Weighting non-covalent forces in the molecular recognition of C_{60}. Relevance of concave–convex complementarity†

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The relative contributions of several weak intermolecular forces to the overall stability of the complexes formed between structurally related receptors and [60]fullerene are compared, revealing a discernible contribution from concave–convex complementarity.

The construction of molecular receptors for fullerenes continues to be a very active area of research, with their purification from fullerite and the construction of self-organized electroactive nanostructures as main driving forces.[1–11] To achieve these objectives, the formation of stable associates with fullerenes is a prerequisite. In this regard, the group of Kawase has recently coined the term "concave–convex interactions"[5–8] to denote the increase in non-covalent interactions between curved aromatic hosts and guests, and suggested these might play a distinct role in the stabilization of the complexes. A fair and quantitative comparison of the stability of the complexes formed between fullerenes and receptors based on flat or concave recognizing fragments would require a collection of receptors with enough structural similarity—that is, dissimilar only with regard to the recognizing units—to be studied under experimentally identical conditions.

Herein, we investigate the relative contributions of π–π, van der Waals, electrostatic, and concave–convex interactions to the molecular recognition of C_{60} by a series of related receptors.

We have reported receptors that exploit the concave, electron-rich, aromatic surface of π-extended tetrathiafulvalene derivatives to associate [60]fullerene.[9,10] Receptor **1** features 2-[9-(1,3-dithiol-2-ylidene)anthracen-10(9*H*)-ylidene]-1,3-dithiole (exTTF) as the recognizing element (Chart 1).[9] Despite the lack of preorganization in its design, **1** forms stable associates with C_{60} (see Table 1). Since a charge-transfer band is experimentally observed in the UV–Vis titrations ($\lambda_{max} \approx 482$ nm) of **1** against C_{60}, up to four "separate" contributions to the stability of the complex can be envisaged: π–π aromatic interactions, van der Waals forces, electrostatic interactions, and concave–convex complementarity. With the aim of weighting those contributions separately, we designed and synthesized a collection of tweezer-like receptors, **1–4**, in which the size, shape and electronic character of the recognizing motifs are selectively tuned. The solubility of receptors **1–4** at the concentrations employed in titration experiments (≤ 1 mM) is sufficient to rule out solvophobic effects as a major factor in the stability of the complexes.

As shown in Chart 1, receptors **1–4** consist of an isophthalic diester spacer to which two units of the corresponding recognizing moieties are attached. All the receptors were synthesized from the commercially available or previously reported methylene alcohols and isophthaloyl dichloride by standard condensation reactions in good to excellent yields, and unambiguously characterized.†

The 1 : 1 binding constants of receptors **1–4** towards [60]fullerene were estimated by ^1H NMR titrations. The values are shown in Table 1 and are the average of at least two titration experiments (for details, see the Supplementary Information†). Unfortunately, all attempts at growing single crystals of the complexes for X-ray diffraction studies have been unsuccessful so far. These experimental data were complemented by density functional theory (DFT) calculations performed at the BH&H/6-31G** and BH&H/6-31+G** levels for all the associates found experimentally (see the Supplementary Information† for computational details). Fig. 1 shows the BH&H/6-31G** energy-minimized structures of the complexes and selected distances. The recognizing units in both **1** and **2** show butterfly-shaped conformations, consistent with previously reported structures,[12–14] in which the

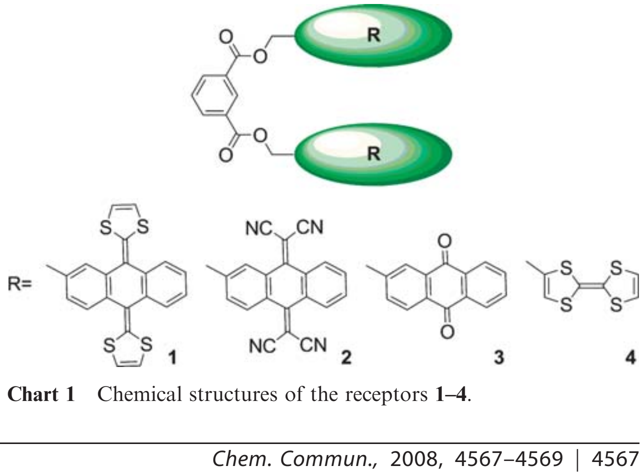

Chart 1 Chemical structures of the receptors **1–4**.

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Table 1 Comparison of the binding motifs, binding constants (values are the average of at least two ^{1}H NMR titrations, 300 MHz, 298 K, $CDCl_3$–CS_2 1 : 1) and calculated BH&H/6-31+G** binding energies (including BSSE correction) of receptors **1–4**

	Aromatic rings	Area	Electronic character	Shape	K_a/M^{-1}	$\Delta E_{binding}{}^{a}$/kcal mol^{-1}
1	2 + 2 + 1	Large	Rich	Concave	3000 ± 120	−13.4
2	2 + 2 + 1	Large	Very poor	Concave	1540 ± 150	−12.5
3	2 + 2 + 1	Large	Poor	Planar	790 ± 50	−13.1
4	0 + 0 + 1	Small	Rich	Planar	—	—

[a] Binding energies are calculated as the difference between the total energy of the complex and the sum of the total energies of the receptor and C_{60}.

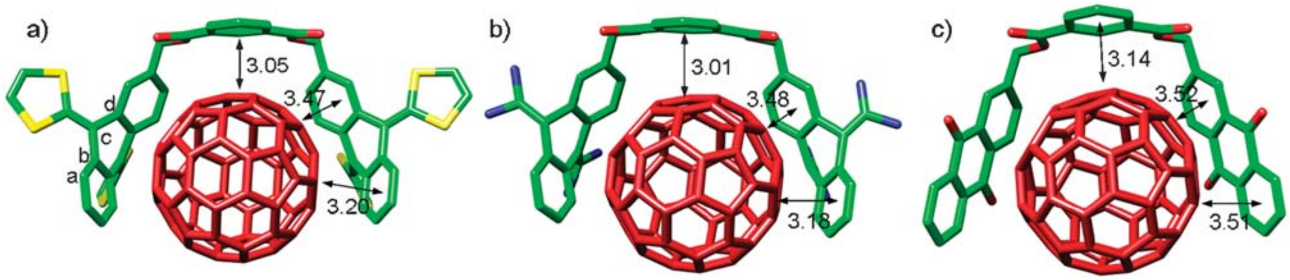

Fig. 1 Structures of (a) **1**·C_{60}, (b) **2**·C_{60} and (c) **3**·C_{60} complexes calculated at the BH&H/6-31G** level. The distances shown are given in Å, and represent the distance between a centroid on each of the aromatic rings and the closest fullerene atom. The C_a–C_b–C_c–C_d dihedral angle is taken as a measure of the curvature of the anthracene units.

anthracene moiety adopts a concave configuration that matches the convex surface of C_{60}. In contrast, the anthraquinone moiety in receptor **3** shows an almost planar structure. Association binding energies calculated with the more extended 6-31+G** basis set and including correction for the basis set superposition error (BSSE) are provided in Table 1.[15]

Receptor **1** incorporates five aromatic rings, two per recognizing unit plus the isophthalic spacer, a large and concave surface and is electronically complementary to C_{60}. Unsurprisingly, **1** is the strongest binder for C_{60}, with a $K_a = (3.00 \pm 0.12) \times 10^3$ M^{-1}.‡ Receptor **2** utilizes 11,11,12,12-tetracyano-9,10-anthraquinodimethane (TCAQ)[16] as the recognizing element. Thus, as compared to **1**, it presents an equal number of aromatic rings and surfaces available for recognition, with close to identical curvature (dihedral angle C_a–C_b–C_c–C_d = 144.7° for **1**·C_{60}, 146.1° for **2**·C_{60}, averaged values), but electron-poor character. The change in electronic nature results in a decrease of K_a to $(1.54 \pm 0.15) \times 10^3$ M^{-1}. DFT calculations reproduce this trend by predicting a slightly higher binding energy for **1**·C_{60}. A similar drop-off in the association constant is observed when moving from **2** to **3**. In this case, the surface available for van der Waals interactions is similar to that of **1** and **2**, but **3** lacks both the concave–convex and the electronic complementarity. This results in a binding constant of $(0.79 \pm 0.05) \times 10^3$ M^{-1}. In this case, DFT calculations seem to overestimate non-covalent interactions and predict a slightly more stable complex for **3**·C_{60} compared to **2**·C_{60}. It should, however, be noted that calculations were performed in the gas phase without taking into account solvent effects. Finally, no sign of association with C_{60} was observed in either the ^{1}H NMR or the electronic absorption spectra of receptor **4**, which is decorated with the electron rich, small and non-aromatic tetrathiafulvalene (TTF) unit.[17]

All these data point to an overwhelming preponderance of π–π and van der Waals interactions, since only the receptors featuring five aromatic rings and large recognizing units are capable of binding C_{60}, and they all do so with binding constants in the order of 10^3 M^{-1}. Comparison of the binding constants of **1** and **2** towards C_{60} suggests a noticeable contribution of coulombic interactions, which is in accordance with previous observations.[1–5] However, the fact that **4** does not show any sign of complexation towards C_{60} implies that this contribution is not quantitatively comparable to those of π–π and van der Waals forces. Finally, and centrally to the point of this study, concave–convex complementarity does seem to make its own contribution, even if quantitatively small, as illustrated by the cases of receptors **2** and **3**. In spite of the more electron-poor character of **2** when compared to **3**, its binding constant towards C_{60} is larger. This can only be justified by the concave shape of the TCAQ recognizing units. Observing the energy-minimized structures of the complexes, one can easily sense that this stabilization arises primarily from the fact that the curvature of **2** allows the outer aromatic ring of the recognizing fragment to come closer to [60]fullerene when compared to **3** (3.18 Å and 3.51 Å, respectively). Theoretical calculations show that the anthraquinone moieties in **3**·C_{60} slightly deviate from planarity (C_a–C_b–C_c–C_d average dihedral angle of 175.6° *vs.* 180.0° in **3**) to approach the surface of C_{60} and thereby maximize the association energy. A similar "concavization" effect has been observed for porphyrins in the solid-state structures of their complexes with C_{60}.[3]

To conclude, the data presented here support the perceptible contribution of concave–convex complementarity to the stabilization of supramolecular associates. This augurs well for the supramolecular systems where this kind of interaction plays a role.[18,19] Whether concave–convex interactions should be treated as a separate kind of intermolecular force or just a particular case of preorganization is surely a tricky subject. In fact, given that bonding between two atoms is necessarily depicted as a straight line, one might say that even the very concept of curvature in a (necessarily finite) molecule would admit of some argument. In this respect, we agree with Hoffmann and Hopf that "words mislead much less than they encourage"[20] and intend to use the term concave–convex interactions in the future.[21]

The extension of this work to a broader collection of molecular receptors and different solvent systems will be the subject of future studies.

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Notes and references

‡ No sign of cooperative binding was observed under these experimental conditions.

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21 In fact, all non-covalent forces are fundamentally electrostatic interactions (see: C. A. Hunter, *Angew. Chem., Int. Ed.*, 2004, **43**, 5310–5324) and their separation into different categories such as van der Waals forces and π–π interactions is more a response to tradition and chemical intuition than to strict physical criteria.