37,40-[2,5-dimethoxy-1,3-phenylenebis(methylenoxy)]calix[6]arene (26). Method A: **a**, 27%; **b**, 10%; **c**, 3%. Method B: **a**, 87%.

26a: colorless crystals, mp 231-235 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 3H), 1.02 (s, 36H), 1.43 (s, 18H), 3.19 (d, J = 14.3 Hz, 2H), 3.32 (d, J = 15.3 Hz, 4H), 3.36 (s, 3H), 4.21 (s, 4H), 4.55 (d, J = 15.3 Hz, 4H), 4.55 (d, J = 14.3 Hz, 2H), 4.60 (s, 8H), 6.68 (s, 2H), 6.71 (d, J = 2.1 Hz, 4H), 7.04 (d, J = 7.5 Hz, 8H), 7.09 (t, J = 7.5 Hz, 8H), 7.15 (t, J = 7.5 Hz, 4H), 7.18 (d, J = 2.1 Hz, 4H), 7.29 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.70 (t), 30.90 (t), 31.54 (q), 31.71 (q), 34.05 (s), 34.20 (s), 54.82 (q), 60.23 (q), 69.06 (t), 74.74 (t), 111.07 (d), 123.92 (d), 125.35 (d), 127.00 (d), 127.14 (d), 128.00 (d), 128.16 (d), 132.26 (s), 132.85 (s), 133.03 (s), 133.77 (s), 137.87 (s), 144.85 (s), 144.91 (s), 149.93 (s), 152.22 (s), 152.81 (s), 154.17 (s). Anal. Calcd. for $C_{104}H_{118}O_8 \cdot 0.5H_2O$: C, 83.00; H, 7.97. Found: C, 82.97; H, 7.86.

26b: colorless crystals, mp >300 °C; ^{1}H NMR (270 MHz, $CDCl_3$, 60 °C) δ 0.99 (s ×2, 36H), 1.33 (s, 9H), 1.34 (s, 9H), 2.14 (s, 3H), 3.05 (s, 3H), 3.33 (d, J = 15.5 Hz, 2H), 3.33 (d, J = 15.6 Hz, 2H), 3.72 (d, J = 12.8 Hz, 2H), 3.79 (d, J = 12.8 Hz, 2H), 3.96 (s, 2H), 3.98 (s, 2H), 4.14 (d, J = 3.0 Hz, 1H), 4.15 (d, J = 15.5 Hz, 2H), 4.19 (d, J = 11.2 Hz, 2H), 4.45 (d, J = 11.2 Hz, 2H), 4.49 (d, J = 15.6 Hz, 2H), 4.75 (d, J = 10.7 Hz, 2H), 4.87 (d, J = 10.7 Hz, 2H), 6.18 (d, J = 3.0 Hz, 1H), 6.82 (brs, 4H), 6.98 (d, J = 2.3 Hz, 2H), 7.10 (d, J = 2.3 Hz, 2H), 7.14 (s, 2H), 7.26-7.42 (m, 14H), 7.45-7.52 (m, 8H); ^{13}C NMR (68 MHz, $CDCl_3$, 60 °C) δ 29.05 (t), 29.51 (t), 31.17 (q),

31.40 (q), 31.69 (q), 31.74 (q), 34.13 (s ×2), 34.16 (s ×2), 35.38 (t), 54.96 (q), 61.83 (q), 65.58 (t), 69.51 (t), 74.21 (t), 75.10 (t), 115.90 (d), 117.13 (d), 123.22 (d), 126.09 (d), 127.54 (d), 127.61 (s), 127.78 (d), 127.85 (d), 128.11 (d), 128.20 (d), 128.26 (d), 128.41 (d ×2), 128.64 (d), 128.89 (d), 129.94 (s), 131.31 (s), 131.40 (s), 131.67 (s), 132.81 (s), 133.11 (s ×2), 137.78 (s), 138.40 (s), 143.78 (s), 144.53 (s), 144.81 (s), 145.76 (s), 150.00 (s), 151.74 (s), 152.71 (s), 153.07 (s), 153.63 (s), 155.69 (s). Anal. Calcd for $C_{104}H_{118}O_8$: C, 83.49; H, 7.95. Found: C, 83.26; H, 7.78.

26c: colorless solid; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.64 (s, 9H), 0.77 (s, 9H), 1.00 (s, 9H), 1.16 (s, 9H), 1.34 (s, 9H), 1.36 (s, 3H), 1.40 (s, 9H), 3.06 (d, J = 14.2 Hz, 1H), 3.19 (d, J = 16.5 Hz, 1H), 3.27 (d, J = 14.1 Hz, 1H), 3.31 (d, J = 11.8 Hz, 1H), 3.35 (d, J = 12.3 Hz, 1H), 3.36 (d, J = 11.8 Hz, 1H), 3.37 (s, 3H), 3.39 (d, J = 16.3 Hz, 1H), 3.62 (d, J = 15.6 Hz, 1H), 3.69 (d, J = 12.3 Hz, 1H), 3.89 (d, J = 13.5 Hz, 1H), 4.02 (d, J = 13.5 Hz, 1H), 4.05 (d, J = 13.4 Hz, 1H), 4.08 (d, J = 13.4 Hz, 1H), 4.20 (d, J = 16.3 Hz, 1H), 4.25 (d, J = 16.5 Hz, 1H), 4.42 (d, J = 14.2 Hz, 1H), 4.50 (d, J = 15.6 Hz, 1H), 4.58 (s, 2H), 4.65 (d, J = 11.4 Hz, 1H), 4.67 (d, J = 11.4 Hz, 1H), 4.82 (d, J = 11.7 Hz, 1H), 4.85 (d, J = 14.1 Hz, 1H), 4.94 (d, J = 11.7 Hz, 1H), 6.14 (d, J = 1.8 Hz, 1H), 6.39 (d, J = 3.0 Hz, 1H), 6.47 (d, J = 2.0 Hz, 1H), 6.87 (d, J = 7.4 Hz, 2H), 6.94 (d, J = 2.2 Hz, 1H), 7.03 (d, J = 1.9 Hz, 1H), 7.04 (d, J = 3.0 Hz, 1H), 7.06 (d, J = 2.1 Hz, 1H), 7.09-7.19 (m, 8H), 7.21-7.24 (m, 2H), 7.26-7.35 (m, 11H), 7.38 (d, J = 2.2 Hz, 1H), 7.39 (d, J = 2.4 Hz, 1H), 7.45 (d, J = 7.7 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 25.40 (t), 29.70 (t), 30.14 (t), 30.88 (q), 31.08 (q), 31.41 (q), 31.55 (q), 31.66 (q), 31.71 (q), 32.72 (t), 33.72 (s), 33.82 (s), 33.90 (t), 34.01 (s), 34.19 (s), 34.26 (s), 34.29 (s), 35.64 (t), 55.26 (q), 60.92 (q), 68.05 (t), 73.19 (t), 74.02 (t), 74.64 (t), 74.84 (t), 76.65 (t), 111.36 (d), 112.57 (d), 123.66 (d), 123.92 (d), 124.23 (d), 124.57 (d), 125.63 (d ×2), 126.00 (d), 126.40 (d), 126.93 (d), 127.08 (d), 127.27 (d), 127.37 (d), 127.42 (d), 127.49 (d), 127.63 (d), 127.65 (d), 127.96 (d), 128.19 (d ×2), 128.28 (d), 128.48 (d), 128.64 (d), 128.73 (d), 129.04 (d), 131.59 (s), 131.89 (s), 132.61 (s), 132.65 (s), 133.13 (s), 133.43 (s × 2), 133.58 (s), 133.62 (s), 133.87 (s), 133.95 (s), 134.08 (s), 134.24 (s), 134.88 (s), 137.52 (s), 138.11 (s), 138.26 (s), 138.95 (s), 144.59 (s), 144.84 (s), 145.37 (s), 145.53 (s), 145.63 (s), 145.98 (s), 149.03 (s), 152.85 (s), 153.00 (s), 153.16 (s), 153.37 (s), 154.42 (s), 154.86 (s), 156.59 (s). Anal. Calcd for $C_{104}H_{118}O_8$: C, 83.49; H, 7.90. Found: C, 83.23; H, 7.90.

38,39,41,42-Tetrabenzyloxy-37,40-[5-bromo-2-methoxy-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene (27). Method A: **a**, 35%; **b**, 7%; **c**, 7%. Method B: **a**, 93%.

27a: colorless crystals, mp 291-300 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 3H), 1.00 (s,

36H), 1.43 (s, 18H), 3.12 (d, J = 14.5 Hz, 2H), 3.25 (d, J = 15.3 Hz, 4H), 4.10 (s, 4H), 4.47 (d, J = 15.3 Hz, 4H), 4.50 (d, J = 14.5 Hz, 2H), 4.64 (d, J = 12.1 Hz, 4H), 4.67 (d, J = 12.1 Hz, 4H), 7.01 (d, J = 1.5 Hz, 4H), 7.08-7.19 (m, 24H), 7.26 (s, 4H), 7.40 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.78 (t), 30.84 (t), 31.49 (q), 31.69 (q), 34.04 (s), 34.22 (s), 60.54 (q), 68.55 (t), 74.84 (t), 115.07 (s), 123.88 (d), 125.22 (d), 127.11 (d $\times$2), 127.93 (d), 128.13 (d), 128.87 (d), 132.19 (s), 133.39 (s), 133.70 (s), 134.45 (s), 137.78 (s), 144.85 (s), 145.25 (d), 152.26 (s), 152.77 (s), 155.67 (s). Anal. Calcd for $C_{103}H_{115}BrO_7 \cdot H_2O$: C, 79.15; H, 7.54; Br, 5.11. Found: C, 79.15; H, 7.40; Br, 5.31.

27b: colorless crystals, mp >300 °C; ^{1}H NMR (270 MHz, $CDCl_3$, 60 °C) δ 0.98 (s, 18H), 1.06 (s, 18H), 1.32 (s, 9H), 1.38 (s, 9H), 2.21 (s, 3H), 3.33 (d, J = 15.5 Hz, 2H), 3.33 (d, J = 15.8 Hz, 2H), 3.72 (d, J = 12.8 Hz, 2H), 3.81 (d, J = 12.8 Hz, 2H), 3.95 (s, 2H), 3.99 (s, 2H), 4.09 (d, J = 15.5 Hz, 2H), 4.18 (d, J = 11.5 Hz, 2H), 4.46 (d, J = 15.8 Hz, 2H), 4.51 (d, J = 11.5 Hz, 2H), 4.73 (d, J = 11.0 Hz, 2H), 4.75 (d, J = 2.5 Hz, 1H), 4.87 (d, J = 11.0 Hz, 2H), 6.75 (d, J = 2.5 Hz, 1H), 6.79 (s, 2H), 6.94 (s, 2H), 7.00 (d, J = 2.3 Hz, 2H), 7.10 (d, J = 2.6 Hz, 2H), 7.12 (s, 2H), 7.28 (s, 2H), 7.30-7.42 (m, 12H), 7.50 (d, J = 6.6 Hz, 8H); ^{13}C NMR (68 MHz, $CDCl_3$, 60 °C) δ 28.75 (t), 29.51 (t), 31.40 (q), 31.43 (q), 31.62 (q), 31.72 (q), 34.13 (s $\times$2), 34.25 (s), 34.29 (s), 35.47 (t), 62.00 (q), 65.00 (t), 68.62 (t), 74.07 (t), 75.15 (t), 113.83 (s), 123.10 (d), 126.07 (d), 127.55 (d), 127.76 (d $\times$2), 127.88 (d), 128.16 (d), 128.27 (d), 128.35 (d), 128.44 (d), 128.68 (d), 128.93 (d), 130.58 (s), 131.12 (s), 131.18 (s), 131.86 (s), 132.15 (s), 132.59 (s), 133.15 (s), 133.17 (s), 133.51 (d), 133.77 (d), 137.70 (s), 138.32 (s), 143.97 (s), 144.57 (s), 145.34 (s), 146.22 (s), 151.21 (s), 152.99 (s), 153.52 (s), 155.51 (s). Anal. Calcd for $C_{103}H_{115}BrO_7$: C, 80.08; H, 7.50; Br, 5.17. Found: C, 79.85; H, 7.32; Br, 5.54.

27c: colorless crystals, mp 269-272 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.62 (s, 9H), 0.77 (s, 9H), 0.98 (s, 9H), 1.14 (s, 9H), 1.35 (s, 9H), 1.39 (s, 9H), 1.40 (s, 3H), 2.93 (d, J = 14.2 Hz, 1H), 3.12 (d, J = 14.0 Hz, 1H), 3.14 (d, J = 16.2 Hz, 1H), 3.34 (d, J = 12.5 Hz, 1H), 3.36 (d, J = 12.1 Hz, 1H), 3.37 (d, J = 12.1 Hz, 1H), 3.39 (d, J = 16.3 Hz, 1H), 3.63 (d, J = 15.7 Hz, 1H), 3.69 (d, J = 12.5 Hz, 1H), 3.89 (d, J = 13.5 Hz, 1H), 4.02 (d, J = 13.5 Hz, 1H), 4.10 (d, J = 13.1 Hz, 1H), 4.13 (d, J = 13.1 Hz, 1H), 4.19 (d, J = 16.2 Hz, 1H), 4.21 (d, J = 16.3 Hz, 1H), 4.30 (d, J = 14.2 Hz, 1H), 4.47 (d, J = 15.7 Hz, 1H), 4.62 (s, 2H), 4.65 (d, J = 11.7 Hz, 1H), 4.67 (d, J = 14.0 Hz, 1H), 4.76 (d, J = 11.7 Hz, 1H), 4.81 (d, J = 11.6 Hz, 1H), 4.91 (d, J = 11.6 Hz, 1H), 6.16 (d, J = 1.4 Hz, 1H), 6.47 (d, J = 1.9 Hz, 1H), 6.90 (d, J = 7.4 Hz, 2H), 6.99 (d, J = 2.0 Hz, 1H), 6.99 (d, J = 2.1 Hz, 1H), 7.04 (d, J = 2.1 Hz, 1H), 7.05 (d, J = 2.2 Hz, 1H), 7.14-7.16 (m, 4H), 7.21-7.24 (m, 7H),

7.27-7.38 (m, 12H), 7.42-7.44 (m, 2H), 7.75 (d, J = 2.2 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 25.63 (t), 30.04 (t), 30.25 (t), 30.90 (q), 31.05 (q), 31.41 (q), 31.52 (q), 31.64 (q), 31.69 (q), 32.60 (t), 33.71 (s), 33.82 (s), 34.00 (t), 34.07 (s), 34.16 (s), 34.29 (s ×2), 35.47 (t), 61.07 (q), 67.53 (t), 73.30 (t), 73.72 (t), 73.97 (t), 75.00 (t), 76.57 (t), 76.75 (t), 115.16 (s), 123.46 (d), 124.03 (d), 124.17 (d), 124.48 (d), 125.72 (d), 125.95 (d), 126.65 (d), 126.82 (d), 127.23 (d), 127.37 (d), 127.44 (d), 127.52 (d), 127.61 (d), 127.68 (d), 127.97 (d), 128.15 (d), 128.35 (d ×2), 128.42 (d), 128.47 (d), 128.57 (d), 128.62 (d), 128.89 (d), 129.68 (d), 130.48 (d), 131.87 (s), 132.58 (s), 133.02 (s), 133.23 (s), 133.34 (s), 133.45 (s), 133.63 (s), 133.67 (s), 133.83 (s), 133.95 (s), 134.00 (s), 134.09 (s), 134.19 (s), 134.38 (d), 135.02 (s), 137.65 (s), 138.04 (s), 138.12 (s), 138.58 (s), 144.62 (s), 144.99 (s), 145.30 (s), 145.62 (s), 145.82 (s), 146.22 (s), 152.84 (s), 152.90 (s), 152.91 (s), 153.32 (s), 154.55 (s), 154.67 (s), 156.13 (s). Anal. Calcd for $C_{103}H_{115}BrO_6 \cdot H_2O$: C, 79.15; H, 7.54; Br, 5.11. Found: C, 79.34; H, 7.51; Br, 5.58.

38,39,41,42-Tetrabenzyloxy-37,40-[5-bromo-2-methylthio-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene (28). Method B: **a**, 48%.

28a: colorless crystals, mp 281-292 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ –0.25 (s, 3H), 1.01 (s, 36H), 1.43 (s, 18H), 3.18 (d, J = 14.5 Hz, 2H), 3.30 (d, J = 15.1 Hz, 4H), 4.34 (s, 4H), 4.45 (d, J = 14.5 Hz, 2H), 4.52 (d, J = 15.1 Hz, 4H), 4.56 (d, J = 11.9 Hz, 4H), 4.66 (d, J = 11.9 Hz, 4H), 6.78 (d, J = 1.8 Hz, 4H), 7.08 (d, J = 6.7 Hz, 8H), 7.13-7.20 (m, 16H), 7.29 (s, 4H), 7.36 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 19.79 (q), 26.85 (t), 30.84 (t), 31.48 (q), 31.71 (q), 34.07 (s), 34.19 (s), 71.00 (t), 74.98 (t), 121.90 (s), 124.25 (d), 125.65 (d), 127.19 (d), 127.23 (d), 128.16 (d), 128.48 (d), 128.60 (d), 132.11 (s), 132.24 (s), 133.88 (s), 134.61 (s), 137.61 (s), 144.44 (s), 144.94 (s), 145.08 (s), 152.49 (s), 152.71 (s). Anal. Calcd for $C_{103}H_{115}BrO_6S \cdot H_2O$: C, 78.35; H, 7.69; S, 2.03. Found: C, 78.26; H, 7.35; S, 2.29.

38,39,41,42-Tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butyl-37,40-[2-butylseleno-1,3-phenylenebis(methylenoxy)]calix[6]arene (29).[28b] Method A: **a'**, 59%; **b**, 4%. Method B: **a'**, 92%.

Synthesis of 37,40-[2-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39-bis(4-pyridylmethoxy)calix[6]arene-41,42-diol (32). According to method B, except for the use of 2 equivalents of 4-(chloromethyl)pyridine hydrochloride instead of 6 equivalents, the disubstituted product **32** was obtained in 17% yield along with starting material **2B** (23%), 1,2,3-alternate isomer **20b** (4%), and cone isomer **15a** (15%). **32**: colorless crystals, mp 221-227 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.88 (s, 18H), 1.15 (s, 18H), 1.36 (s, 18H),

3.35 (d, J = 13.7 Hz, 2H), 3.38 (d, J = 12.8 Hz, 1H), 3.42 (d, J = 14.0 Hz, 1H), 3.46 (d, J = 14.0 Hz, 1H), 3.50, (d, J = 15.6 Hz, 2H), 4.16 (d, J = 13.7 Hz, 2H), 4.45 (d, J = 9.9 Hz, 2H), 4.51 (d, J = 12.8 Hz, 1H), 4.88 (d, J = 13.4 Hz, 2H), 4.89 (d, J = 15.6 Hz, 2H), 4.96 (d, J = 13.4 Hz, 2H), 5.66 (d, J = 9.9 Hz, 2H), 6.43 (d, J = 2.3 Hz, 2H), 6.78 (brs, 2H), 6.93 (s, 4H), 7.08 (d, J = 2.3 Hz, 2H), 7.23 (d, J = 2.3 Hz, 2H), 7.31 (d, J = 2.3 Hz, 2H), 7.31 (t, J = 7.5 Hz, 1H), 7.42 (d, J = 7.5 Hz, 2H), 7.51 (d, J = 4.9 Hz, 8H), 8.49 (br, 8H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 29.11 (t), 30.93 (t), 31.11 (q), 31.49 (t), 31.49 (q), 31.53 (q), 32.52 (t), 33.78 (s), 33.98 (s), 34.28 (s), 73.86 (t), 77.33 (t), 121.86 (d), 123.89 (d), 124.92 (d), 125.51 (d), 125.77 (d), 126.61 (s), 126.77 (s), 126.84 (d), 127.10 (d), 128.26 (d), 129.32 (s), 131.54 (d), 132.44 (s), 132.51 (s), 132.61 (s), 133.35 (s), 138.16 (s), 142.17 (s), 146.12 (s), 146.80 (s), 147.16 (s), 148.82 (s), 149.72 (d), 151.71 (s), 153.26 (s). Anal. Calcd for $C_{86}H_{99}BrN_2O_6 \cdot 2H_2O$: C, 75.25; H, 7.56; N, 2.04; Br, 5.82. Found: C, 75.50; H, 7.24; N, 2.18; Br, 5.52.

Synthesis of 37,40-[2-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,41-bis(4-pyridylmethoxy)calix[6]arene-39,42-diol (33). According to method A except for the use of 2 equivalents of 4-(chloromethyl)pyridine hydrochloride instead of 6 equivalents, the disubstituted product **33** was obtained in 8% yield. **33**: colorless crystals; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.92 (s, 18H), 1.02 (s, 18H), 1.45 (s, 18H), 3.35 (d, J = 15.2 Hz, 2H), 3.39 (d, J = 13.6 Hz, 2H), 3.57 (d, J = 15.1 Hz, 2H), 3.93 (d, J = 13.6 Hz, 2H), 4.78 (d, J = 15.1 Hz, 2H), 4.83 (d, J = 15.2 Hz, 2H), 4.87 (br, 2H), 4.93 (d, J = 11.9 Hz, 2H), 4.96 (br, 2H), 5.05 (d, J = 11.9 Hz, 2H), 6.25 (br, 2H), 6.60 (d, J = 2.1 Hz, 2H), 6.61 (t, J = 7.4 Hz, 1H), 6.80 (d, J = 2.0 Hz, 2H), 6.89 (d, J = 2.0 Hz, 2H), 6.99 (d, J = 2.1 Hz, 2H), 7.31 (d, J = 7.4 Hz, 2H), 7.32 (d, J = 2.4 Hz, 2H), 7.43 (d, J = 2.4 Hz, 2H), 7.61 (d, J = 5.3 Hz, 4H), 8.75 (br, 4H). Anal. Calcd for $C_{88}H_{99}BrN_2O_6 \cdot 0.75CHCl_3$: C, 73.06; H, 7.05; N 1.96; Br, 5.60. Found: C, 73.15; H, 7.02; N, 1.96; Br, 5.24.

Synthesis of 37,40-[2-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetraethoxycalix[6]arene (34). According to method B except for the use of iodoethane instead of arylmethyl halide, tetraethyl derivative **34** was obtained in 65% yield. **34**: colorless crystals, mp >300 °C; mixture of conformational isomers, **a/b** = 28:72, **34a**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 36H), 1.13 (t, J = 7.0 Hz, 12H), 1.46 (s, 18H), 3.21 (d, J = 14.9 Hz, 2H), 3.39 (d, J = 15.0 Hz, 4H), 3.47-3.54 (m, 8H), 3.99 (s, 4H), 4.26 (d, J = 14.9 Hz, 2H), 4.50 (d, J = 15.0 Hz, 4H), 6.80 (d, J = 1.8 Hz, 4H), 7.10 (d, J = 1.8 Hz, 4H), 7.18 (t, J = 7.4 Hz, 1H), 7.31 (d, J = 7.4 Hz, 2H), 7.34 (s, 4H). **34b**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.17 (s, 18H), 1.20 (s,

18H), 1.30 (s, 9H), 1.33 (s, 9H), 1.48 (t, J = 7.0 Hz, 6H), 1.56 (t, J = 7.1 Hz, 6H), 3.25 (d, J = 15.9 Hz, 2H), 3.32 (d, J = 15.8 Hz, 2H), 3.59 (dd, 7.6, 1.5 Hz, 1H), 3.71 (d, J = 12.5 Hz, 2H), 3.76 (d, J = 12.5 Hz, 2H), 3.81-3.96 (m, 10H), 3.98 (s, 2H), 4.04 (s, 2H), 4.37 (d, J = 15.8 Hz, 2H), 6.12 (t, J = 7.6 Hz, 1H), 6.62 (brs, 2H), 6.73 (brs, 2H), 6.79 (dd, J = 7.6, 1.5 Hz, 1H), 7.12 (s, 2H), 7.13 (s, 2H), 7.23 (d, J = 2.3 Hz, 2H), 7.38 (d, J = 2.4 Hz, 2H). Anal. Calcd for $C_{82}H_{109}BrO_6 \cdot 0.4CHCl_3$: C, 75.30; H, 8.08; Br, 6.08; Cl, 3.24. Found: C, 75.03; H, 7.99; Br, 5.83; Cl, 3.18.

Synthesis of 5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetraethoxy-37,40-[2-ethynyl-1,3-phenylenebis(methylenoxy)]calix[6]arene (35). According to method B except for the use of iodoethane instead of arylmethyl halide, tetraethyl derivative **35** was obtained in 58% yield. **35**: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) mixture of conformational isomers, **a/b** = 40:60, **35a**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.46 (s, 1H), 1.01 (s, 36H), 1.14 (t, J = 6.8 Hz, 12H), 1.41 (s, 18H), 3.22 (d, J = 15.0 Hz, 2H), 3.40 (d, J = 14.6 Hz, 4H), 3.44-3.48 (m, 4H), 3.54-3.58 (m, 4H), 4.02 (s, 4H), 4.35 (d, J = 15.0 Hz, 2H), 4.48 (d, J = 14.6 Hz, 4H), 6.74 (d, J = 1.8 Hz, 4H), 7.12 (d, J = 1.8 Hz, 4H), 7.18 (t, J = 7.5 Hz, 1H), 7.27 (s, 4H), 7.35 (d, J = 7.5 Hz, 2H). **35b**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.18 (s, 18H), 1.22 (s, 18H), 1.28 (s, 9H), 1.32 (s, 9H), 1.48 (t, J = 6.9 Hz, 6H), 1.54 (t, J = 7.0 Hz, 6H), 2.17 (s, 1H), 3.22 (d, J = 14.0 Hz, 2H), 3.30 (d, J = 15.9 Hz, 2H), 3.55 (dd, J = 7.7, 1.5 Hz, 1H), 3.71 (d, J = 12.7 Hz, 2H), 3.76 (d, J = 12.7 Hz, 2H), 3.80-3.96 (m, 12H), 3.98 (s, 2H), 4.37 (d, J = 15.9 Hz, 2H), 6.20 (t, J = 7.7 Hz, 1H), 6.62 (brs, 2H), 6.78 (brs, 2H), 6.82 (dd, J = 7.7, 1.5 Hz, 1H), 7.10 (s, 2H), 7.12 (s, 2H), 7.22 (d, J = 2.6 Hz, 2H), 7.30 (d, J = 2.3 Hz, 2H). Anal. Calcd for $C_{94}H_{106}O_6$: C, 83.26; H, 8.82. Found: C, 82.96; 8.78.

Synthesis of 38,39,41,42-tetraallyloxy-37,40-[2-bromo-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene (36). According to method B except for the use of allyl bromide instead of arylmethyl halide, tetraethyl derivatives **36a** (36%) and **36b** (37%) were obtained after separation on silica gel.

36a: colorless crystals, mp 259 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.00 (s, 36H), 1.44 (s, 18H), 3.22 (d, J = 14.8 Hz, 2H), 3.39 (d, J = 15.1 Hz, 4H), 3.90-3.96 (m, 8H), 4.07 (s, 4H), 4.26 (d, J = 14.8 Hz, 2H), 4.48 (d, J = 15.1 Hz, 4H), 5.08 (dd, J = 10.6, 1.3 Hz, 4H), 5.19 (dd, J = 17.3, 1.3 Hz, 4H), 5.77-5.85 (m, 4H), 6.79 (d, J = 1.8 Hz, 4H), 7.13 (d, J = 1.8 Hz, 4H), 7.18 (t, J = 7.5 Hz, 1H), 7.32 (s, 4H), 7.35 (d, J = 7.5 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.12 (t), 30.87 (t), 31.52 (q), 31.74 (q), 34.09 (s), 34.19 (s), 72.58 (t), 74.03 (t), 115.92 (t), 123.96 (s), 124.67 (d),

125.57 (d), 125.62 (d), 126.37 (d), 128.55 (d), 131.82 (s), 131.90 (s), 133.94 (s), 134.68 (d), 137.30 (s), 144.34 (s), 145.06 (s), 152.17 (s), 152.62 (s). Anal. Calcd for $C_{86}H_{105}BrO_6$: C, 78.57; H, 8.05; Br, 6.08. Found: C, 78.37; H, 7.92; Br, 5.88.

36b: colorless crystals, mp 233-239 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.16 (s, 18H), 1.18 (s, 18H), 1.30 (s, 9H), 1.33 (s, 9H), 3.23 (d, J = 15.7 Hz, 2H), 3.31 (d, J = 15.9 Hz, 2H), 3.65 (dd, J = 7.5, 1.5 Hz, 1H), 3.72 (d, J = 12.6 Hz, 2H), 3.78 (d, J = 12.6 Hz, 2H), 3.96 (d, 15.7 Hz, 2H), 4.01 (s, 2H), 4.08 (s, 2H), 4.27 (dd, J = 12.6, 4.6 Hz, 2H), 4.33-4.37 (m, 4H), 4.39 (d, J = 15.9 Hz, 2H), 4.43 (dd, J = 12.1, 6.3 Hz, 2H), 5.28 (dd, J = 10.6, 1.3 Hz, 2H), 5.31 (dd, J = 10.4, 1.1 Hz, 2H), 5.50 (dd, J = 17.2, 1.3 Hz, 2H), 5.53 (dd, J = 17.2 Hz, 1.1 Hz, 2H), 6.11-6.19 (m, 2H), 6.15 (t, J = 7.5 Hz, 1H), 6.22-6.30 (m, 2H), 6.62 (br, 2H), 6.75 (br, 2H), 6.80 (dd, J = 7.5, 1.5 Hz, 1H), 7.11 (s, 2H), 7.12 (s, 2H), 7.20 (d, J = 2.3 Hz, 2H), 7.35 (d, J = 2.3 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.84 (t), 29.30 (t), 31.55 (q), 31.60 (q), 31.65 (q × 2), 34.06 (s), 34.16 (s), 34.20 (s), 34.32 (s), 35.12 (t), 71 28 (t), 72.89 (t), 73.18 (t), 73.77 (t), 116.44 (t), 117.39 (t), 123.83 (d), 125.13 (d × 2), 126.74 (s), 127.04 (d), 127.35 (d), 127.82 (d), 128.12 (d), 130.76 (d), 131.31 (d), 131.80 (s), 132.03 (s), 132.25 (s), 132.46 (s), 132.56 (s), 132.76 (s), 133.24 (s), 134.65 (d), 134.74 (d), 136.31 (s), 144.42 (s), 144.45 (s × 2), 144.98 (s), 150 09 (s), 153.74 (s), 154.03 (s), 154.47 (s). Anal. Calcd for $C_{86}H_{105}BrO_6 \cdot H_2O$: C, 77.51; H, 8.09; Br, 6.00. Found: C, 77.71; H, 7.88; Br, 6.78.

X-ray crystallographic analysis of 2A and 2C. Single crystals of **2A**·CH_3CN·C_6H_6 and **2C**·CH_3CN·C_6H_6 were grown in their benzene/acetonitrile solution. The intensity data were collected at 120 K on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation (λ = 0.71069 Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-6. The structures were solved by the direct method and refined by full-matrix least squares on F^2 using SHELXL 97.[44] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were idealized by using the riding model.

X-ray crystallographic analysis of 2B and 2J. Single crystals of **2B**·5$CHCl_3$ and **2J**·5$CHCl_3$ were grown in their chloroform solution. The intensity data were collected at 150 K (**2B**) and 120 K (**2J**) on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation (λ = 0.71069 Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-6. The structures were solved by the direct method and refined by full-matrix least

squares on F^2 using SHELXL 97.[44] The non-hydrogen atoms were refined anisotropically except for the minor component of the disordered bridging unit (0.90:0.10 for **2B** and 0.93:0.07 for **2J**). Hydrogen atoms were idealized by using the riding model.

Table 2-6. Crystallographic data for **2A**·CH_3CN·C_6H_6, **2C**·CH_3CN·C_6H_6, **2B**·$5CHCl_3$, and **2J**·$5CHCl_3$

	2A·CH_3CN·C_6H_6	**2C**·CH_3CN·C_6H_6	**2B**·$5CHCl_3$	**2J**·$5CHCl_3$
formula	$C_{62}H_{69}NO_6$	$C_{62}H_{68}BrNO_6$	$C_{79}H_{84}Br_2Cl_{15}O_6$	$C_{81}H_{85}Cl_{15}O_6$
temperature (K)	120	120	150	120
crystal system	monoclinic	monoclinic	triclinic	triclinic
space group	$P2_1/a$	$P2_1/a$	$P\bar{1}$	$P\bar{1}$
a (Å)	17.965(1)	18.014(1)	16.022(2)	15.971(1)
b (Å)	23.652(1)	23.970(2)	17.403(2)	17.359(1)
c (Å)	18.081(1)	18.184(1)	17.491(2)	17.526(1)
α (deg)			63.310(5)	63.545(3)
β (deg)	110.920(2)	112.643(4)	79.249(6)	79.228(3)
γ (deg)			79.050(6)	79.201(2)
V (Å^3)	7176.3(6)	7246.6(8)	4249.5(8)	4243.4(5)
Z	4	4	2	2
calculated density (g cm^{-3})	1.106	1.167	1.369	1.328
reflections collected	48315	43191	26668	27129
unique	13461	13376	14302	14573
R_{int}	0.027	0.037	0.029	0.021
F_{000}	2584	2720	1812	1768
limiting indices	$0 \le h \le 21$	$0 \le h \le 21$	$0 \le h \le 19$	$0 \le h \le 19$
	$0 \le k \le 28$	$0 \le k \le 29$	$-20 \le k \le 21$	$-20 \le k \le 21$
	$-21 \le l \le 20$	$-22 \le l \le 20$	$-20 \le l \le 21$	$-20 \le l \le 21$
restraints/parameters	0/857	0/834	21/1035	19/1128
goodness of fit (F^2)	1.069	1.037	1.044	1.065
R indices ($I > 2\sigma(I)$)	$R1 = 0.0598$	$R1 = 0.0721$	$R1 = 0.0990$	$R1 = 0.0791$
	$wR2 = 0.1535$	$wR2 = 0.1743$	$wR2 = 0.2385$	$wR2 = 0.1999$
R indices (all data)	$R1 = 0.0772$	$R1 = 0.1189$	$R1 = 0.1543$	$R1 = 0.0860$
	$wR2 = 0.1642$	$wR2 = 0.2066$	$wR2 = 0.2642$	$wR2 = 0.2052$

X-ray crystallographic analysis of 24a, 25a', and 29a'. Single crystals of **24a**, **25a'**, and **29a'** were grown in their benzene/acetonitrile solutions. The intensity data were collected at 120 K on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation ($\lambda = 0.71069$ Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-7. The structures were solved by the direct method and refined by full-matrix least squares on F^2 using SHELXL 97.[44] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were idealized by using the riding model.

Table 2-7. Crystallographic data for **24a**, **25a'**, and **29a'**

	24a	**25a'**	**29a'**
formula	$C_{108}H_{114}O_6$	$C_{110}H_{118}O_6$	$C_{110}H_{118}O_6$
temperature (K)	120	120	120
crystal system	monoclinic	monoclinic	monoclinic
space group	$P2_1/c$	$P2_1/c$	$P2_1/c$
a (Å)	14.051(1)	14.649(1)	14.320(1)
b (Å)	25.367(1)	23.016(1)	23.903(1)
c (Å)	24.129(1)	26.572(1)	25.856(1)
α (deg)			
β (deg)	97.174(2)	99.954(2)	97.128(2)
γ (deg)			
V (Å^3)	8533.0(7)	8824.2(7)	8781.9(7)
Z	4	4	4
calculated density (g cm^{-3})	1.136	1.156	1.188
reflections collected	51155	55346	57351
unique	16080	16159	16878
R_{int}	0.021	0.020	0.031
F_{000}	3144	3304	3360
limiting indices	$0 \le h \le 17$	$0 \le h \le 17$	$0 \le h \le 17$
	$0 \le k \le 30$	$0 \le k \le 27$	$0 \le k \le 29$
	$-29 \le l \le 29$	$-32 \le l \le 31$	$-31 \le l \le 31$
restraints/parameters	0/1059	0/1063	0/1037
goodness of fit (F^2)	1.076	1.023	1.032
R indices ($I > 2\sigma(I)$)	$R1 = 0.0616$	$R1 = 0.0607$	$R1 = 0.0485$
	$wR2 = 0.1435$	$wR2 = 0.1574$	$wR2 = 1181$
R indices (all data)	$R1 = 0.0828$	$R1 = 0.0752$	$R1 = 0.0618$
	$wR2 = 0.1616$	$wR2 = 0.1703$	$wR2 = 0.1263$

X-ray crystallographic analysis of 6b, 25b, and 27c. Single crystals of **6b**, **25b**·4C_6H_6, and **27c** were grown in their dichloromethane/methanol, benzene/ethanol, and chloroform/ethanol solutions, respectively. The intensity data were collected at 120 K on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation (λ = 0.71069 Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-8. The structures were solved by the direct method and refined by full-matrix least squares on F^2 using SHELXL 97.[44] The non-hydrogen atoms were refined anisotropically except for the disordered benzene rings of **6b** and **25b**. Hydrogen atoms were idealized by using the riding model. In the crystal of **27c**, there are two crystallographically independent molecules in the asymmetric unit.

Table 2-8. Crystallographic data for **6b**, **25b**·$4C_6H_6$, and **27c**

	6b	**25b**·$4C_6H_6$	**27c**
formula	$C_{107}H_{113}BrO_6$	$C_{134}H_{142}O_6$	$C_{103}H_{115}BrO_5$
temperature (K)	120	120	120
crystal system	triclinic	triclinic	triclinic
space group	*P*–1	*P*–1	*P*–1
a (Å)	11.524(1)	14.312(1)	14.117(2)
b (Å)	14.598(1)	14.370(1)	25.303(3)
c (Å)	14.925(2)	14.594(1)	25.117(3)
α (deg)	64.885(6)	63.651(3)	88.139(5)
β (deg)	67.264(5)	83.007(3)	83.716(6)
γ (deg)	84.146(6)	83.037(3)	75.785(5)
V (Å^3)	2091.0(4)	2669.6(3)	8645(2)
Z	1	1	4
calculated density (g cm^{-3})	1.203	1.150	1.187
reflections collected	11763	16303	49419
unique	6958	8935	28829
R_{int}	0.017	0.012	0.062
F_{000}	808	994	3296
limiting indices	$0 \le h \le 14$	$0 \le h \le 17$	$0 \le h \le 17$
	$-17 \le k \le 17$	$-17 \le k \le 17$	$-29 \le k \le 31$
	$-16 \le l \le 18$	$-17 \le l \le 17$	$-30 \le l \le 30$
restraints/parameters	0/501	24/759	0/2112
goodness of fit (F^2)	1.033	1.124	1.211
R indices ($I > 2\sigma(I)$)	$R1 = 0.0710$	$R1 = 0.0805$	$R1 = 0.1037$
	$wR2 = 0.1699$	$wR2 = 0.1860$	$wR2 = 2338$
R indices (all data)	$R1 = 0.0868$	$R1 = 0.0863$	$R1 = 0.2008$
	$wR2 = 0.1825$	$wR2 = 0.1892$	$wR2 = 0.2612$

X-ray crystallographic analysis of 20a, 20b, and 22a. Single crystals of **20a**·$5C_2H_2Cl_4$, **20b**·$2CHCl_3$, and **22a**·2THF were grown in their 1,1,2,2-tetrachloroethane, chloroform/methanol, and THF solutions, respectively. The intensity data were collected on a MAC Science DIP-2030 imaging plate area detector (**20a**·$5C_2H_2Cl_4$ and **22a**·2THF) or a Rigaku AFC5R diffractometer (**20b**·$2CHCl_3$) with MoK_α radiation (λ = 0.71069 Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-9. The structures were solved by the Patterson method and refined by full-matrix least squares on *F*. The non-hydrogen atoms were refined anisotropically except for the disordered benzene rings of **20b** and the carbon atoms of the disordered solvent molecules in **20a**. Hydrogen atoms were included but not refined.

Table 2-9. Crystallographic data for **20a**·5$C_2H_2Cl_4$, **20b**·2$CHCl_3$, and **22a**·2THF

	20a·5$C_2H_2Cl_4$	**20b**·2$CHCl_3$	**22a**·2THF
formula	$C_{108}H_{119}BrCl_{20}N_4O_6$	$C_{109}H_{111}BrCl_6N_4O_6$	$C_{103}H_{115}BrO_7$
temperature (K)	150	296	120
crystal system	monoclinic	triclinic	triclinic
space group	C_c	$P\bar{1}$	$P\bar{1}$
a (Å)	12.2440(2)	13.488(3)	15.137(1)
b (Å)	36.038(2)	15.124(4)	15.233(1)
c (Å)	26.1300(9)	12.699(2)	15.541(1)
α (deg)		103.37(2)	99.545(3)
β (deg)	100.220(2)	95.76(2)	92.008(3)
γ (deg)		111.97(2)	110.720(3)
V (Å^3)	11346.9(6)	2286.6(2)	3288.0(4)
Z	4	1	2
calculated density (g cm^{-3})	1.380	1.276	1.340
reflections collected	32595	10964	23486
unique	9888	10517	11341
R_{int}	0.029	0.040	0.021
F_{000}	4872	924	1392
limiting indices	$0 \le h \le 13$	$0 \le h \le 17$	$0 \le h \le 18$
	$0 \le k \le 43$	$-19 \le k \le 18$	$-18 \le k \le 16$
	$-31 \le l \le 31$	$-16 \le l \le 16$	$-18 \le l \le 18$
data/restraints/parameters	8323/0/1266	3857/0/512	9046/0/856
goodness of fit (F^2)	3.714	2.731	3.550
R indices ($I > 3\sigma(I)$)	$R = 0.059$	$R = 0.080$	$R = 0.054$
	$R_w = 0.059$	$R_w = 0.079$	$R_w = 0.059$

X-ray crystallographic analysis of 32, 33, 34, and 35. Single crystals of **32**·2$CHCl_3$, **33**·3$CHCl_3$, and **34**·2$CHCl_3$ were grown in their chloroform/methanol solutions and those of **35**·2C_6H_6 in its benzene/acetonitrile solution. The intensity data were collected on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation (λ = 0.71069 Å). Reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. Crystallographic and experimental data were listed in Table 2-10. The structures were solved by the direct method and refined by full-matrix least squares on F. The non-hydrogen atoms were refined anisotropically except for the disordered benzene rings of **33** and **34** and carbon atoms of the disordered chloroform. Two chloroform molecules of **32**·2$CHCl_3$ were located at crystallographically independent three sites (0.75:0.75:0.50). Hydrogen atoms were included but not refined.

Table 2-10. Crystallographic data for **32**·2$CHCl_3$, **33**·3$CHCl_3$, **34**·2$CHCl_3$, and **35**·2C_6H_6

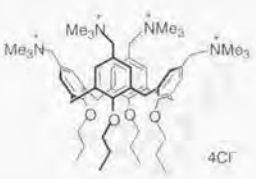
	32·2$CHCl_3$	**33**·3$CHCl_3$	**34**·2$CHCl_3$	**35**·2C_6H_6
formula	$C_{88}H_{101}BrCl_6N_2O_6$	$C_{89}H_{102}BrCl_9N_2O_6$	$C_{84}H_{107}BrCl_6O_6$	$C_{96}H_{118}O_6$
temperature (K)	120	150	120	120
crystal system	triclinic	monoclinic	monoclinic	triclinic
space group	*P*–1	$P2_1/c$	$P2_1$	*P*–1
a (Å)	13.302(1)	12.795(1)	13.321(1)	12.392(1)
b (Å)	15.375(3)	17.454(1)	14.721(1)	17.180(1)
c (Å)	23.292(3)	40.171(1)	20.678(1)	20.161(1)
α (deg)	103.370(7)			72.785(3)
β (deg)	101.019(8)	98.837(2)	93.106(2)	82.023(2)
γ (deg)	102.78(1)			86.782(3)
V (Å^3)	4370(1)	8864.4(7)	4049.0(4)	4059.7(4)
Z	2	4	2	2
calculated density (g cm^{-3})	1.197	1.268	1.235	1.119
reflections collected	16728	48371	26509	24635
unique	10957	15872	7767	13606
R_{int}	0.027	0.031	0.018	0.013
F_{000}	1656	3536	1592	1484
limiting indices	$0 \le h \le 14$	$0 \le h \le 15$	$0 \le h \le 16$	$0 \le h \le 15$
	$-18 \le k \le 17$	$0 \le k \le 21$	$0 \le k \le 17$	$-20 \le k \le 21$
	$-28 \le l \le 27$	$-48 \le l \le 44$	$-25 \le l \le 25$	$-23 \le l \le 24$
data/restraints/parameters	7426/0/964	11444/0/1040	9046/0/856	11437/0/919
goodness of fit (F^2)	5.85	7.16	9.12	4.76
R indices ($I > 3\sigma(I)$)	$R = 0.108$	$R = 0.087$	$R = 0.071$	$R = 0.065$
	$R_w = 0.123$	$R_w = 0.098$	$R_w = 0.086$	$R_w = 0.083$

Chapter 3

Aggregating Properties of Conformationally Frozen Isomers of a Water-Soluble Bridged Calix[6]arene

3.1. Introduction

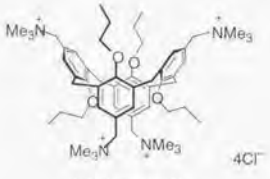
A variety of water-soluble derivatives of calixarenes have been synthesized so far and their aggregating properties have been studied.[45] Recently, much attention has been paid to regulating the three-dimensional architecture of aggregates by designing the corresponding monomeric molecule elaborately. Shinkai and co-workers synthesized water-soluble, conformationally frozen calix[4]arenes with cone and 1,3-alternate conformations **1a** and **1b**, respectively, and demonstrated that they have considerably different aggregating properties.[46]



cone **1a**

10^{-5} M

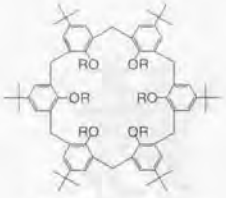
CMC



1,3-alternate **1b**

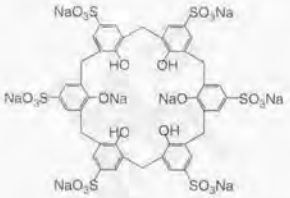
$> 10^{-2}$ M

As for calix[6]arene derivatives with much greater flexibility such as compounds **2** and **3**, however, the structure of a monomer molecule in the aggregates is quite obscure owing to the conformational equilibrium, and it has been very difficult to control their aggregation modes by the monomer structure.[47]



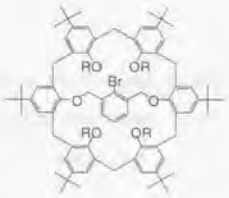
R = $CH_2CH_2CH_2SO_3Na$

2



3

The author has reported in the former chapter on the structures of two conformationally frozen isomers of calix[6]arenes, where the lower rim of the *m*-xylylene-bridged calix[6]arene such as compound **4**[2Kb] is arylmethylated. Their water-soluble derivatives are expected to solve the problem of the conformational flexibility of calix[6]arenes in aggregate formation. In this chapter, the synthesis of conformationally frozen isomers (cone and 1,2,3-alternate) of water-soluble calix[6]arene **5** is described as well as the relation between their structures and aggregating properties.



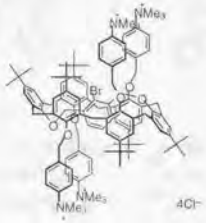
4 R = H

5 R = CH_2–  –$\overset{+}{N}Me_3$ Cl^-

3.2. Synthesis of water-soluble calix[6]arene isomers

In compound **5**, the trimethylammonio groups are appended to the lower-rim aromatic rings to increase water-solubility. The bromide functionality was introduced on the bridging unit in order to increase the yield of the 1,2,3-alternate isomer **b** in the arylmethylation reaction.

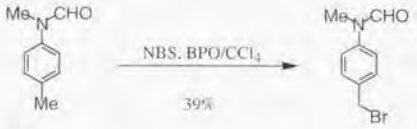
cone **5a**



1,2,3-alternate **5b**

The preparation of its conformational isomers, **5a** (cone) and **5b** (1,2,3-alternate), was effected according to Scheme 3-2. The arylmethyl unit, *N*-[4-(bromomethyl)phenyl]-*N*-methylformamide (**7**) was prepared by bromination of **6**[48] in 39% yield (Scheme 3-1).

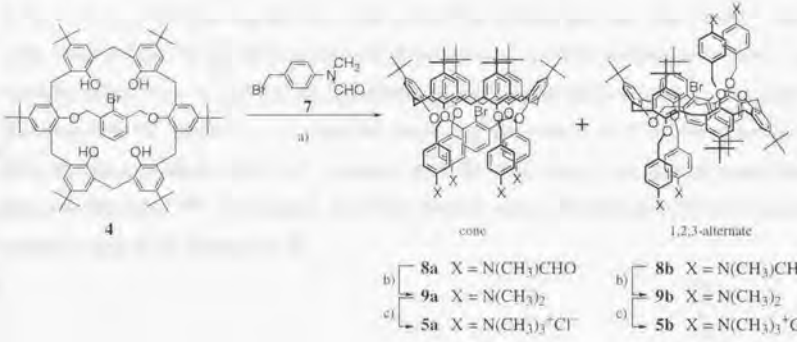
Scheme 3-1



6 **7**

The reaction of the bridged calix[6]arene **4** with bromide **7** under basic conditions resulted in the formation of two tetrabenzylated conformational isomers, **8a** (83%) and **8b** (9%), with cone and 1,2,3-alternate conformations, respectively, which were separated by silica-gel chromatography. The amide groups of **8a** and **8b** were then reduced to give the corresponding dimethylamino derivatives **9a** and **9b**, and subsequent quaternization with methyl iodide followed by subjection to an ion-exchange column afforded **5a** and **5b**, respectively. Compounds **5a** and **5b** were soluble in water, methanol, and ethanol.

Scheme 3-2

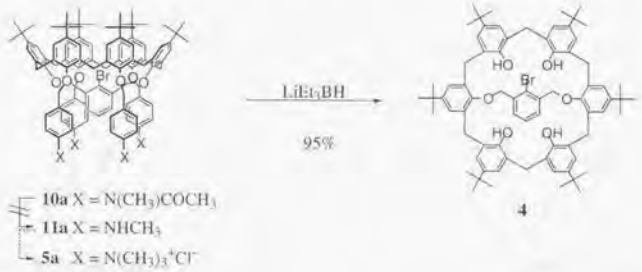


4

Reagents and conditions: (a) NaH, THF-DMF (10:1), reflux, **5a**: 83%, **5b**: 9%; (b) BH_3, THF, rt, (c) CH_3I, rt, then Dowex® 1X8 (Cl^-), **4a**: 94% for 2 steps, **4b**: 68% for 2 steps.

Synthetic route to **5a** and **5b** by deacetylation of the acetamide derivatives **10a** and **10b** followed by methylation (Scheme 3-2) was not effective because the reaction of **10a** with $LiEt_3BH$ was found to give the debenzylated product **4** instead of the deacetylated product **11a** (Scheme 3-3).

Scheme 3-3



3.3. Spectral features of water-soluble bridged calix[6]arenes

In the ^1H NMR spectra in methanol-d_4, both isomers **5a** and **5b** showed the spectral features essentially the same as other arylmethylated bridged calix[6]arenes described in chapter 2; the well-resolved sharp signals were observed both at room temperature and at 60 °C. On the other hand, in D_2O, **5a** and **5b** showed spectral behaviors quite different from each other. In the spectrum of the cone isomer **5a**, the signals are significantly broadened at 30 °C, although they are sharp at 90 °C (Figure 3-1A). The line broadening observed at 30 °C is considered to result from micelle formation, as has been reported for other monocyclic water-soluble calix[6]arenes and calix[8]arenes.[47b,c] In contrast, the 1,2,3-alternate isomer **5b** showed well-resolved spectra at both 30 and 90 °C (Figure 3-1 B).

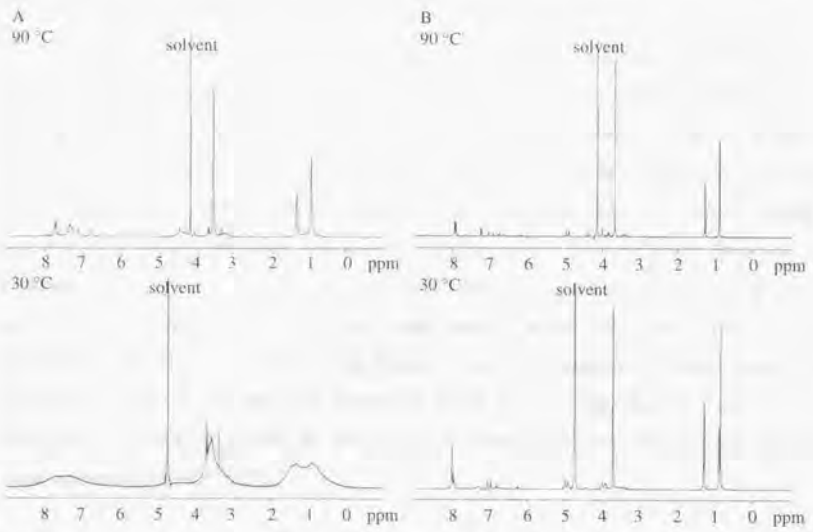


Figure 3-1. ^{1}H NMR spectra of the cone isomer **5a** (A) and 1,2,3-alternate isomer **5b** (B) of water-soluble bridged calixarenes. (270 MHz, D_2O, 5×10^{-4} M)

3.4. Critical micelle concentrations of water-soluble bridged calix[6]arenes

The spectral behavior described in the previous section indicates that the two isomers, **5a** and **5b**, have quite different ability for micelle formation. The critical micelle concentrations (CMCs) of the isomers **5a** and **5b** were determined by light-scattering, electric-conductivity, and NMR methods (Table 3-1).

Table 3-1. Critical micelle concentrations (CMCs) of the water-soluble calix[6]arenes in aqueous solution

	cone (**5a**)	1,2,3-alternate (**5b**)
light-scattering method	7.6×10^{-6} M	6.2×10^{-4} M
conductivity	1.3×10^{-5} M	$>3 \times 10^{-4}$ M
NMR method	–[a]	5×10^{-4} M

[a] Not determined because of severe broadening of the signals.

The CMC of the cone isomer **5a** (about 1×10^{-5} M) was considerably lower than that of the 1,2,3-alternate isomer **5b** (about 6×10^{-4} M). The large difference between the CMCs of **5a** and **5b** can be reasonably explained in terms of the surface shape of these isomers. In the cone isomer **5a**, all four charged groups are directed to one side of the cavity to form both hydrophobic and hydrophilic faces in the same molecule. On the other hand, the 1,2,3-alternate isomer **5b** has two ammonio groups on one face and the other two on the opposite face to form a smaller hydrophobic surface. Apparently, the rather high CMC value of **5b** results from the absence of conformational equilibrium including the cone isomer **5a**, which is more prone to form aggregates. Similar results have been reported for conformationally frozen water-soluble calix[4]arenes **1a** and **1b**; the cone isomer **1a** forms micellar aggregates at around 10^{-5} M, whereas the 1,3-alternate isomer **1b** with a cylindrical shape does not form such aggregates for concentrations up to 10^{-2} M.[146]

Experimental

General. Melting points were determined on a Yanaco micro melting point apparatus. All melting points were uncorrected. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker DRX-500, a JEOL JNM-A500, or a JOEL EX-AL270 spectrometer and probe temperatures were not corrected. ^{1}H and ^{13}C NMR chemical shifts were referenced to the resonances of tetramethylsilane except for those in D_2O, which was referenced to the resonance of sodium 3-(trimethylsilyl)-1-propanesulfonate. THF was purified by distillation from sodium diphenylketyl under argon atmosphere before use. DMF (special grade) was purchased from Wako Pure Chemical Industries Ltd. and used without purification. Preparative TLC was carried out with Merck Kieselgel 60PF254 Art. 7747. The intensity of light scattering was measured on a HITACHI Fluorescence Spectrophotometer 650-50. Elemental analyses were performed by the Microanalytical Laboratory of the Department of Chemistry, Faculty of Science, the University of Tokyo.

Materials. *N*-Methyl-*N*-(4-methylphenyl)formamide (**6**)[48] and bridged calix[6]arene **4**[28b] were prepared according to the literature. The synthesis of the acetamide derivatives **10a** and **10b** is described in chapter 2.

***N*-[4-(Bromomethyl)phenyl]-*N*-methylformamide (7).** A mixture of **6**[48] (1.49 g, 10 mmol), *N*-bromosuccinimide (2.49 g, 14 mmol), and benzoyl peroxide (50 mg) in carbon tetrachloride (20 mL) was refluxed for 4 h. After filtration and removal of the solvent, the residue was chromatographed on silica gel (chloroform) to give a yellow oil, which was crystallized from chloroform/hexane to give colorless crystals (890 mg, 39%); mp 51-55 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.32 (s, 3H), 4.50 (s, 2H), 7.15 (d, J = 8.5 Hz, 2H), 7.45 (d, J = 8.5 Hz, 2H), 8.51 (s, 1H).

Tetraamides 8a and 8b. To a suspension of NaH (60% in oil, 160 mg, 4.0 mmol) in THF (1 mL) was added a solution of **4**[28b] (230 mg, 0.20 mmol) in THF (9 mL) and DMF (1 mL). After the mixture was stirred at room temperature for 1 h, bromide **7** (274 mg, 1.2 mmol) was added and the reaction mixture was refluxed for 2 d. After the addition of water, the mixture was poured into aqueous NH_4Cl and extracted with chloroform. The extract was dried over anhydrous magnesium sulfate and the chloroform was evaporated. The residue was subjected to preparative TLC (silica gel, chloroform/ethyl acetate, 1:1) to afford the cone isomer **8a** (290 mg, 83%) and the 1,2,3-alternate isomer **8b** (32 mg, 9%). **8a**: colorless crystals, mp 240-242 °C; ^{1}H NMR (500 MHz, $CDCl_3$, 55 °C) δ 1.04 (s, 36H), 1.45 (s, 18H), 3.20 (d, J = 15.0 Hz, 2H), 3.25 (s,

12H), 3.33 (d, J = 15.0 Hz, 4H), 3.88 (s, 4H), 4.33 (d, J = 15.0 Hz, 2H), 4.47 (s, 8H), 4.49 (d, J = 15.0 Hz, 4H), 6.77 (t, J = 7.5 Hz, 1H), 6.84 (s, 4H), 6.92 (d, J = 8.2 Hz, 8H), 7.11 (d, J = 8.2 Hz, 8H), 7.15 (d, J = 7.5 Hz, 2H), 7.21 (s, 4H), 7.32 (s, 4H), 8.36 (s, 4H). Anal. Calcd. for $C_{110}H_{125}BrN_4O_{10}\cdot H_2O$: C, 75.02; H, 7.27; N, 3.18; Br, 4.54. Found: C, 74.89; H, 7.11; N, 3.67; Br, 4.72. **8b**: colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.92 (s, 18H), 0.94 (s, 18H), 1.28 (s, 9H), 1.31 (s, 9H), 3.32 (d, J = 16.0 Hz, 2H), 3.38 (s × 2, 12H), 3.41 (d, J = 15.9 Hz, 2H), 3.57 (dd, J = 7.6, 1.6 Hz, 1H), 3.76 (d, J = 12.6 Hz, 2H), 3.81 (d, J = 12.6 Hz, 2H), 3.95 (s, 2H), 4.06 (d, J = 16.0 Hz, 2H), 4.08 (s, 2H), 4.40 (d, J = 15.9 Hz, 2H), 4.79 (d, J = 11.0 Hz, 2H), 4.79 (d, J = 10.7 Hz, 2H), 4.87 (d, J = 11.0 Hz, 2H), 4.93 (d, J = 10.7 Hz, 2H), 6.10 (t, J = 7.6 Hz, 1H), 6.58 (brs, 2H), 6.70 (brs, 2H), 6.82 (dd, J = 7.6, 1.6 Hz, 1H), 6.93 (d, J = 2.2 Hz, 2H), 7.04 (d, J = 2.2 Hz, 2H), 7.12 (s × 2, 4H), 7.25 (d, J = 8.2 Hz, 4H), 7.26 (d, J = 8.2 Hz, 4H), 7.62 (d, J = 8.2 Hz, 4H), 7.69 (d, J = 8.2 Hz, 4H), 8.53 (s × 2, 4H). Anal. Calcd for $C_{110}H_{125}BrN_4O_{10}\cdot 2H_2O$: C, 74.26; H, 7.31; N, 3.15; Br, 4.49. Found: C, 74.31; H, 7.16; N, 3.18; Br, 4.35.

Water-soluble calix[6]arene 5a. To a solution of tetraamide **8a** (70 mg, 0.040 mmol) was added a solution of borane in THF (1.0 M, 1.6 mL) and the mixture was stirred at room temperature for 3 h. After the addition of water, the organic layer was extracted with chloroform. The extract was dried over anhydrous magnesium sulfate and the chloroform was evaporated to give the crude product of tetraamine **9a**, which was dissolved in methyl iodide (3 mL); the mixture was stirred for 12 h. Removal of the excess methyl iodide afforded the iodide analog of **5a**. A methanol solution of the iodide was subjected to an ion-exchange column (Dowex® 1X8-400, Cl^-) to give the crude product of chloride **5a**, which was recrystallized from methanol/ether to give colorless crystals of **5a** (71 mg, 94%); ^{1}H NMR (500 MHz, CD_3OD, 30 °C) δ 1.04 (s, 36H), 1.45 (s, 18H), 3.16 (d, J = 15.1 Hz, 2H), 3.31 (d, J = 14.7 Hz, 4H), 3.71 (s, 36H), 3.93 (s, 4H), 4.27 (d, J = 15.1 Hz, 2H), 4.41 (d, J = 14.7 Hz, 4H), 4.55 (d, J = 13.0 Hz, 4H), 4.61 (d, J = 13.0 Hz, 4H), 6.88 (d, J = 2.0 Hz, 4H), 7.26 (d, J = 2.0 Hz, 4H), 7.37 (s, 4H), 7.39-7.47 (m, 3H), 7.43 (d, J = 9.0 Hz, 8H), 7.93 (d, J = 9.0 Hz, 8H); ^{13}C NMR (125 MHz, CD_3OD, 30 °C) δ 27.89 (t), 31.62 (t), 32.20 (q), 32.24 (q), 35.12 (s), 35.23 (s), 58.03 (q), 73.83 (t), 74.74 (t), 121.15 (d), 123.99 (s), 126.17 (d), 127.14 (d), 127.27 (d), 127.60 (d), 129.85 (d), 130.38 (d), 132.93 (s), 133.21 (s), 135.23 (s), 138.59 (s), 142.09 (s), 146.13 (s), 146.91 (s), 147.77 (s), 153.40 (s), 153.93 (s). Anal. Calcd for $C_{114}H_{145}BrCl_4N_4O_6\cdot 7H_2O$: C, 67.94; H, 7.95; N, 2.78. Found: C, 67.72; H, 8.11; N, 3.29.

Water-soluble calix[6]arene 5b. Compound **5b** was prepared from **8b** (35 mg, 0.020 mmol) in a manner similar to that of **5a** in 68% yield. **5b**: colorless crystals; ^{1}H NMR (500 MHz, CD_3OD, 60 °C) δ 1.00 (s, 18H), 1.02 (s, 18H), 1.28 (s, 9H), 1.31 (s, 9H), 3.27 (d, J = 16.0 Hz, 2H), 3.39 (d, J = 15.7 Hz, 2H), 3.738 (s, 18H), 3.742 (s, 18H), 3.77 (dd, J = 7.5, 1.7 Hz, 1H), 3.83 (d, J = 12.8 Hz, 2H), 3.89 (d, J = 12.8 Hz, 2H), 4.01 (s, 2H), 4.02 (d, J = 16.0 Hz, 2H), 4.18 (s, 2H), 4.45 (d, J = 15.7 Hz, 2H), 4.89 (d, J = 11.8 Hz, 2H), 4.94 (d, J = 11.6 Hz, 2H), 5.04 (d, J = 11.8 Hz, 2H), 5.10 (d, J = 11.6 Hz, 2H), 6.02 (t, J = 7.5 Hz, 1H), 6.67 (br, 2H), 6.77 (d, J = 2.4 Hz, 2H), 6.82 (dd, J = 7.5, 1.7 Hz, 1H), 7.03 (d, J = 2.1 Hz, 2H), 7.12 (d, J = 2.4 Hz, 2H), 7.145 (s, 2H), 7.154 (s, 2H), 7.89 (d, J = 8.9 Hz, 4H), 7.97 (d, J = 9.0 Hz, 4H), 8.04 (d, J = 8.9 Hz, 4H), 8.05 (d, J = 9.0 Hz, 4H); ^{13}C NMR (125 MHz, CD_3OD, 60 °C) δ 30.09 (t), 30.53 (t), 31.99 (q), 32.04 (q × 2), 32.20 (t), 34.96 (s), 35.04 (s), 35.14 (s), 35.19 (s), 35.93 (t), 58.21 (q), 58.24 (q), 72.62 (t), 73.81 (t), 74.44 (t), 74.72 (t), 121.39 (d), 121.47 (d), 125.50 (d), 126.51 (d), 126.61 (d), 128.15 (s), 128.34 (d), 128.82 (d), 129.49 (d), 129.26 (d), 130.88 (d), 131.49 (d), 131.92 (d), 132.95 (d), 133.21 (s), 133.44 (s), 133.77 (s), 133.84 (s), 133.95 (s), 134.74 (s), 137.91 (s), 142.40 (s), 142.67 (s), 146.11 (s), 146.43 (s), 146.48 (s), 146.87 (s), 148.18 (s), 148.32 (s), 151.03 (s), 154.28 (s), 155.16 (s), 155.65 (s). Anal. Calcd for $C_{114}H_{145}BrCl_3N_4O_6 \cdot 11H_2O$: C, 65.60; H, 8.06; N, 2.68. Found: C, 65.64; H, 7.75; N, 2.81.

Attempted deacetylation of tetraamide 10a. To a solution of tetraamide **10a** (18.4 mg, 10.2 mmol) in THF (5 mL) were added a solution of $LiEt_3BH$ in THF (1.0 M, 400 μL) and stirred at room temperature for 2 h. After addition of water, THF was removed to form white precipitates, which were collected to afford **4** (11.0 mg, 95%).

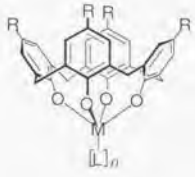
Determination of critical micelle concentrations (CMCs). The critical micelle concentrations were determined using the following three methods: (a) Light-scattering method: the intensity of light scattering at 90° at a wavelength of 375 nm at 300 K was plotted against the concentration of the aqueous solution of each isomer, and the break point where the slope increased was determined. (b) Conductivity method: the electric conductivity of the degassed aqueous solution of each isomer at 300 K was plotted against the concentration, and the break point where the slope decreased was determined. (c) NMR method: the concentration dependence of the chemical shifts of the ^{1}H NMR spectra of each isomer in D_2O at 300 K was monitored, and the break point where the chemical shifts became dependent on the concentration was determined.

Chapter 4

Application
of
a Conformationally Frozen Bridged Calix[6]arene
as
a Ligand for Transition Metals

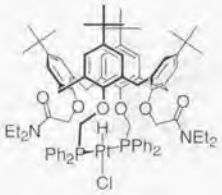
4.1. Introduction

Calixarenes have been widely used as ligands for transition metals.[33] Especially, much attention has been paid to the application of the reactions of a metal center fixed on rigid calixarene matrices such as **1** and **2**.[49,50] Switching of the fluorescence intensity was achieved by changing the oxidation state of calixquinone complex **3** bearing ruthenium atoms.[51]

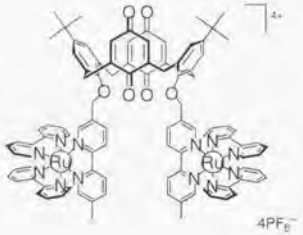


M = Zr, Ti, Mo, W...

1

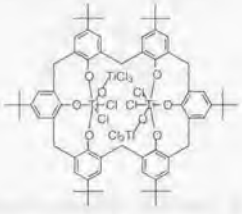


2

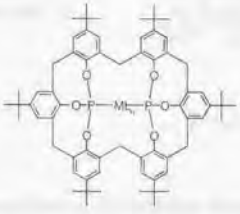


3

On the other hand, fewer examples have been reported for metal complexes of larger class of calixarenes ($n \geq 5$), which is partly because of difficulty in controlling the geometry of the complexes. Compounds **4** and **5** are the examples of metal complexes bearing a calix[6]arene ligand, but it was difficult to know what geometry the complex adopts without X-ray analysis.[52] For construction of multi-functionalized molecules based on calixarene frameworks, it is important to control the conformation of the calixarenes.



4



5: $ML_n = PdCl_2$, $PtCl_2$, $Re(CO)_3Cl$ etc

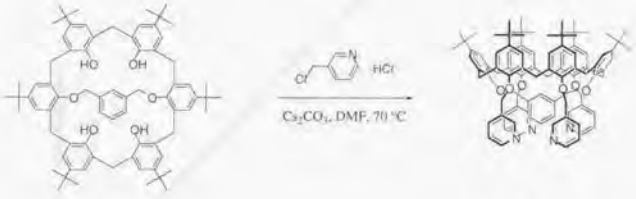
In Chapter 2, the author delineated the synthesis and structures of the conformationally frozen isomers of the bridged calix[6]arenes. It is expected that synthesis of conformationally well-defined complexes will be facilitated by using the ligand based on these rigid frameworks. In this chapter, the author describes the development of a calix[6]arene ligand **6**, whose framework is fixed in the cone conformation, and its usage for the synthesis of the copper(II) and platinum(II) complexes.

6

4.2. Synthesis of a ligand

Calix[6]arene ligand **6** was prepared by pyridylmethylation of bridged calix[6]arene **7**[25a] using cesium carbonate as a base as described in Chapter 2 (Scheme 4-1). In these conditions, only the cone isomer was obtained and other isomers were not isolated.

Scheme 4-1



7 **6**: 76%

Using the ligand **6**, synthesis of the complexes which contain transition metal ions in square planar geometry was investigated. It was found that stable complexes were formed when the metal were Cu(II) and Pt(II) whereas Ni(II) or Pd(II) complexes were not isolated in pure form.

4.3. Synthesis of copper(II) complexes

When a solution of the ligand **6** was added to a solution of copper(II) perchlorate, the color of the solution changed from pale blue to dark blue, which suggests the formation of a copper(II) complex of ligand **6**. The absorption spectra of the solution are shown in Figure 4-1 (A) and the absorptivity was plotted toward the molar ratio of **6**/Cu in Figure 4-1 (B).

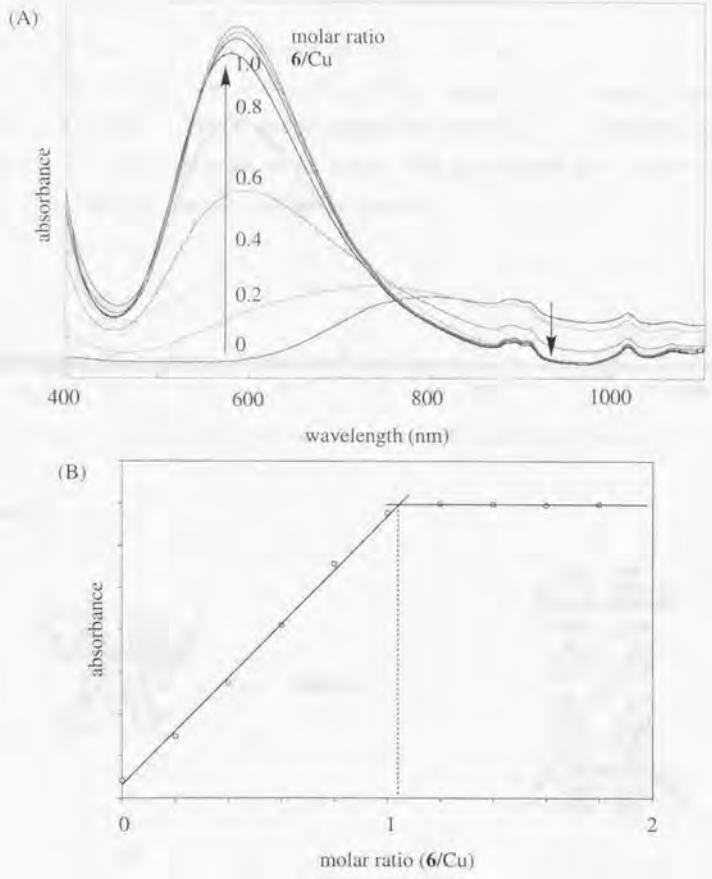


Figure 4-1. Spectroscopic titration for the complex between ligand **6** and Cu(II) in acetone-chloroform (1:1) solution. Concentration of Cu(II) is 4.5×10^{-3} M.

The broad absorption around 800 nm decreased and the absorption at 589 nm increased as the molar ratio of **6**/Cu increased until **6**/Cu = 1.0. However, the absorptivity became constant when the ratio of **6**/Cu was over 1.0. These results indicate the formation of a complex which has an equimolar amount of calixarene ligands and copper atoms. It was also found that the spectra have no isosbestic point, indicating that some other complexes were involved during the formation of the copper complex.

Elemental analysis of the complex also suggests the formation of 1:1 complex but the mass spectra show the fragment of [**6** + 2Cu + ClO_4], which can be reasonably explained by assuming a 2:2 complex. These results indicate the formation of 2:2 complex such as **8** (Scheme 4-2) although the structure of the complex was not definitely determined because the crystals suitable for X-ray analysis could not be obtained.

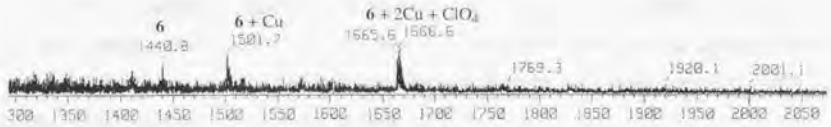
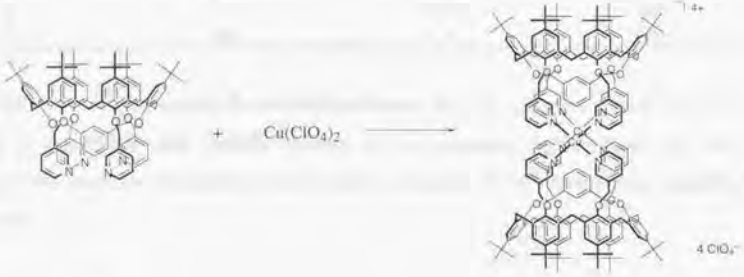


Figure 4-2. Part of the FAB-MS spectrum of the copper(II) complex of ligand **6**.

Scheme 4-2



6 **8**

4.4. Synthesis of platinum complexes

Generally, platinum(II) complexes are known to be stable toward oxygen and moisture and in some cases they have enough stability to be purified by silica gel chromatography. It was found that in the reaction of **6** with different equivalence of the Pt(II) source, K_2PtCl_4, two different Pt(II) complexes were formed (Scheme 4-3).

Scheme 4-3

6

$\xrightarrow{K_2PtCl_4}$ **6**·$PtCl_2$ (= **9**) + **6**·Pt_2Cl_4 (= **10**)

Both complexes showed high stability and they were separated by silica gel chromatography. Based on the analytical data and mass spectrometry, one was determined to be a mononuclear complex **6**·$PtCl_2$ (= **9**) and the other was identified as a binuclear complex **6**·Pt_2Cl_4 (= **10**). Their yields are summarized in Table 4-1.

Table 4-1. Yields of the platinum(II) complexes

equiv. of K_2PtCl_4	**9**	**10**	recovered **6**
1.0	51%	14%	26%
2.1	9%	35%	20%
5.7	0%	52%	0%

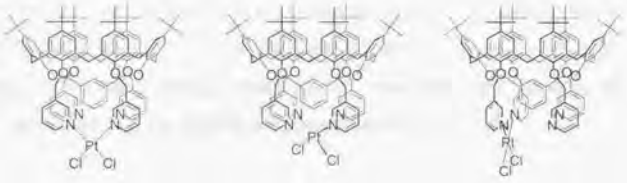
The mononuclear complex **9** remained unchanged in $CDCl_3$ solution for 12 h at 25 °C. Treatment of isolated **9** with K_2PtCl_4 resulted in the exclusive formation of **10**, which demonstrates the stepwise formation of the binuclear complex **10** via mononuclear complex **9** (Scheme 4-4).

Scheme 4-4

6·$PtCl_2$ (= **9**) $\xrightarrow{K_2PtCl_4}$ **6**·Pt_2Cl_4 (= **10**)

There are three possible structures **A**, **B**, and **C** depicted in Scheme 4-5 for neutral mononuclear complex **9**, but they are considered to have different patterns of NMR signals (Table 4-2). The structure of **9** was determined to be **A** based on the signal patterns of ^{1}H and ^{13}C NMR spectra of **9**, which shows three singlets for *tert*-butyl groups, four pairs of doublets for $ArCH_2Ar$, and three pairs of doublets for $ArOCH_2Ar$.

Scheme 4-5



A B C

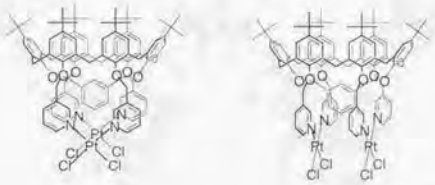
Table 4-2. Patterns of the ^{1}H NMR signals for the possible structure of complex **9**.

Pattern	R (= *t*-Bu, H)	$ArCH_2Ar$	$ArOCH_2Ar$
A	s × 3 (2:2:2)	pair of d × 4 (2:2:1:1)	pair of d × 3 (2:2:2)
B	s × 3 (2:2:2)	pair of d × 3 (2:2:2)	pair of d × 3 (2:2:2)
C	s × 4 (2:2:1:1)	pair of d × 3 (2:2:2)	pair of d × 2 (2:2), s × 2 (1:1)

Figures in parentheses indicate the integral ratios of the signals.

Similarly, binuclear complex **10** has two possible structures **D** and **E** depicted in Scheme 4-6. Because **D** and **E** have the same symmetry, the structure of **10** cannot be determined by the signal pattern of the NMR spectra. However, the fact that the reaction of mononuclear complex **9** with K_2PtCl_4 afforded **10** strongly supports the structure **D**.

Scheme 4-6



D E

4.5. Crystal structure of the binuclear complex

The structure of binuclear complex **10** was finally determined by X-ray crystallographic analysis (Figure 4-3). It was found that both of the two platinum atoms are coordinated by the adjacent two pyridine moieties, which were separated by the central bridging unit of the calixarene part. The geometry around the platinum atoms was found to be *cis*, which is similar to the parent pyridine complex, $[Pt(py)_2Cl_2]$, prepared from the reaction of K_2PtCl_4 with pyridine. It was also found that the intramolecular distance between the two platinum atoms is considerably longer (10.6 Å) than the intermolecular distance (4.6 Å). This intermolecular interaction between Pt-Cl interaction results in the formation of one-dimensional zigzag chain along the crystallographic [110] axis. Similar interaction are reported in the literature for the simpler compounds (*cis*-$[Pt(py)_2Cl_2]$, *cis*-$[Pt(NH_3)_2Cl_2]$, and $[Pt(en)Cl_2]$).[53]

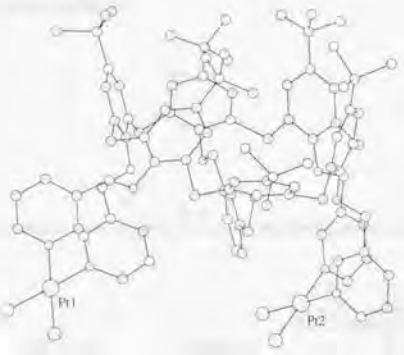


Figure 4-3. X-ray structure of the binuclear complex **10**.

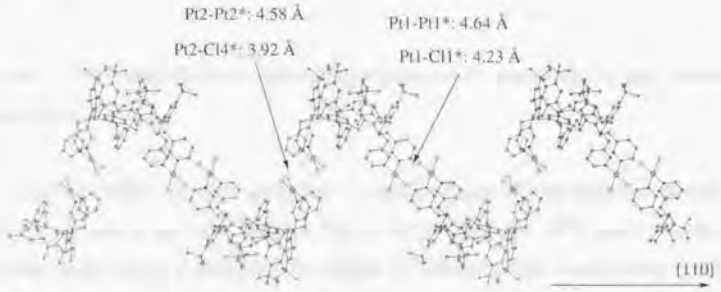


Figure 4-4. Crystal structure of complex **10** showing the intermolecular interaction.

As discussed above, only one kind of complex was formed for each of mono- and binuclear complexes. This selectivity suggests that the bridging by the platinum over the central bridging unit of the calixarene is less favorable probably due to the steric reasons.

4.6. Conformation of the complex in solution

The structures of the platinum complexes were also investigated using their ^{195}Pt NMR chemical shifts. The chemical shifts of some platinum(II) complexes including **9** and **10** are summarized in Figure 4-5. The chemical shifts of the reference compounds, *cis*-$[PtCl_2(py)_2]$, *trans*-$[Pt(Cl_2(py)_2]$, and $[Pt(py)_4]Cl_2$ which were synthesized according to the literature,[54] were also measured under the same conditions.

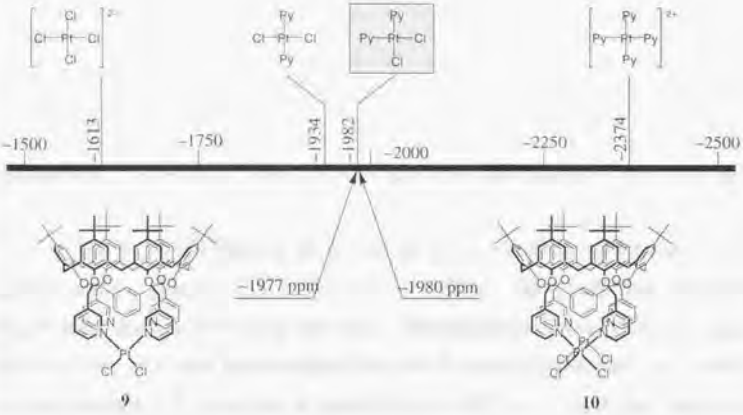


Figure 4-5. ^{195}Pt NMR chemical shifts of some platinum(II) complexes (in ppm, reference to external K_2PtCl_6 in D_2O).

The ^{195}Pt NMR signals of calixarene complexes **9** and **10** were observed around –1980 ppm, which are almost the same value as that of *cis*-$[PtCl_2(py)_2]$ (–1982 ppm). These results support that the geometry of mononuclear complex **9**, whose structure was not determined by X-ray analysis, is *cis* as well as the binuclear complex **10**.

The structures of the complexes can also be deduced from the ^{1}H NMR chemical shifts. It is of note that the chemical shifts of the protons on the central bridging unit were drastically changed during the complex formation (Figure 4-6).

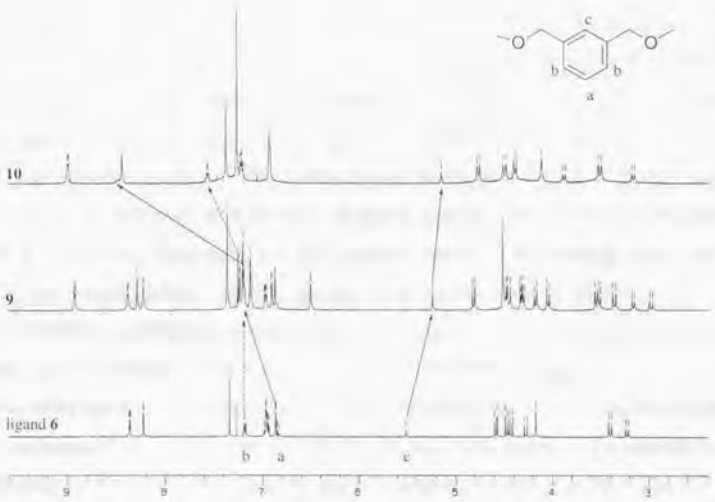


Figure 4-6. Part of the ^{1}H NMR spectra of the complexes **9** and **10** as well as the ligand **6**.

The downfield shifts of the H_a and H_b are ascribable to the fixation of pyridylmethyl groups near the bridging units by Pt atoms. It is of note that the chemical shift of H_c, far from the Pt atom, was also affected by the metal. This upfield shift observed for H_c suggests that the cavity of the calixarene gets collapsed after the Pt complex is formed; as is indicated by the crystal structure of **4**, where one of the *tert*-butyl groups at the upper rim fills the cavity of the calixarene.

Experimental

General. Melting points were determined on a Yanaco micro melting point apparatus. All melting points were uncorrected. DMF (special grade) and acetone was purchased from Wako Pure Chemical Industries Ltd. and used without purification. Dichloromethane was distilled from calcium hydride. Preparative TLC was carried out with Merck Kieselgel 60PF254 Art. 7747. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker DRX-500, a JEOL JNM-A500, and a JEOL EX-AL270 spectrometers. ^{1}H NMR and ^{13}C NMR chemical shifts were referenced to the resonances of tetramethylsilane. Assignments of NMR signals were based on 2D-COSY, HMQC, and HMBC spectra. ^{195}Pt NMR spectra were recorded on a JEOL JNM-A500 spectrometer at 107 MHz in $CDCl_3$ solvent and chemical shifts were referenced to the absorption of K_2PtCl_6 in D_2O (= 0 ppm) as an external standard. Mass spectra were recorded on a JEOL SX-102 mass spectrometer. UV/vis spectra were recorded on a JASCO V-530 UV/vis spectrophotometer. Elemental analyses were performed by the Microanalytical Laboratory of the Department of Chemistry, Faculty of Science, the University of Tokyo.

Synthesis of ligand 6. To a suspension of bridged calix[6]arene **7**[25a] (537 mg, 0.50 mmol) and cesium carbonate (2.45 g, 7.6 mmol) in DMF (50 mL) was added 3-(chloromethyl)pyridine hydrochloride (419 mg, 2.5 mmol) and the reaction mixture was stirred at 70 °C for 1 d. After the addition of aq. NH_4Cl, the mixture was extracted with chloroform, dried over $MgSO_4$. After removal of the solvent, the crude product was recrystallized from chloroform/methanol to afford **6** (544 mg, 76%) as colorless crystals, mp 279-280 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 36H), 1.44 (s, 18H), 3.23 (d, J = 14.2 Hz, 2H), 3.40 (d, J = 15.4 Hz, 4H), 4.17 (s, 4H), 4.27 (d, J = 14.2 Hz, 2H), 4.42 (d, J = 15.4 Hz, 4H), 4.47 (d, J = 12.3 Hz, 4H), 4.58 (d, J = 12.3 Hz, 4H), 5.51 (s, 1H), 6.84 (t, J = 7.6 Hz, 1H), 6.86 (d, J = 2.1 Hz, 4H), 6.93-6.94 (m, 4H), 6.96 (d, J = 2.1 Hz, 4H), 6.97 (d, J = 7.6 Hz, 2H), 7.17 (d, J = 7.8 Hz, 4H), 7.33 (s, 4H), 8.22 (s, 4H), 8.37 (d, J = 4.8 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.62 (t), 30.26 (t), 31.19 (q), 31.62 (q), 34.07 (s), 34.27 (s), 71.32 (t), 72.19 (t), 120.76 (d), 122.49 (d), 123.16 (d), 124.54 (d), 125.26 (d), 127.00 (d), 128.08 (d), 132.32 (s), 132.82 (s), 132.90 (s), 132.98 (s), 134.96 (d), 138.04 (s), 145.88 (s), 146.18 (s), 148.28 (d), 148.54 (d), 151.36 (s), 152.38 (s). Anal. Calcd for $C_{98}H_{110}N_4O_6 \cdot H_2O$: C, 80.73; H, 7.74; N, 3.84. Found: C, 80.96; H, 7.59; N, 3.95.

Synthesis of copper(II) complex 8. To a solution of **6** (29 mg, 0.02 mmol) in chloroform (1 mL) and acetone (2 mL) was added a solution of $Cu(ClO_4)_2 \cdot 6H_2O$ (9.4 mg, 0.025 mmol) at room temperature. After the addition of toluene, the mixture was evaporated to give blue precipitates,

which were collected and dried to afford **8** (27 mg, 74%) as blue powder, mp >300 °C. Anal. Calcd for $C_{98}H_{110}Cl_2CuN_4O_{14}\cdot 2H_2O$: C, 66.33; H, 6.70; N, 3.16; Cl, 4.00. Found: C, 66.33; H, 6.49; N, 3.07; Cl, 4.21.

Spectroscopic titration of copper(II) complex 8. A solution of $Cu(ClO_4)_2$ (4.5×10^{-3} M) in chloroform/acetone (1:1) was titrated with a solution of ligand **6** (5×10^{-2} M) containing $Cu(ClO_4)_2$ (4.5×10^{-3} M) in chloroform/acetone (1:1) by UV/vis spectroscopy.

Synthesis of mononuclear platinum(II) complex 9. To a solution of **6** (58 mg, 0.04 mmol) in dichloromethane (1 mL) and acetone (8 mL) was added a solution of potassium tetrachloroplatinate (17 mg, 0.04 mmol) in water (3 mL) and acetone (2 mL) at room temperature. After standing for 2 d at room temperature, the mixture was extracted with chloroform, dried over Na_2SO_4, and evaporated to dryness. The residue was subjected to preparative TLC (silica gel, chloroform/acetone, 3:1) afforded mononuclear complex **9** (35 mg, 51%) and binuclear complex **10** (11 mg, 14%) as well as starting material **6** (15 mg, 26%). **9**: colorless crystals, mp 160 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.74 (s, 18H), 1.12 (s, 18H), 1.46 (s, 18H), 2.99 (d, J = 14.8 Hz, 1H), 3.18 (d, J = 13.4 Hz, 1H), 3.37 (d, J = 15.3 Hz, 2H), 3.53 (d, J = 14.8 Hz, 1H), 3.56 (d, J = 15.9 Hz, 2H), 4.06 (d, J = 12.7 Hz, 2H), 4.19 (d, J = 12.7 Hz, 2H), 4.32 (d, J = 13.4 Hz, 1H), 4.33 (d, J = 12.2 Hz, 2H), 4.46 (d, J = 15.3 Hz, 2H), 4.51 (d, J = 15.9 Hz, 2H), 4.53 (s, 4H), 4.83 (d, J = 12.2 Hz, 2H), 5.25 (s, 1H), 6.51 (d, J = 1.2 Hz, 2H), 6.88 (d, J = 1.8 Hz, 2H), 6.92 (d, J = 1.2 Hz, 2H), 6.96-6.99 (m, 2H), 7.13-7.14 (m, 4H), 7.19-7.21 (m, 5H), 7.24 (d, J = 1.8 Hz, 2H), 7.37 (s, 4H), 8.24 (s, 2H), 8.30 (s, 2H), 8.40 (d, J = 3.7 Hz, 2H), 8.93 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 27.88 (t), 29.47 (t), 29.54 (t), 30.86 (t), 30.97 (q), 31.32 (q), 31.65 (q), 33.93 (s), 34.24 (s), 34.32 (s), 71.72 (t), 71.45 (t), 72.12 (t), 121.45 (d), 122.70 (d), 123.14 (d), 123.93 (d), 125.03 (d), 125.47 (d × 2), 125.84 (d), 127.38 (d), 127.62 (d), 128.86 (d), 130.90 (s), 132.22 (s), 132.61 (s), 132.76 (s), 132.79 (s), 132.93 (s), 133.22 (s), 135.23 (d), 136.51 (s), 137.46 (d), 138.48 (s), 145.95 (s), 146.26 (s), 146.36 (s), 148.61 (d × 2), 150.61 (d), 151.31 (s), 151.36 (s), 152.24 (s), 152.54 (d); ^{195}Pt NMR (107 MHz, $CDCl_3$) δ –1977. Anal. Calcd. for $C_{98}H_{110}Cl_2N_4O_6Pt\cdot 4H_2O$: C, 66.20; H, 6.69; N, 3.15; Cl, 3.99. Found: C, 66.42; H, 6.32; N, 3.18; Cl, 4.32.

Synthesis of binuclear platinum(II) complex 10. To a solution of **6** (30 mg, 0.02 mmol) in dichloromethane (0.5 mL) and acetone (4 mL) was added a solution of potassium tetrachloroplatinate (50 mg, 0.12 mmol) in water (1.5 mL) and acetone (1 mL) at room temperature. After standing for 2 d at room temperature, the mixture was extracted with

chloroform, dried over Na_2SO_4, and evaporated to dryness. The residue was subjected to preparative TLC (silica gel, chloroform/acetone, 3:1) to afford binuclear complex **10** (22 mg, 52%) as colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.94 (s, 36H), 1.45 (s, 18H), 3.17 (d, J = 14.7 Hz, 2H), 3.51 (d, J = 15.4 Hz, 4H), 3.88 (d, J = 14.7 Hz, 2H), 4.11 (s, 4H), 4.39 (d, J = 12.5 Hz, 4H), 4.50 (d, J = 15.4 Hz, 4H), 4.77 (d, J = 12.5 Hz, 4H), 5.15 (s, 1H), 6.93 (s, 8H), 7.19-22 (m, 4H), 7.26 (m, 4H), 7.37 (s, 4H), 7.56 (d, J = 6.1 Hz, 2H), 8.44 (s, 4H), 8.50 (brt, 1H), 9.00 (d, J = 4.6 H, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.08 (t), 30.22 (t), 31.14 (q), 31.64 (q), 34.11 (s), 34.30 (s), 71.19 (t), 71.84 (t), 121.87 (d), 123.29 (d), 124.83 (d), 125.22 (d), 125.90 (d), 128.17 (d), 129.44 (d), 131.64 (s), 132.39 (s), 132.44 (s), 136.27 (s), 136.99 (d), 138.59 (s), 146.20 (s), 146.30 (s), 150.02 (d), 151.28 (s), 152.42 (s), 152.93 (d); ^{195}Pt NMR (107 MHz, $CDCl_3$) δ –1974. Anal. Calcd. for $C_{98}H_{110}Cl_4N_4O_6Pt_2 \cdot H_2O$: C, 59.15; H, 5.67; N, 2.82; Cl, 7.13. Found: C, 58.97; H, 5.68; N, 2.81; Cl, 6.84.

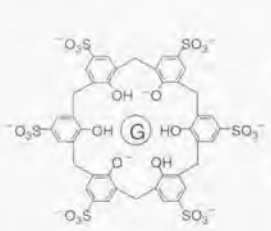
X-ray crystallographic analysis of binuclear complex. Single crystals of **10**·5.3CH_2Cl_2 were grown in dichloromethane. $C_{103.3}H_{120.6}Cl_{14.6}N_4O_6Pt_2$, M = 2422.11, triclinic, $P\bar{1}$, a = 15.097 (3) Å, b = 18.073(4) Å, c = 24.126(5) Å, α = 88.06(1)°, β = 76.464(9)°, γ = 71.11(1)°, V = 6049(2) Å^3, Z = 2, D_{calcd} = 1.330 g cm^{-3}. The intensity data were collected at 297 K on a MAC Science DIP-2030 imaging plate area detector with MoK_α radiation (λ = 0.71069 Å). 20094 reflections were collected. The platinum and chlorine atoms were refined anisotropically and atoms in aromatic rings and solvent molecules were refined using rigid group models. Other non-hydrogen atoms were calculated and were not refined. Hydrogen atoms were not included. The final cycle of full-matrix least-squares refinement on F was based on 2992 observed reflections [$I > 4.00\sigma(I)$]. R = 0.114, R_w = 0.136 for 225 parameters.

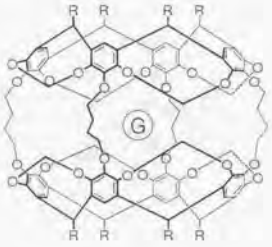
Chapter 5

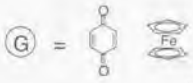
Synthesis, Structure, and Redox Properties of Quinone-Bridged Calix[6]arenes

5.1. Introduction

The inner space of macrocyclic molecules provides a unique microenvironment to the included guest species.[2-6] Recently, the electrochemical behavior or reactions of redox-active species such as quinones included in the cavity of calixarenes, carcerands, and cyclophanes have been reported.[32,55,56] Typical examples of such complexes are shown below.



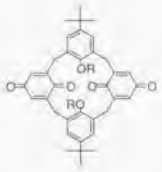


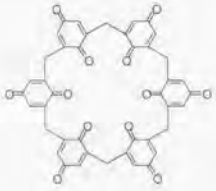


etc.

1 2 3 X = N, CH

In these complexes based on the non-covalent interaction, however, only the averaged properties of the complexed and dissociated guest species are observable. Furthermore, the geometry of the guest molecule in the cavity of the macrocycle is often ambiguous. If a redox-active species is covalently anchored in the cavity with well-defined geometry, it is expected that the effect of the surrounding macrocycle on the properties of the species can be elucidated much more definitely. Although a large number of macrocyclic quinones such as calixquinones **4-6** have been reported so far,[57] there has been no example of a compound bearing a quinone moiety covalently fixed in the cavity.





4 5 6

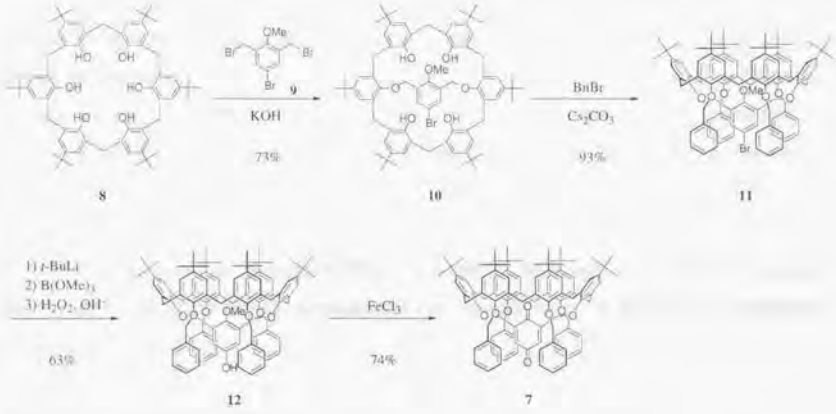
The author has discussed in Chapters 2 to 4 on the synthesis and applications of calix[6]arenes bridged by a functionalized *m*-xylylene unit, whose cavity is expected to serve also as a reaction field for a redox-active moiety covalently anchored in it. In this chapter, the synthesis, structure, and redox properties of the quinone-bridged calix[6]arene **7** with a rigid cone conformation are delineated.

7

5.2. Synthesis of quinone-bridged calix[6]arenes

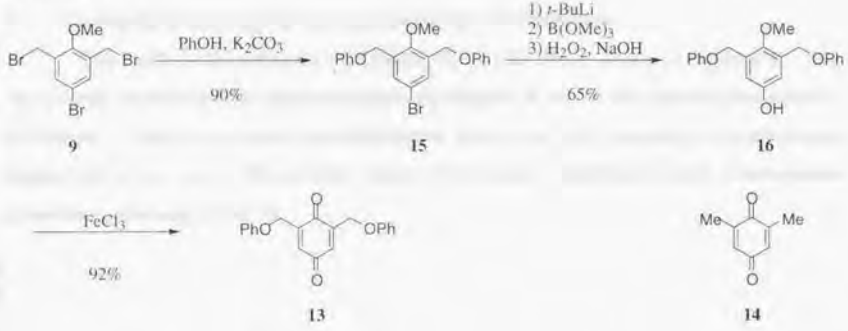
Synthesis of **7** was effected by the route shown in Scheme 5-1, where *p*-bromoanisole derivative **11** was used as a synthetic intermediate of the 1,4-benzoquinone moiety. Bridged compound **10** was prepared by the reaction of *p-tert*-butylcalix[6]arene (**8**)[18] and tribromide **9**[38] in 73% yield as depicted in Chapter 2. Benzylation of the four hydroxyl groups of **10** in the presence of cesium carbonate afforded exclusively cone isomer **11** of the tetrasubstituted product in 93% yield. The bromide functionality of **11** was converted to a hydroxyl group via lithiation followed by the reaction with trimethyl borate and treatment with an alkaline solution of hydrogen peroxide. Oxidation of *p*-methoxyphenol derivative **12** by iron(III) chloride afforded the target compound (**7**) as pale yellow crystals. Compound **7** was also found to adopt a cone conformation, indicating that no conformational change occurred during the chemical modification of the bridging unit.

Scheme 5-1



The reference compounds without a calixarene framework were also prepared. The synthesis of 2,6-bis(phenoxymethyl)-1,4-benzoquinone (**13**) was shown in Scheme 5-2. 2,6-Dimethyl-1,4-benzoquinone (**14**) was prepared according to the literature.[58]

Scheme 5-2



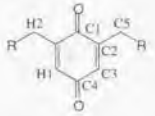
5.3. Spectral properties of quinone-bridged calix[6]arene

In the infrared spectrum of **7**, the C=O absorption was observed at 1653 cm^{-1}, which is almost the same as those of the reference compounds **13** (1657 cm^{-1}) and **14** (1653 cm^{-1}) without the calixarene framework. On the other hand, in the ^1H NMR spectrum, a strong upfield shift of H1 and H2 was observed for **7** in comparison with phenoxymethyl derivative **13** (Table 5-1), indicating that the quinone moiety of **7** is magnetically shielded by the surrounding aromatic rings of the calixarene framework. This effect was also found in the ^{13}C NMR spectrum of **7**, which shows the upfield shift of C1 and C3. In the electronic absorption spectra, it was difficult to determine the maximum absorption wavelength and the absorption coefficient of the quinone moiety of **7** due to the strong absorption of ten benzene rings of the bridged calix[6]arene framework.

Table 5-1. ^1H and ^{13}C NMR Chemical shifts (δ)[a] of quinones **7**, **13**, and **14**.

Compd.	H1	H2	C1	C2	C3	C4	C5
7	6.36	2.47	182.99	143.58	127.44	187.28	67.38
13	6.96	4.96	186.29	144.03	132.09	186.86	63.11
14	6.56	2.06	187.59	145.76	133.26	188.16	15.93

[a] Measured in $CDCl_3$.



5.4. Electrochemical properties of quinone-bridged calix[6]arenes

The cyclic voltammograms of quinones **7**, **13**, and **14** are shown in Figure 5-1. Two waves were observed for the quinone-bridged calix[6]arene **7**, the second one being considerably broadened. These two waves are considered to correspond to the formation of a monoanion radical and a dianion of the quinone moiety, respectively, similarly to other benzoquinone derivatives including **13** and **14**.

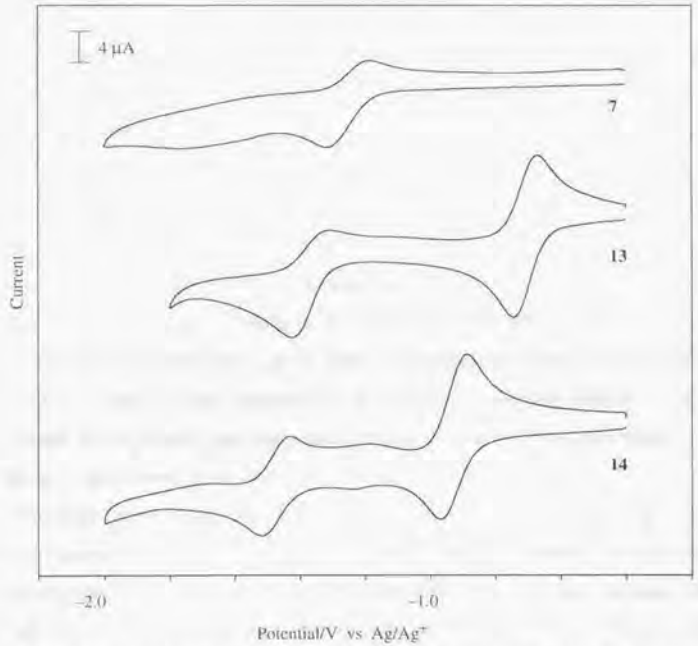


Figure 5-1. Cyclic voltammograms of **7**, **13**, and **14** (5×10^{-4} M) in dichloromethane containing 0.1 M tetrabutylammonium perchlorate on a glassy carbon electrode. Reference electrode, Ag/Ag^+, scan rate, 100 $mV \cdot s^{-1}$.

The reduction/oxidation potentials of these quinones are summarized in Table 5-2. The reduction potential of **7** is shifted to a more negative region than that of the methyl derivative **14**, indicating that the quinone-bridged calix[6]arene **7** is more difficult to be reduced. Similar negative shift is reported for the oxidation potential of ferrocene incorporated in a water-soluble calix[6]arene **1**.

Table 5-2. Oxidation/reduction potentials ($E_{1/2}$/V) of **7**, **13**, and **14**.

	7	**13**	**14**
0/–1	–1.25	–0.71	–0.91
–1/–2	–1.6 (br)	–1.37	–1.44

[a] Measured in 5×10^{-4} M dichloromethane solution containing 0.1 M tetrabutylammonium perchlorate on a glassy carbon electrode. Reference electrode, Ag/Ag^+, scan rate, 100 $mV \cdot s^{-1}$.

Electrons are known to be one of the particles for which the tunneling is very important and, therefore, the steric factors of the macrocyclic framework consisting of six benzene rings are unlikely to interfere with the access of electrons to the central quinone moiety. In fact, sterically hindered 2,5- and 2,6-di-*tert*-butyl-1,4-benzoquinone are known to have reduction potentials not so different from those of the corresponding methyl derivatives.[39] It is obvious, however, that in compound **7** the calixarene framework affects the redox properties of the quinone moiety.

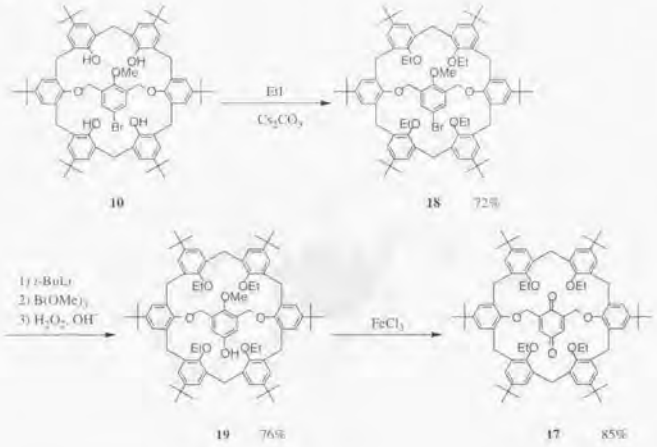
There are two factors which can explain the negative shift of the reduction potentials. One is the effect of the counter cation in the electrochemical measurements. Usually, ionic species generated in the redox processes of cyclic voltammetry are stabilized by forming tightly bound ion pair. The calixarene macrocycle of **7**, however, interfere with the access of the counter cations to the anionic quinone moiety, which is considered to destabilize the reduced form of the quinone to result in the negatively shifted potentials.

The other factor is the through-space interaction between the quinone moiety and the macrocyclic framework rather than the effect derived from the steric bulkiness of the macrocycle. On considering the fact that the potential of the phenoxymethyl substituted quinone **13** is more positive than that of the methyl derivative **14**, the two CH_2OAr substituents at the 2,6-positions of the quinone moiety of **7** seem not to be responsible for the observed negative shift. Instead, the through-space interaction between the quinone moiety and the calixarene framework or the lower-rim benzyl group is considered to be more important as depicted in the following section.

5.5. The effect of lower-rim substituents on the reduction potentials

If the negative shift of the reduction potentials of quinone-bridged calix[6]arene **7** is ascribed to the electronic effect of the aromatic rings of benzyl groups at the lower rim, the shift is expected be reduced to some extent if the alkyl groups without an aromatic ring are introduced at the lower rim. As the alkyl groups to be introduced, ethyl groups were chosen because it is easy to recognize which kind of isomer exists in solution by NMR spectroscopy; the conformational isomerization of the tetraethoxy derivatives is restricted on the NMR time scale as described in section 2.10. The ethyl derivative **17** was prepared according to Scheme 5-3, almost the same procedure as those of the benzyl derivative **7**.

Scheme 5-3



10 **18** 72%

19 76% **17** 85%

The ethyl derivatives **17**-**19** are expected to be mixtures of the conformational isomers, as discussed in chapter 2. The NMR study, however, showed that the ethylated compounds **17**-**19** in Scheme 5-3 exist exclusively as the cone isomer in $CDCl_3$ solution, which means that the cone isomer is thermodynamically stable than other isomers. The spectroscopic properties of the quinone-bridged calix[6]arene **17** were found to be not so different from those of the benzyl derivative **7**.

It was also found that the electrochemical properties of ethyl derivative **17** are almost the same as the benzyl derivative **7**; the first reduction potential was determined to be $E_{1/2} = -1.27$ V (vs. Ag/Ag^+) under the same conditions, and the broad second wave was observed around –1.6 V. This fact means that the negative shift of the reduction potential of **7** is attributable not to the lower-rim benzyl group, but to other part of the calix[6]arene framework.

5.6. Structural features of a quinone-bridged calix[6]arene

As discussed above, the through-space interaction between the quinone moiety and the calixarene framework is considered to be the major factor for the negative shifts of the reduction potentials of **7** and **17**. For clarification of the three-dimensional arrangements of the quinone

moiety and the calixarene, the crystal structure of **7** was determined by X-ray analysis (Figure 5-2).

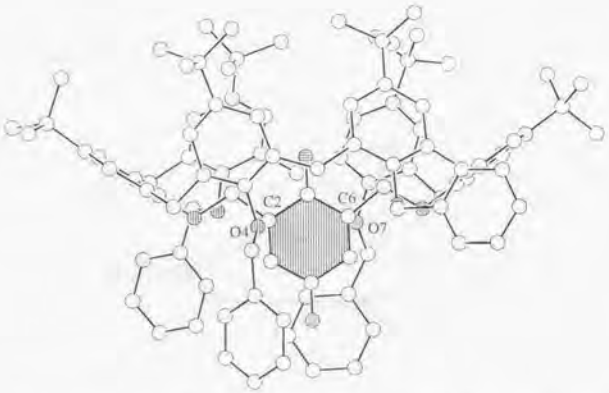


Figure 5-2. X-ray structure of **7**. Solvent molecules and hydrogen atoms are omitted for clarity.

It was revealed that the quinone moiety is located inside the cone-shaped calixarene framework and surrounded by the benzyloxy groups at the lower rim. The bond lengths and the angles around the atoms of the quinone moiety are shown in Figure 5-3.

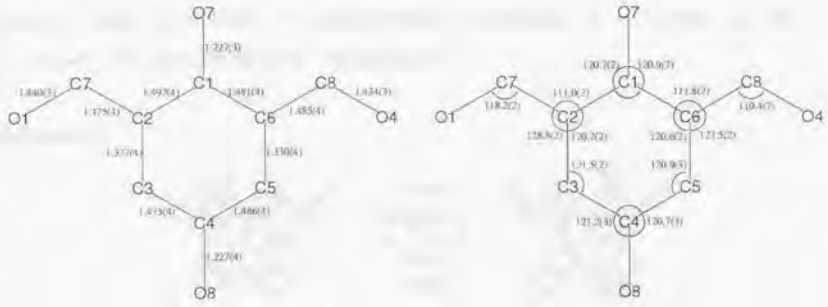


Figure 5-3. Selected bond lengths (Å) and angles (deg).

The two carbonyl groups of the quinone moiety are not so close to the six aromatic rings

of the calixarene macrocycle and the benzyl groups at the lower rim. On the other hand, there are significant non-bonded contacts observed between the olefinic carbon atoms of the quinone moiety and the oxygen atoms of the calixarene lower-rim (C2-O4: 3.172(3) Å, C6-O7: 3.218(3) Å) (Figure 5-4). This interaction is considered to raise the LUMO level of the quinone, which results in the more negative reduction potential of **7**.

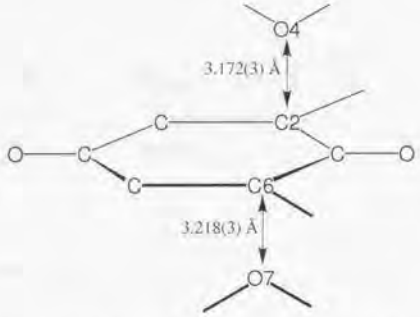
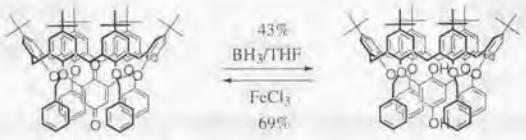


Figure 5-4. Non-bonded contact between the quinone moiety and ether oxygen atoms.

5.7. Chemical reduction of the quinone-bridged calix[6]arene

Chemical reduction/oxidation of the quinone-bridged calix[6]arene **7** was also investigated. Reduction of **7** with borane/THF afforded hydroquinone derivative **20** in 43% yield, which can be oxidized to **7** again by iron(III) chloride (Scheme 5-4). The reversible chemical reduction/oxidation of quinone-bridged calix[6]arene **7** is possible in spite of incomplete reversibility of its cyclic voltammogram.

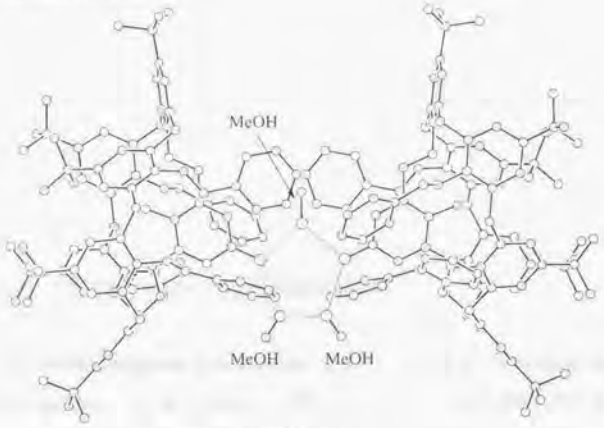
Scheme 5-4



7 **20**

The structure of hydroquinone derivative **20** was established by X-ray crystallographic analysis, showing its dimeric structure with cyclic hydrogen bonding network including three

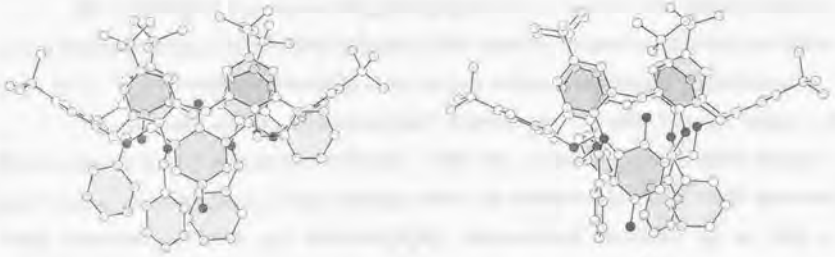
molecules of methanol (Figure 5-5).



$\mathbf{20}_2$·$(MeOH)_3$

Figure 5-5. Crystal structure of hydroquinone **20** showing its dimeric structure $\mathbf{20}_2$·$(MeOH)_3$.

It was also revealed that the conformation of the central bridging unit has changed slightly, which pushed down the bridge to some extent (Figure 5-6). It is of note that there is the intramolecular hydrogen bonding in the molecule of **20** (O4-O7: 2.621(4) Å). The selected bond lengths and angles are shown in Figure 5-7.



7 **20**

Figure 5-6. Molecular structure of hydroquinone derivative **20** compared with that of the quinone derivative **7**.

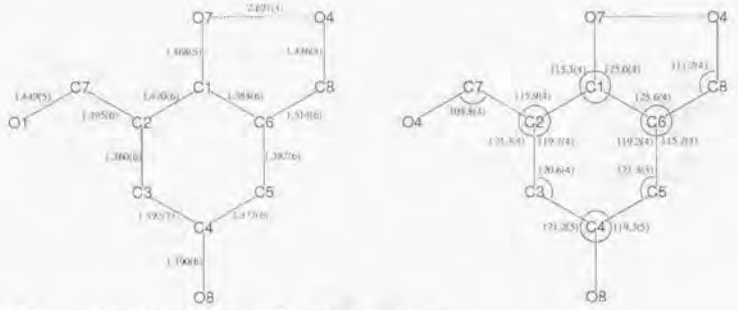


Figure 5-7. Selected bond lengths (Å) and angles (deg).

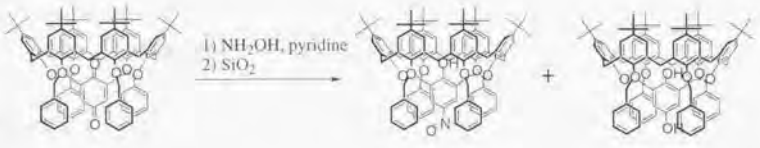
This structural change was also observed in solution, which is confirmed by the ^{1}H NMR signals. As to compound **7**, the signal of the methylene protons connected to the quinone moiety was observed at 2.47 ppm, whereas that of **20** is observed at 4.14 ppm. It was also revealed that there is no significant non-bonded interaction between the hydroquinone moiety and the lower-rim oxygen atoms found in the crystal structure of **20**. This structural change can be ascribed to the electron density of the central bridging unit as well as the presence of intramolecular hydrogen bonding.

5.8. Reaction of the quinone-bridged calix[6]arene with amines

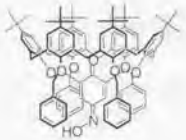
The reactivity of the quinone-bridged calix[6]arene is expected to be different from the parent quinones because the reduction potentials of the quinone-bridged calix[6]arene are shifted negatively. In this section, the reactivity of the quinone-bridged calix[6]arene **7** is described.

The reaction of the quinone-bridged calix[6]arene **7** with excess amount of hydroxylamine was investigated (Scheme 5-5). After the reaction, the crude mixture contained mono-oxime derivative **22** as a major product, which was confirmed by the ^{1}H NMR spectrum. After separation by silica gel chromatography, nitrosophenol derivative **21** as well as hydroquinone **20** were obtained. These results indicate that the reaction toward the intracavity carbonyl group of **7** was hampered by the calix[6]arene macrocycle to give the mono-adduct **22**, which readily isomerized on silica gel to afford nitrosophenol **21**.

Scheme 5-5



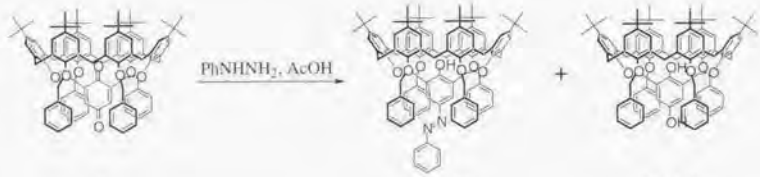
7 **21** 68% **20** 26%



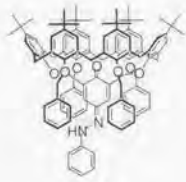
22

Similarly, the reaction with excess amount of phenylhydrazine gave azophenol derivative **23**, which seems to be formed by addition of hydrazine to one of the carbonyl group to form mono-adduct **24** followed by isomerization (Scheme 5-6). In this reaciton, the major product was the hydroquinone **20.**

Scheme 5-6



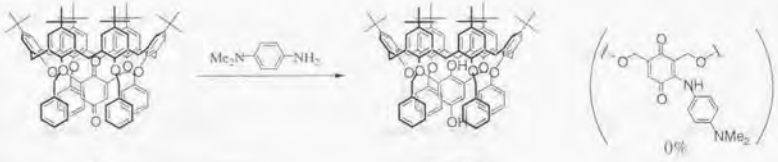
7 **23** 12% **20** 45%



24

On the other hand, the reaction of **7** with *N,N*-dimethylphenylenediamine gave only the reduced product **20**, no adduct being found in the reaction mixture (Scheme 5-7).[60]

Scheme 5-7



7 **20** 72%

The compound **20** was considered to be formed by reduction involving an electron transfer from the amine, however, the process is not considered to be favored in view of the negatively shifted reduction potentials, which imply the reduced ability as an electron acceptor. Instead, this can be explained in terms of the steric hidrance as well as high electron donating ability of the amine. The addition of the amine to the carbonyl group of the quinone moiety is expected to be so hindered and slowered by the calix[6]arene framework that the electron transfer from the amine proceeds faster than the addition despite the unfavorably negative potentials. This is one of the reactions which reflect the structural features of quinone-bridged calix[6]arene **7**.

Experimental

General. Melting points were determined on a Yanaco micro melting point apparatus. All melting points were uncorrected. THF was purified by distillation from sodium diphenylketyl under argon atmosphere before use. Benzene was distilled from lithium aluminum hydride. DMF and acetonitrile (special grade) were purchased from Wako Pure Chemical Industries Ltd. and used without purification. Tetrabutylammonium perchlorate was supplied from Tomiyama Chemicals as lithium battery grade. Dichloromethane for electrochemical measurements was purchased from Kanto Chemicals as an HPLC grade and used without purification. Column chromatography and preparative TLC were carried out with Wakogel C-200 and Merck Kieselgel 60PF254 Art. 7747, respectively. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker DRX-500, a JEOL JNM-A500, and a JEOL EX-AL270 spectrometers. ^{1}H NMR and ^{13}C NMR chemical shifts were referenced to the resonances of tetramethylsilane. Assignments of NMR signals were based on 2D-COSY, HMQC, and HMBC spectra. IR spectra were recorded on a JASCO FT/IR-300E spectrometer. Elemental analyses were performed by the Microanalytical Laboratory of the Department of Chemistry, Faculty of Science, the University of Tokyo.

Materials. The bridged calix[6]arenes **9**, **10**, and **11** were prepared by the procedures described in Chapter 2. 2,6-Dimethyl-1,4-benzoquinone (**14**) was prepared according to the literature.[58]

Synthesis of 4-methoxy-3,5-[38,39,41,42-tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene-37,40-diyl)bis(oxymethylene)]phenol (12). To a solution of bromide **11** (228 mg, 0.15 mmol) in THF (25 mL) was added *t*-butyllithium (1.68 M in pentane, 280 μL) and the mixture was stirred for 20 min. at –78 °C. After the addition of trimethyl borate (100 μL, 0.9 mmol), the mixture was stirred for 1 h at –78 °C and then at room temperature for 14 h. To the solution was added a solution of NaOH (600 mg) and 30% hydrogen peroxide (3 mL) in water (10 mL) and the mixture was stirred for 5 h at room temperature. After the addition of water and aq. NH_4Cl, the mixture was extracted by chloroform, dried over $MgSO_4$, and evaporated to dryness. The residue was subjected to preparative TLC (silica gel, chloroform/hexane, 2:1) to give phenol **12** (65%). **12**: colorless crystals, mp 222-225 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.82 (s, 3H), 1.01 (s, 36H), 1.43 (s, 18H), 3.25 (d, J = 14.4 Hz, 2H), 3.34 (d, J = 15.2 Hz, 4H), 3.38 (s, 1H), 4.15 (s, 4H), 4.53 (d, J = 15.2 Hz, 4H), 4.60 (d, J = 11.8 Hz, 4H), 4.60 (d, J = 14.4 Hz, 2H), 4.64 (d, J = 11.8 Hz, 4H), 6.55 (s, 2H), 6.70 (d, J = 1.9 Hz, 4H), 7.09-7.20 (m, 20H), 7.23 (d, J = 1.9 Hz, 4H), 7.28 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.55 (t), 31.00 (t), 31.54 (q), 31.71 (q), 34.07 (s), 34.22 (s), 60.37 (q), 68.94 (t), 74.95 (t), 113.86 (d), 123.99 (d), 125.33

(d), 127.11 (d), 127.37 (d), 128.09 (d), 128.14 (d), 132.34 (s), 132.76 (s), 133.13 (s), 133.75 (s), 138.01 (s), 144.94 (s), 145.10 (s), 149.96 (s), 150.03 (s), 152.39 (s), 153.01 (s). Anal. Calcd for $C_{180}H_{116}O_8$: C, 83.47; H, 7.93. Found: C, 83.21; H, 7.93.

Synthesis of 2,6-[38,39,41,42-tetrabenzyloxy-5,11,17,23,29,35-hexa-*tert*-butylcalix[6]arene-37,40-diyl)bis(oxymethylene)]-1,4-benzoquinone (7). To a solution of **12** (100 mg, 0.68 mmol) in benzene (5 mL) was added dropwise a solution of iorn(III) chloride (250 mg, 1.5 mmol) in acetic acid (0.5 mL) and acetonitrile (10 mL). After 10 min, yellow precipitates were collected and dried to afford **7** (73.6 mg, 74%) as pale yellow crystals, mp 187-198 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.00 (s, 36H), 1.46 (s, 18H), 2.47 (s, 4H), 3.23 (d, J = 16.5 Hz, 2H), 3.31 (d, J = 14.7 Hz, 4H), 4.48 (d, J = 14.7 Hz, 4H), 4.50 (d, J = 16.5 Hz, 2H), 4.63 (d, J = 11.4 Hz, 4H), 4.68 (d, J = 11.4 Hz, 4H), 6.36 (s, 2H), 6.86 (s, 4H), 7.02 (s, 4H), 7.17-7.25 (m, 20H), 7.38 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.78 (t), 29.80 (t), 31.41 (q), 31.75 (q), 34.19 (s), 34.39 (s), 67.38 (t), 75.35 (t), 125.19 (d), 125.43 (d), 127.44 (d), 127.72 (d), 127.76 (d), 127.79 (d), 128.38 (d), 130.99 (s), 133.90 (s), 134.45 (s), 137.31 (s), 143.58 (s), 145.41 (s), 146.16 (s), 152.71 (s), 153.54 (s), 182.99 (s), 187.28 (s); IR (KBr) 1653 cm^{-1} (C=O). Anal. Calcd for $C_{180}H_{112}O_8 \cdot 0.5H_2O$: C, 83.06; H, 7.71. Found: C, 82.92; H, 7.71.

Synthesis of 5-bromo-2-methoxy-1,3-bis(phenoxymethyl)benzene (15). A suspension of tribromide **9** (358 mg, 1.0 mmol), phenol (243 mg, 2.6 mmol), and potassium carbonate (691 mg, 5 mmol) in DMF (80 mL) was stirred for 24 h at room temperature. After the addition of water and aq. NH_4Cl, the mixture was extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. The residue was purified by chromatography (silica gel, chloroform/hexane, 1:2) to give **15** (359 mg, 90%) as colorless oil, which was pure enough for the next reaction. **15**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.84 (s, 3H), 5.08 (s, 4H), 7.00-7.03 (m, 6H), 7.36 (t, J = 7.9 Hz, 4H), 7.72 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 62.68 (q), 64.28 (t), 114.70 (d), 117.41 (s), 121.21 (d), 129.52 (d), 132.36 (d), 132.55 (s), 155.20 (s), 158.54 (s).

Synthesis of 4-methoxy-3,5-bis(phenoxymethyl)phenol (16). To a solution of bromide **15** (360 mg, 0.90 mmol) in THF (20 mL) was added *t*-butyllithium (1.58 M, 1.7 mL) and the mixture was stirred for 20 min at –78 °C. After the addition of trimethyl borate (600 µL, 5.4 mmol), the mixture was stirred for 1 h at –78 °C and then at room temperature for 14 h. To the solution was added a solution of NaOH (3.6 g) and 30% hydrogen peroxide (9 mL) in water (30 mL) and the mixture was stirred for 8 h at room temperature. After the addition of water and aq. NH_4Cl, the mixture was extracted by chloroform, dried over $MgSO_4$, and evaporated to dryness.

The residue was chromatographed on silica gel (chloroform) to afford phenol **16** (198 mg, 65%) as colorless crystals, mp 107-110 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.77 (s, 3H), 5.05 (s, 4H), 5.50 (brs, 1H), 6.90 (s, 2H), 6.94-6.98 (m, 6H), 7.26-7.30 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 62.81 (q), 64.78 (t), 114.79 (d), 116.08 (d), 121.09 (d), 129.52 (d), 131.44 (s), 149.58 (s), 152.18 (s), 158.51 (s). Anal. Calcd for $C_{21}H_{20}O_4 \cdot 0.25H_2O$: C, 73.99; H, 6.06. Found: C, 73.94; H, 6.13.

Synthesis of 2,6-bis(phenoxymethyl)-1,4-benzoquinone (13). To a solution of **16** (17 mg, 0.05 mmol) in benzene (5 mL) was added dropwise a solution of iorn(III) chloride (250 mg, 1.5 mmol) and acetic acid (0.5 mL) in acetonitrile (10 mL). After 10 min, the solvent was removed and chromatographic separation on silica gel (benzene) afforded yellow solids, which were recrystallized from acetone/hexane to give **13** (14.6 mg, 92%) as yellow crystals, mp 140-142 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.95 (s, 4H), 6.96 (s, 2H), 6.97 (d, J = 7.4 Hz, 4H), 7.01 (t, J = 7.4 Hz, 2H), 7.32 (t, J = 7.4 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 63.11 (t), 114.71 (d), 121.81 (d), 129.71 (d), 132.09 (d), 144.03 (s), 157.74 (s), 186.29 (s), 186.86 (s); IR (KBr) 1657 cm^{-1}; UV ($CHCl_3$) λ_{max} 309.5 nm (ε 5.6 $\times$ 10^2). Anal. Calcd. for $C_{20}H_{16}O_4$: C, 74.99; H, 5.03. Found: C, 74.72; H, 5.11.

Synthesis of 37,40-[5-bromo-2-methoxy-1,3-phenylenebis(methylenoxy)]-5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetraethoxycalix[6]arene (18). To a suspension of bridged calix[6]arene **8** (476 mg, 0.40 mmol) and cesium carbonate (1.57 g, 4.8 mmol) in DMF (40 mL) was added iodoethane (200 µL, 2.4 mmol) and the reaction mixture was stirred at 70 °C for 1 d. After the addition of aq. NH_4Cl, the mixture was extracted with chloroform, dried over $MgSO_4$, and the solvent was evaporated to dryness. The crude product was purified by recrystallization (chloroform/methanol) to give **18** (372 mg, 72%) as colorless crystals, mp >300 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.90 (s, 3H), 0.98 (s, 36H), 1.24 (t, J = 6.9 Hz, 12H), 1.45 (s, 18H), 3.21 (d, J = 14.3 Hz, 2H), 3.39 (d, J = 15.0 Hz, 4H), 3.64-3.74 (m, 8H), 4.15 (s, 4H), 4.42 (d, J = 14.3 Hz, 2H), 4.49 (d, J = 15.0 Hz, 4H), 6.70 (d, J = 1.7 Hz, 4H), 7.08 (d, J = 1.7 Hz, 4H), 7.33 (s, 4H), 7.38 (s, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.51 (q), 27.19 (t), 30.73 (t), 31.47 (q), 31.71 (q), 34.00 (s), 34.24 (s), 60.31 (q), 68.45 (t), 68.66 (t), 114.28 (s), 123.81 (d), 125.17 (d), 128.11 (d), 128.65 (d), 132.27 (s), 133.19 (s), 133.67 (s), 134.76 (s), 144.60 (s), 145.12 (s), 152.39 (s), 152.76 (s), 155.83 (s). Anal. Calcd for $C_{83}H_{107}BrO_7 \cdot 0.5H_2O$: C, 76.35; H, 8.34; Br, 6.12. Found: C, 76.20; H, 8.19; Br, 6.16.

Synthesis of 4-methoxy-3,5-[5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetraethoxycalix-

[6]arene-37,40-diyl)bis(oxymethylene)]phenol (19). Compound **19** was prepared in 76% yield from bromide **10** (323 mg, 0.25 mmol) in a manner similar to that of **12**. **19**: colorless crystals, mp 248-252 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.80 (s, 3H), 0.98 (s, 36H), 1.24 (t, J = 7.0 Hz, 12H), 1.45 (s, 18H), 3.23 (d, J = 14.0 Hz, 2H), 3.40 (d, J = 15.3 Hz, 4H), 3.60 (dq, J = 9.4, 7.0 Hz, 4H), 3.71 (dq, J = 9.4, 7.0 Hz, 4H), 4.19 (s, 4H), 4.43 (d, J = 14.0 Hz, 2H), 4.51 (d, J = 15.3 Hz, 4H), 4.88 (br, 1H), 6.68 (d, J = 1.8 Hz, 4H), 6.75 (s, 2H), 7.12 (d, J = 1.8 Hz, 4H), 7.32 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.53 (q), 27.05 (t), 30.79 (t), 31.48 (q), 31.71 (q), 33.97 (s), 34.19 (s), 60.04 (q), 68.62 (t), 68.74 (t), 112.81 (d), 123.77 (d), 125.21 (d), 128.21 (d), 132.34 (s), 132.92 (s), 133.18 (s), 133.64 (s), 144.53 (s), 144.81 (s), 149.87 (s), 150.20 (s), 152.34 (s), 152.75 (s). Anal. Calcd for $C_{83}H_{108}O_6 \cdot H_2O$: C, 79.64; H, 8.86. Found: C, 79.31; H, 8.62.

Synthesis of 2,6-[5,11,17,23,29,35-hexa-*tert*-butyl-38,39,41,42-tetraethoxycalix[6]arene-37, 40-diyl)bis(oxymethylene)]-1,4-benzoquinone (17). Compound **17** was prepared in 85% yield from **19** (20 mg, 0.017 mmol) in a manner similar to that of **7**. **17**: pale yellow crystals, mp 224 °C (dec); ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.98 (s, 36H), 1.32 (t, J = 6.9 Hz, 12H), 1.47 (s, 18H), 2.34 (s, 4H), 3.32 (d, J = 16.6 Hz, 2H), 3.39 (d, J = 14.8 Hz, 4H), 3.79 (dq, J = 9.8, 6.9 Hz, 4H), 3.82 (dq, J = 9.8, 6.9 Hz, 4H), 4.34 (d, J = 16.6 Hz, 2H), 4.47 (d, J = 14.8 Hz, 4H), 6.62 (s, 2H), 6.87 (s, 4H), 6.96 (s, 4H), 7.42 (s, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 15.68 (q), 26.92 (t), 29.61 (t), 31.37 (q), 31.76 (q), 34.14 (s), 34.42 (s), 67.45 (t), 69.27 (t), 125.12 (d), 125.45 (d), 126.80 (d), 127.76 (d), 130.93 (s), 133.92 (s), 134.72 (s), 144.78 (s), 145.15 (s), 146.26 (s), 153.12 (s), 153.48 (s), 183.16 (s), 189.06 (s). Anal. Calcd for $C_{82}H_{104}O_8 \cdot H_2O$: C, 79.70; H, 8.65. Found: C, 79.70; H, 8.42.

Reduction of quinone 7. To a solution of freshly prepared quinone **7** (25.8 mg, 0.018 mmol) in THF (4 mL) was added a solution of borane/THF (1.0 M, 60 μL) and the mixture was stirred at room temperature for 2 d. After the addition of water, the mixture was extracted with chloroform, dried over $MgSO_4$, and evaporated to dryness. The residue was purified by preparative TLC (silica gel, chloroform/hexane, 1:1) to afford hydroquinone **20** (11.2 mg, 43%) as well as starting material **7** (5.6 mg, 21%). **20**: colorless crystals, mp 242-246 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.99 (s, 36H), 1.42 (s, 18H), 3.26 (d, J = 14.3 Hz, 2H), 3.37 (d, J = 15.3 Hz, 4H), 3.48 (br, 1H), 4.14 (s, 4H), 4.45 (d, J = 15.3 Hz, 4H), 4.54 (d, J = 14.3 Hz, 2H), 4.57 (d, J = 11.9 Hz, 4H), 4.63 (d, J = 11.9 Hz, 4H), 5.25 (s, 1H), 6.34 (s, 2H), 6.75 (d, J = 1.8 Hz, 4H), 7.05-7.08 (m, 12H), 7.11-7.16 (m, 12H), 7.29 (s, 4H); ^{13}C NMR (500 MHz, $CDCl_3$) δ 27.75 (t), 30.72 (t), 31.41 (q), 31.64 (q), 34.10 (s), 34.28 (s), 70.71 (t), 74.77 (t), 111.87 (d), 123.94 (s), 124.14 (d),

125.28 (d), 127.04 (d), 127.26 (d), 127.85 (d), 128.04 (d), 132.10 (s), 133.08 (s), 133.63 (s), 137.94 (s), 145.26 (s), 146.06 (s), 146.27 (s), 146.83 (s), 152.03 (s), 152.52 (s). Anal. Calcd for $C_{102}H_{114}O_8 \cdot H_2O$: C, 82.44; H, 7.87. Found: C, 82.69; H, 7.79.

Reaction of 7 with hydroxylamine. To a solution of freshly prepared quinone **7** (15 mg, 0.01 mmol) in pyridine-d_5 (0.6 mL) was added hydroxylamine hydrochloride (7.2 mg, 0.10 mmol) and the mixture was heated at 60 °C for 4 h. After the addition of aqueous methanol, the precipitates were collected to give a crude product of oxime **25**. The precipitates were separated by preparative TLC (silica gel, chloroform/hexane 2:1) to give nitrosophenol **21** (9.3 mg, 68%) and hydroquinone **20** (3.9 mg, 26%). **21**: pale green crystals, mp 237-241 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.95 (s, 36H), 1.46 (s, 18H), 3.24 (d, J = 14.5 Hz, 2H), 3.39 (d, J = 15.4 Hz, 4H), 4.13 (brs, 4H), 4.49 (d, J = 15.4 Hz, 4H), 4.53 (d, J = 11.5 Hz, 4H), 4.54 (d, J = 14.5 Hz, 2H), 4.58 (d, J = 11.5 Hz, 4H), 6.44 (s, 1H), 6.78 (d, J = 2.1 Hz, 4H), 6.95-6.97 (m, 12H), 7.02 (d, J = 2.1 Hz, 4H), 7.02-7.06 (m, 8H), 7.34 (s, 4H). Anal. Calcd for $C_{102}H_{113}NO_8 \cdot H_2O$: C, 81.73; H, 7.73; N, 0.93. Found: C, 81.56; H, 7.57; N, 1.15.

Reaction of 7 with phenylhydrazine. To a solution of freshly prepared quinone **7** (15 mg, 0.01 mmol) in benzene-d_6 (0.6 mL) was added phenylhydrazine (10 μL) and acetic acid (10 μL) and the mixture was heated at 60 °C for 2 h. The mixture was evaporated and the residue was subjected to preparative TLC (silica gel, chloroform/hexane, 2:1) to give azophenol **22** (2.1 mg, 12%) and hydroquinone **20** (7.0 mg, 45%). **22**: yellow solids; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.00 (s, 36H), 1.44 (s, 18H), 3.26 (d, J = 14.7 Hz, 2H), 3.35 (d, J = 15.4 Hz, 4H), 4.21 (brs, 4H), 4.49 (d, J = 15.4 Hz, 4H), 4.54 (d, J = 14.7 Hz, 2H), 4.57 (d, J = 12.2 Hz, 4H), 4.64 (d, J = 12.2 Hz, 4H), 6.03 (s, 1H), 6.77 (d, J = 1.8 Hz, 4H), 6.95-7.04 (m, 20H), 7.16 (d, J = 1.8 Hz, 4H), 7.31 (s, 4H), 7.46 (t, J = 7.7 Hz, 1H), 7.56 (t, J = 7.7 Hz, 2H), 7.62 (brs, 2H), 7.91 (d, J = 7.7 Hz, 2H).

Reaction of 7 with *N,N*-dimethylphenylenediamine. To a solution of freshly prepared quinone **7** (20 mg, 0.014 mmol) in THF (2 mL) was added a solution of *N,N*-dimethylphenylenediamine (1×10^{-4} M in THF, 50 μL, 5 mmol) and the mixture was refluxed for 2 d. After removal of the solvent, the residue was subjected to preparative TLC (silica gel, chloroform/hexane, 3:1) to give hydroquinone **20** (15.0 mg, 72%).

Electrochemical measurements. A glassy carbon rod (outside diameter 3 mm, Tokai Carbon GC-20) was embedded in Pyrex glass, and a cross-section was used as a working electrode. Cyclic voltammetry was carried out in a standard one-compartment cell under an argon atmosphere equipped with a platinum-wire counter electrode and an Ag/Ag^+ reference electrode

(10 mM $AgClO_4$ in 0.1 M *n*-Bu_4NClO_4-MeCN. E° (ferrocene/ferrocenium in 0.1 M *n*-Bu_4NClO_4/CH_2Cl_2) = 0.214 V *vs.* Ag/Ag^+) with a BAS CV-50W voltammetric analyzer. All runs were performed in 0.5 mM solutions in dry dichloromethane in the presence of 0.1 M *n*-Bu_4NClO_4 under argon.

X-ray crystallographic analysis of quinone 7. Single crystals of **7**·0.5C_6H_6 were grown in benzene/acetonitrile. $C_{105}H_{115}O_8$, M = 1505.06, monoclinic, $C2/c$, a = 47.782(2) Å, b = 11.969(1) Å, c = 30.850(1) Å, β = 99.895(1)°, V = 17381(1) Å^3, Z = 8, D_{calcd} = 1.150 g cm^{-3}, reflection collected, 47445, unique, 16813 (R_{int} = 0.050). The intensity data were collected at 120 K on a MAC Science DIP-2030 imaging plate area detector with MoK_{α} radiation (λ = 0.71069 Å). The reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement on F was based on 11856 observed reflections [$I > 3.00\sigma(I)$]. R = 0.068, R_w = 0.073 for 1018 parameters.

X-ray crystallographic analysis of hydroquinone 20. Single crystals of **20**·1.5MeOH·$CHCl_3$ were grown in chloroform/methanol. $C_{104.5}H_{121}Cl_3O_{9.5}$, M = 1635.46, monoclinic, $C2/c$, a = 51.115(3) Å, b = 20.274(1) Å, c = 18.132(1) Å, β = 95.732(3)°, V = 18696(2) Å^3, Z = 8, D_{calcd} = 1.162 g cm^{-3}, reflection collected, 53963, unique, 16556 (R_{int} = 0.047). The intensity data were collected at 150 K on a MAC Science DIP-2030 imaging plate area detector with MoK_{α} radiation (λ = 0.71069 Å). The reflection data were corrected for Lorentz and polarization factors, and for absorption using the multi-scan method. The structures were solved by the direct method and refined by full-matrix least squares on F^2 using SHELXL 97.[44] The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were idealized by using the riding model. $R1$ = 0.097 ($I > 2.00\sigma(I)$), $wR2$ = 0.2455 (all data).

References

[1] (a) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 2495. (b) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.

[2] Gokel, G. *Crown Ethers & Cryptands* in "Monographs in Supramolecular Chemistry"; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge; 1991.

[3] (a) Gutsche, C. D. *Calixarenes* in "Monographs in Supramolecular Chemistry"; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge; 1989. (b) *Calixarenes: A Versatile Class of Macrocyclic Compounds*; Vicens, J., Böhmer, V., Eds.; Kluwer Academic Publishers, Dordrecht, 1991. (c) Gutsche, C. D. *Calixarenes Revisited* in "Monographs in Supramolecular Chemistry"; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge; 1998.

[4] Diederich, F. *Cyclophanes* in "Monographs in Supramolecular Chemistry"; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge; 1991.

[5] (a) Cram, D. J.; Cram, J. M. *Container Molecules and Their Guests* in "Monographs in Supramolecular Chemistry"; Stoddart, J. F., Ed.; Royal Society of Chemistry: Cambridge; 1994.

[6] Lehn, J.-M. *Supramolecular Chemistry*; VCH, Weinheim, 1995.

[7] (a) Baeyer, A. *Ber.* **1872**, *5*, 25. (b) Baeyer, A. *Ber.* **1872**, *5*, 280. (c) Baeyer, A. *Ber.* **1872**, *5*, 1094.

[8] (a) Zinke, A.; Ziegler, E. *Ber.* **1941**, *B74*, 1729; (b) Zinke, A.; Ziegler, E. *Ber.* **1944**, *77*, 264. (c) Zinke, A.; Zigeuner, G.; Hössinger, K.; Hoffmann, G. *Monatsh* **1948**, *79*, 438. (d) Zinke, A.; Kretz, R.; Leggewie, E.; Hössinger, K. *Monatsh* **1952**, *83*, 1213.

[9] (a) Iqbal, M.; Gutsche, C. D. *Org. Synth.* **1989**, *68*, 234. (b) Gutsche, C. D.; Dhawan, B.; Leonis, M.; Stewart, D. *Org. Synth.* **1989**, *68*, 238. (c) Munch, J. H.; Gutsche, C. D. *Org. Synth.* **1989**, *68*, 243. *p-tert*-Butylcalix[5]arene and *p-tert*-butylcalix[7]arene are also prepared from one-step reaction mixture, but in low yields; (d) Stewart, D. R.; Gutsche, C. D. *Org. Prep. Proced. Int.* **1993**, *25*, 137. (e) Iwamoto, K.; Araki, K.; Shinkai, S. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 1499. (f) Vocanson, F.; Lamartine, R.; Lanteri, P.; Longeray, R.; Gauvrit, J. Y. *New J. Chem.* **1995**, *19*, 825.

[10] Gutsche, C. D.; Lin, L.-G. *Tetrahedron* **1986**, *42*, 1633.

[11] (a) Ninagawa, A.; Cho, K.; Matsuda, H. *Makromol. Chem.* **1985**, *186*, 1379. (b) Gömar, G.; Seiffarth, K.; Schulz, M.; Zimmermann, J.; Flämig, G. *Makromol. Chem.* **1990**, *191*, 81.

(c) Grynszpan, F.; Biali, S. E. *J. Chem. Soc., Chem. Commun.* **1996**, 195.

[12] Cornforth, J. W.; D'Arcy Hart, P.; Nicholls, G. A.; Rees, R. J. W.; Stock, J. A. *Br. J. Pharmacol.* **1955**, *10*, 73.

[13] Gutsche, C. D.; Dhawan, B.; Levine, J. A.; No, K. H.; Bauer, L. J. *Tetrahedron* **1983**, *39*, 409.

[14] Kanamathareddy, S.; Gutsche, C. D. *J. Am. Chem. Soc.* **1993**, *115*, 6572.

[15] (a) Groenen, L. C.; van Loon, J.-D.; Verboom, W.; Harkema, S.; Casnati, A.; Ungaro, R.; Pochini, A.; Ugozzoli, F.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1991**, *113*, 2385. (b) Iwamoto, K.; Araki, K.; Shinkai, S. *J. Org. Chem.* **1991**, *56*, 4955. (c) Araki, K.; Iwamoto, K.; Shinkai, S.; Matsuda, T. *Chem. Lett.* **1989**, 1747. (d) Guelzim, A.; Khrifi, S.; Baert, F.; Loeber, C.; Asfari, Z.; Matt, D.; Vicens, J. *Acta Crystallogr.* **1993**, *C49*, 72.

[16] For examples of R = COAr, see: Iqbal, M.; Mangiafico, T.; Gutsche, C. D. *Tetrahedron* **1987**, *43*, 4917. R = alkyl: see ref 13

[17] (a) Stewart, D. R.; Krawiec, M.; Kashyap, R. P.; Watson, W. H.; Gutsche, C. D. *J. Am. Chem. Soc.* **1995**, *117*, 586. (b) Souley, B.; Asfari, Z.; Vicens, J. *Pol. J. Chem.* **1993**, *67*, 763.

[18] (a) Otsuka, H.; Araki, K.; Shinkai, S. *Chem. Express* **1993**, *8*, 479. (b) Otsuka, H.; Araki, K.; Sakaki, T.; Nakashima, K.; Shinkai, S. *Tetrahedron Lett.* **1993**, *34*, 7275. (c) van Duynhoven, J. P. M.; Janssen, R. G.; Verboom, W.; Franken, S. M.; Casnati, A.; Pochini, A.; Ungaro, R.; de Mendoza, J.; Nieto, P. M.; Prados, P.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1994**, *116*, 5814. Conformational mobility of partially arylmethylated compounds has also been reported: (d) Kanamathareddy, S.; Gutsche, C. D. *J. Org. Chem.* **1992**, *57*, 3160. (e) Janssen, R. G.; Verboom, W.; Reinhoudt, D. N.; Casnati, A.; Freriks, M.; Pochini, A.; Ugozzoli, F.; Ungaro, R.; Nieto, P. M.; Carramolino, M.; Cuevas, F.; Prados, P.; de Mendoza, J. *Synthesis* **1993**, 380. (f) Neri, P.; Pappalardo, S. *J. Org. Chem.* **1993**, *58*, 1048. (g) Kanamathareddy, S.; Gutsche, C. D. *J. Org. Chem.* **1994**, *59*, 3871.

[19] (a) Ungaro, R.; Pochini, A.; Andreetti, G. D. *J. Inclusion Phenom. Mol. Recognit. Chem.* **1984**, *2*, 199. (b) Arduini, A.; Pochini, A.; Reverberi, S.; Ungaro, R. *Tetrahedron* **1986**, *42*, 2089. (c) Loeber, C.; Matt, D.; de Cian, A.; Fischer, J. *J. Organometallic Chem.* **1994**, *475*, 297. (d) Alhieri, C.; Dradi, E.; Pochini, A.; Ungaro, R. *J. Chem. Soc., Chem. Commun.* **1983**, 1075.

[20] (a) Reinhoudt, D. N.; Dijstra, P. J.; in't Veld, P. J. A.; Bugge, K.-E.; Harkema, S.; Ungaro,

R.; Ugozzoli, F.; Ghidini, E. *J. Am. Chem. Soc.* **1987**, *109*, 4761. (b) Bakker, W. I. I.; Haas, M.; Khoo-Beattie, C.; Ostaszewski, R.; Franken, S. M.; den Hertog Jr., H. J.; Verboom, W.; de Zeeuw, D.; Harkema, S.; Reinhoudt, D. N. *J. Chem. Soc. Chem.* **1994**, *116*, 123.

[21] (a) Kubo, Y.; Hamaguchi, S.-i.; Tokita, S. *Chem. Express* **1993**, *8*, 459. (b) Kubo, Y.; Maruyama, S.; Ohhara, N.; Nakamura, M.; Tokita, S. *J. Chem. Soc., Chem. Commun.* **1995**, 1727.

[22] (a) Arnecke, R.; Böhmer, V.; Ferguson, G.; Pappalardo, S. *Tetrahedron Lett.* **1996**, *37*, 1497. (b) Kraft, D.; Arnecke, R.; Böhmer, V.; Vogt, W. *Tetrahedron* **1993**, *49*, 6019.

[23] Casnati, A.; Jacopozzi, P.; Pochini, A.; Ugozzoli, F.; Cacciapaglia, R.; Mandolini, L.; Ungaro, R. *Tetrahedron* **1995**, *51*, 591.

[24] (a) Geraci, C.; Piattelli, M.; Neri, P. *Tetrahedron Lett.* **1995**, *36*, 5429. (b) Geraci, C.; Chessari, G.; Piattelli, M.; Neri, P. *J. Chem. Soc., Chem. Commun.* **1997**, 921. (c) Geraci, C.; Piattelli, M.; Neri, P. *Tetrahedron Lett.* **1996**, *37*, 3899. (d) Geraci, C.; Piattelli, M.; Neri, P. *Tetrahedron Lett.* **1996**, *37*, 7627.

[25] (a) Otsuka, H.; Araki, K.; Shinkai, S. *J. Org. Chem.* **1994**, *59*, 1542. (b) Otsuka, H.; Araki, K.; Shinkai, S. *Tetrahedron* **1995**, *51*, 8757.

[26] (a) Kraft, D.; Böhmer, V.; Vogt, W.; Ferguson, G.; Gallagher, J. F. *J. Chem. Soc., Perkin Trans. 1* **1994**, 1221.

[27] (a) Ross, H.; Lüning, U. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2555. (b) Ross, H.; Lüning, U. *Liebigs Ann. Chem.* **1996**, 1367. (c) Ross, H.; Lüning, U. *Tetrahedron Lett.* **1996**, *52*, 10879. (d) Ross, H.; Lüning, U. *Tetrahedron Lett.* **1997**, *38*, 4539. (e) Lüning, U.; Ross, H.; Thondorf, I. *J. Chem. Soc., Perkin Trans. 2* **1998**, 1313.

[28] (a) Tokitoh, N.; Saiki, T.; Okazaki, R. *J. Chem. Soc., Chem. Commun.* **1995**, 1899. (b) Saiki, T.; Goto, K.; Tokitoh, N.; Goto, M.; Okazaki, R. *Tetrahedron Lett.* **1996**, *37*, 4039. (c) Saiki, T.; Goto, K.; Tokitoh, N.; Okazaki, R. *J. Org. Chem.* **1996**, *61*, 2924. (d) Saiki, T.; Goto, K.; Okazaki, R. *Chem. Lett.* **1996**, 993. (e) Saiki, T.; Goto, K.; Okazaki, R. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2223. (f) Saiki, T. Thesis for the Degree of Doctor of Science, The University of Tokyo, **1997**.

[29] (a) Araki, K.; Akao, K.; Otsuka, H.; Nakashima, K.; Inokuchi, F.; Shinkai, S. *Chem. Lett.* **1994**, 1251. (b) Otsuka, H.; Araki, K.; Matsumoto, H.; Harada, T.; Shinkai, S. *J. Org. Chem.*, **1995**, *60*, 4862.

[30] (a) Cunsolo, F.; Piattelli, M.; Neri, P. *J. Chem. Soc., Chem. Commun.* **1994**, 1917. (b) Cunsolo, F.; Consoli, G. M. L.; Piattelli, M.; Neri, P. *Tetrahedron Lett.* **1996**, *37*, 715. (c) Ikeda, A.; Akao, K.; Harada, T.; Shinkai, S. *Tetrahedron Lett.* **1996**, *37*, 1621.

[31] Wieser, C.; Dieleman, C. B.; Matt, D. *Cood. Chem. Rev.* **1997**, *165*, 93.

[32] (a) Alvarez, J.; Wang, Y.; Gómez-Kaifer, M.; Kaifer, A. E. *Chem. Commun.* **1998**, 1455. (b) Wang, Y.; Alvarez, J.; Kaifer, A. E. *Chem. Commun.* **1998**, 1457.

[33] (a) Goto, K.; Akine, S.; Hayashi, T.; Okazaki, R. *Chem. Lett.* **1998**, 291. (b) Akine, S.; Goto, K.; Okazaki, R. *Chem. Lett.* **1999**, 681.

[34] (a) Newcomb, M.; Moore, S. S.; Cram, D. J. *J. Am. Chem. Soc.*, **1977**, *99*, 6405. (b) Vögtle, F. *Chem. Ber.* **1969**, *102*, 1784.

[35] (a) Sherrod, S. A.; da Costa, R. L.; Barnes, R. A.; Boekelheide, V. *J. Am. Chem. Soc.* **1974**, *96*, 1565. (b) Müller, W.; Kipfer, P.; Lowe, D. A.; Urwyler, S. *Helv. Chim. Acta* **1995**, *78*, 2026.

[36] Cao, D.; Kolshorn, H.; Meier, H. *Tetrahedron Lett.* **1996**, *37*, 4487.

[37] Witiak, D. T.; Loper, J. T.; Ananthan, S.; Almerico, A. M.; Verhoef, V. L.; Filppi, J. A. *J. Med. Chem.* **1989**, *32*, 1636.

[38] Tashiro, M.; Mataka, S.; Takezaki, Y.; Takashita, M.; Arimura, T.; Tsuge, A.; Yamato, T. *J. Org. Chem.* **1989**, *54*, 451.

[39] Mohamadi, F.; Richards, N. G. J.; Guida, W. C.; Liskamp, R.; Lipton, M.; Caufield, C.; Chang, G.; Hendrickson, T.; Still, W. C. *J. Comput. Chem.* **1990**, *11*, 440.

[40] A number of molecular capsules based on hydrogen-bonded dimers of calixarene derivatives have been reported. For reviews, see: (a) Rebek, Jr., J. *Acta Chem. Scand.* **1996**, *50*, 707. (b) Rebek, Jr., J. *Chem. Soc. Rev.* **1996**, 255. (c) Rebek, Jr., J. *Pure Appl. Chem.* **1996**, *68*, 1261. (d) Andreu, C.; Beerli, R.; Branda, N.; Conn, M.; de Mendoza, J.; Galán, A.; Huc, I.; Kato, Y.; Tymoschenko, M.; Valdez, C.; Wintner, E.; Wyler, R.; Rebek, Jr., J. *Pure Appl. Chem.* **1993**, *65*, 2313.

[41] Ohno, A.; Tsutsumi, A.; Yamazaki, N.; Okamura, M.; Mikata, Y.; Fujii, M. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1679.

[42] Moran, W. J.; Schreiber, E. C.; Engel, E.; Behn, D.; Yamins, J. L. *J. Am. Chem. Soc.* **1952**, *74*, 127.

[43] Witiak, D. T.; Kamat, P. L.; Allison, D. L.; Liebowitz, S. M.; Glaser, R.; Holliday, J. E.; Moeschberger, M. L.; Schaller, J. P. *J. Med. Chem.* **1983**, *26*, 1679.

[44] G. M. Sheldrick, SHELXL 97. Program for crystal structure refinement, University of Göttingen 1997.

[45] A nmuber of water-soluble calixarenes have been reported, see: (a) Arduini, A.; Pochini, A; Reverberi, S.; Ungaro, R. *J. Chem. Soc., Chem. Commun.* **1984**, 981. (b) Gutsche, C. D.; Pagoria, P. F. *J. Org. Chem.* **1985**, *50*, 5795. (c) Gutsche, C. D.; Alam, I. *Tetrahedron* **1988**, *44*, 4689. (d) Shinkai, S.; Mori, S.; Tsubaki, T.; Sone, T.; Manabe, O. *Tetrahedron Lett.* **1984**, *25*, 5315. (e) Shinkai, S.; Araki, K.; Tsubaki, T.; Arimura, T.; Manabe, O. *J. Chem. Soc., Perkin Trans. 1* **1987**, 2297. (f) Gutsche, C. D.; Nam, K. C. *J. Am. Chem. Soc.* **1988**, *110*, 6153.

[46] Arimori, S.; Nagasaki, T.; Shinkai, S. *J. Chem. Soc., Perkin Trans. 1* **1993**, 887.

[47] (a) Shinkai, S.; Mori, S.; Koreishi, H.; Tsubaki, T.; Manabe, O. *J. Am. Chem. Soc.* **1996**, *108*, 2409. (b) Shinkai, S.; Kawabata, H.; Arimura, T.; Matsuda, T.; Satoh, H.; Manabe, O. *J. Chem. Soc., Perkin Trans. 1* **1989** 1073. (c) Shinkai, S.; Arimura, T.; Araki, K.; Kawabata, H.; Sato, H.; Tsubaki, T.; Manabe, O.; Sunamoto, J. *J. Chem. Soc., Perkin Trans. 1* **1989**, 2039.

[48] Meth-Cohn O.; Taylor, D. L. *Tetrahedron* **1995**, *51*, 12869.

[49] For examples, see: (a) Giannini, L.; Solari, E.; Zanotti-Gerosa, A.; Floriani, C.; Chiesi-Villa, A.; Rizzoli, C. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 85. (b) Giannini, L.; Caselli, A.; Solari, E.; Floriani, C.; Chiesi-Villa, A.; Rizzoli, C.; Re, N.; Sgamellotti, A. *J. Am. Chem. Soc.* **1997**, *119*, 9198. (c) Giannini, L.; Caselli, A.; Solari, E.; Floriani, C.; Chiesi-Villa, A.; Rizzoli, C.; Re, N.; Sgamellotti, A. *J. Am. Chem. Soc.* **1997**, *119*, 9709. (d) Casselli, A.; Giannini, L.; Solari, E.; Floriani, C. *Organometallics* **1997**, *16*, 5457.

[50] (a) Wieser, C.; Matt, D.; Toupet, L.; Bourgeois, H.; Kintzinger, J.-P. *J. Chem. Soc., Dalton Trans.* **1996**, 4041. (b) Loeber, C.; Wieser, C.; Matt, D.; de Cian, A.; Fischer, J.; Toupet, L. *Bull. Soc. Chim. Fr.* **1995**, *132*, 166.

[51] Harriman, A.; Hissler, M.; Jost, P.; Wipff, G.; Ziessel, R. *J. Am. Chem. Soc.* **1999**, *121*, 14.

[52] (a) Bott, S. G.; Coleman, A. W.; Atwood, J. L. *J. Chem. Soc., Chem. Commun.* **1986**, 610. (b) Andretti, G. D.; Calestani, G.; Ugozzoli, F.; Arduini, A.; Ghidini, E.; Pochini, A.; Ungaro, R. *J. Incl. Phenom.* **1987**, *5*, 123.

[53] (a) Colamarino, P.; Orioli, P. L. *J. Chem. Soc., Dalton Trans.* **1975**, 1656. (b) Milburn, G. H. W.; Truter, M. R. *J. Chem. Soc. (A)*, **1966**, 1609. (c) Martin, Jr., D. S.; Jacobson, R. A.; Hunter, L. D.; Benson, J. E. *Inorg. Chem.* **1970**, *9*, 1276.

[54] Kauffman, G. B. *Inorg. Synth.* **1963**, *7*, 249.

[55] (a) Robbins, T. A.; Cram, D. J. *J. Am. Chem. Soc.* **1993**, *115*, 12199. (b) Robbins, T. A.; Knobler, C. B.; Bellew, D. R.; Cram, D. J. *J. Am. Chem. Soc.* **1994**, *116*, 111.

[56] (a) Brooksby, P. A.; Hunter, C. A.; McQuillan, A. J.; Purvis, D. H.; Rowan, A. E.; Shannon, R. J.; Walsh, R. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2489. (b) Hunter, C. A.; Shannon, R. J. *Chem. Commun.* **1996**, 1361.

[57] For examples, see: (a) Morita, Y.; Agawa, T.; Kai, Y.; Kanehisa, N.; Kasai, N.; Nomura, E.; Taniguchi, H. *Chem. Lett.* **1989**, 1349. (b) Suga, K.; Fujihara, M.; Morita, Y.; Agawa, T. *J. Chem. Soc., Faraday Trans.* **1991**, *87*, 1575. (c) Morita, Y.; Agawa, T.; Nomura, E.; Taniguchi, H. *J. Org. Chem.* **1992**, *57*, 3658. (d) Casnati, A.; Comelli, E.; Fabbi, M.; Bocchi, V.; Mori, G; Ugozzoli, F.; Lanfredi, A. M. M.; Pochini, A.; Ungaro, R. *Recl. Trav. Chim. Pays-Bas* **1993**, *112*, 384.

[58] Sumerford, W.; Dalton, D. N. *J. Am. Chem. Soc.* **1944**, *66*, 1330.

[59] Chambers, J. Q. *The Chemistry of the Quinonoid Compound*; Patai, S. ed.; John Wiley & Sons: London, 1974, Chapter 14.

[60] Finley, K. T. *The Chemistry of the Quinonoid Compound*; Patai, S. ed.; John Wiley & Sons: London, 1974, Chapter 17.

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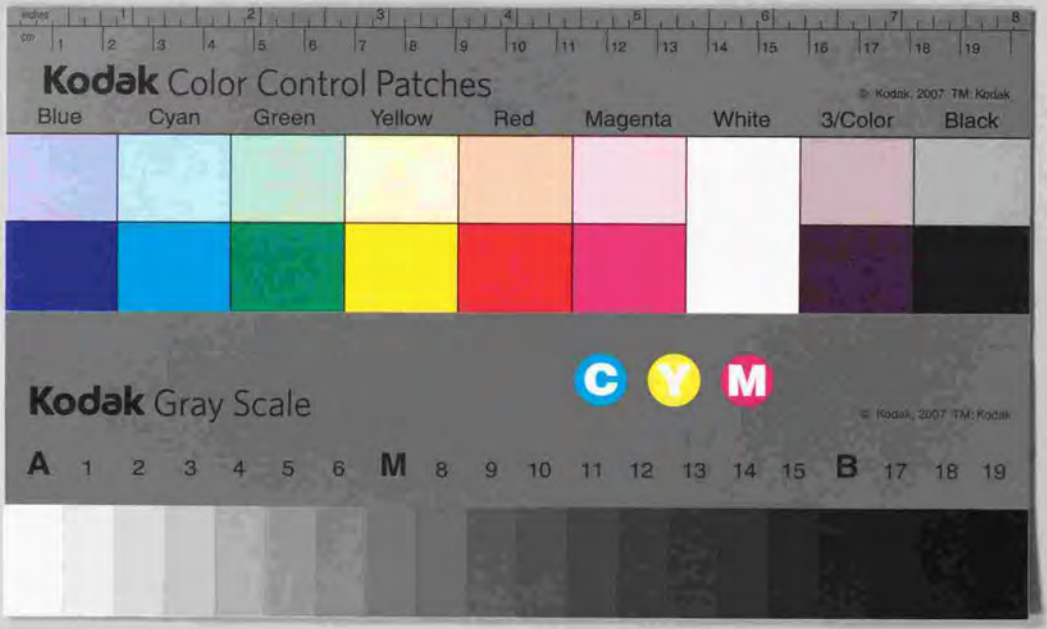
List of Publications

(1) "Different Aggregating Properties of Two Conformationally Frozen Isomers of a Water-Soluble Bridged Calix[6]arene" Akine, S.; Goto, K.; Kawashima, T.; Okazaki, R. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 2781.

(2) "Crystal Structures and Solvate Formation of Two Conformationally Frozen Isomers of a Bridged Calix[6]arene" Akine, S.; Goto, K.; Kawashima, T. *J. Inclusion Phenom. Macrocycl. Chem.* **2000**, *36*, 117.

(3) "Synthesis, Structure, and Redox Properties of a Quinone-Bridged Calix[6]arene" Akine, S.; Goto, K.; Kawashima, T. *Tetrahedron Lett.* in press.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