Synthesis, structures and inclusion properties of *distal*-bis-[(2-pyridylmethyl)oxy]tetrathiacalix[4]arenes

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Bis[(2-pyridylmethyl)oxy]tetrathiacalix[4]arenes with 1,3-*alternate* conformation show strong Ag^+ affinity and high Ag^+ selectivity. The conformational changes of the pyridine moiety from the original outward orientation of the ring nitrogen to the inside orientation toward the thiacalixarene cavity were observed in the process of Ag^+ complexation. The structure of a representative thiacalixarene compound in the 1,3-*alternate* conformation has been determined by X-ray crystallography.

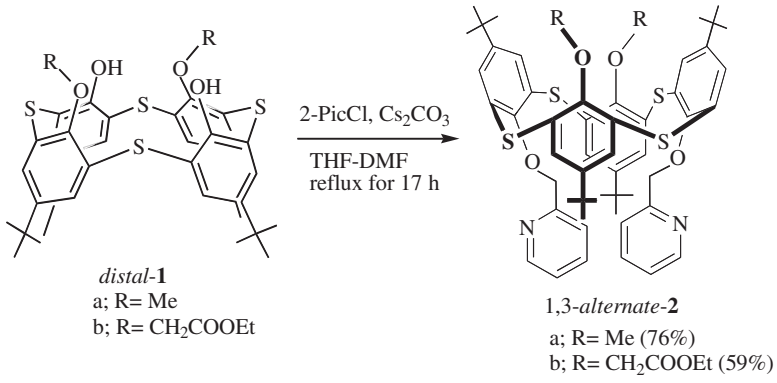
Keywords: thiacalix[4]arene, *O*-alkylation, conformation, ionophores, metal complexation

The introduction of larger alkyl groups on the phenolic oxygens of calix[4]arenes led to a situation where the OR groups within a cyclophane ring cannot pass each other by oxygen-through-the-annulus rotation.[1] There exist four possible conformational isomers in calix[4]arenes; *i.e.* cone, partial-cone, 1,2-alternate and 1,3-alternate.[1] Similarly, four conformational isomers are possible in the case of tetrathiacalix[4]arene.[2] The inhibition of interconversion between conformers derived from tetrathiacalix[4]arene by *O*-substitution differs from that of the calix[4]arenes. On the other hand, the regioselective *O*-alkylation of hydroxy groups in calixarenes is important for many purposes, in particular for the construction of multiple binding receptors or larger molecules starting from several calixarene building units.[3,4] In fact, we previously reported[5] that 5,11,17,23-tetra-*tert*-butyl-25,26,27,28-tetra hydroxytetrathiacalix[4]arene when treated with 2-(chloromethyl)pyridine in the presence of Na_2CO_3 under THF reflux yielded none of the pure regioselective isomers such as 1,2- or 1,3-di-*O*-substitution. Only a trace amount of a mixture of partial (2-pyridyl)methylation products were obtained along with the recovery of the starting compound. Recently, we have reported that the regioselective synthesis of *distal*-di-*O*-alkoxythiacalix[4]arenes is accomplished by a protection-deprotection method using benzyl groups as a protecting group.[6] We now report the synthesis of *distal*-bis[(2-pyridylmethyl)oxy]tetrathiacalix[4]arenes from *O*-alkylation of *distal*-di-*O*-alkoxythiacalix[4]arenes with 2-(chloromethyl) pyridine. Conformational studies of *distal*-bis[(2-pyridylmethyl)oxy]tetrathiacalix[4]arenes in solution and in the solid state, as well as their inclusion properties are also described.

Results and discussion

O-Alkylation of 1,3-*distal*-dimethoxytetrathiacalix[4]arene *distal*-**1a**[6] with 2-(chloromethyl)pyridine in the presence of Cs_2CO_3 as base in THF and DMF under reflux for 17 h yielded the desired product 1,3-*alternate*-**2a** in 76 % yield. Similarly, *O*-alkylation of *distal*-**1b** with 2-(chloromethyl)pyridine in the presence of K_2CO_3 or Cs_2CO_3 afforded 1,3-*alternate*-**2b** in 55 and 59 % yields, respectively. However, no formation of the other possible conformational isomers such as partial-cone or cone isomers was observed. In the case of Na_2CO_3 only the recovery of starting compounds resulted in spite of the conditions of large excess of Na_2CO_3 and 2-(chloromethyl)pyridine.

The ^{1}H NMR spectrum of 1,3-*alternate*-**2a** shows two singlets for the *tert*-butyl protons at δ 0.83 and 1.29 ppm, in which the former peak can be observed at a higher field and the singlet signal of the methoxy protons in 1,3-*alternate*-**2a** was also observed at higher field (δ 3.53 ppm) due to the ring current effect arising from the two inverted calix benzene rings.[7] Similar upfields of *tert*-butyl protons and methylene protons of CH_2COOEt group were observed in **2b**. These observations strongly suggest **2b** also adopts the 1,3-*alternate* conformation. Other signals in the ^{1}H NMR spectrum may correspond to both the *cone* or 1,3-*alternate* conformer differing only slightly in their observed chemical shifts. Fortunately, recrystallisation from MeOH and $CHCl_3$ produces X-ray quality colourless crystals of 1,3-*alternate*-**2a**. Figure 1 shows the structure of 1,3-*alternate*-**2a** analysed by single crystal X-ray diffraction. In the solid state, it is clear that compound **2a** adopts a "1,3-*alternate* conforma-



distal-**1**
a; R= Me
b; R= CH_2COOEt

1,3-*alternate*-**2**
a; R= Me (76%)
b; R= CH_2COOEt (59%)

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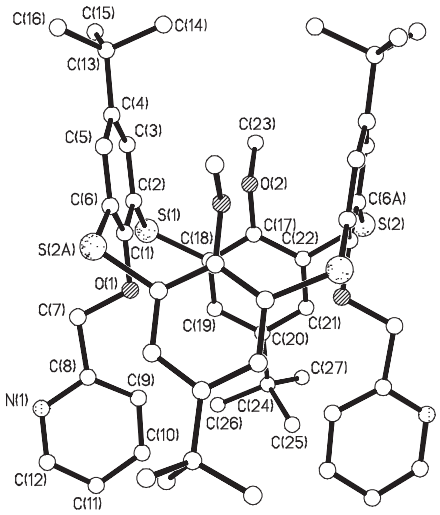


Fig. 1 Ball and stick drawing of 1,3-*alternate*-**2a**.

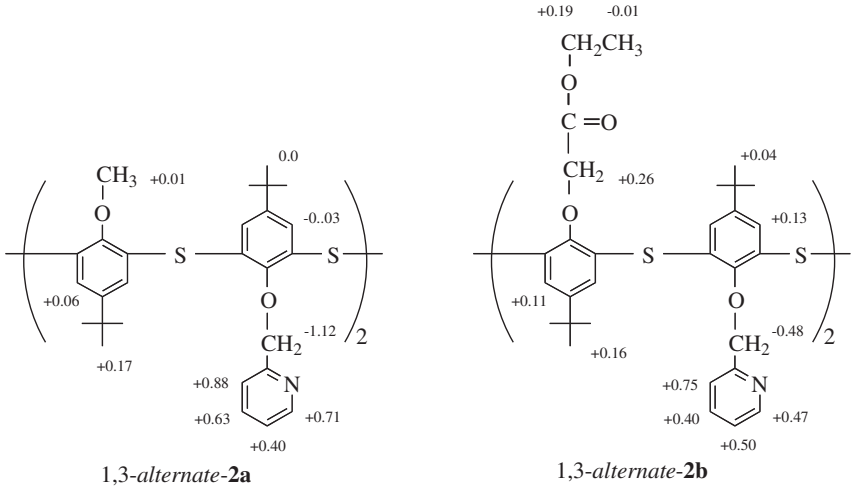
tion" as well as the orientation of the ring nitrogens which are outward of the cavity because of the electron repulsion between nitrogens.

Calixarenes can be converted to neutral ligands by the introduction of ester or amide groups into the OH groups.[1] The metal selectivity is dependent on the ring size and the *O*-alkylated substituents present. The ring size and the ring flexibility of thiacalix[4]arene are different from both calix[4]arene and hexahomotrioxacalix[3]arene.[1] Functionalisation of calix[4]arene by *O*-alkylation with halomethyl *N*-heterocyclic reagents in the presence of the base has been introduced in order to obtain "universal" ligands for both hard and soft metal ions, which in principle should exhibit some advantages over ester and amide structures, because of high stability over a wide pH range.[8] Recently, Pappalardo has reported the synthesis of calix[4]arenes bearing pendant pyridine groups at the lower rim as potential ligands for transition metal cations.[9] Similar investigations were also carried out using hexahomotrioxacalix[3]arene and homocalix[3]arene as the platform.[10] Therefore, it is interesting to assess the type of ionophoric cavity provided by the bis[(pyridylmethyl)oxy] derivatives 1,3-*alternate*-**2**. Usually, calixarenes form a 1:1 complex with guest molecules, but various other types of complexation were observed depending on the calix ring size and functional groups present. A 1:2 complex of calix[8]arene with ammonium ions was reported by Shinkai.[11] The 1,3-*alternate* conformer of calix[4]arene derivatives can also form a 1:2 complex with metal cations.[12]

Due to the existence of the three potential metal-binding sites, namely the pyridine moieties, two methoxy moieties and calix benzene rings, there are several possibilities for metal complexation for compound 1,3-*alternate*-**2a** with guest molecules. Both 1:1 or 1:2 metal complexation might be possible, attributable to the electrostatic interactions as well as cation-π interactions. The Job plots of compound 1,3-*alternate*-**2a** were carried out in the H_2O/CH_2Cl_2 phases. The percent extractions reach a maximum at 0.5 mole fraction when the 1,3-*alternate*-**2a** and silver cation are changed systematically. This fact clearly indicates that Ag^+ forms a 1:1 complex with 1,3-*alternate*-**2a**. This result suggests the major contribution is from the binding of Ag^+ to pyridyl nitrogen, but not a cation-π-interaction with calix benzene rings or the sulfur on the bridged linkage. Similar findings were observed in the case of 1,3-*alternate*-**2b** in spite of having two ester groups.

Preliminary studies of the binding ability of 1,3-*alternate*-**2a** and 1,3-*alternate*-**2b** are carried out by ion-pair extraction [M^+Pic^- (M^+ = Ag^+ or K^+)]. The *E* % values of 99 and 98 % for 1,3-*alternate*-**2a** and 1,3-*alternate*-**2b**, respectively, show that both 1,3-*alternate*-**2a** and 1,3-*alternate*-**2b** strongly extract Ag^+. In contrast, no significant *E*% is observed for K^+ (1.5 %) for 1,3-*alternate*-**2a**. The association constant K_{ass} for the 1,3-*alternate*-**2a**⊃Ag^+ and 1,3-*alternate*-**2b**⊃Ag^+ are $K_{ass} = 2.88 \times 10^3\ M^{-1}$ and $K_{ass} = 2.90 \times 10^3\ M^{-1}$, respectively were calculated by non-linear fitting analysis of the observed chemical shift changes of OCH_2Py protons.[13]

^{1}H NMR titration experiments in $CDCl_3$–CD_3CN and with KSO_3CF_3 and $AgSO_3CF_3$ are carried out. The addition of an equiv. of KSO_3CF_3 to 1,3-*alternate*-**2a** causes negligible chemical shift. On the other hand, titration with an equiv. of $AgSO_3CF_3$ causes a dramatic upfield shift for the methylene protons of OCH_2Py (Δδ = –1.12 ppm) while the *Py* protons shifted to lower field by δ 0.71, 0.40, 0.63 and 0.88 ppm for H_6, H_5, H_4, and H_3 protons, respectively (Fig. 2). Due to the interaction of N---Ag^+, protons H_6, H_5 and H_4 of the pyridine rings shift to lower fields.[7] Thus, the 1,3-*alternate*-**2a** complexes Ag^+ through the metal-oxygen electrostatic interactions and metal-nitrogen interactions. Interestingly, contrary to the observation of upfield shift of H_3 protons in the classical calixarenes, the protons H_3 in the present thiacalix [4]arene shifted shifted down field after complexation (Δδ= +0.88), which might be affected by the sulfur atom of the diarylthiaether linkage.



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

Fig. 2 Chemical shift changes of 1,3-*alternate*-**2a** and 1,3-*alternate*-**2b** induced in the presence of $AgSO_3CF_3$; + denotes the downfield and – denotes the upfield shift.

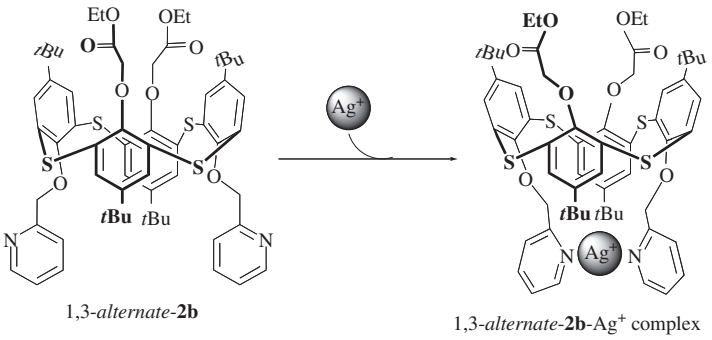


Fig. 3 Binding mode of 1,3-*alternate*-**2b** and Ag^+ complex.

Similar phenomena were also observed in the complexation of 1,3-*alternate*-**2b** with Ag^+. The down-field shift of the methylene protons of ester moieties ($\Delta\delta$ = +0.26) may be attributed to the conformational change of the 1,3-*alternate*-**2b** upon complexation. As shown in Fig. 3, the nitrogen atom in the pyridine ring points away from the calix cavity in the free 1,3-*alternate*-**2b** because of the electron repulsion between nitrogens. After complexation, the nitrogen turns inwards towards the cavity to complex with Ag^+ and thus affects H_6, H_5 and H_4 which shift to lower field. Like 1,3-*alternate*-**2a** proton H_3 might be affected by the sulfur atom of the diarylthiaether linkage and shifts to lower field ($\Delta\delta$ + 0.75). Furthermore, the C_{2V}-symmetrical conformation of 1,3-*alternate*-**2b** is still retained after complexation.

Conclusions

We have demonstrated for the first time that the stereoselective synthesis of *distal*-bis[(2-pyridylmethyl)oxy]tetrathiacalix[4] arenes **2** with 1,3-alternate conformation has been accomplished by *O*-alkylation of *distal*-di-*O*-alkoxythiacalix[4]arenes **1** with 2-(chloromethyl)pyridine. C_{2V}-Symmetrical dipyridyl-substituted thiacalix[4]arenes, 1,3-*alternate*-**2** can bind Ag^+ ion and the complexation mode was elucidated clearly in this paper. The nitrogen atom in the pyridine ring turned from facing out of the cavity to inside the cavity to interact with Ag^+ in 1,3-*alternate*-**2**. After complexation of 1,3-*alternate*-**2** with Ag^+, the original C_{2V}-symmetry has been retained. Further studies on the application to the synthetic receptors for use in metal controlled biomimetic systems are now in progress.

Experimental

All melting points are uncorrected. ^{1}H NMR spectra were recorded at 300 MHz on a Nippon Denshi JEOL FT-300 NMR spectrometer in deuteriochloroform with Me_4Si as an internal reference. IR spectra were measured as KBr pellets on a Nippon Denshi JIR-AQ2OM spectrometer. Mass spectra were obtained on a Nippon Denshi JMS-HX110A Ultrahigh Performance Mass Spectrometer at 75 eV using a direct-inlet system. Elemental analyses were performed by Yanaco MT-5.

Materials

Distal-25,27-dihydroxy-26,28-dimethoxy-5,11,17,23-tetra-*tert*-butyl-2,8,14,20-tetrathiacalix[4]arene *distal*-**1a**[6] and *distal*-5,11,17,23-tetra-*tert*-butyl-25,27-bis[(ethoxycarbonyl)methoxy]-26,28-dihydroxy-2,8,14,20-tetrathiacalix[4]arene *distal*-**1b** were prepared according to the reported procedure.[2c]

Synthesis of 1,3-alternate–5,11,17,23-tetra-tert-butyl-25,27-dimethoxy-26,28-bis- [(2-pyridylmethyl)oxy]-2,8,14,20-tetrathiacalix[4] arene (1,3-alternate-**2a**): A mixture of *distal*-**1a** (400 mg, 0.44 mmol) and Cs_2CO_3 (1.60 g, 4.92 mmol) in dry tetrahydrofuran (THF) (4 cm^3) was heated at reflux for 1 h under N_2. A solution of 2-(chloromethyl)pyridine (4.92 mmol) [prepared by neutralisation of 2-(chloromethyl)pyridine hydrochloride (807mg, 4.92 mmol) in DMF (8 cm^3) with a solution of triethylamine (0.68 cm^3, 4.92 mmol) in THF (8 cm^3) at room temperature] was then added and the mixture heated at reflux for an additional 17 h. After cooling the reaction mixture to room temperature, it was acidified with 1 M HCl (10 cm^3) and extracted with CH_2Cl_2 (100 cm^3 × 2). The combined extracts were washed with water (50 cm^3 × 2), and dried (Na_2SO_4) and condensed under reduced pressure to give a yellow oil. The residue was washed with methanol to give a mixture of tetra-*O*-alkylated products as a colourless precipitate. The precipitate was washed with ether (5 cm^3) to give 1,3-*alternate*-**2a** (340 mg, 73%) as a colourless solid. Recrystallisation from MeOH:$CHCl_3$ (3:1) gave 1,3-*alternate*-**2a** as colourless prisms, m.p. 271–274 °C; ν_{max} (KBr)/cm^{-1} 2970, 2858, 1588, 1362, 1272, 1082, 1026, and 784; δ_H ($CDCl_3$) 0.83 (18H, s, *t*Bu), 1.29 (18H, s, *t*Bu), 3.53 (6H, s, *CH$_3$*), 5.23 (4H, s, *CH$_2$*Py), 6.84 (2H, d, *J* = 8.8, Py–*H$_3$*), 7.06 (4H, s, Ar–*H*), 7.10 (2H, m, Py–*H$_5$*), 7.35 (2H, m, Py–*H$_4$*), 7.54 (4H, s, Ar–*H*), 8.52 (2H, d, *J* = 4.9, Py–*H$_6$*); *m/z* 930.36 (M$^+$) (Found: C, 69.56; H, 6.73; N, 2.98. $C_{54}H_{62}N_2O_4S_4$ (931.35) requires C, 69.64; H, 6.71; N, 3.01 %).

Similarly, the compound (1,3-*alternate*-**2b**) was synthesised in the same manner as described above for 1,3-*alternate*-**2a** in 59% yield.

5,11,17,23-Tetra-*tert*-butyl-25,27-bis[(ethoxycarbonyl)methoxy]-26,28-bis[(pyridylmethyl)oxy]-2,8,14,20-tetrathiacalix[4]arene (1,3-*alternate*-**2b**) was obtained colourless prisms [MeOH–$CHCl_3$ (3:1)], m.p. 282–286 °C; ν_{max} (KBr) /cm^{-1} 1766 (C=O); δ_H ($CDCl_3$) 0.81 (18H, s, *t*Bu), 1.22 (6H, t, *J* = 7.4, CH_2CH_3), 1.28 (18H, s, *t*Bu), 4.13 (4H, q, *J* = 7.4, CO_2CH_2), 4.53 (4H, s, OCH_2CO_2), 5.20 (4H, s, OCH_2Py), 6.84 (2H, d, *J* = 7.3, Py*H$_3$*), 7.07 (4H, s, Ar*H*), 7.11 (2H, m, Py–*H$_5$*), 7.31 (2H, m, Py–*H$_4$*), 7.49 (4H, s, Ar–*H*) and 8.51 (2H, d, *J* = 4.4, Py–*H$_6$*). *m/z* 1074.40 (M$^+$) (Found: C, 67.00; H, 6.57; N, 2.67. $C_{60}H_{70}N_2O_8S_4$ (1075.48) requires C, 67.01; H, 6.56; N, 2.60 %).

Similarly, *O*-alkylation of *distal*-**1b** with 2-(chloromethyl)pyridine in the presence of K_2CO_3 afforded 1,3-*alternate*-**2b** in 55 % yield.

Extraction experiments

Metal picrates (2.5 × 10^{-4} M) were prepared *in situ* by dissolving the metal hydroxide (0.01 mol) in 2.5 × 10^{-4} M picric acid (100 cm^3); triply distilled water was used for all aqueous solutions. Two-phase solvent extraction was carried out between water (5 cm^3, [alkali picrate] = 2.5 × 10^{-4} M) and CH_2Cl_2 (5 cm^3, [ionophore] = 2.5 × 10^{-4} M). The two-phase mixture was shaken in a stoppered flask for 2 h at 25 °C. We confirmed that this period is sufficient to attain the distribution equilibrium. This was repeated 3 times, and the solutions were left standing until phase separation was complete. The extractability was determined spectrophotochemically from the decrease in the absorbance of the picrate ion in the aqueous phase as described by Pedersen.[14]

^{1}H NMR complexation experiments

To a $CDCl_3$ solution (4 × 10^{-3} M) of 1,3-*alternate*-**2** in the NMR tube was added a CD_3CN solution (4 × 10^{-3} M) of $AgSO_3CF_3$ and KSO_3CF_3. The spectrum was registered after addition and the temperature of NMR probe kept constant at 27 °C.

The ^{1}H NMR data of the most representative complexes is given below.

$Ag^+\subset$1,3-*alternate*-**2a**: δ_H ($CDCl_3$:CD_3CN, 1:1) 1.00 (18H, s, *t*Bu), 1.29 (18H, s, *t*Bu), 3.54 (6H, s, *CH$_3$*), 4.11 (4H, s, *CH$_2$*Py), 7.12 (4H, s, Ar–*H*), 7.51 (4H, s, Ar–*H*), 7.53 (2H, m, Py-*H$_5$*), 7.72 (2H, d *J* = 8.8, Py–*H$_3$*), 7.98 (2H, m, Py–*H$_4$*) and 9.23 (2H, d, *J* = 4.9, Py–*H$_6$*).

$Ag^+\subset$1,3-*alternate*-**2b**: δ_H ($CDCl_3$:CD_3CN, 1:1) 0.97 (18H, s, *t*Bu), 1.21 (6H, t, *J* = 7.4, CH_2CH_3), 1.26 (18H, s, *t*Bu), 4.32 (4H, q, *J* = 7.4, CH_2CH_3), 4.79 (4H, s, OCH_2CO_2), 4.72 (4H, broad s, OCH_2Py), 7.18 (4H, s, Ar–*H*), 7.59 (2H, d, *J* = 7.3, Py–*H$_3$*), 7.61 (2H, m, Py–*H$_5$*), 7.62 (4H, s, Ar–*H*), 7.71 (2H, m, Py–*H$_4$*) and 8.98 (2H, d, *J* = 4.4, Py*H$_6$*).

*Crystallographic data for 1,3-alternate-***2a**

Crystal data for 1,3-*alternate*-**2a**: $C_{54}H_{62}N_2O_4S_4$, $M = 931.3$, monoclinic, $C2/c$, $a = 10.4456(12)$, $b = 28.334(3)$, $c = 17.0474(19)$ Å, $\beta = 93.434(2)°$, $V = 5036.4(10)$ Å^3, $Z = 4$, $D_c = 1.228$ g cm^{-3}, μ(Mo-K$_\alpha$) = 0.235 mm^{-1}, $T = 150(2)$ K, colourless prisms; 22352 reflections measured on a Bruker SMART 1000 CCD diffractometer, of which 6107 were independent ($R_{int} = 0.039$), data corrected for absorption on the basis of symmetry equivalent and repeated data (min and max transmission factors: 0.946, 0.979) and Lp effects, structure solved by direct methods, F^2 refinement, $R_1 = 0.0461$ for 4108 data with $F^2 > 2\sigma(F^2)$, $wR_2 = 0.1142$ for all data, 327 parameters. Programs used: Bruker SMART and SAINT for diffractometer control and frame integration respectively; Bruker SHELXTL for structure solution and refinement and molecular graphics; and local programs. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 283812. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: 144-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

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References

1 For a comprehensive review of all aspects of calixarene chemistry, see: (a) C.D. Gutsche, *Calixarenes*; the Royal Society of Chemistry, Cambridge, 1989; (b) J. Vicens and V. Böhmer, *Calixarenes: A Versatile Class of Macrocyclic Compounds*; Kluwer Academic Publishers, Cambridge, 1990; (c) S. Shinkai, *in Advances in Supramolecular Chemistry*, 3, pp.97, G.W. Gokel, (Ed.) Jai Press Inc Ltd., London, 1993; (d) C.D. Gutsche, *Calixarenes Revisited*; Royal Society of Chemistry, Cambridge, 1998.

2 (a) T. Sone, Y. Ohba, K. Moriya, H. Kumada and K. Ito, *Tetrahedron,* 1997, **53**, 5394; (b) H. Kumagai, M. Hasegawa, S. Miyanari, Y. Sugawa, Y. Sato, T. Hori, S. Ueda, H. Kamiyama and S. Miyano, *Tetrahedron Lett.,* 1997, **38**, 3971; (c) N. Iki, N. Morohashi, F. Narumi, T. Fujimoto, T. Suzuki and S. Miyano, *Tetrahedron Lett*., 1999, **40**, 7337

3 (a) J.D. van Loon, W. Verboom and D.N. Reinhoudt, *Org. Prep. Proced. Int.* 1992*,* **24**, 437; (b) V. Böhmer, *Angew. Chem., Int. Ed. Engl.,* 1995, **34**, 713.

4 (a) K. Iwamoto, A. Yanagi, K. Araki and S. Shinkai, *Chem. Lett.,* 1991, 473; (b) K. Iwamoto, K. Araki and S. Shinkai, *J. Chem. Soc., Perkin Trans. 1,* 1991, 1611; (c) K. Iwamoto, K. Araki and S. Shinkai, *J. Org. Chem.,* 1991, **56**, 4955; (d) K. Araki, K. Iwamoto, S. Shigematsu and S. Shinkai, *Chem. Lett., 1992,* 1095; (e) K. Iwamoto and S. Shinkai, *J. Org. Chem.,* 1992, **57**, 7066; (f) L.C. Groenen, J.-D van Loon, W. Verboom, S. Harkema, A. Casnati, R. Ungaro, A. Pochini, F. Ugozzoli and D.N. Reinhoudt, *J. Am. Chem. Soc.,*1991, **113**, 2385; (g) K. Iwamoto, K. Araki and S. Shinkai, *Tetrahedron,* 1991*,* **47**, 4325.

5 T. Yamato, F. Zhang, K. Kumamaru and H. Yamamoto, *J. Inclusion Phenom.* 2002*,* **42**, 51.

6 C. Pérez Casas, H. Yamamoto and T. Yamato, *J. Chem. Res.,* 2005, 694.

7 (a) F. Vögtle, *Cyclophane Chemistry*, John Wiley & Sons Ltd., 1993; (b) M. Tashiro and T. Yamato, *J. Org. Chem.,* 1981, **46**, 4556; (c) M. Tashiro and T. Yamato, *J. Org. Chem.,* 1983, **48**, 1461.

8 (a) F. Bottino, L. Giunta, and S. Pappalardo, *J. Org. Chem.,* 1989, **54**, 5407; (b) S. Shinkai, T. Otsuka, K. Araki, and T. Matsuda, *Bull. Chem. Soc. Jpn.* 1989, **62**, 4055.

9 (a) S. Pappalardo, G. Ferguson, P. Neri and C. Rocco, *J. Org. Chem.,* 1995, **60**, 4576; (b) N. de Danil, F. Angela, E.O. Piro, S. Pulcha, E. Lupe, C. Aguilar, F. Adolfo, N. Al-Rawi, E.E. Castellano, V. Sueros and J. Felix, *J. Chem. Soc. Faraday Trans.,* 1998, **94**, 3097.

10 (a) T. Yamato, M. Haraguchi, T. Iwasa and H. Tsuzuki, *Anales Química Int. Ed.,* 1997, **93**, 301; (b) T. Yamato, M. Haraguchi, J. Nishikawa, S. Ide and H. Tsuzuki, *Can. J. Chem.,* 1998, **76**, 989; (c) T. Yamato, M. Haraguchi and S. Ide, *J. Chem. Soc., Pekin Trans. 1,* 1998, 609; (d) T. Yamato: *J. Inclusion Phenom.* 1998, **32**, 195.

11 (a) S. Shinkai, H. Oreishi, K. Ueda, T. Arimura and O. Manabe, *J. Am. Chem. Soc.,* 1987, **109**, 6371; (b) R.M. Williams and J.W. Verhoeven, *Recl, Trav. Chim. Pays-Bas.,* 1992, **111**, 531; (c) T. Suzuki, K. Nakashima and S. Shinkai, *Chem. Lett.,* 1994, 699; (d) S. Shinkai, A. Araki and O. Manabe, *J. Am. Chem. Soc.,* 1998 **110**, 7214.

12 A. Ikeda and S. Shinkai, *J. Am. Chem. Soc.,* 1994, **116**, 3102.

13 H.A. Benesi and J.H. Hildebrand, *J. Am. Chem. Soc*., 1949, **71**, 2073.

14 C.J. Pedersen, *J. Am. Chem. Soc*., 1967, **89**, 2495.