Back to Table of Contents

August Search & Discovery:

Researchers Can Now Vary the Atomic Interactions in a Bose-Einstein Condensate

An Optical Spoon Stirs Up Vortices in a Bose-Einstein Condensate

Galaxy Survey Finds Limit of Cosmic Structure Size

An Optical Spoon Stirs Up Vortices in a BoseEinstein Condensate

Multiple vortices form regular arrangements in a condensate in a rotating trap.

Since the early days of BoseEinstein condensates (BECs) in atomic gases, comparisons have been drawn to the other familiar bosonic systems: liquid helium-4 and the Cooper pairs of superconductors. Two of the early questions asked of BECs were whether they had similar coherence properties and whether they were superfluids. In ^{4}He, it is rather difficult to study properties of the condensate, such as the condensate fraction, whereas the measurement of superfluidity is fairly straightforward. The opposite has proved true for atomic condensates: The condensate fraction as a function of temperature was found early on, but only recently has their superfluidity been placed on firm footing (see *Physics Today*, November 1999, page 17).

One property associated with superfluids is the ability to support quantized circulation. Normal fluids, such as a stirred cup of coffee, rotate like a rigid body. In contrast, the velocity of a one-component superfluid like^4 He is related to the gradient of the phase of its wavefunction. Consequently, such superfluids only support flow with zero curl, which precludes rigid-body rotation. But superfluids can support quantized circulation through the introduction of vortices. Each vortex is characterized by a node where the condensate wavefunction (and hence its density) goes to zero. Along any closed path surrounding one vortex, the wavefunction phase changes by 2π--and thus the fluid circulates around the vortex.

Last fall, researchers at JILA in Boulder, Colorado, succeeded in creating a vortex in a BEC using microwaves and a rotating laser beam to "imprint" the characteristic 2π phase winding in a two-component condensate.[1] Now Kirk Madison, Frédéric Chevy, Wendel Wohlleben, and Jean Dalibard at Ecole Normale Supérieure (ENS) in Paris have demonstrated another method for generating vortices: rotating an asymmetric trapping potential.[2,3] This new technique can readily produce multiple vortices, and it also allows quantitative studies of vortex nucleation and decay.

Optical spoon

In the classic "rotating bucket" experiments on superfluid ^{4}He, a cylindrical container is rotated as the liquid within it is cooled. (See Physics Today's special issue on superfluid helium, February 1987.) Imperfections in the walls provide the transfer of angular momentum that is required to introduce vortices into the liquid. But a cylindrically symmetric magnetic trap is perfectly smooth, so another route is needed to get a BEC spinning.

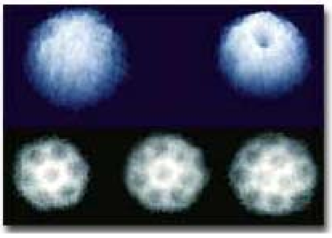
The technique implemented by the ENS team in many ways resembles the rotating-bucket approach of liquid He experiments. Dalibard and company start with a IoffePritchard magnetic trap, which produces cigar-shaped condensates--in this case with a radius of 2.5 μm and a length of 100 μm. Except for a small static inhomogeneity, the trap is axially symmetric about the length of the cigar.

The researchers introduce a transverse asymmetry using a laser tuned far from the atomic resonance. The laser beam, with a diameter of 20 μm, induces a dipole moment in the atoms, which then couples to the laser's electric field. The beam is aligned parallel to the long axis of the trap but isn't centered in the trap. Instead, it is toggled rapidly back and forth between two points symmetrically located about 8 μm from the center. With a sufficiently high toggle rate, the atoms feel the time-averaged potential of two laser beams.

The additional potential from the toggled laser beam squashes the condensate's cigar shape, giving it a slightly elliptical cross section. By rotating the toggling about the long axis of the trap, the researchers rotate the asymmetric potential, which stirs the condensate.

"Toggling the laser beam is essential," notes Dalibard. Otherwise, the laser would merely shift the trap's center--the trap would remain axisymmetric. Rotating the beam would then just move the trap in a circle, which would not stir the condensate. "It's the difference between moving a coffee cup around in a circle and inserting a spoon and rotating it," explains Madison.

To introduce vortices into condensates, the researchers load their trap with about half a billion spin-polarized rubidium atoms. With the stirring laser on and rotating at a fixed frequency, they evaporatively cool the atoms through the BEC transition temperature down to a temperature of about 100 nK, at which most of the remaining 10^5 atoms are in the condensate.



Stirred BoseEinstein condensates show no vortices when the stirring frequency is below the critical frequency for vortex nucleation (top left). Once the critical frequency is crossed, a vortex appears at the center of the condensate (top right). Arrays of vortices are found for higher stirring frequencies. Shown below are images of 7, 8, and 11 vortices. (Courtesy of K. Madison and F. Chevy.)

Early surprises

Dalibard and coworkers have found that below a critical stirring frequency, which depends on the steepness of the magnetic trapping potential, no vortices appear in the condensate. For a range of frequencies above the critical frequency, a single vortex is observed as a pronounced density dip in the center of the condensate, shown in figure (left). Recent measurements of the angular momentum of the stirred condensate confirm a jump from 0 to $\hbar$ per atom at the critical frequency, as expected for a single vortex in the center of the trap.[3] Surprisingly, the critical frequency determined experimentally is about 50% higher than expected from calculations of when the one-vortex state becomes the lowest-energy state of the rotating condensate.

At even higher stirring frequencies, multiple vortices appear and form regular arrangements that resemble those found in rotating superfluid ^{4}He and the triangular Abrikosov vortex lattices found in type-II superconductors in a magnetic field. The cores of the BEC vortices are relatively large compared to the size of the trapped condensate, and so only a small number of vortices can be cleanly observed. At sufficiently high stirring frequencies, a turbulent structure is seen instead in the condensate. Ultimately, at stirring frequencies approaching the restoring frequencies of the trapping potential, the condensate is lost.

In their more recent experiments, Dalibard and company have varied their condensate preparation protocol: Instead of cooling with the stirring laser on, they have begun stirring after the condensate is formed. In another surprise, they find the nucleation of vortices with essentially the same critical frequency as when they cool while stirring. In contrast, a higher rotation frequency is needed to nucleate vortices in superfluid ^{4}He if the spinning starts after the liquid is cooled than when the liquid is cooled while the bucket is rotating.

Open questions

The ENS work joins three other results that demonstrate the superfluid properties of condensates. By dragging a laser beam through a condensate, Wolfgang Ketterle's group at MIT has demonstrated frictionless flow below a critical dragging velocity.[4] Chris Foot and coworkers at the University of Oxford[5] have observed undamped irrotational oscillation of the condensate--the so-called scissors mode--when a slightly asymmetric trap is given a quick twist, as predicted by David Guéry-Odelin and Sandro Stringari of the University of Trento in Italy.[6] Meanwhile, the JILA researchers have continued to explore vortices with the phase imprinting technique, and have recently observed vortex precession in condensates.[7]

Theorists and experimenters alike have been given much to ponder and explore with the ongoing revelations into the behavior of condensates. Why the critical frequency for vortex nucleation is so much higher than predicted remains an outstanding puzzle, as is why no vortices are observed in condensates too close to the transition temperature. Vortices may help elucidate the interactions between the condensed and noncondensed atoms. The nature of the excitations of the vortices themselves is also being examined.

The behavior of superfluid ^{4}He is dominated by strong interactions between atoms and with the walls. Detailed models and simulations are consequently difficult. In contrast, BECs have weak interactions that are well described by microscopic theories, and magnetic traps are inherently clean. Furthermore, the vortex cores in BECs are about a thousand times larger than those in ^{4}He. With BECs, notes David Feder of NIST in Gaithersburg, Maryland, "many of the questions that have dogged the liquid helium community for years can be addressed directly for the first time." Eric Cornell of JILA adds, "Two of the most interesting things in a vortex's life are its birth and death. Now we can look at both."

Richard Fitzgerald

References

1. M. R. Matthews, B. P. Anderson, P. C. Haljan, D. S. Hall, C. E. Wieman, E. A. Cornell, Phys. Rev. Lett. **83**, 2498 (1999).

2. K. W. Madison, F. Chevy, W. Wohlleben, J. Dalibard, Phys. Rev. Lett. **84**, 806 (2000); http://xxx.lanl.gov/abs/cond-mat/0004037, to be published in J. Mod. Opt.

3. F. Chevy, K. W. Madison, J. Dalibard, http://xxx.lanl.gov/abs/cond-mat/0005221.

4. C. Raman, M. Köhl, R. Onofrio, D. S. Durfee, C. E. Kuklewicz, Z. Hadzibabic, W. Ketterle, Phys. Rev. Lett. **83**, 2502 (1999). R. Onofrio, C. Raman, J. M. Vogels, J. Abo-Shaeer, A. P. Chikkatur, W. Ketterle, http://xxx.lanl.gov/abs/cond-mat/0006111.

5. O. M. Maragò, S. A. Hopkins, J. Arlt, E. Hodby, G. Hechenblaikner, C. J. Foot, Phys. Rev. Lett. **84**, 2056 (2000).

6. D. Guéry-Odelin, S. Stringari, Phys. Rev. Lett. **83**, 4452 (1999).

7. B. P. Anderson, P. C. Haljan, C. E. Wieman, E. A. Cornell, http://xxx.lanl.gov/abs/cond-mat/0005368.

Table of Contents About Physics Today Contact us