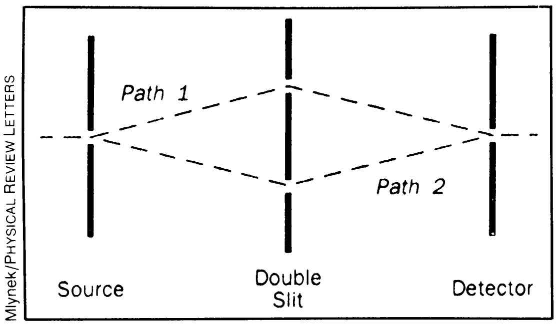
Riding the Atomic Waves

By JOHN TRAVIS

With the magic of quantum mechanics, an atom goes two ways at once



Mlynek/PHYSICAL REVIEW LETTERS

In 1802, British physicist Thomas Young split individual photons into two different wave paths with his double-slit apparatus. This year, German researchers managed a similar trick with a beam of helium atoms passing through microscopic slits in thin gold foil.

Physicists have added a new trick to their experimental repertoire. In their latest feat, called atom interferometry, they paradoxically divide and recombine single atoms, aided by a beautiful but enigmatic assistant known as quantum mechanics.

Four teams have recently performed atom interferometry, each using a different technique to accomplish this same bit of seeming magic. Unlike real magicians, however, these physicists eagerly explain the mysteries of their craft. In the past few months, all four groups have shared the secrets of their atom interferometers.

Interferometers are highly sensitive instruments that provide exact measurements of extremely small distances and physical properties such as wavelength. Scientists use them mainly for experimentation, but the devices have several commercial applications as well. Laser interferometers, for instance, play a vital part in advanced gyroscopes.

In the past, interferometers accomplished their precise measurements by manipulating electrons, neutrons or light. Researchers have now made even more sensitive instruments that extend those manipulations to atoms.

In the paradoxical world of quantum mechanics, an atom – like a photon – can be thought of as both a particle and a wave. But atoms have a great advantage over photons when it comes to interferometry. The wavelength of an atom, known as its de Broglie wavelength, is based on its momentum and can be 10,000 times shorter than that of visible light. The smaller the wavelength used, the greater an interferometer's precision.

With the new atom interferometers, physicists plan to conduct difficult tests of atomic properties, general relativity and quantum mechanics. One such device shows promise for measuring gravitational acceleration with record-breaking precision.

The key to all types of interferometry lies in quantum mechanics' wave-particle duality. The instruments take a particle and break the single wave that represents it into multiple (usually two) distinct components. In an atom interferometer, for example, "each atom has been split and is going both ways at once," explains David E. Pritchard of the Massachusetts Institute of Technology in Cambridge. Yet an observer attempting to witness this counterintuitive split will see only one wave – a phenomenon arising from the quirks of quantum mechanics. With quantum mechanics, notes Pritchard, "you beat your intuition into submission."

After traveling their divergent paths, the wave components recombine at an awaiting detector. If their path difference is exactly the particle's wavelength or an integer multiple of it, the waves are "in phase" and harmoniously merge with each other – an effect known as constructive interference. In other words, the crests and troughs of each wave coincide and reinforce one another.

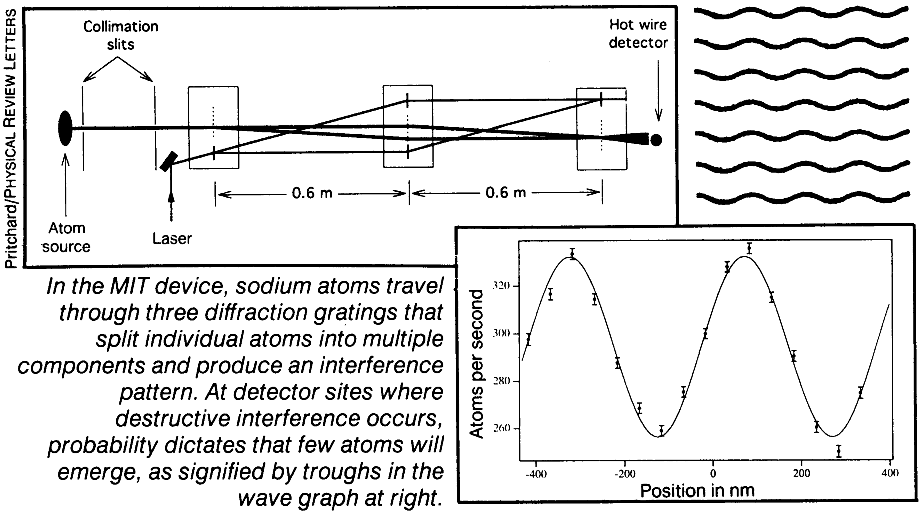
But at other spots on the detector, the path difference amounts to only a fraction of the wavelength, and the components are out of phase. The waves still recombine, but with destructive interference. At these places, where the merging waves are out of alignment, probability dictates that fewer particles will appear.

Light interferometers, for example, often produce an interference pattern consisting of a series of dark strips, where few photons emerge, and light strips, where many photons are detected. Atom interferometers show similar patterns based on the number of atoms at each spot on the detector. In effect, "you get light and dark spots of atoms," Pritchard says.

Careful examination of these interference patterns can reveal the minute fraction of a wavelength by which the atom's paths differed (the phase shift) and can even reveal the particle's wavelength.

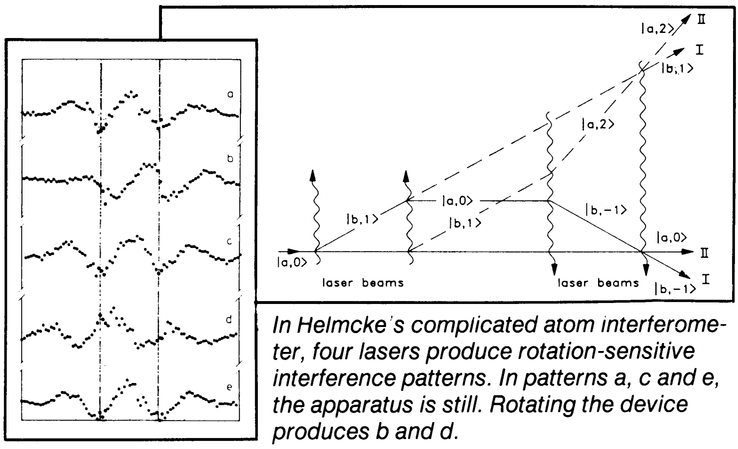
Pritchard's team and a German group unveiled their atom interferometers in the May 27 PHYSICAL REVIEW LETTERS. The German researchers, led by Jürgen Mlynek of the University of Konstanz, created their device by adapting the classic double-slit experiment of English physicist Thomas Young, who in 1802 used photons to demonstrate interference.

In Mlynek's atom interferometer, a supersonic beam of helium atoms passes through a 2-micrometer-wide opening in a thin gold foil. This "spreads" the atom into a wider wave before it travels through two smaller slits. While passing through the two smaller slits, the waves scatter again and eventually recombine into the original atom's single wave. Mlynek and co-worker Olivier Carnal suggest the device can resolve a phase shift equal to 0.053 of the atom's wavelength. Since an atom's wavelength is



Pritchard/PHYSICAL REVIEW LETTERS

In the MIT device, sodium atoms travel through three diffraction gratings that split individual atoms into multiple components and produce an interference pattern. At detector sites where destructive interference occurs, probability dictates that few atoms will emerge, as signified by troughs in the wave graph at right.



In Helmcke's complicated atom interferometer, four lasers produce rotation-sensitive interference patterns. In patterns a, c and e, the apparatus is still. Rotating the device produces b and d.

Helmcke/Physical Review Letters

known, the researchers can translate that phase shift into the minute distance by which the wave paths differed.

Pritchard's device – which uses a thin silicon-nitride membrane with a series of extremely fine slits cut into it for a diffraction grating – is even more sophisticated. A beam of sodium atoms must travel through three of these diffraction gratings before yielding an interference pattern. This instrument can resolve a phase shift of 0.016 wavelength, a significant improvement over Mlynek's device, Pritchard says. Moreover, the use of sodium allows additional precision, since sodium atoms are heavier than helium atoms and therefore have a shorter de Broglie wavelength.

That precision wasn't easy to achieve. To preserve the instrument's sensitivity, the MIT researchers had to incorporate a number of features merely to eliminate vibrations and maintain the alignment of the three diffraction gratings. They even included a laser interferometer to continuously monitor the gratings' alignment.

Physicists have long used atoms – in the form of solid objects such as diffraction gratings, mirrors and lenses – to manipulate light. Some of the new interferometers do just the opposite: Light – in the form of laser pulses – manipulates atoms. In the July 8 Physical Review Letters, two groups describe atom interferometers that accomplish this reversal.

In one such device, a calcium atomic beam is divided into four wave paths by two laser beams perpendicular to the atoms. A second pair of lasers, aimed in the opposite direction of the first pair of laser beams, redirects the waves to either of two detection areas, where the atoms are counted. Both detectors reveal interference patterns, although chance determines which detector will tally a given atom.

This complex instrument is sensitive to rotational changes, report Jürgen Helmcke of the Federal Agency for Technical and Scientific Research in Braunschweig, Germany, and his colleagues. By rotating their instrument on a turntable at different speeds, the researchers can influence the paths of the wave components, thereby shifting the resulting interference patterns. The laser gyroscopes on many of today's airplanes work by a similar principle, but theory indicates that an atom-based system would offer 10 billion times as much sensitivity, useful for general-relativity experiments.

At Stanford University, Steven Chu and his colleagues manipulate atoms of a slightly different sort. While other research teams work with fast-moving atomic beams, Chu slowly pumps laser-cooled atoms through his interferometer with an "atomic fountain" (SN: 8/19/89, p.117). The languid atoms spend up to 0.5 second within the device – an important consideration in measurements of minute effects. "The sensitivity [of an interferometer] increases when you use slow atoms," Chu explains.

Pritchard agrees and says he plans to try slower atoms in his own devices. He adds, however, that the "brightness" of such sources needs improvement. Chu's fountain can deliver atoms much more slowly than an atomic beam, he says, but it cannot yet match the beam's intensity – the number of atoms delivered.

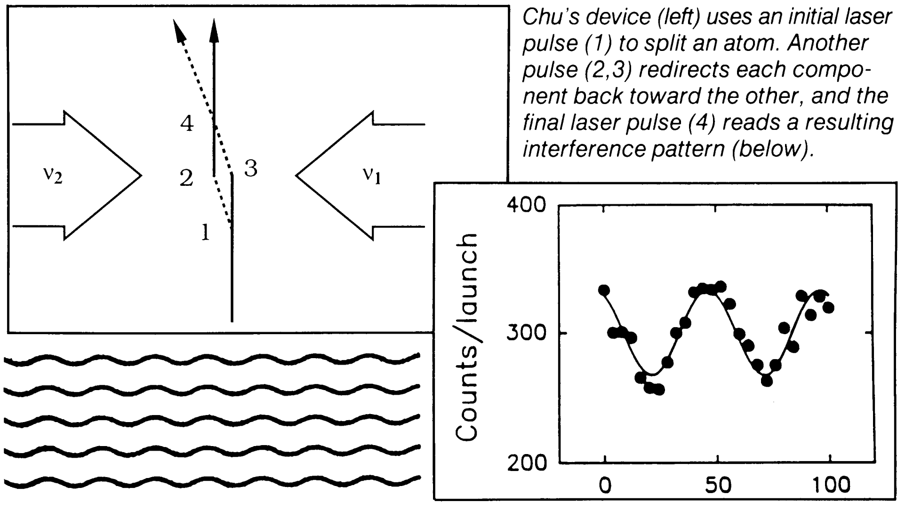
In Chu's interferometer, lasers not only precool atoms but also lie at the heart of the device. Two lasers – one on each side of the atom's path – provide an initial pulse that splits the atom into a superposition of two different energy states. The higher energy state, recoiling from the laser pulse, moves away from the lower energy state so that the atom appears to be in two places at once. A second pulse reverses the action, causing the atom to reconverge. A third laser pulse ultimately reads the interference pattern.

For another experiment, Chu directed the lasers along, rather than across, the path of the crawling atoms. As a result, an atom's components actually travel the same path at slightly different speeds, so that they move apart from each other in space. This setup should allow the most precise measurement yet of a single atom's gravitational acceleration, potentially achieving a resolution of 1 part in 10 billion, the Stanford researchers assert.

With further refinement, atom interferometers could compete with the laser technology now used in gyroscopes, says Pritchard. But these new devices will shine their brightest in probing the minute details of physics, he maintains. For experimental physicists, improving measurements by a single decimal place can represent a life's goal – a goal now achievable with atom interferometers.

This added precision should help to test the predictions of general relativity and might finally lay to rest the controversial issue of a fifth force, physicists say. It might also dispel any remaining doubts about the charge neutrality of atoms. To confirm atomic neutrality, experimenters would apply an electric field to only one wave component of an atom. If the atom is not neutral, the field will create a discernible change in the interference pattern.

While the new interferometers provide a powerful tool for unveiling atomic properties, "we're not going to find that quantum mechanics is wrong," cautions Pritchard. That's fortunate – because without the perplexing theory, physicists could never have performed their latest show-stopping trick. □



Chu's device (left) uses an initial laser pulse (1) to split an atom. Another pulse (2,3) redirects each component back toward the other, and the final laser pulse (4) reads a resulting interference pattern (below).

Chu/Physical Review Letters