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Fullerene receptor based on calix[5]arene through metal-assisted self-assembly

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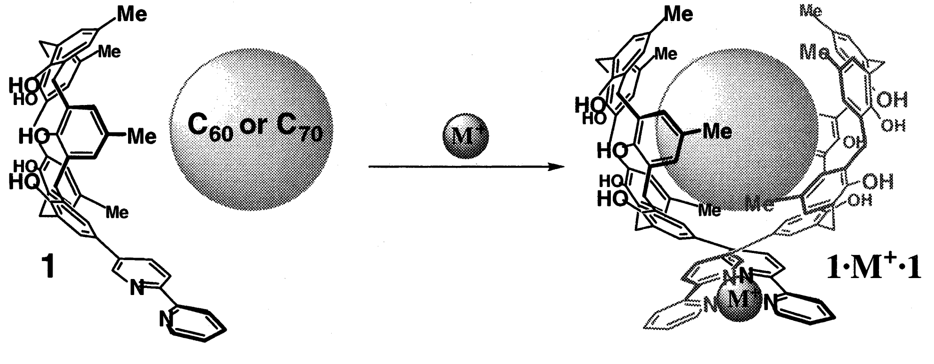
Abstract—A self-assembled fullerene receptor based on calix[5]arene has been developed. Silver cation complexation held together the two calix[5]arenes with bipyridine units providing a large enough cavity to take up C_{60} or C_{70}. The formation of the supramolecular complex with C_{60} or C_{70} was established by using the electrospray mass spectrometry. © 2001 Elsevier Science Ltd. All rights reserved.

There have been many reports on synthetic receptors[1] having multiple binding sites implemented within their covalent frameworks. It takes multi-step synthesis to achieve a proper orientation of the binding groups. An alternative approach can be envisioned in which the easy construction of a large and elaborate molecular architecture can be achieved by self-assembly. In this approach, modular components are held together by self-assembly with non-covalent interactions, bringing together the key groups in the active site.

Such self-assembly is commonly seen in biological systems.[2] Viruses and enzymes are well-known examples. Synthetic self-assembly is a new field in organic chemistry, and has become a current focus of molecular recognition studies.[3] One of the convenient ways to construct the elaborate supramolecular architecture is a coordination-driven self-assembly methodology,[4] which offers an alternative and extended function.

We have studied a number of calixarene-based receptors capable of binding neutral guests through non-covalent forces in organic media,[5,6] and have reported that the covalent linking of the two calix[5]arenes brings strong binding to C_{60} or C_{70} within the cavity composed of the two calix[5]arenes.[6b] In this paper we describe an alternative way to construct the large cavity with the two calix[5]arenes by self-assembly through metal complexation. The complexation of the two calix[5]arene subunits **1** with Ag^+ will give a tetrahedral Ag^+-bis-bipyridine complex, bringing the two binding sites to close proximity. This approach has the advantage of not only bringing together the host units by metal-chelation, but it can also detect the formation of the supramolecular complex by mass spectrometry due to the presence of the metal ion.

The key subunit **1** was prepared from calix[5]arene **2**[7] by straightforward steps according to Scheme 1.



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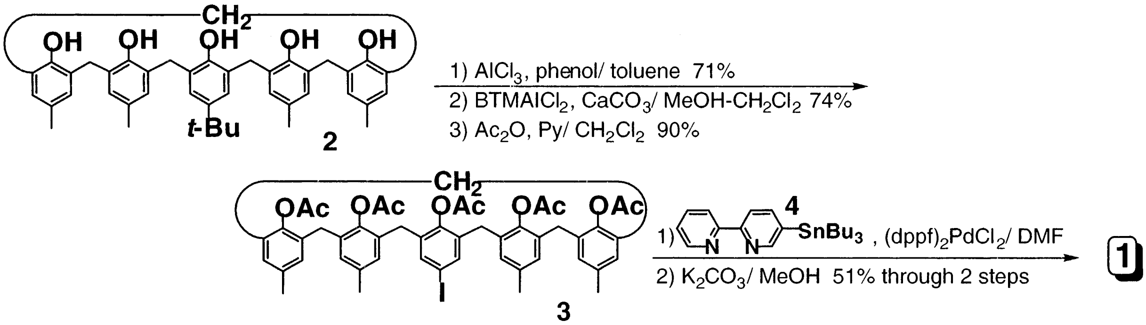

Scheme 1.

Deprotection of the *t*-butyl group under retro Friedel–Crafts conditions proceeded smoothly. Following iodination with BTMAICl$_2$, protection of the hydroxyl groups gave iodide **3** in good yield. Introduction of the metal-binding unit to **3** was carried out by palladium catalyzed coupling reaction with **4**.[8] Deprotection of the acetyl groups gave the desired compound **1**.

The formation of the metal complex with Ag$^+$ was achieved by simply mixing 2 equivalents of **1** with 1 equivalent of AgOTf in nitromethane. The resulting complex **1**·Ag$^+$·**1** is a pale yellow and air stable solid. The NMR signals of the complex **1**·Ag$^+$·**1** in CDCl$_2$CDCl$_2$ were rather broadened. The downfield shifted signals of the bipyridine unit in the subunit **1** clearly indicated that the silver cation bound to the bipyridine nitrogens. The spectra were concentration dependent, which comes from the dynamic equilibrium between the subunit **1** and the ternary complex **1**·Ag$^+$·**1**. The plotting analysis of the chemical shift changes around the bipyridine protons gave the dimerization constant[9] to be 5700±300 M^{-1} at 27°C.

The binding study for C$_{60}$ was carried out with ^{13}C NMR spectroscopy. The ^{13}C resonance of C$_{60}$ appeared at 143 ppm in CDCl$_2$CDCl$_2$ (Fig. 1a). During the addition of the complex **1**·Ag$^+$·**1**, the C$_{60}$ signal shifted upfield by the formation of the complex C$_{60}$@**1**·Ag$^+$·**1**. Finally, the upfield shift value reached 1.8 ppm (Fig. 1b), which is consistent with that of the covalently linked double-calix[5]arene reported previously.[6a] The large upfield shift suggests that C$_{60}$ resides within the shielded interior of the cavity composed of the calix[5]arenes, and gives promising support on the formation of the C$_{60}$@**1**·Ag$^+$·**1**.

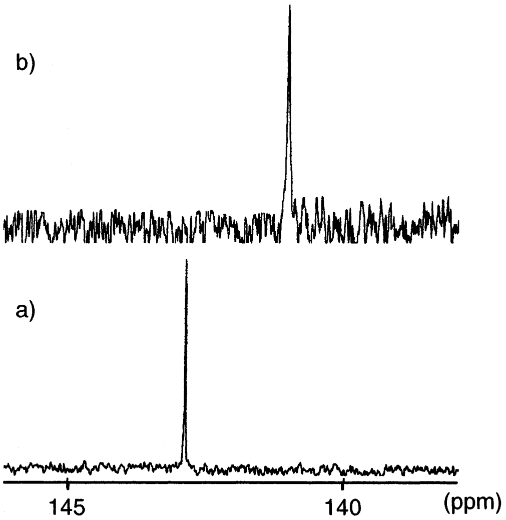

Figure 1. ^{13}C NMR spectra at 125 MHz of (a) C$_{60}$ (3.3 mmol/L) and (b) C$_{60}$ with 4.1 equiv. of complex **1**·Ag$^+$·**1** in CDCl$_2$CDCl$_2$.

The study of non-covalently bound complexes by electrospray ionization mass spectrometry[10] has rapidly gained momentum. A large number of reports have dealt with the mass spectrometric characterization of noncovalent complexes, such as supramolecular metal complexes,[11] knots and catenanes,[12] cavitand and guest[13] and capsule and guest.[14] ESI-MS spectrometry has proven to be an indispensable tool in supramolecular chemistry. In our system, the silver cation labeling of the assembly was an advantage for ESI-MS measurements in nonpolar aprotic solvent. CHCl$_2$CHCl$_2$ was used for the ESI measurements because both fullerenes and the complex are easily soluble in it.

The ESI-MS measurement of the complex **1**·Ag$^+$·**1** gave a peak attributable to the loss of the triflate counterion, [M–OTf]$^+$ {avg. $m/z=1590$ for [**1**·Ag$^+$·**1**]}. The measured isotope pattern for [**1**·Ag$^+$·**1**] nicely matched the calculated abundance, (Fig. 2a) and confirmed the elemental composition and the monocationic nature of the complex. The addition of 2 equivalents of C$_{60}$ into the solution of complex **1**·Ag$^+$·**1** brought a peak [C$_{60}$@**1**·Ag$^+$·**1**]{avg. $m/z=2310$}, indicating that C$_{60}$ comes into the cavity provided by the assembly. A new peak [C$_{70}$@**1**·Ag$^+$·**1**] {avg. $m/z=2430$} was observed in the case of C$_{70}$. Both complexes contain only one guest within the cavity. In comparison with the relative intensities for the complexes [C$_{60}$@**1**·Ag$^+$·**1**] and [C$_{70}$@**1**·Ag$^+$·**1**] the difference should arise from the binding ability of complex **1**·Ag$^+$·**1** toward C$_{60}$ and C$_{70}$. Complex **1**·Ag$^+$·**1** seems to bind C$_{60}$ more strongly than C$_{70}$ in the opposite sense from the covalently linked double calix[5]arenes,[6b] which prefer to bind C$_{70}$ to C$_{60}$. The size and shape of the cavity provided by the assembly should fit nicely to C$_{60}$ rather than C$_{70}$.

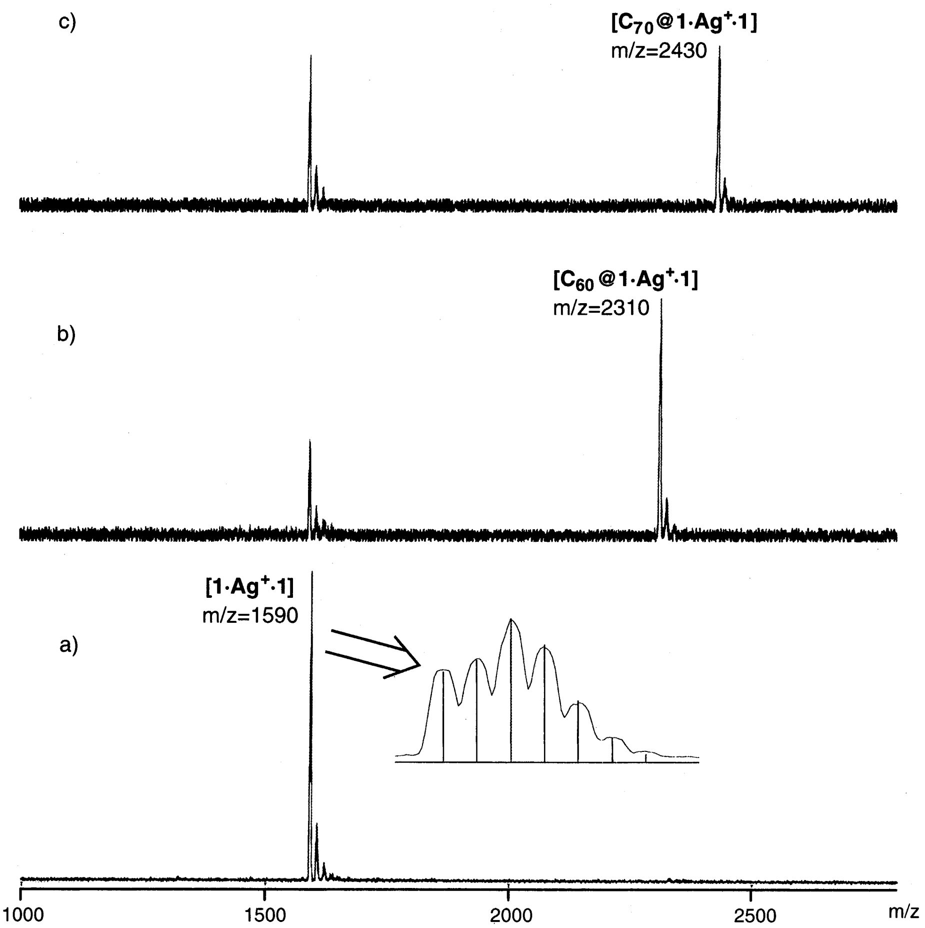

Figure 2. ESI mass spectra of $CHCl_2CHCl_2$ solution of (a) **1**·Ag^+·**1** (5.0 mmol/L), (b) **1**·Ag^+·**1** and C_{60} (10.0 mmol/L) and (c) **1**·Ag^+·**1** and C_{70} (10.0 mmol/L). The inset shows the calculated (straight lines) and experimental isotope pattern (curve).

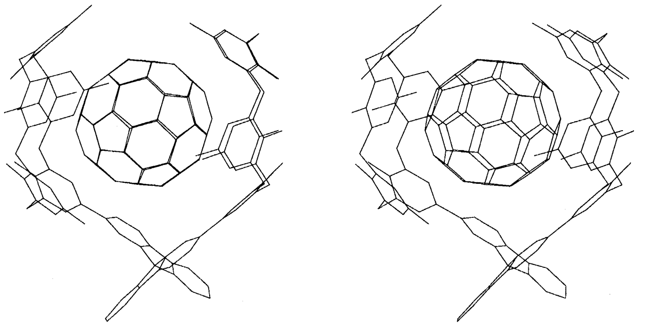

Figure 3. Stereoview of the complex structure C_{60}@**1**·Ag^+·**1** based on a molecular mechanics calculation.

To visualize how the cavity fits to the outer surface of C_{60}, the molecular mechanics calculation is informative. The molecular mechanics calculation was carried out with the Amber* force field in MacroModel V6.5.[15] The calculated structure is shown in Fig. 3. The structure has a proper cavity for binding C_{60}, which nicely fits within the cavity.

We demonstrated that calix[5]arene subunit **1** has a ligation site assembled to produce the ternary complex **1**·Ag^+·**1**, which acts as a good receptor for C_{60} and C_{70}. The binding property of the complex for C_{60} or C_{70} was established by ion labeling ESI mass spectrometry.

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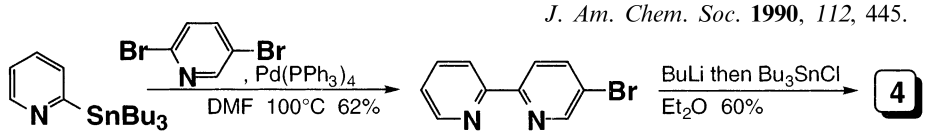

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