ticles warm up inordinately and release the molecules they carry as gas.

As in the interstellar medium, much of the dust from comets consists of silicate minerals, but despite the similarities, there are puzzling differences. For example, interstellar dust shows the absorption signature of amorphous particles with a silicate composition, whereas Hale-Bopp and other comets have crystalline silicate, probably in the form of Mg-rich olivine (*4, 6, 14*). In the interstellar medium, HCN is seen as a gas, whereas in solid interstellar grains, a molecule designated "XCN" is observed, but "X" is unknown. In comets, HCN and CH_3CN are seen in the gas phase at radio wavelengths, as reported by Biver *et al.* (*5*), and CN emission is very strong, as reported by Wagner and Schleicher (*7*). The source of the CN is unknown; HCN and CH_3CN are part of the solution, but there must be some other source of volatile SCN producing the strong CN emmission seen by Wagner and Schleicher (*7*) and by many other investigators (*9*).

Grains of various kinds of ices are also ejected by CO. Particles of frozen H_2O were found in the coma surrounding Hale- Bopp at 6.8 AU from the sun (*15*). The infrared spectrum of the ice particles suggests that the water was probably in the amorphous state of its original condensation in the interstellar cloud. The new radio wavelength data show that water ice grains were still present at 3.5 AU (*5*), but by the time the comet reached about 3 AU, water was evaporating directly from the comet's solid nucleus.

The tons of evaporating ices and dust grains being disgorged by Hale-Bopp each second carry the comet's encrypted secrets into the fields of view of telescopes around the world and in space, and eager astronomers are decoding the spectrum molecule by molecule, from ultraviolet through radio wavelengths. Isotopes of carbon, oxygen, and nitrogen are showing up in the molecules detected with radio telescopes (*16*), and their distributions will provide key information on the starting material of comets and the degree of chemical processing that it has experienced. The increased understanding afforded by this very bright comet bears not only upon the origin of these icy transients from beyond the planetary region of the solar system but upon our own origins as well.

An enhanced version of this Perspective with links to additional resources is available for *Science* Online subscribers at http://www.sciencemag.org/

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APPLIED PHYSICS

Single-Molecule Transistors

Leo Kouwenhoven

Chemistry and condensed matter physics have recently converged in the development of ultrasmall devices with nanometer-length scales. The most interesting and flexible of these structures are basically three-terminal transistors. There are source and drain contacts for sending current through the device, and the third terminal is a gate electrode. An applied voltage to the gate can alter the current from an "on state" to an "off state." In comparison, off-the-shelf silicon transistors have length scales of between 0.3 and 1 μm. These newly developed nanometer-scale transistors consist of only a single molecule, approaching the ultimate limit of miniaturization. This goal was eloquently expressed by Feynman (*1*) in his famous lecture on the possibilities for new devices if one is able to manipulate matter on an atomic or molecular scale. Not only could the device density in an integrated circuit be enormously increased, but also the operation principles of a single transistor could be fundamentally different. Indeed, recent experiments (*2–5*) have shown that the device characteristics of a carbon-based single-molecule transistor is completely governed by the laws of quantum mechanics.

The development of electronics based on molecules has for decades been a promising direction for future nanodevices. This field, however, lacked experimental progress until about a year ago. The difficulty had been twofold. First, it appeared that all long and narrow molecules were either semiconducting or insulating. The reason is that one-dimensional electron systems undergo a Peierls transition, which is a tiny rearrangement of the atoms. However, the atomic rearrangement is precisely such that for electrons, an energy gap is opened at the Fermi energy, as in semiconductors or insulators. Luckily, chemists have recently found a long carbon-based molecule in which the Peierls transition is absent, and thus, it can be a one-dimensional conductor. This long molecule is the carbon nanotube. It is one of the fullerenes whose discoverers were awarded the 1996 Nobel Prize in Chemistry (*6*). The first obstacle was overcome by the group of Smalley, one of the laureates, at Rice University. They were able to synthesize large amounts of conducting nanotubes with a diameters of about 1 nm and lengths up to several micrometers (*7*).

The second difficulty had been attaching electrical wires to a single molecule. This technical problem could be solved thanks to fabrication developments in condensed matter physics. In condensed matter, the electronic properties of nanometer- to micrometer-scale devices has been an active research area during the last decade. This area, known as mesoscopic physics, has not only studied fundamental quantum mechanical properties but also has developed fabrication techniques for attaching wires to small pieces of material.

The synergy between the fullerene chemists and mesoscopic physicists is beautifully illustrated in the figure. The metallic strips were first fabricated with electron beam lithography techniques. Then, carbon nanotubes were randomly laid down. Inspection with an atomic force microscope allows one to pick out those devices where a single nanotube connects two metal strips. Smalley's group synthesized the nanotube seen in the figure

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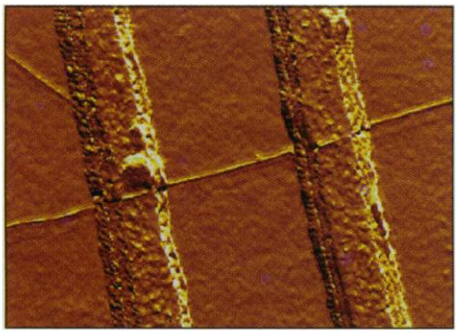

Atomic force microscope image of a single carbon nanotube crossing two platinum strips, which are used as source and drain contacts. On the right, a part is seen of a third electrode which could be used as a gate. The distance between electrodes is 200 nm. In the upper left corner a short tube is seen. [Courtesy of S. J. Tans *et al.*, Delft University of Technology]

and also supplied the nanotubes used in the two recent transport experiments. Tans and colleagues (*4*), from Delft, have studied a single nanotube, and Bockrath and colleagues (*5*), from Berkeley, measured a bundle of nanotubes (see page 1922). The two groups found similar electron transport properties.

So, what is special about these transistor characteristics? As we know, electrons in molecules only occupy quantized orbitals, which correspond to discrete levels in the energy spectrum. The current from source to drain contacts is carried exclusively by electrons that have exactly these particular energies. If one adds an electron to the molecule, one needs to pay more than just the finite energy to occupy the next available molecular state; one must also pay a so-called charging energy to compensate for the extra elementary charge that the molecule now contains. Therefore, both quantization of charge and quantized molecular states govern the electronic properties of a molecular transistor. The energy required to add an electron to the molecule can either be supplied by the voltage source between the two current contacts or by the voltage applied to the gate terminal. These voltages are the spectroscopic tools in the determination of the charging energies and the molecular states (*2–5*).

The physics of charging energies and discrete energy states has been exploited before by the mesoscopic community. These quantum effects were found in ultrasmall transistors known as quantum dots. Those quantum dot transistors are small electron boxes with zero dimensionality fabricated in semiconductor materials. Because charging energy and quantized states resemble so closely the ionization energy and excitation energies of an atom, quantum dots are often nicknamed "artificial atoms" (*8*). Following the same arguments, two or more coupled quantum dots can be regarded as "artificial molecules" (*9*). We can complete the connection between natural and artificial structures by naming the single-molecule transistor a "natural quantum dot." The finite length of the nanotubes makes them effectively zero-dimensional, that is, the same as quantum dots. And indeed, the present transport experiments on carbon nanotubes are well explained by the theory developed for quantum dots (*4*, *5*). The hope is that in future experiments, the physical consequences from the narrow and long geometry will be revealed. One-dimensional conductors have attracted a lot of theoretical interest because they are model systems for strongly interacting many-body physics. Maybe the carbon nanotubes will serve as the experimental system in which these exotic theories can be tested.

Whereas quantum dots show their quantum properties only when cooled to low temperatures (a few kelvin above absolute zero), the small size of single-molecule transistors allow them to operate at much higher temperatures. In fact, scanning tunneling studies on a C_{60} molecule by Porath and Millo (*2*) and on a carbon cluster by Soldatov *et al.* (*3*) still show transistor operation at room temperature. In this transistor, a single electron again makes the difference between an on state and an off state. Although the persistence up to room temperature is very promising, we still have a long way to go before we can integrate or couple different nanotubes to make a little electronic circuits. On the other hand, nanotubes have an interesting connection between their mechanical and electrical properties. For instance, a kink in a nanotube can change it from metallic to semiconducting (*10*). So, one can imagine building a specific electronic circuit by stretching and bending a couple of nanotubes here and there.

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IMMUNOLOGY

A Gut Reaction: Lymphoepithelial Communication in the Intestine

Fergus Shanahan

Different parts of the body require different defenses against pathogens. The immune system is therefore regionally specialized and compartmentalized, in large part by the conditioning effect of the local microenvironment. On page 1937 of this issue, Wang and colleagues focus on the intestine and provide important new insight into the immunoregulatory effects on intestinal T cells of local hormonal networks, specifically thyrotropin-releasing hormone (TRH) and thyroid-stimulating hormone (TSH) (*1*). Their work illustrates the importance of studying the immune system in its natural environment.

The intestinal mucosa separates the external environment (the gut) from the internal milieu, forming the most extensive of such barriers in the body. The large surface area facilitates effective absorption of essential nutrients, but presents a problem—only a single layer of epithelium separates the intestinal lumen from the internal environment. So this anatomic design may not be optimal for excluding infectious, toxic, and otherwise harmless immunogenic material from the body. The dilemma is solved by adaptation of versatile immunologic and nonimmunologic defenses (*2*).

Strategic adaptation of the intestinal immune system is reflected in the molecular and cellular components of the mucosal immune system, which differ in several respects from their counterparts at other sites within the systemic immune system (*2*). Interspersed among the epithelial cells (enterocytes) lining the intestine are the intraepithelial lymphocytes (IELs) (see figure). The IELs are an important immunologic compartment; collectively, they represent a pool of cells comparable in size to that of all peripheral lymphocytes in the spleen. They are not only functionally and phenotypically distinct

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