Materials Jamboree

Materials scientists are an electic bunch, as demonstrated by the 1990 Fall Meeting of the Materials Research Society, held in Boston from 26 November through 1 December. The session topics ranged from soccer-ball-shaped carbon clusters to the engineering lessons to be learned from a blade of grass.

Buckyball Bash

As the starting time approached, some researchers were making joking comparisons to the "Woodstock of Physics"—that madhouse session at a March 1987 meeting of the American Physical Society where the first results on high-temperature superconductors were reported. And certainly there were some similarities. This was the first meeting called to discuss a breakthrough in making a potentially valuable material, and some scientists would be reporting data that were only a few days old. The hastily organized session had attracted more than 20 speakers, some of them added less than 24 hours beforehand, and at 20 minutes per talk, the 5:15 p.m. gathering would not end until after midnight.

The guest of honor at this party was the buckyball, a spherical molecule of 60 carbon atoms that is expected to have unusual and useful properties, such as being an excellent lubricant and a specific catalyst. (The rather odd name derives from the shape of the molecule—its atoms are arranged at the vertices of a truncated icosahedron, a soccer-ball form popularized by Buckminster Fuller for use in geodesic domes.)

In late September, Donald Huffman at the University of Arizona in Tucson and Wolfgang Krätschmer at the Max Planck Institute for Nuclear Physics in Heidelberg announced the first method of making the relatively large amounts of buckyballs needed for most analytical tests and experiments (*Science*, 12 October, p. 209). The discovery touched off a rush to characterize the physical and chemical properties of buckyballs—paving the way for the Boston gala.

"This is the biggest news in chemistry that I could have imagined," Robert Whetten, a physical chemist at the University of California, Los Angeles, told the participants. "The discovery of new forms of carbon has been a goal of chemists since World War II." Harry Kroto of the University of Sussex in Brighton, England, suggested that buckyballs may open up an entire new area of organic chemistry based on round carbon molecules. Organic chemistry now depends on chains and rings of carbon atoms, and throwing spheres into the mix should lead to chemicals with properties quite different from any now known.

Although the buckyball session did not turn out to be as frenetic as the Woodstock of Physics—there were 300 scientists instead of 3,000, there was no shouting or fighting for seats, and there were no claims that, "Our lives have changed"—many of the scientific results were just as dramatic. In one talk, for example, Robert Haufler told the audience how he and other members of Richard Smalley's team at Rice University in Houston have been able to make up to 10 grams of buckyballs a day, when just a few months ago they would have been happy to get micrograms. And their system, which is based on the Huffman-Krätschmer method, is simple. They attach two graphite rods to an ordinary arc welder bought at a local Sears store. When they bring the tips of the rods close to each other and run a high current between them, the resulting arc vaporizes the graphite, and many of the resulting pieces spontaneously curl around on themselves to form hollow C_{60} molecules—buckyballs.

Don Bethune of IBM's Almaden Research Center in San Jose, California, showed a series of pictures made with a scanning tunneling microscope of the molecules collected on a gold surface. "They seem to be quite skittish and run around quite a lot on the surface," he reported, a finding consistent with the expected chemical inertness of C_{60}. Since each of the 60 carbon atoms is stably bonded to three other carbon atoms in the cluster, none of them is particularly "eager" to bind with any other atoms, so buckyballs should be unreactive and thus not stick well to surfaces. Indeed, that's what leads chemists to think that buckyballs would make highly stable lubricants.

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And several investigators described the physical and chemical properties of buckyballs. For instance, Fred Wudl of the University of California, Santa Barbara, reported that each buckyball can be induced to accept up to 3 extra electrons from other atoms. This suggests, he said, that it might be possible to create semiconductor electronic components from buckyballs instead of silicon or gallium arsenide.

The one disappointment of the evening was that it now appears that buckyballs are not the solution to one of the long-standing mysteries of astronomy. Since the 1930s, astronomers have noted that something in interstellar space is absorbing certain frequencies of starlight before the light reaches the earth, but the spectrum of these absorption lines does not agree with that of any known substance.

Some researchers had suggested that this mystery material could be large carbon atoms, and C_{60} had been a favorite candidate. Indeed, both Huffman and Kroto said it was this astronomical enigma that first enticed them into studying clusters of carbon atoms. But, alas, the two researchers agreed that their search does not appear to be over. Both made enough buckyballs to test the starlight hypothesis, and found that it didn't check out.

A New Role for the STM

When it was invented in 1981, the scanning tunneling microscope (STM) was intended simply as an observational tool, and it has proved to be an excellent one. Scientists have used the instrument to make out details as small as a single atom. But recently, the STM has turned out to be more versatile than anyone expected. Instead of merely making pictures of samples, researchers are now using it to transform them—to move individual atoms from one place to another on a surface, to add or take away atoms, and even to burn lines into a surface. Although few applications are expected in the short run, researchers say that this ability to manipulate matter atom-by-atom should eventually have immense practical and scientific implications for nearly every area of physics, chemistry, and materials science.

At the materials science meeting, physicist Don Eigler described one use of the STM that could allow chemists to study reactions in brand new ways. He seeks to create a fully controlled chemical reaction between two single atoms or molecules by using an STM to bring them together.

Eigler, who works at IBM's Almaden Research Center in San Jose, California, has already shown that he can drag atoms along a surface with the STM. He does this by lowering the tip of the instrument, which is only a few atoms across at its end, until it is just a few angstroms away from an atom deposited on a surface. At this distance, van der Waals forces create an attraction between the tip and the atom, so that when the tip is moved along the surface, the atom is dragged along with it. Once the atom is where Eigler wants it, he withdraws the tip. His control with this technique is so great that earlier this year he was able to spell out "IBM" with xenon atoms on a nickel surface.

Now Eigler has developed a variation on his earlier technique. He reported that he can pick up and carry xenon atoms from one point to another, instead of dragging them. He brings the STM tip close to a xenon atom on a nickel surface and applies a small positive voltage between the tip and the surface. That causes the xenon atom to attach itself to the tip. Eigler then moves the tip to another point on the surface and applies a negative voltage to put the atom back down.

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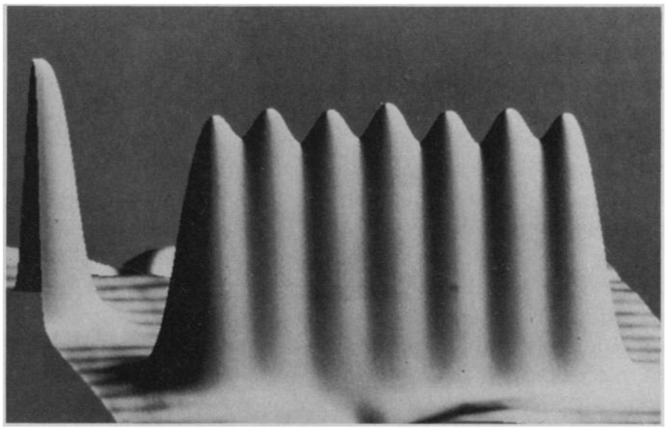

Manmade cluster. *Don Eigler strung together seven xenon atoms one by one.*

Next, Eigler said, he'd like to bring an oxygen atom and a carbon monoxide molecule together to form carbon dioxide. Although he finds he can't move oxygen atoms on a platinum surface—they're too firmly attached—he has been able to move carbon monoxide molecules around. So it may be possible to bring a carbon monoxide molecule next to an oxygen atom and then see what's necessary to initiate the reaction to produce carbon dioxide.

At IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, Urs Staufer is taking a more brute-force approach. In Staufer's hands, the STM becomes a hot knife that can melt lines into a metal surface, affecting thousands of atoms at a stroke. Staufer does this by bringing the STM tip close to the surface and running a current between them. If the surface is a normal metal, the electrons of the current will travel far enough to dissipate their energy harmlessly over a large area. But in certain types of metals called glassy metals, electrons have much smaller mean free paths—they travel shorter lengths on average before hitting one of the metal's atoms. In this case, the energy of the current is concentrated into a small area close to the STM's tip, melting that area. With this technique, Staufer can create patterns only a few nanometers across.

Mark McCord, a colleague of Staufer's at IBM, found that the STM may help him in his studies of magnetic phenomena in very tiny bits of metal. He wants to test theorist's predictions that if a magnet is small enough the spins of all its atoms can flip spontaneously from north to south (or vice versa) by a quantum tunneling phenomenon. But that requires magnets only a few nanometers across, which can't be made by any conventional means.

So McCord has turned to the STM as a way of making the submicroscopic magnets he needs. He puts the STM in a vacuum chamber with the gas $Fe(CO)_5$, brings the STM tip close to a surface, and turns the current on. This attracts the gas to the area between the tip and surface, where it is decomposed by the current, with the iron atoms being deposited on the surface. In this way, McCord has created deposits as small as 20 nanometers across and 80 nanometers high; they are about 50% iron, with the rest being mostly carbon. "We found that these dots do have funny magnetic properties," McCord said, but so far he and his coworkers have not been able to specify exactly what those properties are.

Conveniently, all of the researchers using STMs to manipulate matter were able to use the same instrument in its observational mode to view their handiwork. It's a versatile machine to have around the laboratory.

Lessons From Grass

"Why can grass be trampled, yet come back to its original shape?" Intrigued by that simple question, Julian Vincent of the University of Reading, England, uncovered several facts about the structure of grass that could give materials scientists insights into how to make synthetic materials, such as ceramics, tougher.

Vincent was one of more than 50 scientists who spoke on "Materials Synthesis Based on Biological Processes." Paul Calvert of the University of Arizona in Tucson described the common theme of those presentations this way: "Nature has had millions of years of evolution to perfect things. We would like to look at biological structures and try to transplant them into synthetic systems." The first step is to understand how Mother Nature, the ultimate materials scientist, performs her tricks.

Grass blades are stiff, Vincent said, because of small cellulose fibers that run the length of the blades and provide support. In one species of grass he tested, the fibers took up less than 10% of a blade's volume, yet accounted for more than 95% of its stiffness.

But in addition to being stiff, blades of grass are also tough, or difficult to tear, and this is an unusual combination. Most stiff materials, such as ceramics, fracture quite easily. What makes grass different?

The answer, Vincent said, is that the fibers are embedded in a pliable matrix of parenchyma—the soft tissue in which most essential functions of the plant take place. "When a tear starts, because the matrix is much less stiff than the fibers, it can't transmit the force [of the tear] to the other fibers, so the tearing force is distributed uniformly over the rest of the blade," Vincent said.

Dried grass tears much more readily than fresh grass, he noted, because the loss of water causes the blades to lose their pliability. And that in turn allows enough energy to concentrate at the tip of a crack to keep it spreading.

Plants and animals have evolved a number of other ways to prevent fractures, Vincent said. In fibrous plants, fibers stretch across cracks and absorb the energy of the fracture, either by stretching or by creating friction as the fibers are pulled out of the matrix. In wood, cracks are forced into convoluted paths, which increases the amount of energy needed to propagate them. In fruits, the energy of a flow is distributed over a large area, leading to bruises, but not cracks. And in flexible materials, such as skin, the end of the fracture is rounded off so that there is no sharp tip on which forces can concentrate.

Now the challenge, Vincent noted, is to apply the lessons learned from living organisms to synthetic materials. So far the chemists have proved less successful than Mother Nature. Toughness, Vincent said, is related to the size, shape, and interactions of a material's components—and these are properties that, so far, a blade of grass can control much better than a materials scientist.

■ ROBERT POOL