Atom Interferometers Prove Their Worth in Atomic Measurements

Researchers have used an atom interferometer to measure for the first time the complex index of refraction for an atom wave passing through a gas and to determine the electrical polarizability of an atom more precisely than before.

Thanks to the wave nature of matter, it's possible to build the atomic analog of an optical interferometer, although it's extremely difficult, because the de Broglie wavelengths of atoms are typically 10 000 times shorter than those of light. The feat was accomplished four years ago by a number of groups, each with a different scheme for splitting and recombining the matter waves. (See PHYSICS TODAY, July 1991, page 17.) We are now starting to see the fulfillment of the hopes raised by those first atom interferometers as researchers hone their interferometers to yield ever more precise values of fundamental constants or explore fundamental aspects of quantum mechanics such as Berry's phase. For example, Steven Chu and his colleagues at Stanford University have measured[1] the ratio h/m of Planck's constant to the mass of a cesium atom with a precision of one part in 10^7, although the systematic errors are at the level of 1 part in 10^6. An experiment to improve the absolute accuracy of the h/m measurement to a few parts in 10^9 is underway. This ratio is one factor in the determination of the fine-structure constant.

Recently, David Pritchard of MIT, together with colleagues from MIT and Innsbruck University, Austria, have fruitfully applied their interferometer to the determination of atomic properties. First the group measured the complex index of refraction for sodium atoms[2] (and subsequently for sodium molecules[3]) traveling through various atomic or molecular gases. We aren't used to thinking about the index of refraction for atoms, but it's a simple matter of applying the optical analogy: The imaginary part of the complex index of refraction tells us the attenuation as sodium atom waves pass through a cell filled with, say, helium atoms. The real part of the index of refraction gives the phase shift induced as the sodium atom waves scatter within the gas. Before the atom interferometer there had been no way to determine that phase shift.

In another experiment the MIT–Innsbruck team measured the room temperature electrical polarizability of sodium atoms.[4] Their value is six times more accurate than obtained by any other method; it is precise enough to help distinguish among the many calculations of competing theories.

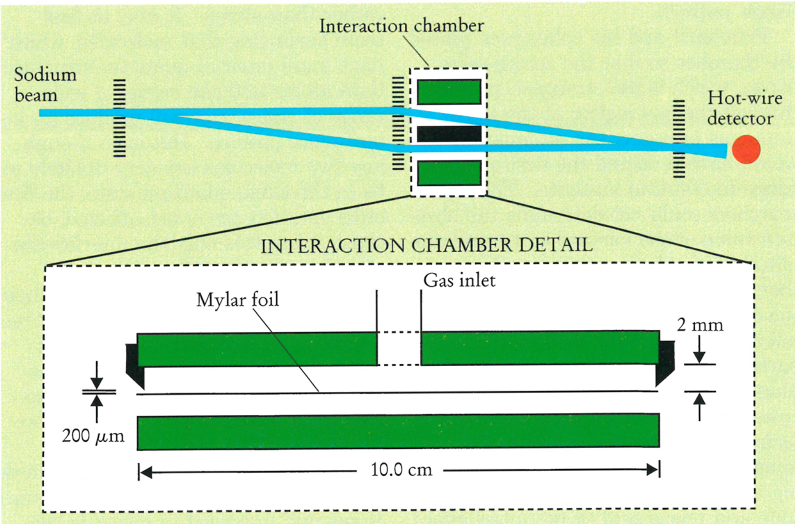
Working with Pritchard on these measurements are Michael Chapman, Christopher Ekstrom, Troy Hammond and Richard Rubenstein of MIT and Jörg Schmiedmayer and Stefan Wehinger of Innsbruck.

Separate paths

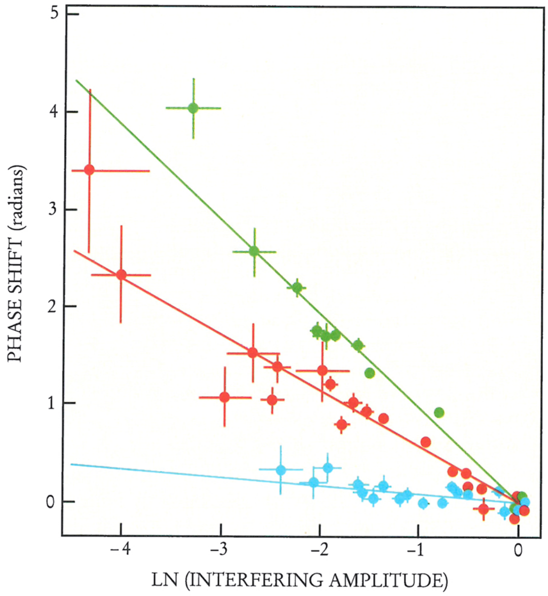
In the interferometer developed by the MIT–Innsbruck group, as in devices one traditionally associates with optical or neutron interferometry, different parts of the wave travel separate paths, and one can insert a physical boundary between those paths. The researchers were thus able to apply some type of interaction only to the portion of the wave on one side of the boundary and measure the phase shift that resulted when the atom wave was recombined.

The experimental setup is shown schematically in the figure below. A beam of sodium atoms passes through a series of three diffraction gratings, each with a 200-nanometer period. The first grating splits each sodium atom's wave into beams of different order. The figure shows the zeroth and first order beams. Diffraction at the second grating creates additional diffracted beams, two of which recombine at the third grating to produce fringes. This third grating is part of the detection scheme: It has the same spacing as the expected fringes, so that as the grating is moved laterally it transmits more atoms to a detector on the far side when the grating is lined up with the fringes.

The MIT–Innsbruck group first set out to determine the complex index of refraction for sodium, which is simply related to the forward-scattering amplitude for an atom passing through a gas. To measure the phase shifts caused by forward scattering of sodium



ATOMIC INTERFEROMETER of the MIT–Innsbruck group uses a series of three diffraction gratings to split and recombine the sodium atoms entering from the left. The zeroth and first-order diffracted beams are shown in blue. A movable hot wire detector (red) maps the fringe pattern. Inset shows the interaction region; gas fills only the top half of the cell, enabling measurement of the phase shift that results when just one of the two beams goes through the gas. (Adapted from ref. 1.)



PHASE SHIFT of the interference pattern as a function of the natural log of the interfering amplitude for sodium atoms in an interferometer one branch of which was filled with neon (green data points), argon (red) or helium (blue). The slope of each straight line is the ratio of the real to the imaginary part of the complex index of refraction for a sodium atom wave in that gas. (Adapted from ref. 1.)

waves in a gas, Pritchard and his colleagues had to introduce along one of the two paths a region filled with the gas to be studied. For that purpose they built a long, thin chamber, several millimeters high and 10 cm long. A 10-μm-thick aluminized Mylar foil partitioned the chamber lengthwise, and the top compartment was filled with gas. This chamber could be placed just beyond the second grating, so that one of the beams passed through the gas-filled chamber and the other through an evacuated channel. Any scattering of the sodium atom waves within the gas introduced a phase difference that shifted the fringe pattern.

Pritchard and his colleagues placed the chamber so that the zeroth-order fringe, which is the strongest, passed through the gas region; at the maximum gas pressure, the attenuation would have rendered the first-order fringe too faint to measure. The researchers could not determine the absolute value of the forward-scattering amplitude from their experiment because they did not have an accurate value for the density of the gas; they could only infer the value of the density by comparing their measurements of the attenuation with calculations of the total cross section. But they were able to determine the *ratio* of the real to the imaginary part of the forward-scattering amplitude by measuring the amplitude and phase shift of the interference pattern. (The amplitude $A(N_c)$ for a given column density N_c is measured relative to the amplitude with no gas in the cell.) The figure above shows the measured phase shift $\Delta\varphi$ as a function of the natural log of the interference amplitude $A(N_c)/A(0)$ for three different gases—helium, neon and argon; the slope $\Delta\varphi/\ln[A(N_c)/A(0)]$ of the data for each gas is the ratio $\mathrm{Re}(f(k,0))/\mathrm{Im}(f(k,0))$ of the real to the imaginary part of the forward scattering amplitude.

Pritchard and his colleagues noted that using different species of gas in the cell affected the measured phase shifts more than the attenuation. From this observation they inferred that the phase shifts were especially sensitive to the shape of the long-range interatomic potential.

Pritchard and his colleagues were able to repeat their index-of-refraction measurements using sodium molecules rather than atoms. It may at first seem surprising that molecules, which have more internal quantum structure than atoms and can occupy a wide range of states, can still produce an interference pattern. But even though any two molecules are very unlikely to be in the same quantum state, the first-order interference is not affected, because it involves only the interference of each molecule with itself.

To get a beam of molecules for their measurements, the MIT–Innsbruck researchers started with a supersonic beam containing both sodium atoms and sodium dimers and applied resonant light forces to selectively remove the atoms. They sent this beam through the same apparatus used to determine the refractive index of sodium atoms and managed to measure the same property for the dimers.

Daniel Greenberger of the City College of New York envisions the refractive-index measurements as a harbinger of more exciting experiments, ones that use the scattering of atoms and molecules to explore objects that have internal quantum structure. Greenberger, who has done interferometry work with neutrons—far simpler objects—sees this work as the first step in proving that quantum mechanics applies to large-scale macroscopic objects.

Measuring electrical polarizability

Placing a gas cell along one leg of an interferometer is only one way to produce a phase shift. Another way is to induce an energy shift. That is the approach the MIT–Innsbruck collaboration took to measure the electrical polarizability of the sodium atoms. They applied a dc electric field $\mathcal{E}$ to one branch of the wavefunction, shifting its energy by the Stark potential, $\Delta E = -\alpha\mathcal{E}^2/2$, where α is the polarizability. The change in energy causes a phase shift $\Delta\varphi = (\Delta E/\hbar t)$, and measurement of the phase shift yields a value for α.

The interaction region for the polarizability experiment was again a long thin chamber, but the partitioning foil divided the chamber into cells with and without a dc electric field. The center foil was made of conducting material, as were the top and bottom of the cell. The top and bottom then functioned as electrodes separated from the foil by insulating spacers. A voltage applied between the foil and either electrode produced a dc field along one of the interferometer paths.

Pritchard and his colleagues passed one part of an atomic wavefunction through the electric field region and determined the phase shift that resulted. They thus found the polarizability of sodium atoms to be 24.11×10^{-24} cm^3 with statistical and systematic errors each equal to $\pm 0.06 \times 10^{-24}$ cm^3. This value is six times more accurate than any previous measurement.

The MIT–Innsbruck team plans to measure more properties, including the velocity dependence of the forward-scattering amplitude, and to study the destruction of atomic coherence by photons scattered by atoms in the interferometer.

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