Catching the Atom Wave

Matter interferometers take quantum mechanics at its word, treating atoms like waves of light. They are coming into their own as tools for high-precision measurement of atomic properties

On a head-scratching scale of 1 to 10, the notion that matter can act as both a particle and a wave rates at least a 9. This concept, central to quantum mechanics, has mystified people for decades, inspiring science fiction and sophomoric philosophizing. Physicists are no more comfortable with it than anyone else, but they have learned to accept the weirdness and put it to work in such devices as the transmission electron microscope, which propagates and focuses electrons just as an ordinary microscope handles light waves.

Now researchers at the Massachusetts Institute of Technology are going even further in exploiting quantum weirdness—and at the same time pushing the head-scratching score up to near 10. Four years ago, a group led by physicist David Pritchard unveiled a prototype "atom interferometer" in which "matter waves" of atoms were split into two components and then recombined to create interference patterns, in much the same way ordinary interferometers treat light waves. The same group has now transformed this device from a curiosity into a practical instrument by learning how to influence one part of the matter wave while leaving the other untouched.

By measuring how the interference pattern changes in response to such influences as electric fields and the long-range effects of other atoms, the group can determine a variety of atomic properties with great precision—how an external field affects an atom's electron cloud, for example, and how the atoms of dilute gases attract or repel one another. "We're demonstrating that atom interferometers are actually good for something," Pritchard says.

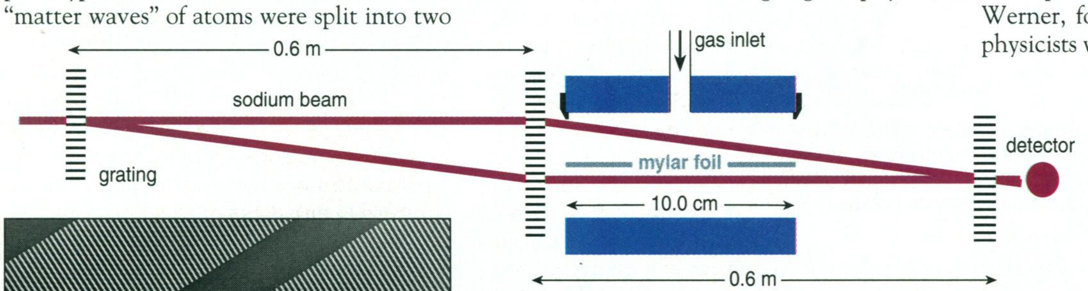
The results, reported in a series of just-published and forthcoming papers, are only the beginning, predicts Sam Werner, a physicist at the University of Missouri, Columbia: "I have the feeling that there are going to be many applications." At the same time, he says, the new experiments underscore the "magic of quantum mechanics." If the notion of treating atoms like light waves isn't astounding enough, Pritchard and his colleagues have now shown that even something the size of a molecule can act like a wave, traveling down two physically separate paths at the same time and then interacting with itself.

Although the interferometers in Pritchard's lab are on the cutting edge of physics, the idea behind them is more than a century old. Physicists in the late 1800s used mirrors and beam splitters—sheets of half-silvered glass that allow part of a light beam through while reflecting the other part—to separate beams of light into two parts and then rejoin them. If a reconstituted beam was shined on, say, a piece of white paper, it produced a series of light and dark lines: an interference pattern. The light areas marked places where the two beams were in phase and their waves added together; the dark areas appeared where the beams were out of phase and canceled each other out.

Because the interference pattern was extremely sensitive to anything that disturbed one of the light beams, researchers could use the interferometer to study subtle properties of light. Passing one beam through a piece of glass, for example, slowed the light wave slightly, changing the relative phase of the beams and shifting the interference pattern. The amount of the shift provided a measure of the refractive index of the glass—the speed of light in the glass versus in the air. The most famous use of interferometry was the Michelson-Morley experiment of 1887, which used a slowly rotating interferometer to show that the round-trip speed of light is the same in all directions.

The quantum revolution of the 1920s opened up a vast new vista for interferometers and other optical devices by showing that electrons, protons, atoms, molecules, and even larger objects all can be thought of as waves traveling through space. The wavelengths of these objects are generally so small that their wave nature is difficult to discern, but even so physicists have developed ways to exploit the wave nature of matter. Werner, for instance, is among a group of physicists who build and operate neutron interferometers to explore how neutrons interact with matter and electromagnetic fields. And over the past decade, atomic physicists have devised mirrors, lenses, and diffraction gratings that can manipulate beams of atoms like beams of light (*Science*, 20 March 1992, p. 1513). They have reflected atoms, focused them, formed diffraction patterns, and even created interference patterns.

But in all that time, no one had been able to build a practical atom interferometer, one that would allow researchers to probe the properties of matter waves in the same way that light interferometers opened up light waves to experimentation.



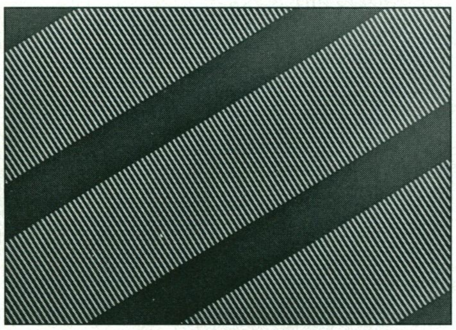


PHOTO BY MIKE ROOKS/NATIONAL NANOFABRICATION FACILITY SOURCE: SCHMIEDMAYER *ET AL.*/PRL

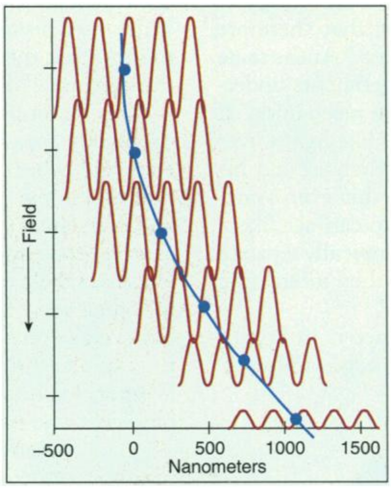
Running interference. An atom interferometer splits a beam of sodium atoms with a diffraction grating like the one at left, which has a spacing of 160 nanometers. The two parts of the "matter wave" rejoin to create an interference pattern that is sensitive, in this case, to how a gas influences part of the wave.

Separation anxieties

The obstacle is easy to state but difficult to get around, Pritchard explains. Building a truly useful atom interferometer demands that the atom beam be split into components that can be exposed to different conditions. To do so, Pritchard and his colleagues rely on a diffraction grating, a picket fence–like device with slats just a few hundred nanometers (billionths of a meter) apart. When a beam of light or atoms passes through a diffraction grating, it spreads out into discrete components that resemble the tines on a leaf rake: a "zeroth-order" component that points straight ahead, two "first-order" components that point to its right and left, and so on. For the atom interferometer, Pritchard uses only the zeroth-order and one of the first-order components. The angle at which the components diverge depends on the ratio between the wavelength of the beam and the spacing of the diffraction grating.

And there's the rub: The typical wavelength of the atoms in a beam is a fraction of an angstrom, while the spacing on the diffraction grating Pritchard and his colleagues used for their first interferometer 4 years ago was 400 nanometers. Because the ratio of the wavelength to the grating size is less than 1/10,000, it takes the diffracted atoms several meters to diverge by the width of the period at the end of this sentence. By passing the two separated parts of the wave through a second grating, the MIT group was able to create two sets of diverging components, some of which intersected to form an interference pattern. But the components that created the pattern were too close together to be influenced separately.

Pritchard's group has now solved the problem with two steps that pushed their equipment to the limit. First, they shrunk the spacing of the diffraction gratings down to as little as 100 nanometers—a step that increases the diffraction angle by a factor of 4 but also makes the interferometer far more sensitive to such outside influences as vibration. Then, taking advantage of the larger separation, the group slipped a piece of metal foil 10 centimeters long and only 10 microns thick between the beams to form a septum. That was much harder than it sounds, Pritchard explains, because the foil had to be almost perfectly flat to avoid blocking one of the atom waves. By creating two distinct channels down which the separated components of the beam can travel, Pritchard says, the septum transforms the device into a practical atom interferometer: "What we have now—although it's just a beginning—is good enough to do some serious science with."



SOURCE: EKSTROM *ET AL.*

Subtle effect revealed. A strengthening electric field shifts the interference pattern in an atom interferometer, reflecting the atoms' electric polarizability.

Getting down to business

Last month, for instance, his group tacked an extra decimal place onto the value of the electric polarizability of sodium atoms, a number that describes how the electrons circling an atom realign themselves when the atom is placed in an external electric field. The previous best measurement was more than 20 years old, and it could not discriminate among the 10 or so theories that had been advanced since then to calculate the electric polarizability figure. Pritchard's group improved the measured value by a factor of 10 by exposing one part of the interferometer beam to an electric field, leaving the other untouched, and observing the effect on the interference pattern as the strength of the field was varied.

As one beam passed through the electric field, the field decreased the beam's energy in a way that depended upon the atoms' polarizability, and this energy drop shifted the phase of the beam, modifying the interference pattern. The new numbers, says Keith Bonin of Wake Forest University, are the "most accurate polarizability measurement for any [solid or liquid in a vapor form]" and give atomic physicists new "benchmarks for theoretical calculations."

Chemists, meanwhile, will likely be interested in another set of atom-interferometer measurements: the indexes of refraction of various gases, including helium, neon, argon, nitrogen, and carbon dioxide, for a sodium matter wave. The work was analogous to measuring the index of refraction of glass with a light interferometer, but instead of putting a piece of glass in the path of one of the light beams, the MIT group placed a low-density gas in one of the arms of its atom interferometer. As the sodium matter wave passed through the gas, interactions with the gas atoms altered the phase of the sodium atoms in the wave, which in turn shifted the interference pattern.

Such atom interferometer experiments may help scientists understand the dynamics of chemical interactions, Werner says. The marriage of two atoms or molecules in a chemical reaction is determined by their interaction potential—the energy of attraction or repulsion between them. The index-of-refraction experiments in effect measure the interaction potential between the atoms in the beam and the molecules of the gas and are especially sensitive to long-range interactions, something that is difficult to measure with other methods. Already, says Werner, the measured refraction indexes of certain rare gases, such as neon and argon, imply that standard theory "needs revising."

Atom interferometers could make waves in still other fields, researchers say. In geophysics, tilting an interferometer and measuring how far its interference pattern shifts under the influence of gravity could provide sensitive measurements of local gravitational fields. And in navigation, interferometers could serve as gyroscopes that could detect very subtle rotational movements.

But one of the Pritchard group's latest results delivers a reminder that, however practical matter interferometry becomes, its underlying strangeness will linger. The experiment measured the index of refraction of neon gas for matter waves, but this time the researchers sent sodium molecules (each with two sodium atoms) through the interferometer in place of atoms. Just how remarkable that is becomes obvious when one considers that only a few thousand molecules per second pass through the beams, and it takes much less than a millisecond for each molecule to zip past the interferometer's septum. Thus, only one molecule will generally be in that section of the interferometer at any given time, and the enigma of wave-particle duality becomes inescapable. Anyone who has taken a chemistry course tends to visualize molecules as solid citizens. Yet in their passage through the interferometer the sodium molecules are indubitably waves, existing on both sides of the septum at the same time.

Could even larger and more complicated particles pass through an interferometer as waves? "I don't see that there's any limitation, at least in a physical sense," Werner says. There are, however, practical limitations, Pritchard points out. Because the wavelength of an atom, molecule, or larger particle is inversely proportional to its mass and velocity, larger masses have to pass through the interferometer more slowly. If not, even the finest conceivable diffraction gratings won't be able to separate the beams. "If you're willing to use a beam so slow that it takes a year between gratings," Pritchard jokes, "then I've calculated that you could use amoebas."

Even without moving up to amoebas, Pritchard says, interferometers may eventually help answer basic questions about quantum mechanics, such as where its limits appear. How big a particle can be used in an interferometer? Where does wave-particle duality break down, if it does? The head-scratching potential is unlimited.

–Robert Pool

Additional Reading

M. S. Chapman *et al.*, "Optics and interferometry with Na_2 molecules," *Phys. Rev. Lett.*, in press.

C. R. Ekstrom *et al.*, "Measurement of the electric polarizability of sodium with an atom interferometer," *Phys. Rev. A* **51**, 3883 (1995).

"Interferometry with Atoms and Molecules," David E. Pritchard *et al.*, in *Fundamental Problems in Quantum Theory* **755**, 192 (1994), D. M. Greenberger and A. Zeilinger, Eds.

J. Schmiedmayer *et al.*, "Index of refraction of various gases for sodium matter waves," *Phys. Rev. Lett.* **74**, 1043 (1995).