

ATOMS ARE THE NEW WAVE IN INTERFEROMETERS

Interferometers based on matter waves are just the kind of precision tools needed to hone the cutting edge of physics. The de Broglie wavelengths of atoms, for example, are about 10 000 times shorter than those of light, and they offer correspondingly greater sensitivity. Electron and neutron interferometers have been around for some time, but atom interferometers have remained just out of grasp.

Although many hands have been reaching for them, it is a stretch: The atomic wavelengths of roughly 1 angstrom set the scale of precision with which the interferometer must be controlled. And atoms have neither the charge of electrons nor the ability of neutrons to penetrate matter, both of which facilitate the design of interferometers.

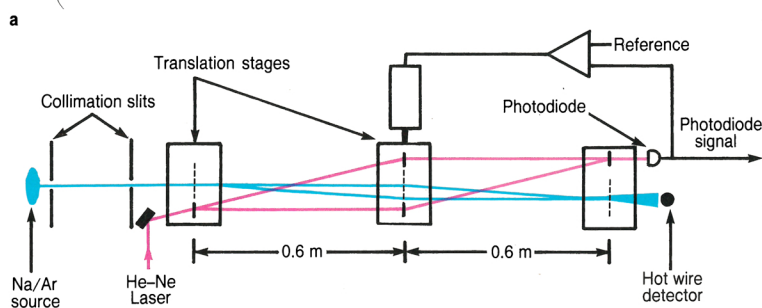
Recently, however, several groups have reported the development of atom interferometers. One of these devices, built by a group at MIT, bears a close resemblance to typical optical interferometers, such as the Michelson interferometer, which feature a beam splitter to divide the wave into two beams and mirrors to recombine them. But the other "interferometers" are all sufficiently different to have spawned some discussion of just what constitutes an interferometer. As a common denominator, they all separate the waves in some way and demonstrate a resulting interference pattern. Jürgen Mlynek of the University of Konstanz in Germany, who conducted a Young's double-slit experiment with atoms, feels that the key question is whether the device can measure a phase shift resulting

from a perturbation introduced into the interferometer.

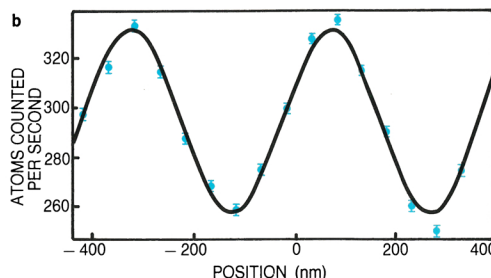
Although they are more difficult to construct than neutron and electron interferometers, atom interferometers may offer some distinct advantages. Atoms have higher masses than neutrons or electrons, so they can have smaller de Broglie wavelengths even at moderately slow velocities.

Like neutrons, atoms have no electric charge, which precludes certain applications. But, unlike neutrons, atoms can be produced easily in beams of high flux. Moreover an atom interferometer can be sensitive to the particular atom's internal degrees of freedom, thus permitting some experiments not possible with neutrons or electrons. Another advantage is that atoms come in many types, so that one can, for example, choose atoms with large or zero magnetic moment, and masses and polarizabilities that vary by factors of 100.

No doubt the new devices will quickly be put to use for fundamental tests of physics. They might be used to repeat with greater accuracy many tests already done by neutron interferometry, such as the validation of the Aharonov-Casher effect (see *PHYSICS TODAY*, January 1990, page 17) or measurements of Berry's phases. Many researchers are eager to check the charge neutrality of atoms. Another category of applica-



Atom interferometer resembling a Michelson light interferometer was built by a group at MIT.² **a:** Beam of sodium atoms (blue) travels through a series of three gratings with 400-nm rulings. Known interference pattern for laser beams (red) is used to calibrate the position of the fringes. **b:** The resulting fringe spacing can resolve the phase to within 0.1 radian.



tions is measurements of atomic properties such as polarizability or phase shifts due to collisions.

On the more practical side, atom interferometers hold great promise for very sensitive measurements of accelerations and rotations, as John Clauser of the University of California at Berkeley pointed out a few years ago.¹ These devices might find their way into inertial guidance navigational systems. They might also be used for very precise determinations of the local acceleration of gravity, aiding searches for a fifth force or—perhaps more profitably—explorations for oil.

Mechanical interferometers

The MIT group that built the Michelson-type interferometer consisted of David W. Keith, Christopher R. Ekstrom, Quentin A. Turchette and David E. Pritchard.² They used a beam of sodium atoms (with a de Broglie wavelength of 0.16 Å) instead of light, and they constructed gratings with line spacings of 400 nm to play the roles of beam splitters and mirrors. As shown in the figure on page 17, the first transmission grating separates the atom wave into fringes of different order. The zeroth- and first-order fringes hit the second grating, which diffracts them. The first order fringes from this second grating converge at the third grating.

The third grating is part of the detection scheme: One could in principle see the fringes without it, but they are only 0.1 μm wide and they have a very low intensity. Thus the MIT group has designed a detection scheme that essentially integrates the fringe intensity. The third grating

has exactly the same spacing as the expected fringe pattern arriving at its plane, so that the grating transmits the waves when its slits coincide with the fringes, and blocks the waves when they do not. The grating is moved back and forth in a plane perpendicular to the atomic beam, and a 25-micron-diameter hot wire behind the grating integrates the intensity at every position.

Pritchard's MIT group had to overcome two major hurdles to make their interferometer work. First, each grating had to maintain the phase of the beam over its entire area, lest the wavefront be distorted so badly that it could not be recombined. Thus the atomic physicists at MIT learned a bit about etching and lithography, working together with Michael Rooks and other staff members at the Cornell's National Nanofabrication Facility to produce high quality gratings.

Second, the group had to eliminate or correct for rotational or translational motion of the apparatus as a whole and for relative motion of the gratings. They used a combination of passive isolation, such as rubber feet, and active feedback for this purpose. The active-feedback system consisted of a laser beam diffracted through gratings in the same planes as the three gratings for the atomic beam.

Rather than trying to measure an absolute position for the fringes, Pritchard and his colleagues determined their position relative to the known pattern of the laser interferometer. Thus if the second grating moved relative to the third, for example, the motion would be seen in the laser pattern, and the measured atom signal would be assigned to the correct position. The fringe pattern is shown in part b of the figure on page 17. With a one-minute measurement, the researchers can determine the phase to within 0.1 radian.

A simpler arrangement—a Young's double-slit experiment for atoms—was developed by Mlynek and Olivier Carnal, also of the University of Konstanz.³ (See the figure on page 18.) They reported their experiment at the meeting of the Optical Society of America in Boston last October. In their device a helium beam contain-

ing some metastable atoms impinges on a microfabricated gold structure consisting of two 1-μm-wide slits that are separated by 8 μm. The fringes from the double-slit interference pattern are detected in a plane containing a single 2-μm slit. Behind the slit is a detector—a secondary electron multiplier—that is sensitive only to the metastable atoms in the beam.

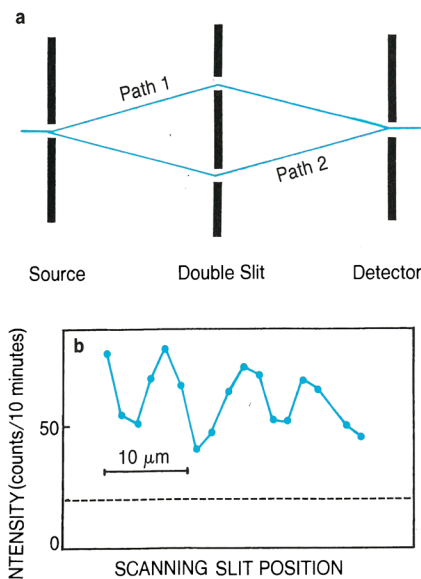
As in the MIT experiment, the slit is moved in the plane perpendicular to the beam. The Konstanz researchers advance their slit in steps of 1.88 μm, and they record the intensity measured by the detector at each position for ten minutes. The results (for an atomic wavelength of 1.03 Å) are shown in part b of the figure on page 18. To get a higher count rate Carnal and Mlynek replaced the detector slit by a grid with the same spacing as the expected fringe pattern. They note that they can measure a differential phase shift of about one third of a radian in a time of 10 minutes.

The Young's experimental arrangement leaves little room, physically, for the Konstanz researchers to introduce a phase change along one of the beam paths. They do have the possibility of introducing some type of external potential, for example, to test the Aharonov-Casher effect or to demonstrate Berry's phase. At present Carnal and Mlynek, together with Tycho Sleator, are preparing to study light-atom interactions such as phase shifts caused by the ac Stark effect. But to spread out the geometry a bit, they hope to use atoms with longer wavelengths, such as they might get from laser-cooled beams of metastable rare gases. In a first step, they have already doubled the helium wavelength to 2 Å by cooling the nozzle to 20 K with liquid helium.

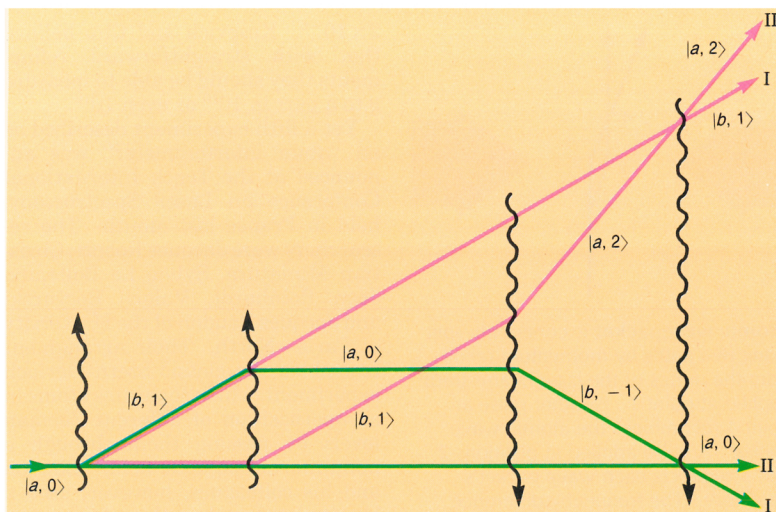
A Young's double-slit experiment is easier to accomplish with atoms than the Michelson-type arrangement of the MIT experiment: The accuracy of the grating is not as critical because the slit width is wider, and the apparatus does not require any active stabilization. Pritchard, however, notes that his group's experiment yields a better signal-to-noise ratio in a collection time of 23 seconds per data point than the Konstanz experiment does in 10 minutes. The Konstanz researchers are optimistic that by applying transverse laser cooling techniques they can increase the spectral brightness of their beam considerably and thus improve their signal-to-noise ratio.

Standing light-wave gratings

In 1986 Pritchard, with Phillip Gould



Young's double-slit experiment with atoms was done at the University of Konstanz.³ **a:** A helium beam (blue) passes through 1-μm slits and creates an interference pattern at the detector. **b:** Fringes for atoms with a de Broglie wavelength of 1.03 Å show the expected spacing of about 8 μm.



Sagnac effect in an atom interferometer. Calcium atoms are sent through two pairs of counterpropagating laser beams (black). As the atoms absorb or emit radiation in making transitions between the states $|a\rangle$ and $|b\rangle$, with different sublevels m , they experience momentum recoils. These recoils direct the partial waves along different paths. The two sets of paths are the two trapezoids shown in green and red lines. The detector records whether the atom arrives in state $|b\rangle$ (corresponding to detection at port I) or state $|a\rangle$ (port II). (Adapted from ref. 5.)

(now at the University of Connecticut) and George A. Ruff (Bates College) showed that one could employ standing light waves in place of material gratings to diffract atomic beams.⁴ These waves can then serve as coherent beam splitters and deflectors. This wave-particle dual to the diffraction of light waves by material gratings had been predicted in the early 1930s by Peter Kapitza and by Paul Dirac.

A light-wave "grating" consists of a standing wave perpendicular to the atomic beam, with its frequency close to a strong resonant absorption line of the atom to be diffracted. Viewing both atoms and light quanta as particles, one says that the atom passing through this grating absorbs a photon and then is stimulated to emit another in such a way that it experiences a transverse momentum recoil of $2\hbar k$, where k is the wavenumber of the standing wave, sending it in a different direction from the undeflected atoms. Alternatively one can explain this deflection as a diffractive wave phenomenon.

Although Pritchard's current MIT group finally opted to build its interferometer from material gratings, other groups have gone the optical route. Two groups that recently reported their results did not have light-wave gratings, but they used light in other ways to separate two parts of an atomic beam. One of these groups, a collaboration of German and French researchers, built an atom-beam interferometer that, like a Sagnac interferometer, is sensitive to the rate of rotation of the instrument.⁵ The collaboration consisted of Fritz Riehle, Thomas Kisters, Axel Witte and Jürgen Helmcke of the Physikalisch-

Technische Bundesanstalt in Braunschweig, Germany; and Christian J. Bordé of both the University of Paris—North and the University of Pierre and Marie Curie.

In a Sagnac interferometer the two beams travel in opposite directions around the perimeter of some area, meeting again at the origin. If the apparatus is rotating, the two beams will have a phase shift relative to each other when they recombine. The phase shift is directly proportional to the area enclosed by the beams and to the rotation rate about an axis perpendicular to the plane of the countercirculating beams. Clauser has pointed out that the light-wave Sagnac interferometer built by Albert A. Michelson and H. G. Gale in 1925 to measure the absolute rotation rate of the Earth enclosed an area many times the size of a soccer field, whereas the same experiment with a neutron interferometer requires only a few square centimeters. The Sagnac effect is the basis for the ring-laser gyroscopes now used on commercial aircraft.

The apparatus of Helmcke and his colleagues differs from a Sagnac interferometer in that the partial beams of calcium ions do not traverse the whole loop but rather meet halfway around. The partial beams are steered along different paths with the help of two sets of laser beams perpendicular to their paths. (See the figure on page 19.) As the atoms cross the first two laser beams some may be excited to the 3P_1 state, acquiring a recoil momentum in the same direction as the laser beams. Other atoms may remain unexcited, or they may be excited by the first beam and deexcited by the second one.

In any case, as the atomic beam emerges from the first two laser beams it has been split into four partial waves: two waves that travel at a small diffraction angle, and two others that are undeflected but separated. When these partial waves cross the next pair of laser beams, which propagate in the direction opposite to the first pair, they are again deflected, and two sets of partial waves converge, as shown in the figure. The various paths of the partial waves end up describing two trapezoids (outlined in different colors in the figure). In each pair of converging partial waves there is one in the ground state (detected at the port marked II) and a second wave in the excited state, as detected at the port marked I). Phase shifts in the partial waves can easily be introduced by changing the frequency of the laser fields. Such phase shifts could also come from a rotation of the apparatus.

The detector in the Braunschweig-Paris experiment is a photomultiplier tube that counts the number of atoms emerging in the excited state. The collimation of the atomic beam was not sufficient to allow the different atomic traces to be detected directly. In any case, the required narrow collimation would severely restrict the signal size. Thus the researchers looked for the excited atoms and detected their fluorescence by means of a photomultiplier.

The probability of finding the atom in the excited state (or equivalently at a given output port) has a harmonically oscillating part that depends on the phase shift between the partial waves. Even without rotation, the atomic beams will have Ramsey

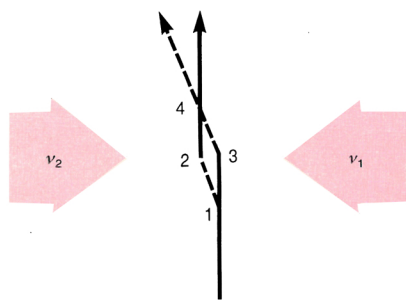
fringes, that is, interference effects between the two angular momentum states. The Ramsey fringes are peaks in the intensity as a function of the detuning of the laser beams. If there is any phase difference in the atomic beam due to rotation of the apparatus, it will show up as a displacement of these Ramsey peaks, with a greater rotation rate giving rise to a larger displacement. In this experiment, the observed shift of 8 kHz was consistent with the rate of the applied rotation, 0.09 rad/sec.

Atomic fountains

At Stanford, Steven Chu and Mark Kasevich have devised⁶ yet another variant on the interferometer—one that exploits the optomagnetic atomic trap and the “atomic fountain” they have developed. Whereas all the experiments described so far rely on an atomic beam, Chu and Kasevich work on cooled sodium atoms that have been launched vertically upward from the trap, which take as long as 0.5 sec to rise and fall. To introduce a momentum shift (and hence a phase shift) they induce a series of two-photon Raman transitions between two hyperfine ground states of the atoms. These transitions are stimulated by two counterpropagating laser beams. When any atom of mass M makes a transition it experiences a recoil velocity of $2\hbar k/M$ parallel to these beams that separates its path from those of atoms not making the transition.

The Stanford team’s interferometer operates by means of a sequence of laser pulses. The first pulse puts the wave packet into a superposition of the two ground states $|1\rangle$ and $|2\rangle$. Because of the velocity recoil, these two states are separated in velocity. The second pulse essentially reverses all the states, giving them velocity recoils in the opposite direction. For example, if the atom was originally in state $|1\rangle$ with momentum p (denoted as $|1, p\rangle$), the first pulse will put it into an equal superposition of the states $|1, p\rangle$ and $|2, p + 2\hbar k\rangle$. The second pulse essentially reverses the state so that the component $|1, p\rangle$ becomes $|2, p + 2\hbar k\rangle$. This second kick causes the separate paths to converge again. Depending on its phase, the final pulse puts the atoms into either state $|1\rangle$ or $|2\rangle$ for detection.

When the laser beams are horizontal, the recoils separate the various paths in space, just as a Mach-Zehnder interferometer does. (See the figure on page 20.) Chu points out that there is a close correspondence between his experiment and MIT’s



Atomic wavepacket is coherently split along two paths by momentum recoil from the pulses of the laser beams (red) applied at point 1. Another pulse at point 4 recombines the atomic wave packet. A pulse applied at positions 2 and 3 redirects each wave packet’s trajectory. The frequency difference $\nu_1 - \nu_2$ is resonant with the ground state hyperfine transition. This version of an atom interferometer was implemented at Stanford University. (Adapted from ref. 6.)

three-grating interferometer. For this Mach-Zehnder configuration, Chu calculates that the atoms were separated by about $84 \mu\text{m}$ in their recent experiments, but he claims that it is possible to get a separation as large as 1 cm by expanding the time between pulses.

When the laser beams are oriented parallel to the momentum of the atoms, the atoms separate longitudinally along their beam path. Operating in this configuration, the Stanford team has separated the atoms by as much as 2.4 mm.

In general the atoms in this apparatus should experience two kinds of phase shifts: one due to the free evolution of the atom from one light pulse to the next, and the other caused by the atom’s interaction with the light pulses. Kasevich and Chu took some pains to insure that the first of these phase shifts was zero. The second phase shift ultimately manifests itself as a Doppler shift in the resonant frequency of the Raman transition.

The Doppler shift depends on the deceleration of the atoms, and hence—for these atoms in free-fall—on the acceleration of gravity. A measurement of the frequency shift can thus, in principle, yield a value for g . In their recent experiment the Stanford team demonstrated that their setup can be used as a sensitive accelerometer. A count of the number of atoms in state $|2\rangle$ as a function of frequency has a 25-Hz linewidth and a frequency resolution of about

2×10^{-6} . Kasevich and Chu believe that with straightforward refinements they should be able to measure g to a part in 10^{10} or even 10^{12} .

Yet a fifth experiment described as an “atom interferometer” was announced at the Tenth International Conference on Laser Spectroscopy, held in France last month. The researchers were Jacques Robert, Christian Miniatura, Sylvie Le Boiteaux, Jean Reinhardt, Valerij Bocvarski and Jacques Baudon of the University of Paris—North. Their arrangement resembled the classic Stern–Gerlach experiment, which separates atoms in a superposition of different Zeeman levels by passing them through a nonuniform magnetic field.⁷ Baudon and his colleagues, however, used a longitudinal rather than transverse magnetic-field gradient. The field thus accelerated or decelerated the atomic spin states, depending on their spin, although it did not send them along physically separate paths.

In this experiment each atom breaks up into spatially separate packets, but the packets follow the same path. The question is whether the interference that results in this way is any different from what one gets in experiments such as Norman Ramsey’s separated-oscillatory-fields method, where atoms in different spin states travel through a uniform magnetic field.

The researchers from the University of Paris—North contend that their experiment is different, because, while one can get a Ramsey-type interference pattern without affecting the external motion, in their experiment the interference pattern results directly from the longitudinal separation of the wave packets associated with each spin state.

With so many atomic interferometers being reported in such rapid-fire succession, can applications be far behind? —BARBARA GOSS LEVI

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