March Madness in Quantum Gases: New Phases and Exotic Fractal Behavior of Atoms in Optical Lattices

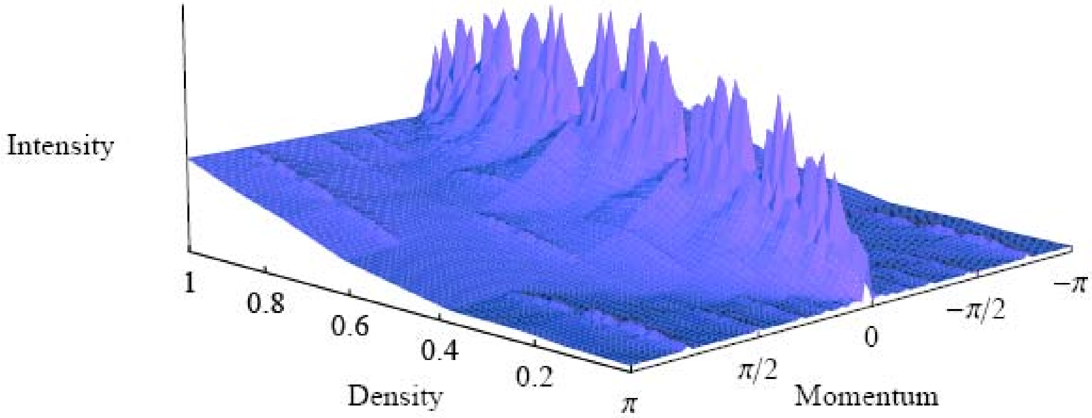
(1) A. M. Rey (arey@ harvard.umd.edu),
(2) I. I. Satija (isatija@physics.gmu.edu),
(3) C. W. Clark (charles.clark@nist.gov).

(1) Institute for Theoretical Atomic, Molecular and Optical Physics, Harvard-Smithsonian Center of Astrophysics, Cambridge, MA, 02138.

(2) Department of Physics, George Mason University, Fairfax, VA, 22030.

(3)National Institute of Standards and Technology, Gaithersburg, MD 20899.

Presentation: R43.00006
"Quantum coherence of hard-core bosons and fermions in one dimensional quasi-periodic potentials: superfluid, Mott and glassy phases."
Wednesday, March 15, 2006, 3:30 p.m.
APS March Meeting, Baltimore Convention Center 346, MD.



Researchers at Harvard University, George Mason University, and the National Institute of Standards and Technology have discovered new quantum effects in ultracold quantum gases that may lead to improved understanding of the electrical conductivity of metals.
These effects also indicate that cold atoms could provide laboratory demonstration of various exotic fractal phenomena.

Why do some metals conduct electricity better than others?

Electric current is due to the movement of electrons in the metal, and good conductors are those in which the electrons can move freely between the metal atoms. The atoms in a metal are arranged in more or less regular crystal structure, like the rows of seats in a basketball stadium; electrons, at least during the month of March, can be thought of as basketball fans moving between seats.

There are two important mechanisms that degrade conductivity of metals: disorder in the atomic array, and mutual blocking of electrons. These are known respectively as Anderson localization and the Mott metal-insulator transition. Phillip Anderson, then at Bell Laboratories, and Sir Neville Mott, then at Cambridge University, were awarded the Nobel Prize in Physics in 1977 for their theories of these two mechanisms, yet unambiguous observations of these effects in real materials has remained elusive.

However, basketball fans often encounter both mechanisms when they enter the stadium well before the start of a game. When there are just a few fans present, there are long rows of empty seats and a fan can wander freely along a row. However, if one encounters a railing or wall at the end of a row, it takes more time to get around it; that is an effect of disorder in seat arrangements. When the stadium is packed, a fan can't move into an adjacent seat, since it is already blocked by another fan; that's the stadium analogue of the Mott transition.

What are fractals and why are they interesting?

Fractals are pictures containing details at every imaginable size: no matter how much a fractal is magnified, it will reveal more detail.

Physicists have long been fascinated by fractal structures that arise in the study of nature. In the research reported here, fractal structure is found in interference patterns that describe the behavior of ultracold atoms.

In work presented at the March Meeting of the American Physical Society, Dr. Ana Maria Rey of Harvard University and her collaborators consider what happens when both Mott and Anderson effects are present in a system of ultracold atoms confined in an “optical lattice,” a synthetic crystal made from beams of light. Such systems have become experimentally realizable during the past decade due to breakthroughs in laser cooling and trapping of atoms, and the production of Bose-Einstein condensates, which were recognized by Nobel Prizes in physics in 1997 and 2001, respectively. These systems allow one to explore aspects of solid state physics with much greater flexibility and control than is possible in ordinary materials, and to simulate the properties of materials that do not yet exist. A key tool used in this work is Hanbury Brown-Twiss interferometry, a technique originally developed for use in radio astronomy by Robert Hanbury Brown and Richard Twiss in 1954,

Some of the highlights of this work include
1) New insulating phases due to interplay between disorder and interaction.
2) An interference pattern consisting of alternating bright and dark spots exists even in the insulating phases. This is like seeing the lattice even in darkness.
3) Fractal behavior: for example a blow up of the region between any two bright spots reveals additional bright and dark spots.
4) A new signature of “fermionization” of bosons.

Optical lattices were first developed in the early 1990s by William Phillips and his collaborators at the National Institute of Standards and Technology, for the purpose of holding isolated atoms in order to obtain improved standards of time and frequency. They have since become of fundamental interest in solid state physics, due to their ability to prototype quantum materials that have not yet been created. The work of Dr. Rey and her collaborators provides a glimpse into the rich phenomena that can emerge in these beguilingly simple systems.

Figure: Interference pattern describing the momentum distribution of Hard Core Bosons. It shows a complex fractal pattern of peaks and valleys describing a cascade of superfluid and Mott states.