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Fermion Superfluidity in an Optical Lattice

In this summer of 2006, while Europe and North America have been buffeted by record high temperatures, Wolfgang Ketterle's lab in Cambridge, Massachusetts, continues to explore matter at record low temperatures. In three new papers -- one each in Nature, Science, and Physical Review Letters Ketterle and his MIT colleagues report on several new forms of quantum behavior in a research area at the crossroads between atomic and condensed matter physics. The samples used are dilute atomic gases (two of them with fermion atoms and one with boson atoms), but the properties studied -- things like conductivity and fluid flow -- are more typical of liquids and solids.

Here are the three new results.

1. First direct observation of phase separation between a fluid and a superfluid.

The MIT group had previously obtained visual proof, in the form of vortex images, that lithium-6 atoms had paired up and condensed into a superfluid (see **PNU 734 (http://www.aip.org/pnu/2005/split/734-1.html)**). As fermions (particles whose net spin has a half-integral value), lithium-6 atoms obey the Pauli exclusion principle, which forbids fermi atoms from joining a common quantum state -- like the one enjoyed when bosonic atoms (whose net spin is an integer) form a Bose-Einstein condensate, or BEC.

On the other hand, lithium-6 atoms can be manipulated with external magnetic fields to interact in a variety of ways. Paired up, they can, like bosons, proceed to form a condensed, superfluid state. In later work, the MIT physicists were able to contrive a lithium-6 superfluid in which there was an imbalance in the population of atoms with opposite spin orientation. This allowed the atomic gas to exist partly as a superfluid and partly as a normal fluid. In new work, this separation of the fluid and superfluid phases has been imaged

Ketterle says he believes this is the first time a quantum-condensed material (e.g., a superfluid or superconductor) has been imaged right along with normal phase. In this case the superfluid phase is seen to lie within a normal-phase cocoon.

Shin *et al.* (http://link.aps.org/abstract/PRL/v97/e030401) , Physical Review Letters, 21 July 2006
See images on the **MIT Web site (http://web.mit.edu/newsoffice/2006/superfluidity.html)**
Also see Nature, 6 July 2006

2. First observation of Mott insulator shells.

A Mott insulator (named for Neville Mott) is a sort of frustrated conductor; even though in the material there ought to be places in a lattice for extra charges to move into, strong interactions among electrons depress conductivity, making the material into an insulator, even when it should be a conductor (see **PNU 645 (http://www.aip.org/pnu/2003/split/645-2.html)**).

In the MIT work, the moving particles are not electrons but neutral atoms (rubidium atoms in a Bose-Einstein condensate), and the underlying lattice is not a matrix of atoms but an optical lattice -- a kind of artificial diffuse "solid," where laser beams trap one or more atoms at the interstices of a criss-crossing light field.

By careful tuning of external magnetic fields, a layered Russian-doll structure is achieved: Mott insulator layers, one inside another, are separated by superfluid layers. This structure was deduced by the careful application of spectroscopy technology used in atomic clocks (locking a microwave transmitter onto the receptive absorbing ability of supercooled atoms). Ketterle says that Mott/BEC vapors might, in their turn, help to make atomic clocks more precise.

Immanuel Bloch's group in Mainz might also be publishing new results in this area.

Campbell *et al.*, Science, 4 August 2006

3. First fermion superfluidity observed in an optical lattice.

This represents the first time the paired fermion particles constituting a quantum fluid were nominally lodged within a crystal-like configuration of forces. This is a big step toward one of the big goals of research with ultracold fermi atoms, namely the ability to create an artificial crystalline superfluid or superconductor where the interaction parameters can be tuned at will. In this case the evidence for the quantum coherence of the atoms in residence within the optical lattice is indirect and consists of an interference pattern emerging when the atoms are released from pairs, a development controlled the an external magnet.

In a subject as fast moving as the study of trapped ultracold atoms, there are plenty of other related results. For example, a Harvard-George Mason-NIST group (including Charles Clark, NIST, charles.clark@nist.gov) has also obtained some insights on Mott insulators in quantum gases: see **Rey *et al.*, (http://link.aps.org/abstract/PRA/v73/e063610)** Physical Review A, June 2006, and **Rey *et al.*, (http://www.aps.org/meet/MAR06/baps/loader.cfm?url=/commonspot/security/getfile.cfm&PageID=72480)** 2006 March Meeting of the American Physical Society.

Randy Hulet and his group at Rice University reported the direct observation of phase separation in an article in Science in January 2006. They too are about to have some new results on imbalanced spin populations.

Physical Review Letters, upcoming article
(See **preprint (http://atomcool.rice.edu/Partridge_PRL_2006.pdf)** on the Rice University Web site)
Journal of Low Temperature Physics, upcoming article
(See **preprint (http://atomcool.rice.edu/Partridge_LowTempPhys_2006.pdf)**)
Chin et al., Nature, 26 October 2006

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