Multiple Connection of 1,3-Alternate-calix[4]arenes. An Approach to Synthetic '*Nano-tubes*'

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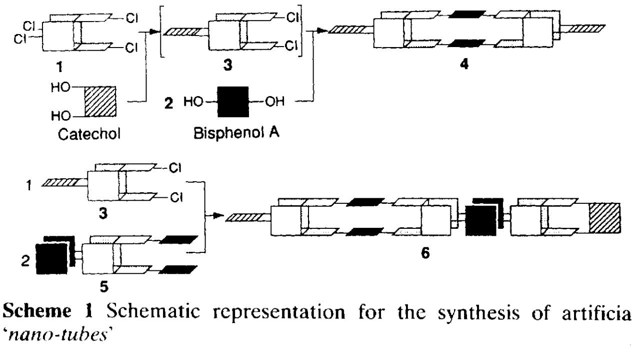
As an approach to synthetic '*nano-tubes*' 1,3-alternate-calix[4]arenes which have a π-basic hole for metal tunneling are connected by a stepwise method.

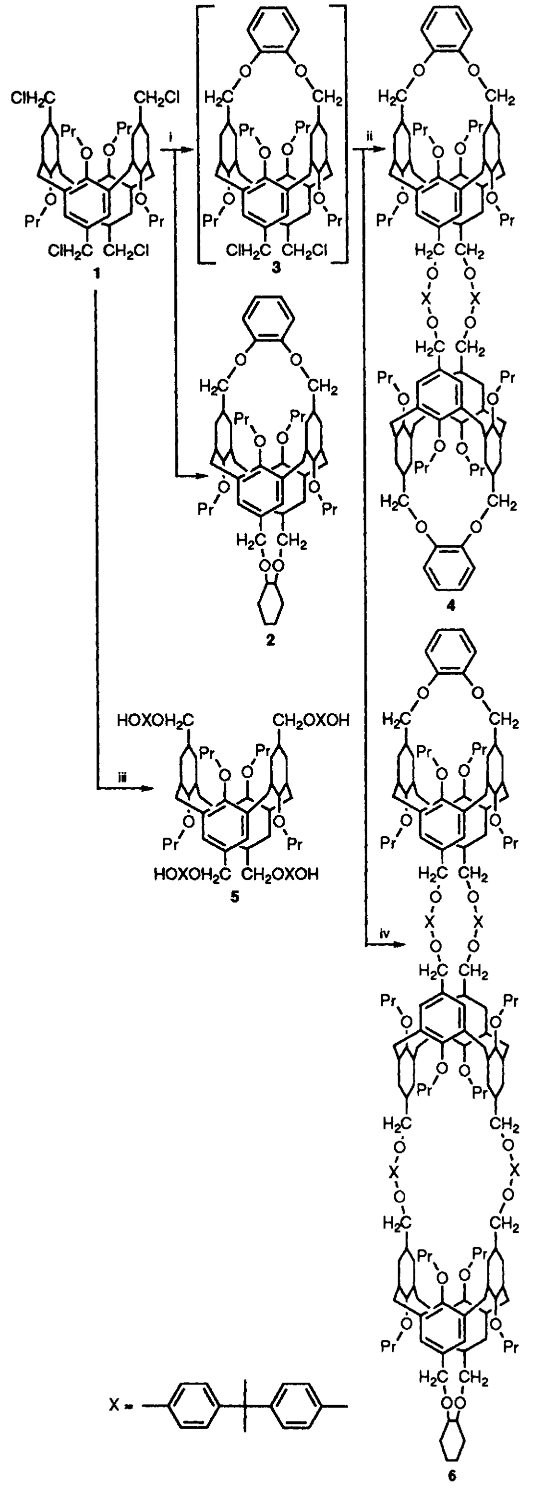
Calix[4]arenes with a 1,3-alternate conformation are unique molecules because of their structural peculiarities: for example, (i) a metal-binding site is composed of two '*hard*' phenolic oxygens and two '*soft*' π-basic benzene rings, (ii) there exist such two binding-sites at the two edges of the calix[4]arene cavity and (iii) the two-binding sites are linked with each other by a π-basic benzene tunnel.[1–3] These structural peculiarities are reflected by their unique metal-binding properties: for example, 1,3-alternate-calix[4]arenes form a 1 : 1 as well as a 1 : 2 complexes with certain metal cations (*e.g.* K^+ and Ag^+) and in the 1 : 1 complex the metal cation vibrates between the two metal-binding sites through the π-basic tunnel.[2,3] This is unequivocal evidence for a prediction that metal cations can easily pass through the π-basic holes or interlayers with the aid of the cation-π interaction,[4] which may play a crucial role in metal transport across ion channels, metal inclusion in fullerenes, intercalation of metal cations into graphite layers, *etc.*[3,4]

Here, it occurred to us that if one can appropriately connect 1,3-alternate-calix[4]arenes which have a π-basic hole for metal-tunneling,[3] a '*nano-tube*' with a well-defined inner diameter for the metal-passage may be synthesized. To organize 1,3-alternate-calix[4]arenes into a one-dimensional array the OH groups are not available for the connection because the substituents bulkier than the ethyl group (*n*-propyl (Pr) in this study) must be introduced there to immobilize the calix[4]arene conformation.[5,6] We thus adopted a strategy to introduce functional groups for the connection into the *para* positions. We here address a novel synthetic approach to calix[4]arene-based '*nano tubes*' with one to three 1,3-alternate-calix[4]arene units (Scheme 1).

'*Nano-tubes*' were synthesized according to Scheme 2. Compound **1** is a calix[4]arene with four chloromethyl groups at the *para* positions. The conformation is immobilized to a 1,3-alternate by *O*-propyl groups.[3] Previously, we reported that treatment of **1** (1.0 equiv.) with catechol (8.0 equiv.) in the presence of K_2CO_3 gives **2** in 81% yield.[3] It was shown that K^+ and Ag^+ are bound to one of the two binding sites, interacting with two phenolic oxygens and two benzene rings and alternate intramolecularly between the two binding sites.[3] Compound **1** (1.0 equiv.) was treated with catechol (1.3 equiv.) in acetone at the reflux temperature in the presence of K_2CO_3 and NaI. The reaction mixture was further treated (without isolating **3**) with Bisphenol A (4,4′-isopropylidenediphenol) (1.0 equiv.). From the product mixture we isolated **4** by the TLC separation [silica gel, acetone–*n*-hexane (1 : 3 *v*/*v*)]



Scheme 1 Schematic representation for the synthesis of artificial '*nano-tubes*'



Scheme 2 *Reagents and conditions*: i, catechol, K_2CO_3, NaI in acetone; ii, Bisphenol A (HOXOH), K_2CO_3, NaI in acetone; iii, Bisphenol A (HOXOH), K_2CO_3 in acetone; iv, **5**, K_2CO_3, NaI in acetone

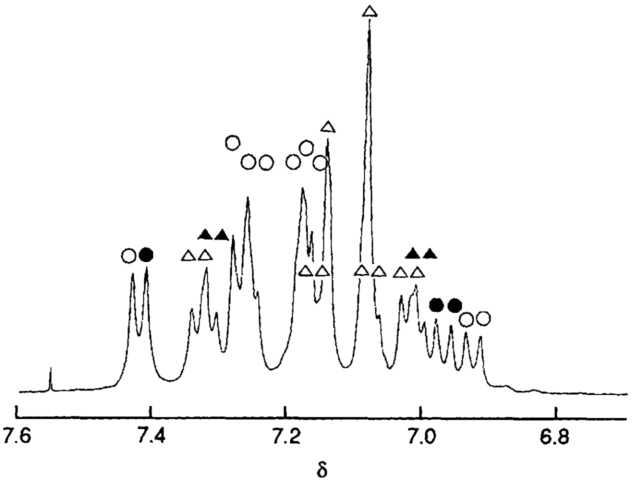


Fig. 1 Partial ^1H NMR spectrum for the ArH protons of **4**. The peaks for free **4** (△) and **4**·$(Ag^+)_2$ (○) can be assigned from ^1H NMR spectra of **4** in the absence of $AgCF_3SO_3$ and a 1 : 2 **4**/$AgCF_3SO_3$ mixture. The residual peaks are assigned to the ArH protons in the metal-complexed site (●) and the metal-uncomplexed site (▲) of **4**·Ag^+.

in 10% yield.† Compound **4** has two π-basic holes end-capped by catechols.

In **1** the distance between the two chloromethyl groups in the distal benzene units is comparable with that between the two OH groups in catechol. Hence, they can be intramolecularly end-capped by catechol. On the other hand, the distance between the two OH groups in Bisphenol A is longer than that between the two chloromethyl groups: hence, Bisphenol A cannot bridge them intramolecularly. Thus, treatment of **1** (1.0 equiv.) with Bisphenol A (80 equiv.) in the similar manner gave **5** with four OH terminal groups in 39% yield.† Thus, compound **1** (1.0 equiv.) was treated with catechol (1.3 equiv.) in acetone at the reflux temperature in the presence of K_2CO_3 and NaI. The reaction mixture was further treated with **5** (0.4 equiv.). From the product mixture we isolated **6** by TLC separation [silica gel, ethyl acetate–*n*-hexane (1 : 5 *v*/*v*)] in 17% yield.† Compound **6** has three π-basic holes organized in a one-dimensional array and end-capped by catechols.

The synthesis of higher oligomers is also possible by the similar stepwise method.[7] When 1 equiv. of **1** is treated with 2 equiv. of **5**, a trimeric intermediate with four OH terminal groups result. When 1 equiv. of this intermediate is treated with 2 equiv. of **3**, the pentamer is yielded. It is clear that the stepwise method is useful to elongate the '*tube*'. On the other hand, polycondensation between **1** and **5** in the presence of the appropriate base may be useful to obtain a high molecular-weight '*tube*'. In this case, however, the polymer inevitably has a polydispersed nature.

The metal-binding properties were estimated by ^1H NMR spectroscopy for a 1 : 1 mixture of **4** and $AgCF_3SO_3$ {400 MHz, CD_2Cl_2–CD_3OD (4 : 1 *v*/*v*), [**4**] = [$AgCF_3SO_3$] = 5.0 mmol dm^{-3}}. As shown in Fig. 1, three different species can be identified separately: they are free **4**, **4**·Ag^+ and **4**·$(Ag^+)_2$ and the integral intensity ratio is 1 : 2 : 1. The result implies that Ag^+ is bound to **4** according to probability. When the temperature was lowered, ○ and ● and △ and ▲ coalesced at −50 °C. The coalescence of ○ and ● is attributed to the intermolecular Ag^+-exchange between **4**·$(Ag^+)_2$ and **4**·Ag^+ and that of △ and ▲ is attributed to the intermolecular Ag^+-exchange between free **4** and **4**·Ag^+. At −85 °C all the peaks were entirely broadened. Hence, we could not obtain unequivocal evidence for the Ag^+-hopping from one calix[4]arene unit to another calix[4]arene unit. We still believe, however, that the fine tuning of the distance between two calix[4]arene units would enable metal-hopping and eventually passage of the metal through the synthetic '*nano-tube*'.

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Footnote

† *Spectroscopic data* for **4**: mp 163–164 °C; yield 10%; Positive SIMS [2-nitrophenyl octyl ether (NPOE)] *m*/*z* 1957 (M^+); δ_H ($CDCl_3$; 25 °C) 1.04, 1.13 (each 6H, each t, CH_3CH_2), 1.78 (6H, s, CH_3C), 1.83–1.94, 1.95–2.11 (each 4H, each m, CH_2CH_3), 3.57 (8H, s, $ArCH_2Ar$), 3.66–3.80 (8H, m, OCH_2CH_2), 4.78, 4.81 (each 8H, each s, $ArCH_2O$), 6.95, 7.00–7.05, 7.07, 7.10–7.16, 7.12, 7.25 (4H, 2H, 4H, 2H, 4H and 4H, resp., d, m, s, m, s and d, resp., ArH). For **5**: mp 98–100 °C; yield 39%; δ_H ($CDCl_3$; 25 °C) 0.91 (3H, t, CH_3CH_2), 1.62–1.78 (9H, m, CH_2CH_3, CH_3C), 3.50–3.72 (4H, m, $OCH_2(CH_2)$, $ArCH_2Ar$), 4.81 (2H, s, $ArCH_2O$), 5.00 (1H, s, OH), 6.71, 6.87, 7.02–7.20 (2H, 2H and 6H, resp., d, d and m, resp., ArH). For **6**: mp 207–210 °C; yield 17%; Positive SIMS [*m*-nitrobenzyl alcohol (NBA), $AgClO_4$] *m*/*z* 1634 (M + $2Ag^+$), (NBA, $KClO_4$) *m*/*z* 1566 (M + 2 K^+); δ_H ($CDCl_3$, 25 °C) 1.04, 1.13 (6H and 12H, resp., each t, CH_3CH_2), 1.77 (12H, s, CH_3C), 1.82–2.08 (12H, m, CH_2CH_3), 3.51 (12H, s, $ArCH_2Ar$), 3.65–3.80 (12H, m, OCH_2CH_2), 4.78, 4.81 (4H and 8H, resp., each s, $ArCH_2O$), 6.94, 7.00–7.19, 7.25 (8H, 16H and 8H, resp., d, m and d, resp., ArH)

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