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Passing Current through Touching Molecules

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The charge flow from a single C₆₀ molecule to another one has been probed. The conformation and electronic states of both molecules on the contacting electrodes have been characterized using a cryogenic scanning tunneling microscope. While the contact conductance of a single molecule between two Cu electrodes can vary up to a factor of 3 depending on electrode geometry, the conductance of the C₆₀-C₆₀ contact is consistently lower by 2 orders of magnitude. First-principles transport calculations reproduce the experimental results, allow a determination of the actual C₆₀-C₆₀ distances, and identify the essential role of the intermolecular link in bi- and trimolecular chains.

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Intermolecular charge transport is central to numerous research fields. In biology electron hopping and tunneling processes between molecules play a vital role. Moreover, tunneling processes between molecular materials have opened new perspectives towards the realization of efficient molecular sensors and solar cells [1]. In a parallel direction the conductance properties of point contacts [2], single atoms [3], or single molecules [4] are intensely being investigated, and give a detailed view of charge transport through individual nanoscopic objects. Recently, experiments realized on 1D extended molecules [5], single conjugated polymers [6], and DNA wires [7] have been reported. A critical issue is now to understand and control the charge transfer from a single molecule to another one.

Here we probe the current passing through a chain of two C₆₀ molecules suspended in a STM junction, where the orientation and electronic states of both molecules have been characterized before connecting them with atomic-scale precision. The experimental results are complemented by first-principles transport calculations which give access to the distance-dependent nature of the intermolecular electron transport and predict the evolution of the transport properties with molecular chain length.

The experiments were performed with a low-temperature STM operated at 5.2 K in ultrahigh vacuum. Au(111) and Cu(111) samples and etched W tips were prepared by Ar⁺ bombardment and annealing. As a final preparation, W tips were indented into the sample surface to coat them with surface material. C₆₀ molecules were deposited from a Ta crucible onto the sample at room temperature. The data shown correspond to a coverage of approximately 0.2 C₆₀ monolayers. All images were recorded in a constant-current mode.

Increased image resolution with molecule-covered STM tips has repeatedly been reported [8]. However, no detailed information about the molecular orientation or their elec-

tronic properties was available. To realize controlled molecular contacts, these details are decisive. We used C₆₀ molecules as their orientation can be determined from submolecularly resolved STM images [9,10]. Figure 1(a) shows a STM image, recorded with a metallic tip, of an array of C₆₀ on a Au(111) surface. Two C₆₀ orientations are observed, which are typical of a $(2\sqrt{3} \times 2\sqrt{3})R30^\circ$ C₆₀ superlattice [11].

To attach a C₆₀ molecule to the tip, the metallic tip was placed over a target molecule and the sample voltage was varied from 2 to 0.01 V and back at a constant current $I = 100$ nA. The success of this procedure can be verified from the removal of the molecule from the substrate (e.g., missing C₆₀ in Fig. 1(b), black arrow). To further characterize C₆₀ tips, structures composed of one (α) and two or three (β) Au adatoms had been deposited by slight contacts of the metallic STM tip with a clean surface area [Fig. 1(a), upper left] [12]. The image of Fig. 1(b) was obtained with a C₆₀ functionalized tip over the same area. The Au clusters, which appear round and featureless with a metallic tip, exhibit a complex pattern which matches the highest occupied molecular orbital (HOMO) of C₆₀ [9]. Obviously the Au adatoms work as tips for "reverse" imaging of C₆₀ at

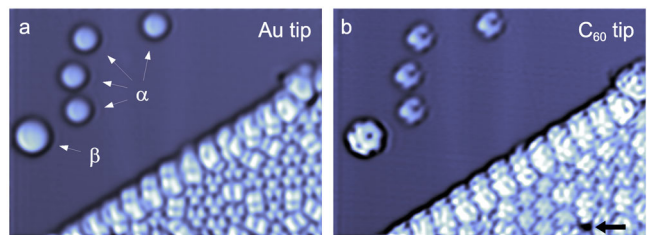


FIG. 1 (color online). STM images ($I = 10$ nA; $V = 2.5$ V; 14×11 nm²) of Au(111) partially covered with C₆₀ molecules (lower right) obtained with a (a) metal and (b) C₆₀ tip over the same area. Gold adatoms (α) and a small gold cluster (β) of two or three adatoms are discernible.

the tip and provide direct access to the orientation of the molecule, e.g., in Fig. 1(b), a 6:6 bond of the C_{60} tip is facing the surface. While this technique has previously been used to determine the number of molecules adsorbed on a STM tip [13], the characterization of submolecular structures was not reported.

To monitor the density of states of C_{60} tips, Fig. 2 displays conductance spectra obtained with (a) a metallic tip on C_{60} and (b) a “reverse” spectrum recorded with a C_{60} tip on bare Au. The spectral peaks are characteristics of the molecular orbitals of C_{60} on Au(111) [11]. The spectra are almost perfect mirror images of each other reflecting that the electronic state of C_{60} at the tip is closely related to those of C_{60} on the surface. “Reverse” images and conductance maps of atomic sized clusters exhibit submolecular patterns [Figs. 2(c)–2(h)] which are typical of the lowest unoccupied molecular orbitals (LUMO + 1, $V \approx -2.5$ V and LUMO, $V \approx -1$ V) and HOMO ($V \approx 2$ V) [9,11]. Once a molecule is attached to the tip it is possible to change its orientation by passing current of up to $\approx 1 \mu\text{A}$ as demonstrated in Figs. 2(i)–2(l). The molecular patterns obtained correspond to different C_{60} orientations at the tip. While this sequence demonstrates control over the orientation of the tip molecule it also highlights an instability of these tips at high currents, which, therefore, were not suitable for the intended contact experiments. We repeated the previous experiments on C_{60} deposited on a Cu(111) substrate [Fig. 3(a)] where the binding of C_{60} is stronger [11]. Transfer of C_{60} from the Cu(111) to the Cu-covered tip remains feasible, although

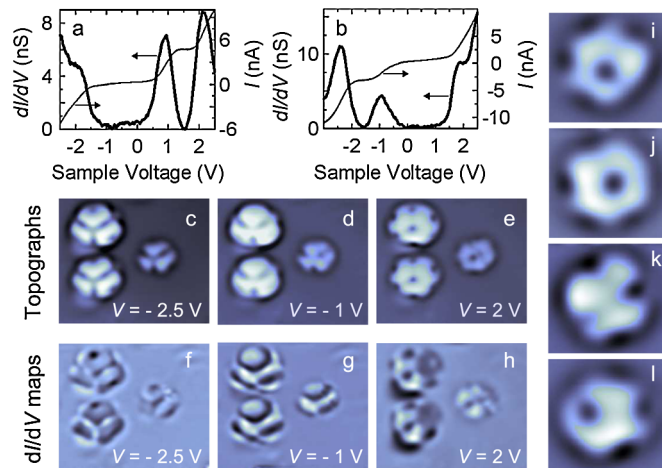


FIG. 2 (color online). Differential conductance (dI/dV) spectra acquired over (a) a C_{60} with a metal tip and (b) the bare metal with a C_{60} tip. (c)–(e) are reverse STM images ($I = 10$ nA; 5×4.2 nm 2) acquired over α and β type atomic clusters with a C_{60} tip at the voltages corresponding to peaks in the spectra of (b). (f)–(h) are dI/dV maps acquired simultaneously with the images. Reverse STM images (i)–(l) of a Au adatom with a C_{60} tip ($V = 2.5$ V; 1.5×1.4 nm 2). Between image acquisitions, the tip was moved to the surface so as to reach $I \approx 1 \mu\text{A}$, where reorientation of the C_{60} at the tip occurred.

the procedure is less reproducible than for Au(111) and μA currents are required. As in the Au case, the structural and electronic properties of the C_{60} tips have been characterized [Fig. 3(b)].

After characterization, metal and C_{60} tips were approached to C_{60} molecules and pristine Cu(111) areas and conductance-distance [$G(z)$] data were recorded [Fig. 3(c)]. No reorientation of the molecules occurred. Curve 1 was obtained with a sharp metallic tip approaching a C_{60} molecule. The right part of the trace corresponds to the tunneling range. Contact is indicated by an inflection of the trace, which defines a contact conductance of $0.3G_0$ (conductance quantum $G_0 = 2e^2/h$) in agreement with previous measurements on similar systems [4,14]. Curve 2 represents a measurement with a C_{60} tip approaching pristine Cu. Surprisingly, the contact conductance of $1.0G_0$ (G up to $\approx 1.5G_0$ were observed for different C_{60}

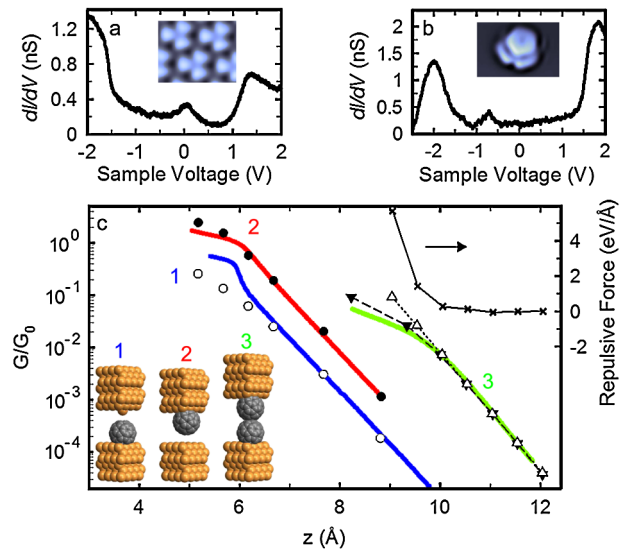


FIG. 3 (color online). (a),(b) dI/dV spectra acquired over (a) a C_{60} molecule on Cu(111) with a metal tip and (b) the bare metal with a C_{60} tip. Insets show (a) a STM image ($V = 2$ V; 2×1.6 nm 2) of a C_{60} array on Cu(111), where all molecules expose hexagons to vacuum, and (b) a reverse STM image ($V = -2$ V; 2.7×1.8 nm 2) of the C_{60} tip used for the contact experiment (a 5:6 bond is exposed to the surface). The inset to (c) displays sketches of the contact experiments performed by approaching (1) a sharp metallic tip to a C_{60} adsorbed on a hexagon on Cu(111), a 5:6 oriented C_{60} tip (2) to the bare Cu(111) surface and (3) to a C_{60} adsorbed on a hexagon. (c) Experimental (solid lines) and calculated (symbols) conductances versus distance. In cases (1) and (2), z is measured from the C_{60} center to the center of the outermost atom of the other electrode. In case (3), z is the C_{60} center to C_{60} center distance. This corresponds to an offset of ≈ 0.36 nm, i.e., half of the maximum atomic distance within the C_{60} cage. The calculated repulsive force (crosses) between two C_{60} molecules suggests an elastic deformation of the junction at small separations that maps real molecule-molecule distances (open triangles) with apparent distances (filled triangles). Sample voltages: (1) 100 mV; (2) -100 mV; (3) 200 mV.

orientations) is substantially higher than with C_{60} on the surface.

To understand the measured conductance traces first-principles transport simulations were carried out. We modeled the fullerene junctions by supercells with one or more C_{60} molecules bridging a 4×4 representation of a slab containing 13 Cu(111) layers. The electronic structure was determined with the SIESTA pseudopotential density functional theory (DFT) code [15] to calculate the transport properties for the TRANSIESTA setup [16]. For details, cf. Ref. [17]. Case 1 was modeled with a C_{60} adsorbed on a hexagon on the substrate side centered underneath a Cu adatom on the tip side, and case 2 with a C_{60} adsorbed on a 5:6 bond on the tip side facing a clean Cu(111) surface. For a transparent interpretation of the experiments we have considered the tip-molecule (sample-molecule) separation as the only variable in case 1 (case 2), and full geometry relaxations were not performed. Except for the structural rearrangements expected with a sharp metallic tip (case 1) [14], this approach reproduces and explains the observed traces. The calculated zero-bias conductances [Fig. 3(c)] enable a calibration of the absolute distances z (outermost Cu atom to C_{60} -center along the surface normal) between tip (sample) and molecule in case 1 (2) by aligning the tunneling part of the traces. Comparison of cases 1 and 2 shows that for a given distance z , depending on the geometry of the molecule-electrode interface, the conductance of a single C_{60} junction can vary by a factor of 3 (10) under contact (tunneling) conditions. The conductance of the $C_{60}/\text{Cu}(111)$ junctions is dominated by the molecular LUMO resonances that lie closest to the Fermi energy E_F . The theoretical maximum is therefore $3G_0$ corresponding to three fully open conductance eigenchannels [16]. Indeed, a decomposition $T = \sum_i T_i$ of the total transmission $T = T(E_F)$ into eigenchannel contributions $\{T_i\}$ confirms that the three most transmitting channels carry about an order of magnitude more current than the fourth. For the sharp-tip contact (case 1 in Fig. 3) the transmissions in contact are of the order of $\{T_i\} \approx \{0.12, 0.08, 0.04, 0.004\}$; hence, the majority of an incoming electron wave is being reflected in this type of junction. Contrary, for the C_{60} -tip contact (case 2 in Fig. 3), three channels are much more open, theoretically in one case as much as $\{T_i\} \approx \{0.97, 0.87, 0.57, 0.02\}$.

To find out *where* the electrons are being scattered, Fig. 4(a) visualizes the most transmitting eigenchannel wave function for the different contacts [18]. Since the absolute square of the wave function corresponds to the density of the traversing electrons, the magnitude of the lobes gives an idea where the electron wave travels. In case 1 (sharp tip) the current is scattered at the single-atom contact to the molecule as indicated by the standing wave pattern at the tip side. In case 2 (C_{60} tip) the channel is almost perfectly open and the wave is propagating with essentially equal amplitude on either side of the molecule.

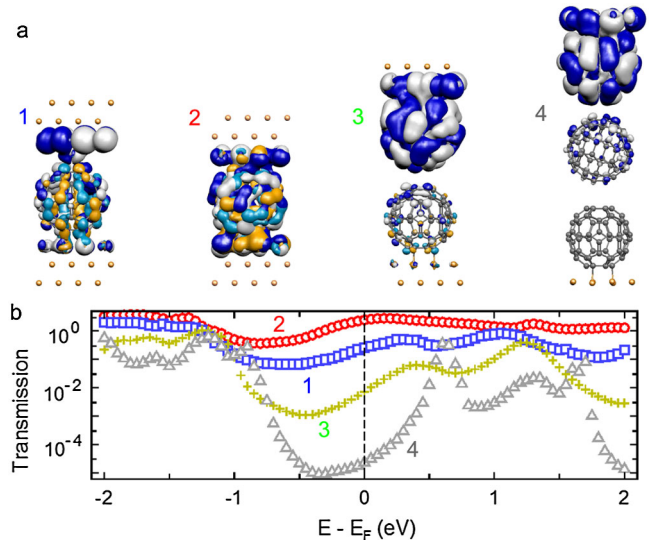


FIG. 4 (color online). (a) Visualizations of the most transmitting eigenchannel wave function (incoming from above) around E_F . Isosurfaces of the real and imaginary parts of the wave function (with sign). White and dark blue (black) corresponds to the real part and orange (light gray) and light blue (darker gray) to the imaginary part. (b) Calculated transmission of suspended chains of one, two, or three C_{60} . The molecular orientations are (1) adatom vs hexagon, (2) 5:6 bond vs flat surface, (3) hexagon vs 5:6 bond, and (4) hexagon vs 5:6 bond vs hexagon.

To disentangle the effects of different molecular orientation as well as of different atomic contacts on the conductance, we have carried out separate calculations with the hexagon orientation contacted with a flat tip. Specifically, between flat Cu(111) electrodes the 5:6 orientation was found to conduct slightly less than the hexagon orientation; e.g., at $z = 6.68 \text{ \AA}$ the conductance is 19% lower for the 5:6 configuration. Moreover, experimental data from various C_{60} orientations [19] show that $0.3G_0$ (case 1) is already an upper limit of the conductance of C_{60} on a Cu surface contacted with a sharp STM tip. We therefore conclude that the higher conductance of $1.0G_0$ (case 2) is due to the multiple-atomic contact which ensures a better connection between the molecule and the electrode. This characterization of the metal-molecule contact could be valuable for fullerene-based anchoring strategies for molecular electronics [20].

Finally, the C_{60} tip of curve 2 in Fig. 3(c) was also approached to a C_{60} molecule on the substrate. Yazdani *et al.* used a similar method to measure the conductance of diatomic xenon chain [21]. Employing the molecular orientations determined in the experiment, this case was modeled with a C_{60} adsorbed on a hexagon on the substrate side under a C_{60} adsorbed on a 5:6 bond on the tip side. Note that the displacement axis now shows the C_{60} to C_{60} center distance. The observed conductance trace [curve 3 in Fig. 3(c)] varies smoothly from tunneling to contact at a molecular separation of $\approx 1 \text{ nm}$. The contact conductance

of $\approx 0.01G_0$ is an order of magnitude smaller than expected for a C_{60} dimer [22]. In contrast to the experimental observation of a plateau, our model predicts an exponential dependence of the conductance on the C_{60} - C_{60} separation [open triangles in Fig. 3(c)] and no significant influence of the C_{60} -surface distance (see Ref. [17]). This difference is due to an intermolecular repulsion at small distances that deforms the contact. Therefore, beyond the point of contact, the experimental data reflect *apparent* molecular separations, the actual distances being somewhat larger. To take into account the elastic deformation of the junction, repulsive forces were estimated from our DFT calculations [crosses in Fig. 3(c)]. By renormalizing the theoretical z coordinates according to the compliance of two soft molecule-surface segments (effective elastic constant $7 \text{ eV}/\text{\AA}$) [17], we obtain agreement with the experimental trace [filled triangles in Fig. 3(c)]. While it is possible to further improve this agreement by considering the elasticity of the other parts of the system [17], the essential feature of the experiment is already captured by inclusion of just the softest segment. Interestingly, the onset of elastic deformation coincides with the intermolecular distance of 1.004 nm in C_{60} crystals, which is controlled by van der Waals bonding and electrostatic repulsion [23].

The picture emerging for chains of two C_{60} molecules is that the transport processes are mainly sensitive to the molecule-molecule interface. It is further supported by Fig. 4(a), part 3, which shows isosurfaces of the dominant eigenchannel with little weight on the lower molecule. This is due to a reduced wave function amplitude beyond the C_{60} - C_{60} interface, which thus acts as conductance bottleneck. Within the chain the intermolecular distance is limited by electrostatic repulsion. In this way the experiment is probing how current passes through two *touching* molecules, the properties and the nature of both being controlled and tunable.

Using the C_{60} - C_{60} contact distance determined above, the transport through a three- C_{60} chain was calculated. In this case the dominant eigenchannel Fig. 4(a), part 4, is strongly attenuated along the chain as revealed by the absence of lobes on the lower molecule. The transmission functions of the molecular chains Fig. 4(b) reveal the opening of a $\sim 1.5 \text{ eV}$ gap around E_F , and hence predict a rapid evolution towards an insulating infinite C_{60} chain.

In summary, the contact conductance for single C_{60} junctions can vary up to a factor of 3 depending on the molecule-metal interfaces, thus corroborating the notion of good and bad contacts. The current passing from one molecule to another one, however, is determined by the

molecule-molecule interface. Our experimental approach can be extended to a range of molecules to address the influence of the molecule-molecule interactions on intermolecular charge transport. Moreover, through detection of photons emitted in a STM junction [24], a suitable fluorescent molecule attached to the STM tip might prove useful as optically active probe [25].

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