Purified sperm sAC has a molecular weight of 48 kD (*6, 8*), whereas its cDNA predicts a protein of 187 kD (*8*). A truncated form of sAC similar to the 48-kD protein exhibits a 20-fold higher specific activity than does the 187-kD form (*8*). This finding argues that proteolytic processing of a larger version of the enzyme is required for full activity. In the testis, the 187-kD protein is the predominant form, whereas sperm contain the 48-kD protein (and other proteolytic fragments). This suggests that sAC is converted from an inactive to an active form as sperm transit through the epididymis. Interestingly, the extracellular bicarbonate ion concentration decreases from 25 to 5 mM along the length of the epididymis (*9*) and rises again when sperm are mixed with seminal fluid during ejaculation. Thus, the proteolytic activation of sAC is likely to be regulated by bicarbonate ions in the extracellular environment.

In the new work, Chen *et al.* demonstrate that the activity of purified sAC, both from rat testis and from a mammalian cell line expressing the sAC gene, is stimulated by physiological concentrations of bicarbonate ions. They further show that AC from cyanobacteria is also sensitive to bicarbonate ions. Thus, sAC appears to be a universal bicarbonate sensor conserved across phyla millions of evolutionary years apart. This finding is likely to have implications beyond the world of sperm and bacteria because sAC has been detected in mammalian kidney and choroid plexus.

What are the molecular targets of cAMP in sperm (see the figure)? Protein kinase A (PKA), the classic cAMP target, catalyzes the phosphorylation of several flagellar proteins, thereby regulating sperm motility (*10*). In mammalian sperm, the cAMP-PKA signaling pathway also induces phosphorylation of several proteins required for the capacitation response (*3*). A second possible target of sperm cAMP is a family of ion pacemaker channels known to control the rhythmic electrical activity of brain neurons and cardiac cells. Unlike other voltage-dependent channels, pacemaker channels open by hyperpolarization rather than by depolarization and their activity is enhanced by cyclic nucleotides in the absence of phosphorylation—hence, they are also called HCN (hyperpolarization-activated, cyclic nucleotide–gated) channels (*11*).

One HCN channel that is exquisitely sensitive to cAMP has been identified in the flagellum of sea urchin sperm (*11*); mRNA transcripts of the mammalian isoform, HCN4, have been found in human testis (*12, 13*). These pacemaker channels may generate the rhythmic activity that controls the beating motion of the sperm flagellum. In fact, sperm cells and rhythmically active neurons contain an astoundingly similar collection of channels including low-threshold T-type Ca^{2+} channels and HCN channels (see the figure) (*14*). Analogous to HCN channels in neurons, sperm HCN channels may open more often in response to increased cAMP, thereby resulting in depolarization of the sperm plasma membrane. This depolarization in turn may result in opening of sperm T-type Ca^{2+} channels and an increase in intracellular Ca^{2+}, which initiates signaling pathways that regulate motility. A third target of cAMP could be a family of guanine nucleotide exchange factors (*15, 16*) that activate Rap1, a member of the small GTP-binding protein superfamily. It will be interesting to discover whether sperm contain cAMP-activated guanine nucleotide exchange factors.

Now that the major players in sperm mobilization—sAC, PKA, and HCN—are unmasked, the next sequence of events regulated by cAMP signaling should soon be revealed.

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PERSPECTIVES: NANOTECHNOLOGY

Beyond Gedanken Experiments

Laszlo Forró

Interest in creating functional devices at nanometer scales is fueled by the desire to shrink the size of electronic integrated circuits and to create mechanical systems at nanoscale. In the minds of most futuristic thinkers, submicrometer-scale machines will move atoms and molecules and create new artificial structures, performing work in a nanoworld. At this scale, however, physical manipulation poses unique challenges. Machining, positioning, and assembling parts by hand are easy at macroscopic scales, but these abilities are far from routine at the molecular scale.

On page 602, Cumings and Zettl (*1*) report an important step toward "machining" building blocks for molecular devices in a controlled manner, by constructing bearings and mechanical switches out of multiwalled carbon nanotubes (MWNTs) with diameters of a few tens of nanometers. Using a manipulator inside a high-resolution electron microscope, they are able to peel off a few outer layers of an MWNT fixed at one end (*2*). By spot-welding a tip to the inner shell(s) and moving it back and forth, they study the mechanical properties of this nanobearing. They find that the system is an ideal low-friction and low-wear bearing. Because of the restoring force of the van der Waals interaction acting on the extruded nanotube, such an assembly can also be used as a switch with a very short reaction time.

The raw materials for making the bearings, MWNTs, have been known since 1991 (*3*). Studies aimed at applications started 4 to 5 years ago, when mass production became possible (*4*) and samples with sufficient purity could be made (*5*). In high-resolution transmission electron microscopy, the carbon nanotubes appear as long fibers consisting of several graphene sheets rolled up and embedded in each other (*3*). The tubes are closed at the end, and each tubule appears to close on itself. The entire structure thus resembles a Russian doll. Their diameters range from a few to many tens of nanometers. Made of hexagonal lattices of carbon atoms, nanotubes are extremely strong, light structures (*6*).

An MWNT bearing is exactly the structure foreseen by Drexler as the most efficient bearing for nanomechanical needs (*7*). His suggestion was to take two flat sheets of graphite, bend them into two cylinders of slightly differing diameter, and insert the smaller one into the larger one. But this idea remained just a gedanken experiment until Cumings and Zettl carved out the bearing from an MWNT with a shaping electrode. The outer layer or layers form the sleeve and the inner ones the shaft. Because the surfaces are atomically perfect and the spacing between the shaft and the sleeve is just the van der Waals distance in graphite, there is no room for grit to enter between them, and consequently the problem of wear can be avoided. The bearing may still get stuck at certain preferred positions where the atomic potentials of the sleeve and the shaft are commensurate, resulting in mini-

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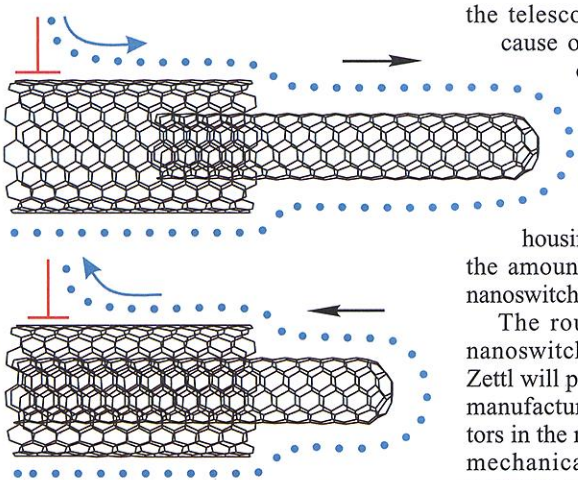
ma in the potential energy. The shaft will thus have certain preferred orientations. The advantage of an MWNT bearing is that each layer is likely to have a different chirality (depending on the way the graphene is rolled up in a cylinder) and that the barrier to rotation should therefore be very small, allowing the sleeve to rotate without difficulty. These properties may make the bearing fabricated by Cumings and Zettl a very efficient part of future molecular motors.

Another extremely interesting application of such a sharpened MWNT would be its use as a nanoswitch. The inner nanotube can be pulled out by a manipulator, and after release, it will "fly" back into the housing. In a simple analysis, Cumings and Zettl show that lowering the van der Waals energy by increasing the tube-tube contact area acts as a constant force on the extruded tube, and because the friction forces are very low, it is telescoped back within on the order of 10^{-9} seconds. Such a fast reaction switch offers the possibility of electronic control of back-and-forth movement. A simple trick would be to put charges on the nanoswitch. The electrons are located only on the surface of the housing and of the telescoped part of the nanotube because of the Faraday cage effect. The change in the electrostatic energy due to the increased surface charge density will be opposite in sign to the gain in van der Waals energy upon reinsertion of the inner tube into the housing (see the figure). By altering the amount of charge on the switch, the nanoswitch could be opened and closed.



Electronic control of a tiny switch. A restoring van der Waals force acts on the extruded nanotube, which is opposite in sign to the electrostatic force exerted by electrons (blue dots) brought to the surface of the nanoswitch. The density of the charge can be changed through the electric contact (red) attached to the nonmoving part of the nanotube, allowing the switch to be opened and closed. Blue arrows indicate the direction of the charge flow, and black arrows indicate the direction of the movement of the extruded tube.

The route toward nanobearings and nanoswitches reported by Cumings and Zettl will play a major role in our ability to manufacture nanomachines and nanomotors in the near future. The extremely light, mechanically and chemically resistant MWNTs represent the ideal starting material for these novel nanodevices.

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PERSPECTIVES: MATERIALS SCIENCE

Weird Gold Nanowires

E. Tosatti and S. Prestipino

When matter is reduced to just a few layers of atoms, very thin wires, or small clusters of atoms, the properties of solid matter do not remain quite the same, and there is room for surprises. In the realm of carbon alone, buckminster fullerenes and nanotubes display an amazing variety of unexpected behavior. A recent addition to the list of surprises is now reported on page 606 by Kondo and Takayanagi (*1*), who provide evidence that very thin gold wires form a helical structure, akin in some respects to carbon nanotubes.

Using transmission electron microscopy (TEM), the authors—whose group solved the structure of the famous Si(111) 7×7 surface in the 1980s—study atomically thin, several nanometers long, very regular gold nanowires formed by thinning down a narrow bridge between two oriented tips (*1*). Shrunken to radii of 3 to 6 Å (roughly one or two times the bulk interatomic spacing of gold, 2.88 Å), these wires display "magic" preferred radii and geometries. This means that they only come in a few discrete sizes and shapes, a property long known for metal clusters. What is more striking is that the internal structure of these magic nanowires, which TEM is able to image and map despite their small size, is weirdly noncrystalline.

The structure consists of coaxial cylindrical tubes, or shells. A shell s contains a well-defined number n_s of strands, each strand a tiny monatomic gold necklace. The number of strands in the shell increases with the shell radius, and each magic wire is characterized by a well-defined n_s sequence. For example, if the outer shell contains seven strands and the inner shell consists of a central strand consisting of a single row of atoms, this is abbreviated as 7–1. Two other nanowires described by the authors are 11–4, or 14–7–1. For n_s larger than 1, the strands are wound up helically side by side, nearly but not exactly parallel to the wire axis, to form the tube. The pitch of the helix differs from one wire and another, but not between successive shells of the same wire: Atoms in successive shells appear to strain a bit to maintain perfect registry.

Had the nanowires retained instead the main features of the regular face-centered cubic (fcc) crystal structure of bulk gold, they would look very different indeed: no tubes, no curly strands, no helicity. Even when regular crystallinity is abandoned and a close-packed nanowire made of tubes centered about a central straight strand is built from hard spheres, a nonhelical shell structure with 6–1, 12–6–1, etc., results, quite different from what is observed.

Cluster physics suggests at least two conceptually different sources for magic wire sizes. The first could be electronic shell closing. A small metal cluster may behave as a giant atom, with the most stable cluster sizes corresponding to closed electronic shells, very much as rare gas atoms are the most stable ones in the periodic table. This kind of shell-closing is observed in clusters of alkali metals such as sodium. The second source of magic sizes, although also electronic, is best explained in terms of packing. Imagine modeling atoms roughly as balls, endowed with some hard core repulsion as well as a soft mutual attraction (representing the electronic cohesive forces) that glue and pack the atoms together in the most effective way. This attraction has a

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