Non-covalent binding of fullerenes and biomolecules at surface-supported metallosupramolecular receptors†

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***In-situ* scanning tunneling microscopy study reveals that two-dimensional metallosupramolecular receptors bind a single or a discrete number of cystine, C_{60}, or diphenylalanine molecules reversibly through non-covalent interactions.**

The inclusion of guest species (ions, molecules) into host systems exploiting non-covalent binding is at the origin of supramolecular chemistry.[1–4] A key feature in supramolecular binding is that the guest components are bound to the hosts reversibly by weak interactions, such as electrostatics forces, hydrogen bonds, van der Waals forces, or metal coordination. Recently several examples have shown that supramolecular systems with open voids can be fabricated from self-assembly of simple molecular components at liquid–solid or vacuum–solid interfaces, which represent model systems to study supramolecular inclusion phenomena.[5–11] In particular, such model systems are addressable by scanning tunneling microscopy (STM), providing real-space structural information at the single molecular level. Here we report a systematic STM investigation on the use of surface self-assembled metallosupramolecular nanocavities as receptors to bind fullerenes and biomolecules through non-covalent interactions.

The STM image reproduced in Fig. 1 depicts the nano-size cavities employed as the metallosupramolecular receptors in this study. They are obtained by hierarchical self-assembly of Fe atoms and trimesic acid (TMA) molecules on a Cu(100) substrate in ultra-high vacuum. Preparation procedure and structural details have been documented in previous publications.[12,13] The inset in Fig. 1 shows the broad-branch X-shape nanocavities with an opening of $\sim$ 1 nm. A single nanocavity is enclosed by eight TMA molecules (*cf.* model in the inset of Fig. 1). The nanocavities are organized as two-dimensional square-lattice arrays with a 3.4 nm periodicity. The structure is thermally stable at temperatures as high as 500 K in vacuum conditions.

The guest species used in the present study are shown in Scheme 1, including cystine (LL enantiomer), LL-diphenylalanine (Phe-Phe) and fullerene C_{60}.‡ Small doses of these molecules were deposited on the nanocavity-covered substrate by thermal sublimation from organic molecular beam evaporators under ultra-high vacuum conditions (temperatures employed were 413 K (cystine), 445 K (Phe-Phe), and 690 K (C_{60}), respectively). The temperature of the substrate supporting the nanocavities was kept at 300 K during the molecular beam exposure. The STM measurements were conducted subsequently *in situ* at room temperature in the same vacuum apparatus.

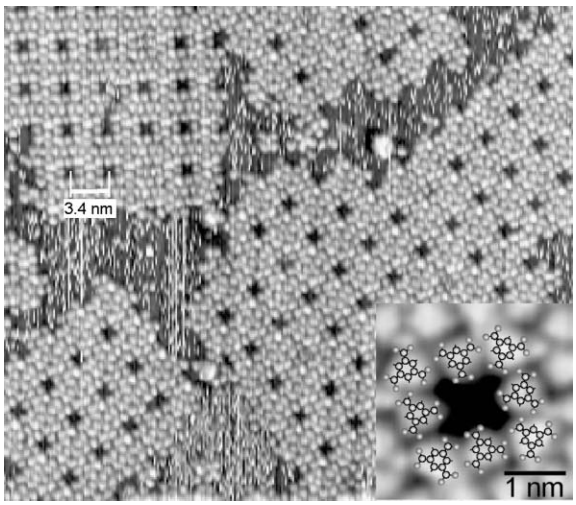
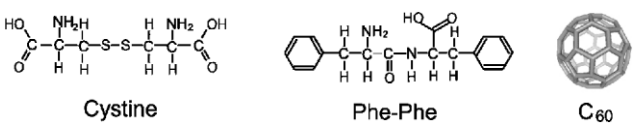


Fig. 1 Arrays of two-dimensional metallosupramolecular nanocavities fabricated on a Cu(100) substrate by hierarchical assembly of trimesic acid molecules and Fe atoms. The tentative model in the inset shows a single nanocavity surrounded by eight uncoordinated carboxylate groups.

In Fig. 2a an STM topograph following exposure to cystine is reproduced. While the nanocavity remains unaffected, at the interior of most nanocavities two protrusions are resolved. These features are exclusively observed upon cystine deposition, and moreover their number increases monotonically with the cystine dosage. Hence they are associated with cystine molecules decorating preferentially the nanocavities. The two-protrusion feature could represent either a single cystine molecule coupled with both carboxylic groups to the residual Cu surface (flat-lying adsorption) or a pair of cystine molecules adsorbed with their long axis perpendicular to the surface (upright standing adsorption). Because some of the nanocavities include three protrusions



Scheme 1 Guest molecules used in this study.

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† Electronic supplementary information (ESI) available: STM data showing the nanocavities after the thermal release of the guest species. See DOI: 10.1039/b603003c

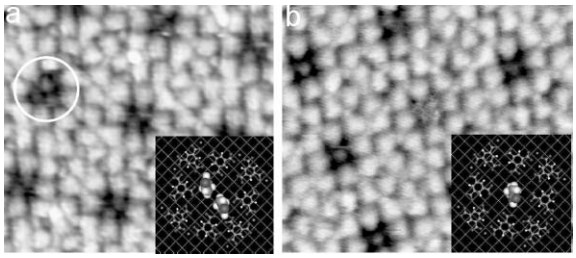

Fig. 2 Binding of cystine molecules in the receptors. (a) Following deposition at 300 K, two-protrusion features are associated with two cystine molecules anchored on the Cu substrate in an upright configuration. A nanocavity comprising three cystine molecules is marked with a white circle. Insets illustrate tentative models of the adsorption. Image size 10 nm × 9 nm. (b) Upon 430 K annealing, the nanocavities typically accommodate a single cystine guest at the center.

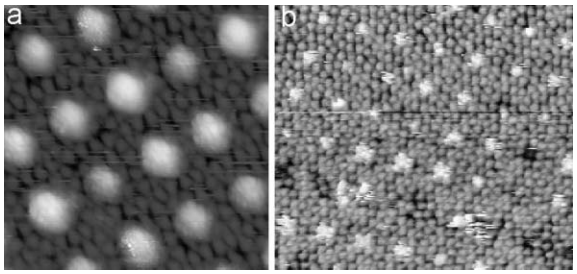

Fig. 3 (a) Binding of single C_{60} molecules in the receptors. The different molecular heights might reflect distinct adsorption configurations. Image size 14 nm × 14 nm. (b) Binding of Phe-Phe molecules in the receptors. The apparent fuzzy protrusion is associated with molecular conformational changes during the STM imaging process. Image size 25 nm × 22 nm.

(as marked by the circle in Fig. 2a), the upright standing adsorption scenario is proposed, in which each protrusion is associated with a single cystine adsorbed in an upright configuration. Due to a lack of spectroscopic information the binding configuration cannot be fully characterized. Nevertheless, the upright adsorption hints that the cystines may bind to the surface *via* their carboxylic endgroups, whereby presumably a carboxylate is formed (*cf.* inset in Fig. 2a). This binding scheme is frequently encountered in the adsorption of carboxylic acids on copper or other surfaces and has been extensively studied.[14–18] A close inspection of Fig. 2a also reveals that the two molecules always reside at two opposite diagonal positions within a nanocavity, suggesting that the surrounding carboxylate groups at the rim of the nanocavity impose steric confinement on the cystine guests.

The trapped cystine molecules can be released by thermal annealing. The removal is a progressive process: at 430 K one cystine is released and the remaining one is shifted to the center of the nanocavity, as shown in Fig. 2b. Upon further increasing the temperature to 490 K the remaining molecule is released and most of the nanocavities are empty. After the guest removal the empty cavities present their original structure, so the binding is completely reversible. The shifting of the single cystine to the nanocavity center indicates the interactions between the cystines and the nanocavity rim are repulsive rather than attractive. Furthermore the two-step release process implies that the binding energy is larger when only single cystines are bound in the nanocavities.

The STM topograph in Fig. 3a reveals the binding of the fullerene C_{60} in the nanocavities. In contrast to cystine binding each nanocavity binds a single C_{60} molecule, which reflects that the size of C_{60} fits well to the nanocavity void (note that the apparent size of the C_{60} molecules is magnified by imaging effects). The apparent height of the adsorbed C_{60} molecules is not a constant for different molecules, which is understood to be a result of C_{60} molecules binding in different configurations (orientation or position). The C_{60} molecules exclusively bind at the nanocavities, *i.e.*, at the metal–organic adlayer no adsorption occurs. Thus the nanocavity arrays can be used as a template to assemble square lattices of individual C_{60} molecules at the surface.

The binding of Phe-Phe is demonstrated by the STM image in Fig. 3b, where a decoration of nanocavities is clearly resolved. Considering the length of this molecule ($\sim$ 1.3 nm) and the bulky phenyl rings at both terminals, the inclusion of a complete molecule within a nanocavity is excluded. As revealed in Fig. 3b, the apparent shape of the bound Phe-Phe molecules is not constant, *i.e.*, they appear as irregular fuzzy objects. This might be associated with a partial accommodation of the Phe-Phe molecules in the nanocavities, presumably with the terminal phenyl ring trapped inside and the long backbone standing out of the nanocavity. The flexible molecule backbone undergoes conformational changes provoked by the fast scanning STM tip, producing the fuzzy STM features.

In order to estimate the binding strength, annealing experiments were performed. Significant release is encountered at 470 K for C_{60}. This temperature is lower than those required for desorption of C_{60} from clean Cu surfaces (730 K in the case of Cu(110)[19]). This is associated with the spatial confinement of C_{60} molecules at the nanocavities, whose $\sim$ 1 nm pore diameter prevents strong interactions with the Cu substrate atoms occurring in the interaction of C_{60} with the pristine Cu surface.[19] The spatial confinement suggests that the nanocavity rim binds to the C_{60} through the carboxylate functions *via* donor–acceptor interaction.[10,20] After the thermal release the nanocavities remain unchanged, confirming the reversibility of the host–guest binding. The Phe-Phe guests are also released reversibly, at a slightly lower temperature of 450 K, which reflects a weaker binding in comparison to C_{60}. We propose that the host–guest binding is determined by the hydrogen bonds between the phenyl rings and the carboxylate groups at the nanocavity rim.

In conclusion, we have demonstrated that supramolecular host–guest binding could be monitored at a single-molecule level. Our STM observations revealed that the binding of cystine, C_{60} and Phe-Phe molecules at the metallosupramolecular receptors is completely reversible, as evidenced by thermal removal of the respective guest species. Last but not least, because the receptors are arranged in a square lattice array with 3.4-nm periodicity, a template is at hand to fabricate two-dimensional nanoarrays of guest molecules at surfaces.

Notes and references

‡ Cystine (> 99%) was purchased from Fluka. Phe-Phe (99%) was purchased from Bachem. C_{60} (> 99.5%) was purchased from Lancaster.

1 D. J. Cram and J. M. Cram, *Science*, 1974, **183**, 803.
2 J. M. Lehn, *Struct. Bonding*, 1973, **6**, 1.
3 J. M. Lehn, *Pure Appl. Chem.*, 1978, **50**, 871.

4 J. M. Lehn, *Supramolecular Chemistry. Concepts and Perspectives*, VCH, Weinheim, 1995.
5 J. A. Theobald, N. S. Oxtoby, M. A. Philips, N. R. Champness and P. H. Beton, *Nature*, 2003, **424**, 1029.
6 J. Lu, S. B. Lei, Q. D. Zeng, S. Z. Kang, C. Wang, L. J. Wan and C. L. Bai, *J. Phys. Chem. B*, 2004, **108**, 5161.
7 S. Stepanow, M. Lingenfelder, A. Dmitriev, H. Spillmann, E. Delvigne, N. Lin, X. Deng, C. Cai, J. V. Barth and K. Kern, *Nat. Mater.*, 2004, **3**, 229.
8 S. J. H. Griessl, M. Lackinger, F. Jamitzky, T. Markert, M. Hietschold and W. M. Heckl, *J. Phys. Chem. B*, 2004, **108**, 11556.
9 S. J. H. Griessl, M. Lackinger, F. Jamitzky, T. Markert, M. Hietschold and W. M. Heckl, *Langmuir*, 2004, **20**, 9403.
10 E. Mena-Osteritz and P. Bäuerle, *Adv. Mater.*, 2006, **18**, 447.
11 H. Spillmann, A. Kiebele, M. Stöhr, T. A. Jung, D. Bonifazi, F. Cheng and F. Diederich, *Adv. Mater.*, 2006, **18**, 275.
12 P. Messina, A. Dmitriev, N. Lin, H. Spillmann, M. Abel, J. V. Barth and K. Kern, *J. Am. Chem. Soc.*, 2002, **124**, 14000.
13 H. Spillmann, A. Dmitriev, N. Lin, P. Messina, J. V. Barth and K. Kern, *J. Am. Chem. Soc.*, 2003, **125**, 10725.
14 L. H. Dubois, B. R. Zegarski and R. G. Nuzzo, *Langmuir*, 1986, **2**, 412.
15 M. Wühn, J. Weckesser and Ch. Wöll, *Langmuir*, 2001, **17**, 7605.
16 D. S. Martin, R. J. Cole and S. Haq, *Phys. Rev. B*, 2002, **66**, 155427.
17 W. S. Sim, P. Gardner and D. A. King, *J. Phys. Chem.*, 1996, **100**, 12509.
18 V. Humblot, M. O. Lorenzo, C. J. Baddeley, S. Haq and R. Raval, *J. Am. Chem. Soc.*, 2004, **126**, 6460.
19 R. Fasel, R. G. Agostino, P. Aebi and L. Schlapbach, *Phys. Rev. B*, 1999, **60**, 4517.
20 L. Fomina, A. Reyes and S. Fomine, *Int. J. Quantum Chem.*, 2002, **89**, 477.