

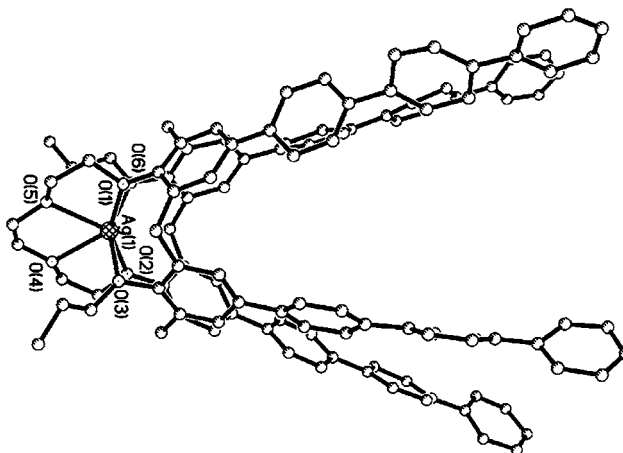
## Synthesis of Oligophenylene-Substituted Calix[4]crown-4s and Their Silver(I) Ion-Induced Nanocones Formation

Man Shing Wong,<sup>\*,†</sup> Ping Fang Xia,<sup>†</sup> Pik Kwan Lo,<sup>†</sup> Xiao Hua Sun,<sup>†</sup>  
Wai Yeung Wong,<sup>†</sup> and Shaomin Shuang<sup>\*,‡</sup>

Department of Chemistry, Hong Kong Baptist University, Kowloon Tong, Hong Kong SAR, China, and  
School of Chemistry and Chemical Engineering, Institute of Advanced Chemistry, Shanxi University,  
Taiyuan 030006, China

mshwong@hkbu.edu.hk; smshuang@sxu.edu.cn

Received September 9, 2005



A novel series of oligophenylene OPP(*n*)-substituted calix[4]crown-4s bearing up to three phenylene units, **1a–d**, has been efficiently synthesized by means of either microwave-assisted or silver(I) ion-assisted Pd-catalyzed Suzuki cross-coupling of tetraiodocalix[4]crown-4 and the corresponding oligophenylboronic acids. Complexation of OPP(*n*)-substituted calix[4]crown-4s with silver (I) ion was substantiated by <sup>1</sup>H NMR spectroscopic and high-resolution ESI– or MALDI-TOF– MS studies. The weak binding affinities of OPP(*n*)-substituted calix[4]crown-4s for silver (I) ion, which were estimated from <sup>1</sup>H NMR titrations with binding association in the range of 30–90 M<sup>-1</sup>, allows reversible disassembling in the presence of KI at ambient temperature. Remarkably, the single-crystal X-ray structures of OPP(*n*)-calix[4]crown-4·Ag<sup>+</sup> complexes indicate the atypical silver (I) ion-crown ether binding mode resulting in the formation of rigid nanocones with volume created up to ~1500 Å<sup>3</sup>. Our results suggested that despite the weak binding affinity of crown ether ligands for silver (I) ion, this weak interaction is still be useful as a tool to construct supramolecular architectures.

### Introduction

There has been tremendous interest in the design and synthesis of novel nanoscale supramolecular architectures based on various noncovalent interactions including metal chelation, hydrogen bonding, and charge-transfer interactions in the past two decades as some of these assemblies show great potential for nanotechnological applications.<sup>1</sup> Knowledge and tools that

can be reliably used to predict and control the formation and structure of supramolecular architectures are fundamentally important, since they are essential toward a rational design and

<sup>†</sup> Hong Kong Baptist University.

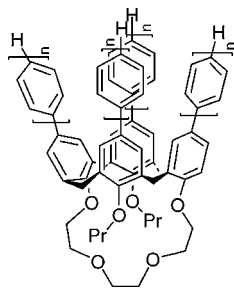
<sup>‡</sup> Shanxi University.

(1) For recent reviews: (a) Lehn, J. M. *Supramolecular Chemistry*; VCH: Weinheim, Germany, 1995. (b) Steed, J. W., Atwood, J. L. *Supramolecular Chemistry*; VCH: Weinheim, Germany, 2000. (c) Leininger, S.; Olenyuk, B.; Stang, P. J. *Chem. Rev.* **2000**, *100*, 853–908. (d) Holliday, B. J.; Mirkin, C. A. *Angew. Chem., Int. Ed.* **2001**, *40*, 2022–2043. (e) Prins, L. J.; Reinhoudt, D. N.; Timmerman, P. *Angew. Chem., Int. Ed.* **2001**, *40*, 2382–2426.

an optimization of the functional assemblies. Design of complementary structural components that can self-assemble into supramolecular architectures requires building in relatively strong and directional adhesive forces, as they are important for the stability of the desirable structure. As a result, the weak affinity of hard base for soft acid is not often considered to be useful as a tool to construct supramolecular architectures.

Calix[4]tubes based on bis-calix[4]arene ethers<sup>2</sup> and calix[4]-bis-crowns<sup>3</sup> have been explored and studied by several groups; however, there are no rigid calix[4]tubes or calix[4]-cones with extended hydrophobic cavity reported so far. One of the logical approaches to construct an elongated hollow structure is to extend the bowl-shaped curvature of the calix[4]arene in the cone conformation. Recently, syntheses of several extended oligophenylenevinyl (OPV)- and oligophenylene (OPP)-substituted calix[4]arenes end-capped with either alkylsulfanyl or alkylsulfonyl groups have been successfully achieved.<sup>4</sup> Nevertheless, simply extending the skeleton with arylenevinyl or arylene units on the upper rim of calix[4]arene does not create an enlarged cavity as the conformationally mobile tetraalkylated calix[4]arene interconverts between two  $C_{2v}$  "pinched or flattened" cone conformers in solution at room temperature and also adopts a pinched cone conformation such as in the solid state.<sup>5</sup>

To create a calix[4]arene-derived hollow cavity, our strategy is first to suppress the mobility of the cone conformer followed by an opening up of the flattened cavity induced by metal complexation. To stabilize the cone conformation and introduce binding sites for metal chelation at the lower rim of calix[4]arene, one of the approaches is to introduce a polyether bridge at the lower rim linked between two distal phenolic rings.<sup>6</sup> We herein describe the efficient protocols for the synthesis of oligophenylene-substituted 25,27-dipropoxy-calix[4]crown-4s **1a–d** and an investigation of silver(I) ion-induced assembling



**1a–d**:  $n = 0-3$

of rigid nanocones. The current work shows for the first time that the weak affinity of the hard base, crown ether ligand, for

the soft acid, silver(I) ion, can be useful as a tool to construct supramolecular architectures: rigid nanocones. The merit of using such weak binding interaction is that it allows the reversibility of this assembling process, which can be easily switched on or off even though this crown ether ligand can interact with other metal ions such as sodium or lithium ions.

## Results and Discussion

Facile syntheses of OPP( $n$ )-substituted 25,27-dipropoxycalix[4]arene-crown ethers are summarized in Scheme 1. Chemo-selective 1,3-dipropylation of calix[4]arene<sup>7</sup> was carried out with an excess of 1-bromopropane and  $K_2CO_3$  in refluxing  $CH_3CN$  affording **2** in 82% yield. Subsequent reaction of **2** with triethylene glycol ditosylate with an excess of NaH as a base in DMF afforded **1a** in an excellent yield (90%). To extend the skeleton of calix[4]arene with phenylene units, previously established palladium-catalyzed Suzuki cross-coupling protocol was employed.<sup>4b,c</sup> Iodination of **1a** with  $CF_3COO^-Ag^+/I_2$  in refluxing chloroform<sup>8</sup> afforded tetraiodocalix[4]arene **3**. Cross-coupling of **3** with various arylboronic acids including 4-methylphenylboronic acid, 4-fluorophenylboronic acid, 4-(trimethylsilyl)phenylboronic acid, phenylboronic acid, and biphenylboronic acid in the presence of a catalytic amount of  $Pd(PPh_3)_4$  complex heating at 80 °C<sup>9</sup> afforded the corresponding arylene-substituted calix[4]crown-4s **4–6**, **1b**, or **1c**, respectively, in poor to good yields (Scheme 1). On the other hand, direct coupling of **3** and terphenylboronic acid under the same conditions gave no desired product in which only trisubstituted product was isolated. The reason for unsatisfactory or incomplete conversion with the conventional protocol is that in contrast to the conformationally mobile tetraalkoxycalix[4]arenes, the immobility of calix[4]crown-4 skeleton with a pinched cone conformation further aggravated the steric crowdedness between partially arylene-substituted calix[4]crown-4s and bulky arylboronic acid particularly for the construction of the fourth OPP arm. As the preparation of 4-(trimethylsilyl)phenyl-substituted calix[4]crown-4 afforded very low yield, the previously established synthetic approach,<sup>4c</sup> which required such TMS-compound as an intermediate, was not explored for the synthesis OPP( $n$ )-calix[4]crown-4s.

Alternatively, a microwave-assisted coupling protocol<sup>10</sup> was explored. Among various conditions examined, temperature gradient mode, in which the reaction mixture was first irradiated at 80 °C for 10 min followed by irradiation at 130 °C for 20–30 min, was found to have the most efficient conditions for the cross-coupling. Microwave-assisted Suzuki cross-coupling of tetraiodocalix[4]arene with terphenylboronic acid in THF afforded the desired product **1d** in 68% isolated yield. Under the microwave heating conditions, syntheses of **1b** and **1c** were greatly improved with isolated yields of 90% and 75%, respectively. All the newly synthesized calix[4]crown-4s were

(2) (a) Ikeda, A.; Shinkai, S. *J. Am. Chem. Soc.* **1994**, *116*, 3102–3110. (b) Matthews, S. E.; Schmitt, P.; Felix, V.; Drew, M. G. B.; Beer, P. D. *J. Am. Chem. Soc.* **2002**, *124*, 1341–1353.

(3) (a) Thuéry, P.; Nierlich, M.; Lamare, E.; Dozol, J. F.; Asfari, Z.; Vicens, J. *J. Incl. Phenom.* **2000**, *36*, 375–408. (b) Kim, J. S.; Lee, W. K.; Kim, J. G.; Suh, I. H.; Yoon, J. Y.; Lee, J. H. *J. Org. Chem.* **2000**, *65*, 7215–7218. (c) Kim, S. K.; Sim, W.; Vicens, J.; Kim, J. S. *Tetrahedron Lett.* **2003**, *44*, 805–809. (d) Kim, S. K.; Vicens, J.; Park, K. M.; Lee, S. S.; Kim, J. S. *Tetrahedron Lett.* **2003**, *44*, 993–997. (e) Kim, S. K.; Lee, J. K.; Lee, S. H.; Lim, M. S.; Lee, S. W.; Sim, W.; Kim, J. S. *J. Org. Chem.* **2004**, *69*, 2877–2880.

(4) (a) Wong, M. S.; Chan, W. H.; Chan, W. Y.; Li, J.; Dan, X. *Tetrahedron Lett.* **2000**, *41*, 9293–9297. (b) Wong, M. S.; Zhang, X. L.; Chen, D. Z.; Cheung, W. H. *Chem. Commun.* **2003**, 138–139. (c) Wong, M. S.; Xia, P. F.; Zhang, X. L.; Lo, P. K.; Cheng, Y.-K.; Yeung, K.-T.; Guo, X.; Shuang, S. M. *J. Org. Chem.* **2005**, *70*, 2816–2819.

(5) Ikeda, A.; Tsuzuki, H.; Shinkai, S. *J. Chem. Soc., Perkin Trans. 2* **1994**, 2073–2080.

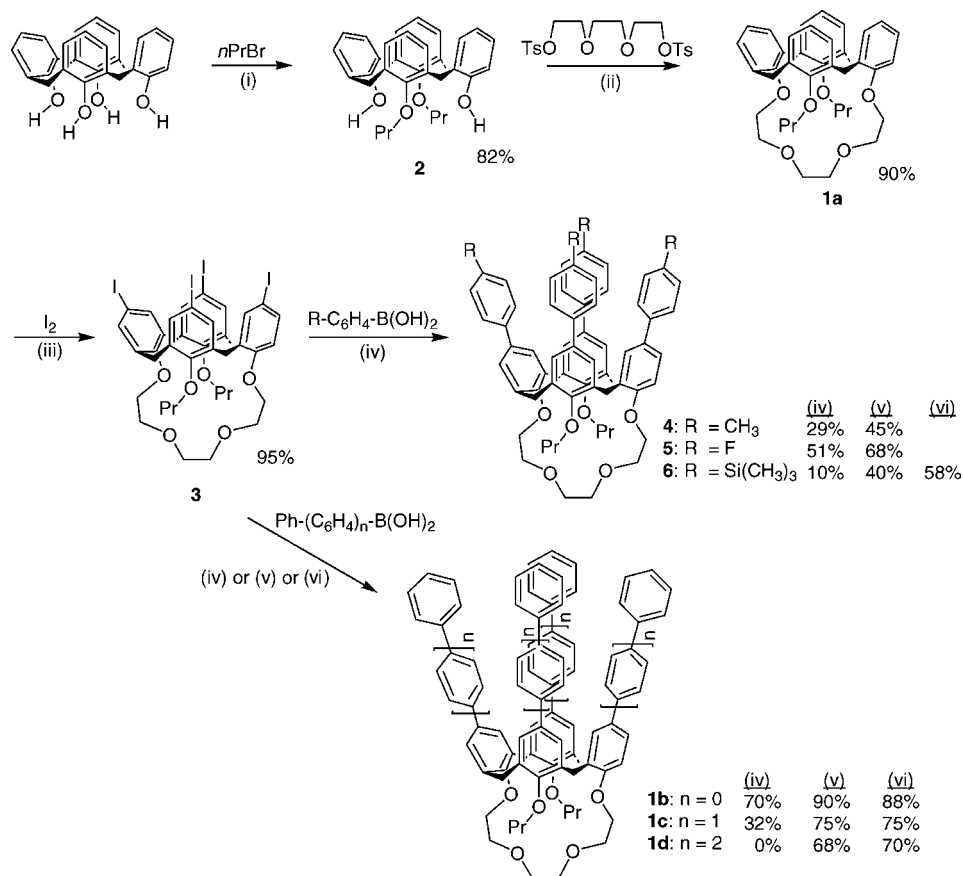
(6) Arduini, A.; Fabbri, M.; Mantovani, M.; Mirone, L.; Pochini, A.; Secchi, A.; Ungaro, R. *J. Org. Chem.* **1995**, *60*, 1454–1457.

(7) van Loon, J. D.; Arduini, A.; Coppi, L.; Verboom, W.; Pochini, A.; Ungaro, R.; Harkema, S.; Reinhoudt, D. N. *J. Org. Chem.* **1990**, *55*, 5639–5646.

(8) Timmerman, P.; Verboom, W.; Reinhoudt, D. N.; Arduini, A.; Sicuri, A. R.; Pochini, A.; Ungaro, R. *Synthesis* **1994**, 185–189.

(9) Suzuki, A. *J. Organomet. Chem.* **1999**, *576*, 147–168.

(10) For a recent review: Kappe, C. O. *Angew. Chem., Int. Ed.* **2004**, *43*, 6250–6284.

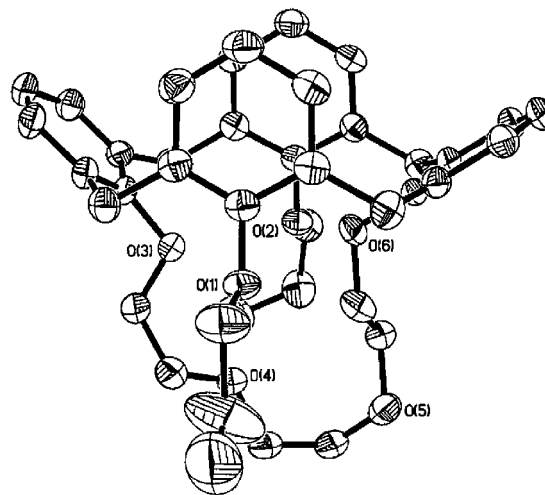
SCHEME 1. Synthesis of Oligophenylene-Substituted 25,27-Dipropoxycalix[4]arene-Crown Ethers<sup>a</sup>

<sup>a</sup> Reagents and conditions: (i) K<sub>2</sub>CO<sub>3</sub>, CHCN, reflux, overnight; (ii) NaH, DMF, 80 °C, overnight; (iii) CF<sub>3</sub>COOAg, CHCl<sub>3</sub>, reflux, 2 h; (iv) Pd(PPh<sub>3</sub>)<sub>4</sub>, 2 M K<sub>2</sub>CO<sub>3</sub>, Tol-CH<sub>3</sub>OH, 80 °C, overnight; (v) Pd(PPh<sub>3</sub>)<sub>4</sub>, 2 M K<sub>2</sub>CO<sub>3</sub>, Tol-CH<sub>3</sub>OH or THF, microwave heat: 80 °C, 10 min and then 130 °C, 20–30 min; (vi) CF<sub>3</sub>COOAg, Pd(PPh<sub>3</sub>)<sub>4</sub>, 2 M K<sub>2</sub>CO<sub>3</sub>, THF, 80 °C, 1–2 h.

fully characterized with <sup>1</sup>H NMR, <sup>13</sup>C NMR, and high-resolution ESI-MS or MALDI-TOF and found to be in good agreement with the structures.

As predicted by the MM2 molecular calculations<sup>11</sup> and revealed by <sup>1</sup>H NMR studies, 25,27-dipropoxy-calix[4]arene-crown-4, **1a**, and its extended analogues, **1b–d**, preferentially adopt a pinched cone conformation stabilized by  $\pi$ – $\pi$  interactions with a limited cavity, in which the propoxy-substituted aryl rings, characterized by the upfield shift of aromatic protons in the <sup>1</sup>H NMR spectrum, are parallel to one another. The variable-temperature <sup>1</sup>H NMR studies further confirmed the mobility-restricted conformation of these calix[4]crown-4s. Indeed, the single-crystal X-ray structure of **1a** shows a pinched cone structure with the bridged phenyl rings leaning outward (Figure 1).

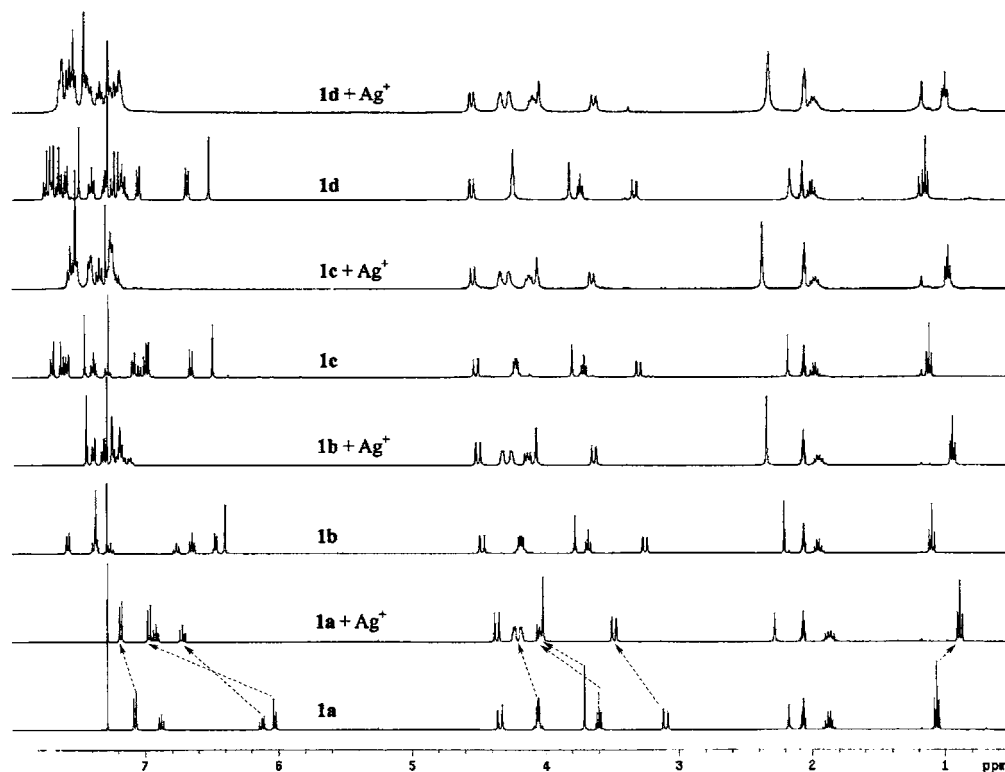
Silver(I) ion has been shown to interact with the  $\pi$ -electron cloud of cone-conformed tetraalkoxycalix[4]arene resulting in a cation– $\pi$  complex.<sup>5</sup> However, <sup>1</sup>H NMR spectroscopic studies showed that there are no observable interactions between arylene-substituted tetraalkoxycalix[4]arenes and the Ag<sup>+</sup> ion. On the other hand, upon an addition of AgCF<sub>3</sub>COO, there are dramatic shifts of proton resonances of calix[4]crown-4s in the <sup>1</sup>H NMR spectra indicating the presence of interaction between calix[4]crown-4s and Ag<sup>+</sup> ion. The patterns or trends of Ag<sup>+</sup>-induced chemical shifts are consistent for all calix[4]crown-4s



**FIGURE 1.** ORTEP drawings of **1a** (25% probability). All hydrogen atoms are omitted for clarity.

**1a–d** as shown in Figure 2 suggesting that they all adopt the same binding mode. In particular, large downfield shifts of protons upon complexation come from two parallel distal propoxy-substituted aryl rings of calix[4]crown-4s (i.e., **1a**:  $\Delta\delta$  for *m*-Ar-*H* and *p*-Ar-*H* = 0.91 and 0.58 ppm, respectively, in CDCl<sub>3</sub>) implying a change in the conformation of the cone structure. Complexation of calix[4]crown-4s with Ag<sup>+</sup> ion was further confirmed by high-resolution ESI-MS or MALDI-TOF-

(11) MM2 molecular calculations were performed by CS Chem 3D Pro, Version 5.0.



**FIGURE 2.**  $^1\text{H}$  NMR spectra of calix[4]crown-4s **1a–d** and the corresponding spectra upon addition of 10 equiv of  $\text{AgCF}_3\text{COO}$  in  $\text{CDCl}_3$  and  $\text{CD}_3\text{COCD}_3$  (10:1).

MS measurements in which the spectra of the solution mixture of the calix[4]crown-4s and  $\text{CF}_3\text{COO}^- \text{Ag}^+$  shows either a base peak or peak at  $m/z$  729.2318, 1035.3631, 1339.4852, and 1643.6117 with expected isotopic distribution patterns which correspond to **[1a + Ag] $^+$** , **[1b + Ag] $^+$** , **[1c + Ag] $^+$** , and **[1d + Ag] $^+$** , respectively (see the Supporting Information).

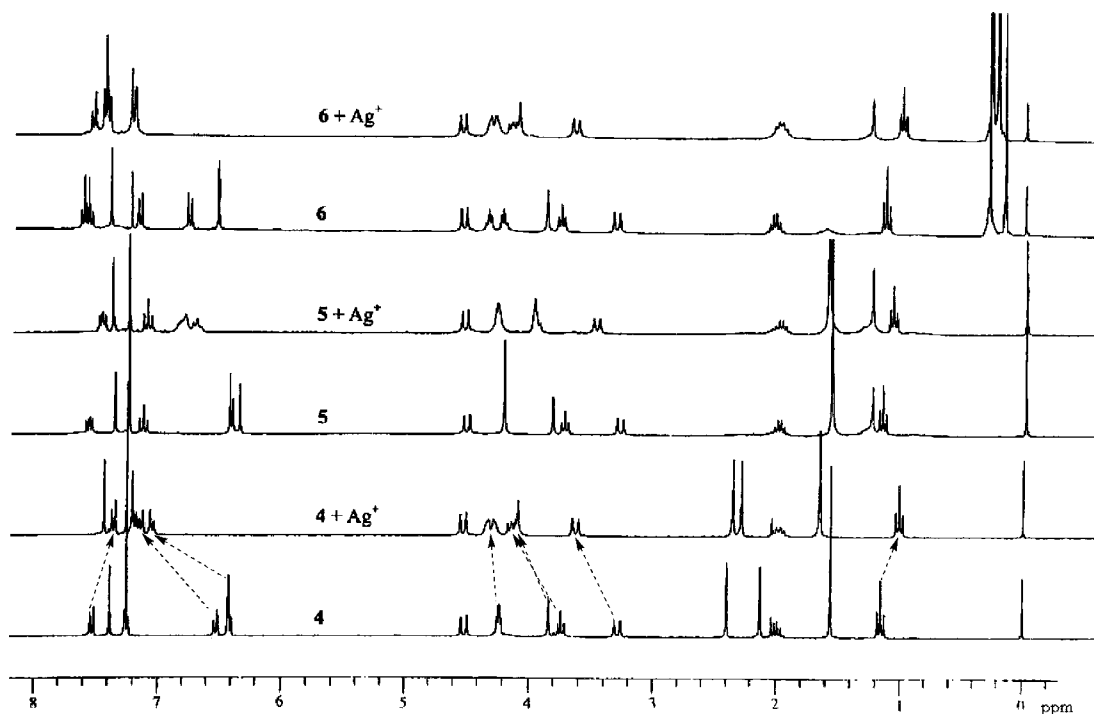
To probe the influence of the upper rim functionality on the binding mode or site, we also prepared a series of para-substituted phenyl-calix[4]crown-4s, **4–6**, bearing either methyl or fluoro or trimethylsilyl substituent. Consistently, the microwave-assisted cross-coupling protocol was found to be superior to the conventional procedure (Scheme 1). An investigation of  $^1\text{H}$  NMR spectroscopic studies revealed that complexation, which is essentially not affected by the electronic and steric properties of aryl rings substituted at the upper rim, was observed in all cases (Figure 3). In addition, complexation of **4–6** with the  $\text{Ag}^+$  ion was again confirmed by high-resolution ESI-MS or MALDI-TOF measurements with a base peak or peak at  $m/z$  1091.4313, 1107.3245, and 1323.5214 corresponding to **[4 + Ag] $^+$** , **[5 + Ag] $^+$** , and **[6 + Ag] $^+$** , respectively. These results further suggested that the  $\text{Ag}^+$  ion is bound to the ether ligands at the lower rim of calix[4]crown-4s. Although the high-resolution ESI-MS measurements indicate a 1:1 binding stoichiometry in all cases, we were unable to confirm the 1:1 binding stoichiometry of **1a**· $\text{AgCF}_3\text{COO}$  and **1b**· $\text{AgCF}_3\text{COO}$  complexes in solution by the Job plots based on the change of chemical shift of  $^1\text{H}$  NMR data, which show an asymmetric graph deviating from a 1:1 binding stoichiometry (see the Supporting Information). The discrepancy could arise from the change in chemical shift induced by conformational change of calix[4]crown-4s upon  $\text{Ag}^+$  ion binding, in addition to complexation-induced chemical shift. The binding constants of **1a**· $\text{Ag}^+$ , **1b**· $\text{Ag}^+$ , **1c**· $\text{Ag}^+$ , and **1d**· $\text{Ag}^+$  complexes were estimated

to be 91, 91, 47, and 30  $\text{M}^{-1}$ , respectively, which were determined by the nonlinear curve fitting analysis<sup>12</sup> with data obtained from  $^1\text{H}$  NMR titrations in  $\text{CDCl}_3$ : $\text{CD}_3\text{COCD}_3$  (10:1), indicating that the binding interaction is not very strong. Even though potassium ion does not form a complex with calix[4]crown-4 as revealed from the  $^1\text{H}$  NMR titration study, reversibility of this assembling process can easily be achieved by stirring the complex with KI at ambient temperature in which the complexation-induced chemical shifts disappear in the  $^1\text{H}$  NMR spectrum upon addition of KI.

Consistent to the relatively small cavity size of these calix[4]crown-4s, only small cations could bind to them, which was confirmed by  $^1\text{H}$  NMR titrations and MALDI-TOF measurements. To evaluate their binding affinities and selectivity,  $^1\text{H}$  NMR titrations in  $\text{CDCl}_3$ : $\text{CD}_3\text{COCD}_3$  (10:1) were again used with various triflate salts. The results are tabulated in Table 1. In contrast to the silver complexes, the binding of lithium and sodium ions to the calix[4]crown-4s was kinetically slow relative to the NMR time scale under the experimental conditions (see the Supporting Information). Lithium ion shows similar binding affinity toward the calix[4]crown-4s but sodium ion exhibits about an order of magnitude stronger binding affinity, which is attributed to the better cavity size matching of sodium ion. In addition, these calix[4]crown-4s show excellent  $\text{Na}^+/\text{K}^+$  ion selectivity as potassium ion does not form a complex with calix[4]crown-4s.

Remarkably, the single-crystal X-ray structure of the **1a**· $\text{Ag}^+$  complex grown from chloroform unambiguously shows the atypical silver(I) ion–crown ether binding mode, in which the  $\text{Ag}^+$  ion is directionally chelated by six ether-type ligands with bond lengths in the range of 2.31–2.49 Å at the lower rim of

(12) Macomber, R. S. *J. Chem. Educ.* **1992**, *69*, 375–378.



**FIGURE 3.**  $^1\text{H}$  NMR spectra of calix[4]crown-4s **4–6** and the corresponding spectra upon addition of 10 equiv of  $\text{AgCF}_3\text{COO}$  in  $\text{CDCl}_3$  and  $\text{CD}_3\text{COCD}_3$  (10:1).

**TABLE 1.** Binding Constant ( $\text{M}^{-1}$ )<sup>a</sup> of Calix[4]crowns-4s with Metal Triflates

compd	$\text{Ag}^+$	$\text{Li}^+$	$\text{Na}^+$	$\text{K}^+$
<b>1a</b>	91	74	1181	no
<b>1b</b>	91	57	643	no
<b>1c</b>	47	38	419	no
<b>1d</b>	30	<i>b</i>	141	no

<sup>a</sup> Determined by  $^1\text{H}$  NMR titrations in  $\text{CDCl}_3:\text{CD}_3\text{COCD}_3$  (10:1).

<sup>b</sup> Precipitation of complex.

calix[4]crown-4s (Figure 4). This is clearly different from the previously reported binding mode of  $\text{Ag}^+$ –calix[4]arene crown ether complexes in which the  $\text{Ag}^+$  ion is generally bonded by three crown ether ligands.<sup>13</sup> Strikingly, the four aryl rings are pseudo- $C_{4v}$  symmetrically conformed creating a rigid hollow cavity. Both intra- and intermolecular interactions such as  $\pi$ – $\pi$  interactions appear insignificant in stabilizing this complex structure in contrast to the structure of calix[4]crown-4 itself. Furthermore, the **1b**· $\text{Ag}^+$  complex adopts the same binding mode resulting in the formation of a more extended rigid hydrophobic cavity with a minor twisting of the phenyl-aryl rings as revealed from the single-crystal X-ray structure. Such a rigid nanocone could further be extended with an increase in phenylene unit. The preliminary X-ray structural results of **1c**· $\text{Ag}^+$  and **1d**· $\text{Ag}^+$  complexes consistently indicate the anticipated silver(I) ion–crown ether binding mode and rigid nanocone supramolecular structures with a more elongated cavity. The estimated nanocone volume created in the **1d**· $\text{Ag}^+$  complex is  $\sim 1500 \text{ \AA}^3$ .

It was thought that complexation of the Ag(I) ion with calix[4]crown-4 leading to the opening up of the pinched cone could

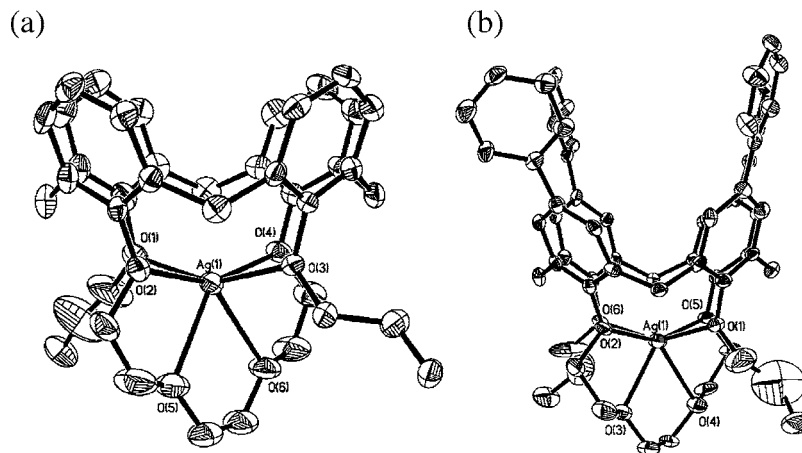
alleviate the steric crowdedness of the coupling reaction site and thus could promote the cross-coupling reaction. Indeed, with an addition of 4 equiv of  $\text{CF}_3\text{COO}^- \text{Ag}^+$  or  $\text{CH}_3\text{COO}^- \text{Ag}^+$ , the cross-coupling reaction of tetraiodocalix[4]crown-4, **3**, and various arylboronic acids proceeded effectively and efficiently under conventional conditions (see Scheme 1). As anticipated, such Ag(I) ion-assisted enhancement was not apparent for the cross-coupling of conformationally mobile tetrakisiodotetraalkoxycalix[4]arene, indicating the importance of the immobility of the calix[4]arene structure. Complexation of tetraiodocalix[4]crown-4 with silver(I) ion was evidenced by the high-resolution MALDI-TOF-MS measurement and  $^1\text{H}$  NMR studies, in which the shifts of proton resonances in the  $^1\text{H}$  NMR spectra upon addition of  $\text{CF}_3\text{COO}^- \text{Ag}^+$  were very similar to those of OPP-calix[4]crown-4s studies shown above, suggesting that the enhancement is related to silver(I) ion–calix[4]crown ether binding. On the other hand, neither lithium nor sodium ion exhibit the enhancement effect for the cross-coupling. As a result, the Ag(I) ion-assisted enhancement could also be contributed to a certain extent by an increase in the rate of oxidative insertion of tetraiodocalix[4]crown-4.<sup>14</sup>

## Conclusions

In summary, we have developed facile and efficient microwave-assisted as well as silver(I) ion-assisted Pd-catalyzed Suzuki cross-coupling protocols for the synthesis of oligophenylene-substituted calix[4]crown-4s. We have also shown that despite the weak binding affinity of crown ether ligands for the silver(I) ion, this weak interaction is useful as a tool to construct supramolecular architectures, rigid nanocones with volume created up to  $\sim 1500 \text{ \AA}^3$  based on silver(I) ion-induced assembly of oligophenylene-substituted 25,27-dipropoxy-calix[4]crown-4s.

(13) (a) Thuéry, P.; Nierlich, M.; Arnaud-Neu, F.; Souley, B.; Asfari, Z.; Vicens, J. *Supramol. Chem.* **1999**, *11*, 143–150. (b) Jeunesse, C.; Dieleman, C.; Steyer, S.; Matt, D. *J. Chem. Soc., Dalton Trans.* **2001**, 881–892.

(14) Malm, J.; Björk, P.; Gronowitz, S.; Hörmfeldt, A.-B. *Tetrahedron Lett.* **1992**, *33*, 2199–2202.



**FIGURE 4.** ORTEP drawings of (a) **1a**·Ag<sup>+</sup> and (b) **1b**·Ag<sup>+</sup> (25% probability). All hydrogen atoms are omitted for clarity.

### Experimental Section

**2:** To a suspension of calix[4]arene (4.25 g, 10 mmol) in CH<sub>3</sub>CN (300 mL) were added 1-iodopropane (18.2 mL, 200 mmol) and K<sub>2</sub>CO<sub>3</sub> (6.9 g, 50 mmol). After the reaction mixture was heated at 90 °C with stirring under N<sub>2</sub> for 30 h, the solvent was evaporated to dryness. The residue was dissolved in dichloromethane (150 mL) and suspension was neutralized by 10% HCl. The organic layer was concentrated and precipitated with methanol affording a pure compound **2** as a white solid (4.15 g, 82%). <sup>1</sup>H NMR (CDCl<sub>3</sub>, 270 MHz, 25 °C): δ 8.30 (s, 2H), 7.03 (d, *J* = 7.3 Hz, 4H), 6.91 (d, *J* = 7.6 Hz, 4H), 6.73 (t, *J* = 7.4 Hz, 2H), 6.62 (t, *J* = 7.4 Hz, 2H), 4.30 (d, *J* = 13.2 Hz, 4H), 3.96 (t, *J* = 6.2 Hz, 4H), 3.36 (d, *J* = 13.0 Hz, 4H), 2.06 (m, 4H), 1.30 (t, *J* = 7.3 Hz, 6H). <sup>13</sup>C NMR (CDCl<sub>3</sub>, 66.5 MHz, 25 °C): δ 153.2, 151.8, 133.4, 128.8, 128.3, 128.1, 125.2, 118.9, 78.3, 31.5, 23.6, 11.0. Mp 275–276 °C.

**1a:** To a solution of **2** (2.04 g, 4.0 mmol) in dry DMF (400 mL) was added NaH (60% in oil, 288 mg, 12 mmol), which was washed twice with petroleum ether before use. The mixture was heated at 70 °C and was added with triethylene glycol ditosylate (2 g, 4.37 mmol) in 10 mL of DMF. The reaction mixture was stirred at room temperature overnight and then heated at 80 °C under N<sub>2</sub> for 15 h. The solvent was evaporated to dryness. The residue was taken up with HCl (10%) and extracted with ethyl acetate. The organic layer was dried over Na<sub>2</sub>SO<sub>4</sub>, filtered, and evaporated. The residue was dissolved in dichloromethane and precipitated with ethanol to obtain a pure white powder of **1a** (1.60 g, 67% yield). The filtrate was evaporated to dryness and then purified by silica gel column chromatography, using petroleum ether and ethyl acetate (v/v 3:1) as eluent affording another batch of **1a** (0.55 g, 23% yield). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, 25 °C): δ 7.14 (d, *J* = 7.2 Hz, 4H), 6.94 (t, *J* = 7.6 Hz, 2H), 6.19 (dd, *J* = 6.8, 8.4 Hz, 2H), 6.09 (d, *J* = 7.6 Hz, 4H), 4.40 (d, *J* = 13.2 Hz, 4H), 4.12 (m, 8H), 3.77 (s, 4H), 3.66 (t, 4H, *J* = 6.8 Hz), 3.16 (d, *J* = 13.2 Hz, 4H), 1.93 (m, 4H), 1.12 (t, *J* = 7.2 Hz, 6H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>, 25 °C): δ 158.2, 154.7, 136.8, 133.0, 129.1, 127.4, 122.2, 122.0, 77.1, 73.7, 71.8, 70.4, 30.4, 23.6, 10.9. FAB (MS) *m/z* 645 (M + Na<sup>+</sup>). HRMS (MALD-TOF): calcd for C<sub>40</sub>H<sub>46</sub>O<sub>6</sub>Na 645.3192; found 645.3176 (M + Na<sup>+</sup>). HRMS (ESI): calcd for C<sub>40</sub>H<sub>46</sub>O<sub>6</sub>Ag 729.2345; found 729.2318 (M + Ag<sup>+</sup>). Mp 163–165 °C.

**General Procedure for Microwave-Assisted Suzuki Cross-Coupling.** A mixture of tetraiodocalix[4]arene **3** (67.6 mg, 0.06 mmol), (1,1'-biphenyl-4-yl)boronic acid (71.3 mg, 0.36 mmol), tetrakis(triphenylphosphine)palladium(0) (7 mg, 10 mol %), THF (3 mL), and 2 M K<sub>2</sub>CO<sub>3</sub> (0.8 mL) in a sealed vial was stirred and irradiated with standard mode for 10 min holding at 80 °C (10–50 W, 100 psi) and then for another 20–30 min holding at 130 °C (100–300 W, 100 psi). After cooling, the product mixture was poured into water (5 mL) and extracted with dichloromethane (3

× 10 mL). The combined organic layer was dried with anhydrous Na<sub>2</sub>SO<sub>4</sub> and evaporated to dryness. The crude product was purified by flash chromatography on basic aluminum oxide, using dichloromethane and ethyl acetate for gradient elution. The final product, **1c**, was recrystallized from dichloromethane:methanol as colorless crystals (0.55 g, 75% yield). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, 25 °C): δ 7.75–7.79 (m, 4H), 7.65–7.71 (m, 8H), 7.43–7.48 (m, 8H), 7.36 (t, *J* = 7.6 Hz, 2H), 7.00–7.17 (m, 14H), 6.72 (d, *J* = 8.4 Hz, 4H), 6.56 (s, 4H), 4.58 (d, *J* = 12.8 Hz, 4H), 4.29 (m, 8H), 3.87 (s, 4H), 3.78 (t, *J* = 7.2 Hz, 4H), 3.36 (d, *J* = 13.2 Hz, 4H), 2.05 (m, 4H), 1.18 (t, *J* = 7.2 Hz, 6H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>, 25 °C): δ 157.8, 154.5, 140.8, 140.4, 140.2, 139.9, 139.6, 138.4, 136.8, 135.8, 134.9, 132.9, 128.8, 128.4, 127.7, 127.5, 127.4, 127.3, 127.1, 127.0, 126.9, 126.6, 126.5, 77.7, 74.1, 71.8, 70.4, 30.8, 23.7, 11.0. HRMS (MALD-TOF): calcd for C<sub>88</sub>H<sub>78</sub>O<sub>6</sub>Na 1253.5696; found 1253.5673 (M + Na<sup>+</sup>). Calcd for C<sub>88</sub>H<sub>78</sub>O<sub>6</sub>Ag 1337.4870; found 1337.44852 (M + Ag<sup>+</sup>). Mp 298–300 °C.

**General Procedure for Silver(I) Ion-Assisted Suzuki Cross-Coupling.** A mixture of tetraiodocalix[4]arene **3** (68 mg, 0.06 mmol) and CF<sub>3</sub>COO<sup>−</sup>Ag<sup>+</sup> (54 mg, 0.24 mmol) in 14 mL of THF was stirred for 5 min under nitrogen at room temperature. After adding 4-terphenylboronic acid (98.7 mg, 0.36 mmol), tetrakis(triphenylphosphine)palladium(0) (7 mg, 0.006 mmol), and 2 M K<sub>2</sub>CO<sub>3</sub> (1 mL), the solution mixture was heated to 80 °C and kept at that temperature for 1–2 h. After cooling, the product mixture was poured into water (5 mL) and extracted with dichloromethane (3 × 20 mL). The combined organic layer was dried with anhydrous Na<sub>2</sub>SO<sub>4</sub> and evaporated to dryness. The crude product was purified by flash chromatography on basic aluminum oxide, using dichloromethane and ethyl acetate for gradient elution. The final product, **1d**, was recrystallized from dichloromethane:methanol as colorless crystals (65 mg, 70% yield). <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>, 25 °C): δ 7.58–7.74 (m, 20H), 7.47 (d, *J* = 4.8 Hz, 4H), 7.40 (t, *J* = 7.6 Hz, 4H), 7.13–7.30 (m, 20H), 7.04 (d, *J* = 8.0 Hz, 4H), 6.67 (d, *J* = 8.4 Hz, 4H), 6.51 (s, 4H), 4.53 (d, *J* = 13.2 Hz, 4H), 4.23 (br s, 8H), 3.81 (br s, 4H), 3.72 (t, *J* = 6.8 Hz, 4H), 3.32 (d, *J* = 13.6 Hz, 4H), 1.99 (m, 4H), 1.13 (t, *J* = 7.2 Hz, 6H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>, 25 °C): δ 157.9, 154.6, 140.7, 140.3, 140.1, 140.0, 139.6, 139.4, 139.1, 139.1, 137.8, 136.9, 135.0, 134.9, 133.0, 128.8, 128.7, 127.7, 127.6, 127.5, 127.4, 127.4, 127.0, 127.0, 126.9, 126.9, 126.7, 126.5, 126.5, 77.7, 74.1, 71.9, 70.4, 30.9, 23.7, 11.0. HRMS (MALD-TOF): calcd for C<sub>112</sub>H<sub>94</sub>O<sub>6</sub>Na 1558.6981; found 1558.6971 (M + Na<sup>+</sup>). Calcd for C<sub>112</sub>H<sub>94</sub>O<sub>6</sub>Ag 1643.613; found 1643.6117 (M + Ag<sup>+</sup>). Mp 336–338 °C.

**X-ray crystallography:** Preliminary examination and intensity data collection were carried out at 293 K on a CCD area-detector diffractometer, using graphite-monochromated Mo K $\alpha$  radiation ( $\lambda$  = 0.71073 Å). The collected frames were processed with the

software SAINT.<sup>15</sup> The data were corrected for absorption with the program SADABS.<sup>16</sup> The structures were solved by direct methods and refined by full-matrix least-squares on  $F^2$ , using the SHELXTL software package.<sup>17</sup> Unless stated otherwise, non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were generated in their idealized positions and allowed to ride on the respective carbon atoms.

**Crystal data for 1a:**  $C_{43}H_{53}O_6$ ,  $M_w = 665.85$ , crystal size =  $0.32 \times 0.24 \times 0.20$  mm<sup>3</sup>, orthorhombic, space group  $Pnn2$ ,  $a = 18.6014(8)$  Å,  $b = 19.2511(9)$  Å,  $c = 10.3718(5)$  Å,  $V = 3714.1(3)$  Å<sup>3</sup>,  $Z = 4$ ,  $\mu(\text{Mo K}\alpha) = 0.078$  mm<sup>-1</sup>. Intensity data were measured on a Bruker-AXS CCD area-detector diffractometer with graphite monochromated Mo K $\alpha$  ( $\lambda = 0.71073$  Å) radiation, 17807 reflections were measured, 5583 unique,  $R(\text{int}) = 0.0192$ . Final  $R1 = 0.0627$  and  $R_w = 0.1724$  for 4647 observed reflections with  $I > 2\sigma(I)$  and GOF = 1.022.

**Crystal data for 1a + Ag:**  $C_{92}H_{92}Ag_6F_{18}O_{24}$ ,  $M_w = 2570.88$ , crystal size =  $0.28 \times 0.20 \times 0.15$  mm<sup>3</sup>, monoclinic, space group  $P2_1/n$ ,  $a = 19.450(6)$  Å,  $b = 25.180(8)$  Å,  $c = 20.114(6)$  Å,  $\beta = 100.102(7)^\circ$ ,  $V = 9698(5)$  Å<sup>3</sup>,  $Z = 4$ ,  $\mu(\text{Mo K}\alpha) = 1.294$  mm<sup>-1</sup>. Intensity data were measured on a Bruker-AXS CCD area-detector diffractometer with graphite monochromated Mo K $\alpha$  ( $\lambda = 0.71073$

Å) radiation, 48242 reflections were measured, 16980 unique,  $R(\text{int}) = 0.0498$ . Final  $R1 = 0.0538$  and  $wR2 = 0.1377$  for 9335 observed reflections with  $I > 2\sigma(I)$  and GOF = 1.018.

**Crystal data for 1b + Ag:**  $C_{79}H_{63}Ag_7Cl_3F_{21}O_{20}$ ,  $M_w = 2592.73$ , crystal size =  $0.24 \times 0.16 \times 0.10$  mm<sup>3</sup>, triclinic, space group  $P1$ ,  $a = 12.5115(11)$  Å,  $b = 14.6376(12)$  Å,  $c = 24.260(2)$  Å,  $\alpha = 89.413(2)^\circ$ ,  $\beta = 80.832(2)^\circ$ ,  $\gamma = 87.561(2)^\circ$ ,  $V = 4382.1(6)$  Å<sup>3</sup>,  $Z = 2$ ,  $\mu(\text{Mo K}\alpha) = 1.736$  mm<sup>-1</sup>. Intensity data were measured on a Bruker-AXS CCD area-detector diffractometer with graphite monochromated Mo K $\alpha$  ( $\lambda = 0.71073$  Å) radiation, 21473 reflections were measured, 14813 unique,  $R(\text{int}) = 0.0446$ . Final  $R1 = 0.0616$  and  $wR2 = 0.1345$  for 6419 observed reflections with  $I > 2\sigma(I)$  and GOF = 0.915.

**Acknowledgment.** This work was supported by a Faculty Research Grant (FRG/03-04/II-58) and a Hong Kong Baptist University and Earmarked Research Grant (HKBU2019/02P) from the Research Grants Council, Hong Kong SAR, China.

**Supporting Information Available:** General experimental details, <sup>1</sup>H NMR, <sup>13</sup>C NMR, and MS data for **1b** and **3–6**, results of <sup>1</sup>H NMR titration and Job plots for **1a**·AgCF<sub>3</sub>COO and **1b**·AgCF<sub>3</sub>COO complexes, results of <sup>1</sup>H NMR titrations for **1a–c**·LiCF<sub>3</sub>COO and **1a–d**·NaCF<sub>3</sub>COO complexes, <sup>1</sup>H NMR and <sup>13</sup>C NMR spectra of all the newly synthesized calix[4]crown-4s, and high-resolution MS spectra of the **1a–d**·Ag complexes. This material is available free of charge via the Internet at <http://pubs.acs.org>.

JO051896Z

(15) Bruker SMART and SAINT+, Version 6.02a; Siemens Analytical X-ray Instruments Inc.: Madison, WI, 1998.

(16) Sheldrick, G. M. SADABS; University of Göttingen: Göttingen, Germany, 1997.

(17) Sheldrick, G. M. SHELXTL-Plus V5.1; Software Reference Manual; Bruker AXS Inc.: Madison, WI, 1997.