Princeton used the new technique in analyzing a relatively small but high-quality set of 87,806 seismic recordings assembled by seismologist Guy Masters of the Scripps Institution of Oceanography in La Jolla, California. In Princeton's final global image, the features beneath the classic hot spots of Hawaii, Tahiti, and Easter Island "really are deep mantle plumes," said Dahlen. Some hot-spot plumes, such as those rising to Réunion in the Indian Ocean and the Azores in the Atlantic, actually branch off one of the two huge "superplumes" rising into the lower mantle beneath the South Pacific and Africa (*Science*, 9 July 1999, p. 187).

Not every hot spot has a deep plume in the Princeton tomography, however. Yellowstone is "iffy," says Nolet, and nothing deep feeds Europe's shallow Eiffel plume or Africa's Tibesti hot spot. Absent plumes might reflect patches of sparse data, says Nolet, but "there are a lot of things we call hot spots and associate with plumes that may be shallow."

"It was very impressive," says seismologist Yang Shen of the University of Rhode Island, Narragansett. From the Princeton presentations and his own work with Hung on Iceland data, he finds that the hollow-banana approach improves plume images substantially, up to 100% in the upper mantle beneath Iceland. Seismologist Adam Dziewonski of Harvard was more cautious after hearing the rapid-fire presentations. "I'm usually pretty skeptical when people say they get images of plumes," he says. In the Princeton case, he wonders if they haven't somehow smeared signals from shallow hot rock down into the lower mantle. He's waiting for the Princeton group to complete its testing of the tomography.

Plumes spanning the mantle would have a stimulating effect on a range of earth science. They could clarify how cooling of the interior drives mantle churning. Geochemists would have a better idea of where to locate the mantle's five compartments that store material for up to billions of years. Geologists might better understand the massive flood basalts—thought to spill from the bulbous heads of rising plumes—that dot the globe and are speculated to have overheated climate and triggered extinctions (*Science*, 6 December 1996, p. 1611). Plumes may even shatter supercontinents. Now that would be true vigor.

–RICHARD A. KERR

Physics

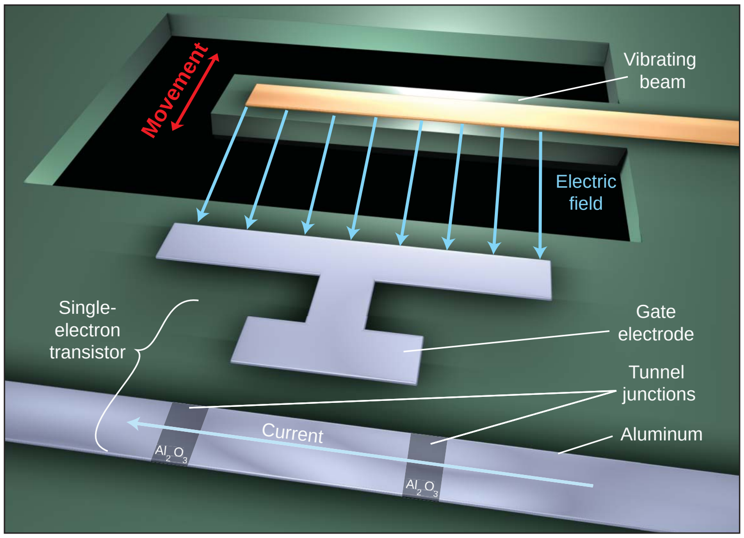
Researchers Race to Put the Quantum Into Mechanics

Machines that make the slightest possible motion could lead to wild new technologies and help reveal why the weird rules of the microscopic realm don't apply to our everyday world

Like fidgety 3-year-olds, tiny objects simply cannot sit still. Atoms, molecules, and other minuscule particles must constantly flit about because of a law of nature that says if you know precisely where something is, you can't know where it's going, and vice versa. The Heisenberg Uncertainty Principle is an unavoidable nuisance; experimental physicists have observed countless times that the smallest bits of stuff in nature wriggle whenever they try to pin them down. However, no one has directly observed the ineluctable quantum quivering—or zero-point motion—of a larger, humanmade object.

That may soon change. Exploiting recent advances in nanotechnology, physicists are racing to fashion vibrating gizmos that can make and measure literally the slightest possible motion. At least four groups hope to reach the quantum limit of motion within months. The feat could open the way for tiny, fingerlike force detectors with the highest possible sensitivity, says Andrew Cleland of the University of California (UC), Santa Barbara. Such detectors might enable researchers to quickly decode DNA and other large molecules, and someday they might serve as the guts of superfast quantum computers.

Quantum machines might even help solve a conundrum as old as quantum mechanics itself: Why can a tiny object like an electron be in two different places at once, whereas a big thing like a pencil or a person cannot?



Shaky connection. Movement of a nanometer-sized beam changes the voltage on the gate electrode of a single-electron transistor, which changes the current running through the transistor, which reveals the motion.

ILLUSTRATION: C. SLAYDEN

"We don't see quantum behavior in our macroscopic world, so in some sense we're protected from quantum mechanics," says Miles Blencowe, a theoretical physicist at Dartmouth College in Hanover, New Hampshire. "What protects us?" To find out, he says, experimenters might try putting progressively bigger mechanical devices into here-and-there "superpositions" to observe what, if anything, goes wrong.

First, though, physicists must reach the quantum limit of mechanical motion. That will require overcoming serious technical challenges, says Michael Roukes of the California Institute of Technology (Caltech) in Pasadena: "This is just damned hard stuff to do."

A subtle vibe

The biggest hurdle is heat. Thermal energy makes large objects wiggle, and at any achievable temperature those vibrations overwhelm the zero-point motion. For example, according to quantum mechanics, a tuning fork can gain or lose energy only in discrete dollops whose size is proportional to the fork's frequency of vibration. Because the frequency is low (440 cycles per second for concert-pitch A), each quantum of energy is so small that the fork contains billions of them even at a degree above absolute zero. To suck out enough of them to see the zero-point motion, the fork would have to be cooled to a few billionths of a degree.

Or an experimenter could

increase the size of each quantum of energy by cranking up the frequency of the fork. Shrinking the thing would work, as a smaller fork will ring at a higher frequency just as a violin produces higher notes than a double bass. That's essentially what physicists are doing by fashioning tiny vibrating beams only dozens of nanometers thick and a few micrometers long out of materials used in microchips, such as gallium arsenide, silicon, and silicon nitride. With masses of several millionths of a nanogram and containing just a few billion atoms, the tiny beams vibrate hundreds of millions of times a second: Roukes and colleagues have just punched through the billion-cycle-per-second barrier. That means researchers might see the zero-point motion of the devices if they can cool them to a few thousandths of a degree—a routinely obtainable temperature.

Of course, such tiny devices move far less than an ordinary tuning fork. The zero-point motion of a typical beam would be less than a thousandth of an atom's width. To track such small movements, most researchers employ an exquisitely sensitive electrical valve known as a single-electron transistor. Electrons can hop one by one from the input to the output of the device, but only if a certain voltage is applied to a controlling "gate" electrode. By having the motion of the beam change the gate voltage, perhaps through an electric field emanating from another electrode on the beam, researchers can take their observations by monitoring the current through the transistor (see figure on p. 36).

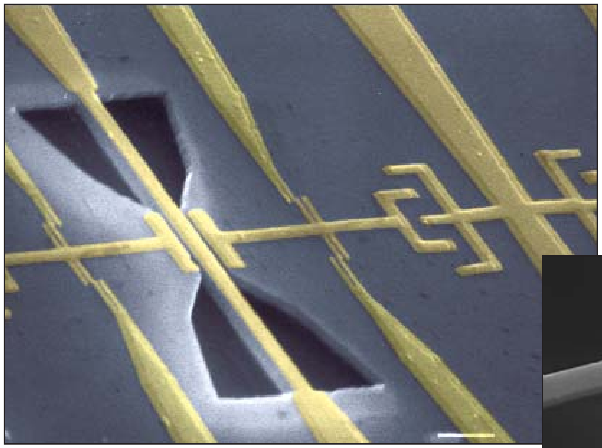
Cobbling together such tiny motion sensors is no mean feat, says Robert Knobel of UC Santa Barbara. "We're definitely leveraging every bit of semiconductor and lithography technologies," he says.

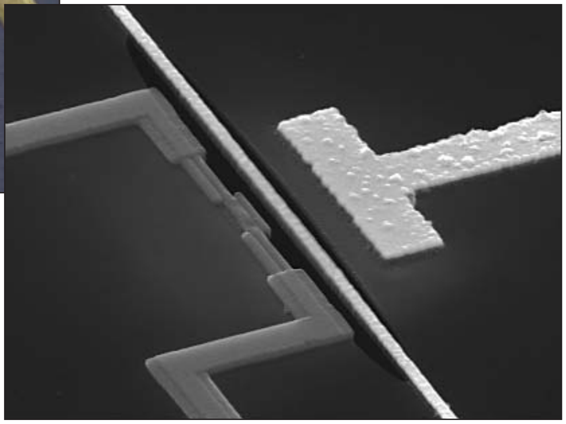
Spin doctors

Reaching the quantum limit of motion could open new avenues of technology, says Chris Hammel of Ohio State University in Columbus. That's because tiny beams and fingerlike appendages called cantilevers make force detectors whose precision is limited by how well researchers can follow their motion. A cantilever with a magnetic tip might even be able to sense the undulating magnetic field of a single twirling atomic nucleus—the ultimate in nuclear magnetic resonance. "If you can look at each nuclear spin in a molecule," Hammel says, "you can take a single molecule and determine its structure."

More immediately, quantum-limit measurements might lead to improved techniques for doing nuclear magnetic resonance on small samples, such as films, or probing the architecture of microchips. Much farther down the road, individual magnetic nuclei might serve as the qubits—bits that can be set to 0, 1, or 0-and-1 at the same time—that will enable quantum computers to crunch many different numbers at once. If so, tiny nanomachines might serve to read out those qubits.

Nanomachines themselves might serve as qubits, says Robert Blick of the University of Munich, Germany. Even as he pushes to reach the quantum limit with a single device, Blick has a plan to string together several machines as qubits. If such fanciful schemes pan out—and that's a big if—the quantum computers of the future might have as much in common with the adding machines of yesteryear as with personal computers.





Humming different tunes. Andrew Cleland and Robert Knobel etch their nanodevice (above) from gallium arsenide; Keith Schwab fashions his (right) from silicon nitride.

CREDITS: (TOP TO BOTTOM) R. KNOBEL; K. SCHWAB

Most speculatively, machines in quantum motion might help explain why large objects never appear in two-ways-at-once superpositions. Many physicists think that quantum mechanics itself provides the solution to the puzzle. An individual atom can persist in a superposition, they say, because it interacts only very weakly with its environment. A big object, on the other hand, inevitably feels the effects of its surroundings much more strongly, so its quantum states entwine with the quantum states of the rest of the universe in a process called decoherence. The environment tips a large object into one possible condition or the other, eliminating the this-and-that superposition, says Wojciech Zurek, a theorist at Los Alamos National Laboratory in New Mexico.

Other theorists, however, suspect that the story is stranger than that. Roger Penrose of the University of Oxford, U.K., theorizes that a large object that's in two places at once interacts with itself through gravity in a way that tugs it to one place or the other. Philip Pearle of Hamilton College in Clinton, New York, speculates that the universe is filled with a strange "noise" that jostles a big object one way or the other. If there is something beyond quantum mechanics, "then there's a huge fish to find out there," says Keith Schwab, a physicist at the National Security Agency (NSA). To find the fish, Schwab says, you have "to take these devices and make them bigger and bigger and bigger."

Working at NSA's Laboratory for Physical Sciences in College Park, Maryland, Schwab has devised a scheme to do just that. He envisions putting a tiny dab of superconducting metal called a "Cooper pair box" on a vibrating beam. Electrons in superconductors travel in pairs, and individual pairs can jump into or out of the box. Electrons in the box will feel a pull, thanks to the electric field between the beam and the gate electrode of the single-electron transistor. As a result, when an extra pair of electrons hops into the box, the beam will draw slightly closer to the gate. Schwab plans to put the box in a superposition of two states that differ by one pair of electrons. If all goes well, he says, the pull of the field should force the beam to occupy two different positions at the same time.

But before researchers can attempt such ambitious stunts, they have to prove that they can perceive the slightest movement. Speeding their progress is a friendly and almost familial rivalry: Schwab, UC Santa Barbara's Cleland, and Munich's Blick all worked as postdocs in Roukes's lab at Caltech. With so many challenges before them and so much competition between them, these researchers have to keep moving—just like the tiny machines they study.

–ADRIAN CHO

Adrian Cho is a writer in Grosse Point Park, Michigan.