Researchers Put a New Spin on Bose–Einstein Condensates

A tiny vortex has been set spinning in a coherent collection of ultracold atoms. And there's a hint of frictionless flow. Such experiments should open the door to further studies of superfluid properties.

The earliest experiments on gaseous Bose–Einstein condensates established that they are coherent collections of atoms, all described by a single wavefunction—just like the known superfluids, liquid helium-4 and superconductors. It was natural to wonder if they would also exhibit some of the behavior that is so characteristic of those larger-scale Bose condensates, such as quantized circulation (vortices) or frictionless flow. Many theorists have proffered ideas on how one would produce vortices in a Bose–Einsten condensate and what their properties might be. One of those ideas has now been experimentally realized. The approach was suggested[1] by James Williams and Murray Holland of JILA and implemented by their experimental colleagues there.[2] (JILA is a jointly operated lab of the University of Colorado at Boulder and the National Institute of Standards and Technology. Williams is now at the University of Toronto.)

In separate work, MIT researchers have looked for evidence of frictionless flow in a Bose–Einstein condensate (BEC) by moving a focused light beam through the condensate. They recently reported evidence for a critical velocity below which little or no heating occurs.[3]

Vortices and frictionless flow are properties of the known superfluids, but what actually establishes a substance as a "superfluid" seems to be a matter of some debate: If a superfluid is a system that is described by a coherent macroscopic wavefunction, then BECs have already passed the test. On the other hand, if superfluids are substances that support persistent currents, even in the presence of a normal-fluid component, the proof will be difficult to achieve in a condensate that only lasts a few seconds. Neither group claims the observation of superfluidity, but they have taken significant steps in that direction.

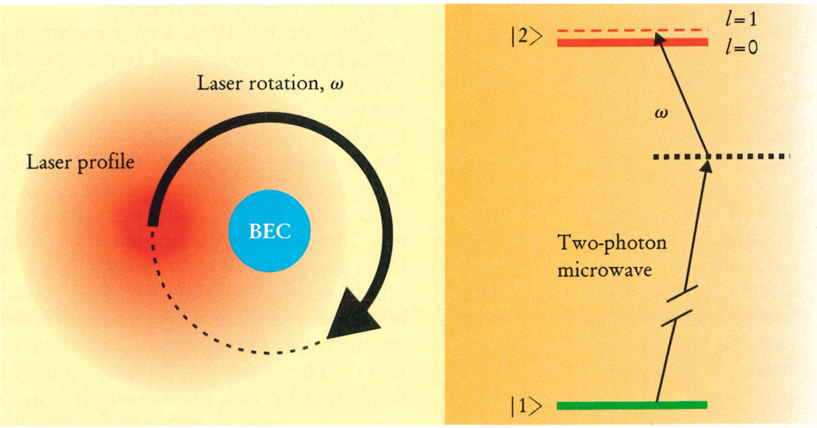
Such proofs aside, the study of superfluid properties is a fruitful direction for BEC research. For example, the rotating circulation seen in BEC offers some interesting opportunities to study vortices, which are so fundamental to liquid helium and superconductors. In the gaseous condensate, the interactions between atoms are weak and well understood, explains Carl Wieman of the JILA experimental group, and thus permit a more quantitative comparison of the calculations to the observed microscopic features than is possible in the more strongly interacting systems. (Some of the properties of a vortex in a Bose gas were discussed as early as 1961, by Lev Pitaevskii, now at the University of Trento in Italy and the Technion in Haifa, Israel.[4]) In addition, notes Sandy Fetter of Stanford University, the particular method used by the JILA group to form vortices introduces a new handle for manipulation that is not present in liquid helium.

The velocity of a simple superfluid like ^{4}He is proportional to the gradient of the phase of the wavefunction describing the condensate, so that demonstrating either linear or rotational flow means introducing a phase structure. Thus, one can think of a vortex either as the physical movement of atoms in a circular whirlpool or as a topological structure in which the phase of the wavefunction changes uniformly around a circle, by an integer multiple of 2π.

Spinning up the condensate

To form vortices in liquid ^{4}He, one usually rotates the cylindrical container before cooling it to form the condensate. The friction of the container walls drags the normal fluid along, providing the necessary angular momentum. In an atomic gas, however, the condensate is held by confining potentials rather than material walls, so that another handle is needed. Some individuals have suggested distorting the potential and rotating the container during cooling; others have proposed "stirring" the condensate with an optical beam. Still others have envisioned introducing angular momentum through interactions of specially tailored laser beams with the internal states of the atoms.

The method proposed by Williams and Holland involves a combination of external and internal interactions; the external interactions are provided



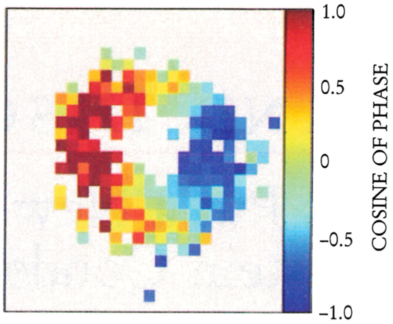
A ROTATING LASER BEAM, circling a Bose–Einstein condensate at a frequency ω, imparts an angular momentum that generates the vortex state (left). The microwave field shining on the condensate is far detuned from the transition between the initial, nonrotating state $|1\rangle$ and state $|2\rangle$ (right). The laser imparts the energy and momentum needed to reach the $l=1$ angular momentum state (dotted red level). (Adapted from ref. 2.)

by a rotating laser beam and the internal ones by the transition between two hyperfine ground states, $|1\rangle$ and $|2\rangle$, of the rubidium-87 atoms. The result of their scheme is to put state $|2\rangle$ atoms into a circulating fluid around a stationary core of state $|1\rangle$ atoms. The rotating laser essentially provides the temporal and spatial perturbation needed to drive atoms from the initial, nonrotating state $|1\rangle$ to a state $|2\rangle$ with one unit of angular momentum.

Here's how it worked in practice: The JILA experimenters started with a uniform cloud of atoms in state $|1\rangle$, already cooled into a condensate. They next applied a microwave field that was far detuned from the transition between states $|1\rangle$ and $|2\rangle$, so that the probability of atoms entering state $|2\rangle$ was small. They then shone a focused laser beam parallel to the trap's axis but offset from the center. They rotated the beam so that it traced a circular path around the axis in a plane perpendicular to the axis (see the figure on page 17).

Wieman likens the effect of the laser to that of a faucet on a hose: Whenever it shone, it turned on the transition from $|1\rangle$ to $|2\rangle$. That's because the laser field, through the AC Stark effect, shifted the energy of state $|2\rangle$, bringing the transition into resonance with the microwave field. When the laser shone on one point, it transferred atoms to state $|2\rangle$. It moved on and transferred more atoms on the next point, and so forth around in a circle. But each atom was created with a time lag behind its neighbor, so that there was a continuous shift in phase around the circle. The experimenters rotated the laser beam at the effective Rabi frequency—that is, the frequency of oscillation between states $|1\rangle$ and $|2\rangle$—so that the phase change as the laser went once around the circle turned out to be exactly 2π—which is just what's required for a quantized vortex.

The JILA experimenters were able to visualize the relative phases of their vortex structures by using a form of phase-contrast microscopy. The images taken by Wieman, Eric Cornell, and their coworkers showed that atoms in $|2\rangle$ were in a circular ring around the center while atoms in $|1\rangle$ resided in the core. The cosine of the phase of $|2\rangle$ relative to the (constant) phase in $|1\rangle$ is shown in the figure above. One can see the expected smooth variation of phase from 0 to 2π as one goes around the core. The stationary core provided the pinning that stabilized the vortex; when the core broke up, as it did after about 600 milliseconds, the vortex dispersed.



RELATIVE PHASE SHIFT of the vortex state as measured in a Bose–Einstein condensate by phase-contrast microscopy. The phase changes by 2π around the circumference, showing that the circulation is quantized. (Adapted from ref. 2.)

Changing symmetries

Williams and Holland came up with their scheme for producing vortices after participating in an earlier study with their JILA colleagues.[5] In that study, they were able to watch the phase structure of the wavefunction twist and untwist as a coupling field controlled the transition between two hyperfine states of a trapped gas.

Such twisting of the condensate's phase was seen in 1976 by the late John Wheatley's group in experiments on He-3A, which is a superfluid with similar internal rotational degrees of freedom. Jason Ho of Ohio State University notes that the two-component ^{87}Rb atomic gas used in the JILA experiments is an example of a spin-$1/2$ Bose gas, which he studied years ago,[6] although he feels that the significance of the vortices in BEC goes beyond the spin-$1/2$ Bose gas: "It is a general phenomenon of quantum Bose ferromagnets."

The recent JILA experiments on vortices and topological twists should intrigue field theorists, says Fetter, because they illustrate the ability in two-level atomic systems to switch dynamically between two symmetries, U(1) and SU(2), by turning on a microwave field to couple the two levels. The standard, single-component Bose gas, like ^{4}He, is described by a single phase that can be represented by a unit vector in a plane, with its tip on a circle; its symmetry is that of U(1). The two-component gas is described by two phases—like a unit vector in three dimensions, with its tip on the surface of a sphere, as in SU(2). In U(1), one has no way to eliminate a topological structure in which the phase changes by 2π. The structure acts like a rubber band encircling the surface of an infinite cylinder; one can't remove it. That's the reason for the persistent currents in ^{4}He and conventional low-temperature superconductors. But if one can switch to SU(2), the rubber band can be lifted off over one of the poles.

Measuring the drag

Chandra Raman and his colleagues at MIT explored linear, as opposed to rotational, motion of an object through a condensate.[3] The "object" was a focused laser beam whose frequency was above the atomic resonance. The beam repelled atoms in the condensate, having much the same effect as the boundaries of a material object. The experimenters oscillated the beam back and forth at constant speed through the condensate at various frequencies and amplitudes and measured the resulting heating by monitoring the temperature and condensate fraction. The heating rate increased for larger amplitudes and higher scan frequencies, and it was found to depend only on the velocity (the product of amplitude and frequency). When the speed was reduced below 1.6 mm/s, the temperature remained about constant. This critical velocity separated a regime of little or no heating from a regime where strong heating occurred.

Wolfgang Ketterle of the MIT group notes that the speed at which he and his colleagues see this change in heating rate is close to where several theoretical papers predicted it. It is well below the speed of sound (6.2 mm/s), which is the speed of propagation of a density disturbance in a condensate, but it is close to the critical velocity to excite vortices, another mechanism for dissipation. The MIT group regards their experiment as a "work in progress," and they want to do more accurate measurements in the regime below the critical velocity.

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