Making Waves With Interfering Atoms

A brace of new interferometers substitutes atoms for light waves and gains impressive boosts in precision

MODERN PHYSICISTS SOMETIMES HAVE TO swallow some outlandish notions about matter. Particles and even whole atoms don't confine themselves to one spot but spread out and flow like waves—existing nowhere and everywhere along the wave fronts. If the conditions are right, a particle encountering a barrier cut with two openings will slip through both holes simultaneously, like a water wave passing through two gaps in a breakwater.

Now, the true believers are making use of the wavy nature of matter. Researchers are building "optical" devices that substitute whole atoms for light. In just the last 4 months, four groups have announced "atom interferometers"—devices that divide and recombine atom waves. The devices—the quantum-mechanical inverse of the optical interferometers often used to make fine measurements—underscore the reality of quantum mechanics' bizarre assertions. And, as a practical matter, they promise to outdo the precision of their optical counterparts.

Conventional interferometers work by splitting up a beam of light, allowing the new beams to follow different paths and then recombining them. The recombined light waves interfere with each other, creating a pattern of bright lines where the waves reinforce each other, separated by dark lines where the waves cancel out. Because this interference pattern is exquisitely sensitive to the path lengths of the split beams and to the wavelength of the light, interferometers can make precise measurements of both variables.

What is possible with light should, according to quantum theory, be possible for matter as well. It's a commonplace of quantum physics that electrons and other particles can be made to act like light; indeed, interferometers based on electrons and neutrons were built more than 20 years ago. But even something as substantial as an atom has a wavelength—one that depends on its momentum. For room temperature atoms, that wavelength is about 10,000 times shorter than the wavelengths of visible light.

The first confirmation that atoms can mimic light waves came in 1929, when atoms were observed diffracting from the surface of a crystal. Diffraction is the process of interference that takes place in light that has been broken up into many separate waves when it passes through a fine grating or is reflected from a grooved surface. The grooves responsible for diffracting the atoms were the minute atomic rows in the crystal lattice.

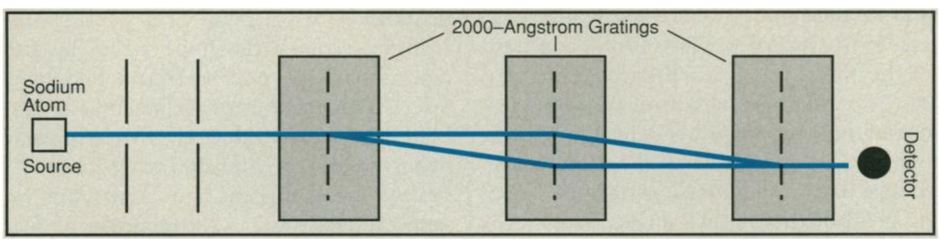
Diffraction is the basis of one of the new interferometers, which a research team headed by David Pritchard of MIT will be announcing in *Physical Review Letters*. By passing sodium atoms through a fine diffraction grating, Pritchard's device first breaks up the matter wave of each atom into separate components—the interference pattern's "bright" spots. Next, another grating sends two of the wave components toward each other, forcing them to interfere a second time. A third grating channels lines in this pattern to a detector. Like conventional interferometers, the device can record tiny shifts in the interference pattern.

What the detector actually picks up at the "bright lines" in the pattern, Pritchard emphasizes, are whole atoms, not some strange fractional entities. The lines are actually the positions at which atoms are most likely to emerge from the apparatus. Thus each atom, after having its matter-wave broken up into myriad separate pieces and interfering with itself twice over, emerges from this ordeal unscathed, like the woman in the magic box who gets sawed in half and then jumps out whole and smiling to take a bow with the magician.

The feat may be easy for atoms, but staging it was a challenge for Pritchard and his colleagues. Ordinary diffraction gratings are far too coarse to diffract atoms. Pritchard spent months trying to create gratings with slits just 2000 angstroms wide—a few thousand atom-widths—and near perfect regularity and straightness. "We had to rely on the latest advances in nanotechnology," says Pritchard. Shielding the device from ordinary room vibrations, which Pritchard says would have obliterated the delicate interference signal, presented a second hurdle.

Pritchard believes these pains will pay off in a host of unique applications. Anything that affects the paths of the diffracted matter waves should shift the resulting interference pattern, and because the wavelength of the atoms is so much smaller than that of light, Pritchard's atom interferometer is far more sensitive than optical devices. "We get a sensitivity to rotation ten orders of magnitude better than a light interferometer," he says.

That sensitivity to rotation may make the device useful for navigation and for testing certain predictions of general relativity—that the spinning earth causes objects to slowly circle, or "precess," for example. Pritchard also looks forward to applying his new gadget to fundamental tests, such as making sure that atoms are really, as we assume, electrically neutral. Applying an electric potential to one side of the device, he says, will shift the paths of the atoms—and hence the interference pattern—if the atom is even the slightest bit positive or negative, even if the difference is only enough to give a single electron's charge to a mass as big as a bowling ball.



Running interference. *In David Pritchard's design, a single atom follows multiple paths before casting its interference pattern onto a detector.*

Pritchard will not be carrying out these exercises without competition: Three other groups announced atom interferometers at about the same time as he did. One device, built by J. Mlynek of the Universität Konstanz in Germany, detects the interference patterns created when helium atoms pass through two tiny slits in a gold foil. The other designs—one developed by Steven Chu's group at Stanford University and the other by F. Reihle of Physikalisch-Technische Bundesanstalt in Braunschweig, Germany—both work by a different principle. Instead of splitting up atom waves by means of solid foils or gratings, these separate and recombine them entirely with laser pulses.

Chu demonstrated his design at last April's meeting of the American Physical Society. He says he didn't have to persist for months to overcome technological hurdles, as Pritchard did. "It worked the first time we tried it." The challenge, he says, came in the conception, since his device has no parallel in earlier optical interferometers.

Chu starts by slowing down vaporized sodium atoms and pinning them in place with a net of lasers known as optical molasses. He then releases them through the interferometer in a slow-flowing "atomic fountain." A kind of quantum dissecting mechanism operates on the atoms as they drift by. It begins by administering jolts from two lasers tuned to give the atoms a 50-50 chance of jumping into a second, slightly higher energy state. As a result, the wave representing each atom—technically known as a probability wave—broadens to encompass both states. In a sense, the atom now exists in both states at once. Chu explains that the higher-energy state, having absorbed the impact of two photons, actually careens away from the first one, creating the two wave paths any interferometer requires. During each atom's leisurely passage through the device, its two guises can move several millimeters apart.

Not that you could peer inside the device and see each atom and its doppelgänger. "If you look, you will see it in [only] one state or the other," says Chu. Like Schrödinger's cat, which is both alive and dead but becomes one or the other when its box is opened, the atoms pursue their double existence only in the utmost privacy. But they do give evidence of their duality in the form of the interference pattern that results as the two states of each atom spread out and overlap. The interference pattern takes the form of a periodic distribution of momenta that Chu reads with a third laser.

Chu explains that for measurement applications, the long-lasting separation of the states gives much greater precision. "With slow atoms, there is enough time for the forces you want to measure to act." That advantage has already allowed him to make one measurement of record-breaking precision—of the earth's gravity.

Chu and Pritchard both see wider futures for their atom interferometers. Pritchard, for example, has wondered whether it might ultimately be possible to interfere chunks of matter bigger than atoms. Bigger objects also have a wavelength, he says, but it is even shorter than that of atoms. To give the matter waves enough time to become well-separated, he would have to send them through the device very slowly. The biggest object he could split up through his grating, Pritchard says, would be a tiny speck, containing about 10^{13} atoms. Any bigger, he says, and its travel through the device would exceed the lifetime of the graduate student assigned to carry out the experiment.

■ FAYE FLAM

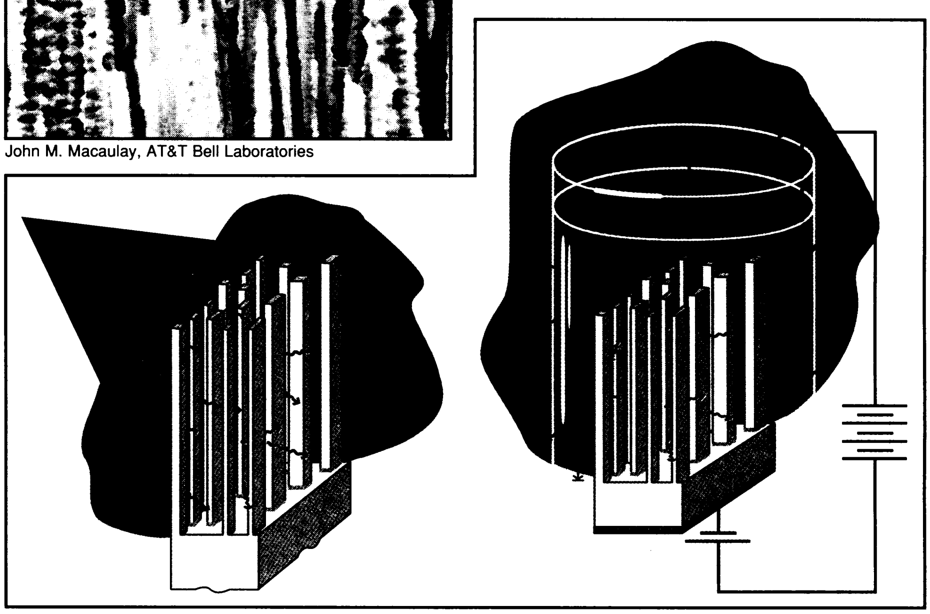
Shine On, Holey Silicon

Already famous for its way with electrons, silicon now shows a tantalizing grace with photons.

AN UNEXPECTED GLOW—IN SHADES OF RED, green, yellow, or orange—emanating from silicon wafers in a pair of French and British laboratories might represent the first glimmers of a bright new future for silicon. The colorful display is the first indication that silicon can be induced to emit light. And if silicon turns out to be as good with light as it is with electrons—and that's a big if—the familiar semiconductor could play as large a role in the emerging technology of optoelectronics as it has in the microelectronics revolution. The merger of optical and electronic circuits, which promises more powerful computers, faster communications, new image displays, and a host of other gizmos, could take place in tried-and-tested silicon rather than in more expensive and unwieldy materials.

At least that's the hope raised by the reports of light-emitting silicon presented on 25 April at the spring meeting of the Materials Research Society (MRS) in Anaheim, California. Already, other laboratories are duplicating the light show. And the semiconductor research community is furrowing its collective brow about how the glowing structures displayed at the MRS meeting could possibly work.

John M. Macaulay, AT&T Bell Laboratories



Making light. *Etched into a forest of micron-high pillars, porous silicon glows under the influence of light or (when immersed in electrolyte) electric current. An electron micrograph* (left) *reveals the structure of a nonluminous sample of porous silicon.*

After all, three decades of attempts to turn silicon into an optical material had been littered with enough failures that most investigators simply had relegated light-emitting silicon to the dream heap. "Up to now, the basic physics has been blocking us," says materials scientist John Bean of AT&T Bell Laboratories in Murray Hill, New Jersey. In the face of that seemingly intractable physics (see box), most materials researchers had turned to other light-emitting materials—the so-called III-V semiconductors, made by combining elements from the third and fifth columns of the periodic table. These compound semiconductors launched the first generation of optoelectronic devices—among them the familiar semiconductor lasers and light-emitting diodes—sales of which have already reached about $1 billion a year.

Still, participants in the worldwide effort to shape III-V (and II-VI) compound semiconductors into next century's technologies sometimes indulge in daydreams of light-emitting silicon. If only silicon could be made to emit light efficiently, it would have several immediate advantages over compound semiconductors. For starters, optical devices of silicon would integrate far more easily with standard silicon-based electronic