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A Bis-exTTF Macrocyclic Receptor That Associates C_{60} with Micromolar Affinity

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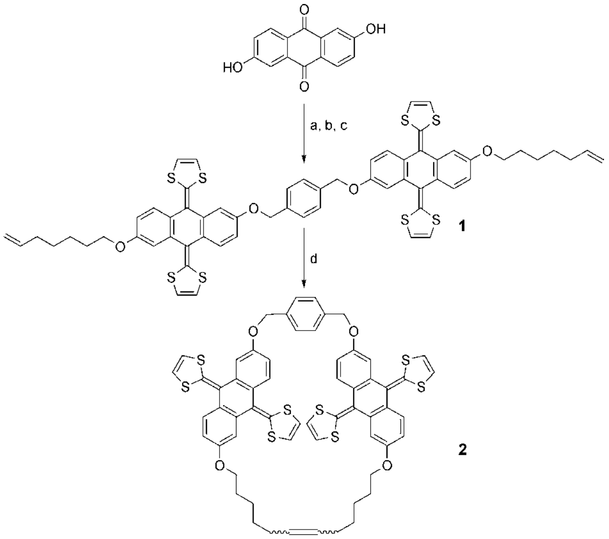
The search for molecular receptors for fullerenes is a very active area of research.[1−3] Various receptors based on concave recognition motifs such as cyclotriveratrylenes,[4,5] corannulenes,[6,7] cyclic paraphenyleneacetylenes,[3,8−10] and π-extended tetrathiafulvalene derivatives[11−14] have been reported, but to date, hosts that exploit porphyrins as recognizing motifs have dominated the literature both in quantity and binding strength.[2] The highest binding constants among porphyrin-based receptors correspond to Aida's bisporphyrin macrocyclic receptors. For example, a Zn(II) metalloporphyrin derivative shows a binding constant toward C_{60} of log $K_a = 5.8$, while the free base shows log $K_a = 5.9$, both in benzene at room temperature.[15] The world record for complex stability toward C_{60}, achieved by an Ir(III) metalloporphyrin, shows log $K_a = 8.1$ in 1,2-dichlorobenzene (oDCB) at room temperature.[16] It is noteworthy that in the latter case, Ir was found to bind a 6,6 junction of the fullerene in an η^2 fashion.

Making use of the perfect match between the concave aromatic surface of 2-[9-(1,3-dithiol-2-ylidene)anthracen-10(9*H*)-ylidene]-1,3-dithiole (exTTF) and the convex surface of the fullerenes, we reported the first exTTF-based receptor for fullerene, which was based on a very simple tweezers-like design.[11,12,14] This receptor was shown to form complexes with C_{60} of considerable stability considering its lack of preorganization (log $K_a = 3.5$ in PhCl at room temperature).[14] We now report the design, synthesis, and fullerene binding abilities of macrocycle **2**.

The design of the macrocyclic receptor conserves the basic features of the tweezers receptor but includes an alkyl linker with terminal alkenes to achieve macrocyclization through ring-closing metathesis. Molecular mechanics showed that the most suitable spacer would be heptene, which afforded flexible macrocyclic cavities of 11−13 Å. Macrocycle **2** was synthesized in just four steps (Scheme 1) and obtained as a chromatographically inseparable mixture of *E* and *Z* isomers that was used as such. The identity and purity of **2** and all of the synthetic intermediates were unambiguously established by standard spectroscopic and analytical techniques (see the Supporting Information).

The binding constants of macrocycle **2** toward C_{60} and C_{70} were estimated through three independent UV−vis titrations at room temperature. In a typical experiment, to a solution of **2** (1.0×10^{-5} M in PhCl) were added aliquots of a solution of C_{60} or C_{70} ($3-4 \times 10^{-5}$ M in PhCl) up to a total of 2−3 molar equiv, working at constant host concentration (see the Supporting Information).

Scheme 1. Synthesis of Macrocycle **2**[a]



[a] Conditions: (a) 7-bromo-1-heptene, K_2CO_3, NaI (cat), DMF, reflux, 2 h; (b) α,α'-*p*-dibromoxylene, K_2CO_3, NaI (cat), DMF, 60 °C, 4 h; (c) dimethyl 1,3-dithiol-2-ylphosphonate, BuLi, THF, −78 °C to rt, 2 h; (d) Grubb's first-generation catalyst, CH_2Cl_2, rt, 2 h.

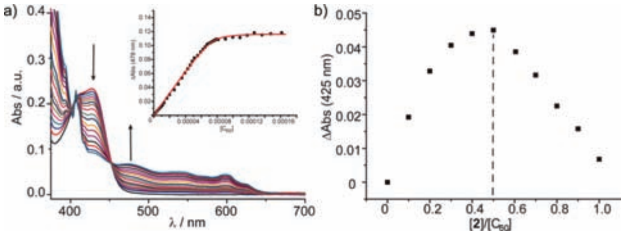


Figure 1. (a) Spectral changes in a UV−vis titration experiment for **2** vs C_{60} in PhCl at room temperature; the inset shows the binding isotherm ($K_a = 1\,087\,200$ M^{-1}, $R^2 = 0.996$). (b) Job's plot demonstrating the 1:1 stoichiometry.

The results of a titration experiment involving **2** and C_{60} are shown in Figure 1a. The spectral features are similar to what we had previously observed for exTTF tweezers.[11,14] With an increase in the concentration of C_{60}, a significant decrease in the absorption at $\lambda = 425$ nm was observed, together with the appearance of a charge-transfer band centered at 478 nm with an isosbestic point at 450 nm. The expected 1:1 stoichiometry, suggested by the presence of the isosbestic point, was confirmed through continuous variation plots (Figure 1b). In the case of C_{70}, the spectral changes were less obvious because of spectral overlap (see the Supporting Information). The binding constant of **2** toward C_{60} in PhCl at room temperature was found to be log $K_a = 6.5 \pm 0.5$ (Specfit) or 6.1 ± 0.2 (Origin). This represents an increase of 3 orders of magnitude with respect to our previously reported receptors[11,14] and is one of the highest binding constants toward C_{60} reported in the literature,[1−3] illustrating the dramatic effect of preorganization.[17] In regard to

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C_{70}, the binding constant was too large to be calculated precisely through UV−vis titrations.[18] With the aim of lowering the binding constant to a more reliable quantity, we changed to oDCB as the solvent. However, despite the fact that both **2** and the fullerenes are soluble in oDCB, when we approached 1:1 stoichiometry during the addition process, the solution immediately turned turbid, precluding UV−vis measurements. The mixture of *E* and *Z* isomers and the flexibility of **2** prevented the formation of single crystals suitable for X-ray diffraction, so we investigated the geometry of the complexes through density functional theory (DFT) calculations using the Becke "half-and-half" (BH&H) functional (see the Supporting Information for full computational details). Figure 2 shows the structure of the complex of (*Z*)-**2** with C_{60} calculated at the BH&H/6-31G** level.[19]

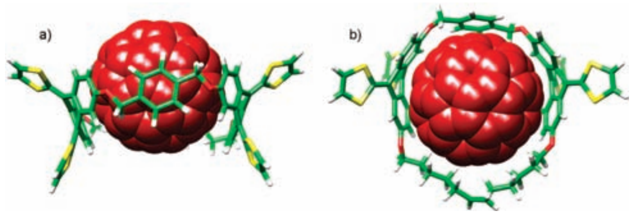

Figure 2. (a) Side view and (b) top view of the energy-minimized structure (BH&H/6-31G** level) of the (*Z*)-**2**−C_{60} complex.

The DFT calculations confirmed that **2** is a close to perfect fit for C_{60}, with both exTTFs, the aromatic xylylene linker, and the alkyl spacer closely wrapping around the fullerene unit. BH&H/6-31+G** calculations including corrections for the basis-set superposition error predicted a binding energy of −24.1 kcal mol^{-1}, which is significantly higher than that calculated for the exTTF tweezers under the same computational conditions,[11,12] in agreement with the experimental results.

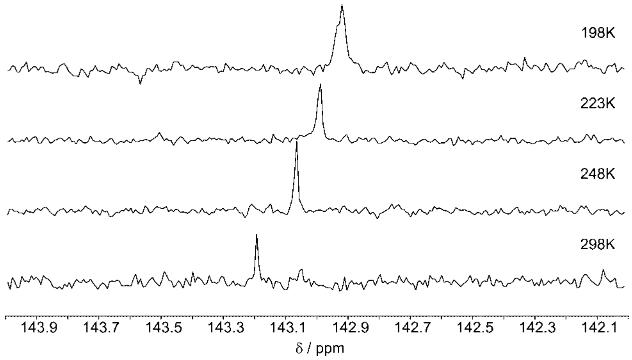

Figure 3. ^{13}C NMR spectra (75 MHz) of a mixture of C_{60} and **2** (1.5:1) in toluene-d_8 at several temperatures.

The binding event was also investigated by ^{13}C NMR spectroscopy, which confirmed the association of **2** with C_{60}. Figure 3 shows variable-temperature ^{13}C NMR spectra (75 MHz) for a mixture of C_{60} and **2** (1.5:1) in toluene-d_8. The spectra were run with a sufficient number of scans to detect the signal of C_{60} only. The signal shifted upfield and broadened upon cooling, as would be expected for the formation of the complex.[20] The association equilibrium remained rapid even at 198 K, although the significant broadening indicates that we were close to the temperature of coalescence.

In conclusion, we have described an exTTF-based macrocyclic receptor that associates C_{60} with a binding constant that is 3 orders of magnitude higher than the previous examples of exTTF-based receptors,[11,12,14] nearly 2 orders of magnitude higher than those reported for metalloporphyrin tweezers,[21,22] and even superior to most of Aida's porphyrin macrocycles, with the exception of the Rh(III)[15] and Ir(III)[16] congeners. These results definitely consolidate exTTF as one of the most suitable fragments for the molecular recognition of fullerenes. The simplicity of the synthetic route to obtain **2** augurs well for its utilization in the construction of electroactive nanostructures.[23−25] This, together with the full structural optimization of the aromatic linker and the alkyl spacer, is the main objective of our future investigations.

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Supporting Information Available: Supporting figures and experimental and computational details. This material is available free of charge via the Internet at http://pubs.acs.org.

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(17) For comparison, the linear precursor **1** showed log $K_a = 3.01$ in PhCl at room temperature.
(18) Utilizing Specfit, we were able to approximate it as log $K_a = 8.4 \pm 2.5$.
(19) The BH&H functional has been shown to provide good performance for supramolecular systems dominated by dispersion interactions (see: Zhao, Y.; Truhlar, D. G. *J. Chem. Theory Comput.* **2007**, *3*, 289). The *Z* and *E* isomers define cavities of similar size.
(20) As might be expected, the magnitude of the shielding effect is significantly smaller than that observed for porphyrin-based receptors (see ref 2) since in our case (as opposed to the strong ring currents of porphyrins) the shielding capacity of **2** is comparable to that of the aromatic solvent.
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