Researchers studying a gas of trapped ultracold atoms have identified a set of conditions, never before observed but in excellent agreement with new theoretical predictions, that determine the onset of a critical “phase transition” in atomic arrays used to model the behavior of condensed-matter systems.

The findings provide a novel insight into the way collections of atoms suddenly cease to be a superfluid, which flows without resistance, and switch to a very different state called a “Mott insulator.” That transition and similar phenomena are of central interest to the science of solid-state materials, including superconductors.

Measuring Gravity over Short Time and Distance

Scientists have developed a novel design for a highly compact, ultra-sensitive quantum device to measure subtle changes in gravity over very short time or distance scales.

Tools of this sort – called atom interferometers (AIs) – are now used to search for natural resources beneath the Earth’s surface, navigate deep underwater or in the air, and measure Newton’s gravitational constant to extraordinary precision.

But the new design, by researchers from the Joint Quantum Institute and its Physics Frontier Center, offers the possibility of unprecedented temporal resolution by harnessing the very recently demonstrated ability to create “synthetic” magnetic fields.

Anatomy of a Phase Shift

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The findings provide a novel insight into the way collections of atoms suddenly cease to be a superfluid, which flows without resistance, and switch to a very different state called a “Mott insulator.” That transition and similar phenomena are of central interest to the science of solid-state materials, including superconductors.
The Physics Frontier Center at the JQI underwent a review from the National Science Foundation on August 11 and 12. The review, customary by all funding agencies of large research centers, was the first for the PFC, which was started in September 2008. A distinguished panel of physicists selected by the NSF visited and were shown the many facets of programs headed by the PFC.

The first day was filled with presentations and was kicked off by PFC Directors Luis Orozco and Bill Phillips, who provided updates to the overall picture and direction of the program. This was followed by talks from JQI Fellows Jake Taylor, Edo Waks, Gretchen Campbell, Victor Galitski, Ian Spielman, and Chris Monroe, who summarized science results on current research funded by the PFC. The afternoon session was devoted to future plans and included presentations by Sankar Das Sarma, Ian Spielman, Chris Monroe, Fred Wellstood, and Glenn Solomon. A final session summarized the education and outreach components of the PFC.

To give the panel a real sense of what goes on in the PFC, the first day concluded with a poster session presented by the students and postdocs involved in PFC research. The lively event featured more than 40 posters that filled the hallways of the CSS building and went well beyond its one-hour schedule; the event was especially notable for the interactions between students and postdocs as they visited each others’ posters. The following day, the panel devoted their time to meeting with the directors and to working on their report.

Although a lot of effort went into planning for the visit, PFC Director Luis Orozco said, “We found the panel’s visit to be very beneficial: both from the insights we gained from their questions and comments as well as from the interactions we had among each other in preparing for the visit.”

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**Phase fluctuations in anisotropic Bose condensates: from cigars to rings**


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To the toroidal trap of the BEC, the decaying ring geometry is defined by the length scale, \( \lambda \), and \( \Delta \).

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“The ability to measure gravity over fine time scales will help in finding oil fields and mineral deposits,” says coauthor and JQI Fellow Victor Galitski. “Imagine an aircraft flying over an unexplored area. If heavy element deposits are hidden underneath, the gravimeter will react promptly by showing strong fluctuations in the local gravity field.”

Atom interferometers rely on a counterintuitive but central precept of quantum mechanics: Everything, including matter – not just subatomic particles, atoms and molecules, but also macroscopic objects such as Buicks and buildings – has wave properties. Just like waves of light or sound, “matter waves” from different objects can interfere with one another constructively (reinforcement) or destructively (cancellation).

In addition, the new design takes advantage of yet another quantum phenomenon: “superposition,” a condition in which objects have multiple values of the same property at the same time – the equivalent, in the classical world, of a ball that is simultaneously completely red and completely blue until someone looks at it. Once it is seen (or measured in any other way), however, the superposition disappears and the ball becomes either red or blue.

Conventional Als exploit interference to measure gravity at a given location, typically by directing a stream of atoms into a beamsplitter, which divides the atoms’ wave functions into two branches. Inside the
device, each branch is propelled on separate – but completely symmetrical, mirror-image – paths down a cylinder. The only difference between the paths is that one is higher than the other – and therefore responds just slightly differently to the force of gravity.

So when the two atom branches are recombined, their matter waves will be out of phase; and the amount of phase difference will be proportional to the difference in gravitational force felt by each.

Although useful, that method does not provide a good way to measure how gravitational force changes over small time periods and short length scales. And it necessarily requires the atoms to travel a relatively large distance, typically tens of centimeters, in order to produce a sufficiently large phase difference.

The JQI/PFC design, by contrast, uses an atom trap only 50 micrometers in diameter – about half the thickness of a human hair – containing millions of atoms chilled to a fraction of a degree above absolute zero. The atoms sit in a weak, inhomogeneous magnetic field, and each has a slightly different spin state (a kind of angular momentum) depending on its position in the field.

The atoms are irradiated by a continuous-wave laser that imparts momentum to each atom, the magnitude and direction of which depends on the atom’s spin state. This arrangement produces “synthetic” magnetism,* a condition which causes neutral atoms to behave as if they were charged particles in a real magnetic field.

“Recently, JQI researchers led by Ian Spielman have demonstrated that a synthetic magnetic field and synthetic spin can be created in cold-atom systems,” says coauthor and JQI Fellow Jacob Taylor of the National Institute of Standards and Technology.

“The proposed gravimeter setup is largely inspired by these amazing advances, and it uses the simplest possible configuration of replicas of a uniform synthetic field, which can be created easily in Spielman’s experiment.”

Then each atom is exposed to microwave radiation tuned to the specific wavelength that will project it into a “superposition” of two opposite spin states. [See Step 1 in the attached figure.] At that point, the trap is displaced by a small amount, about 20 micrometers, which has the effect of moving the atom, with its superposed states, into a different part of the synthetic field. [Step 2 in the figure.]

Each of the two spin states starts to move in a spiral motion, but in opposite directions around the interior of the trap. [Step 3.] While in transit, each superposition state will be affected differently by gravity or any other acceleration. As a result, when their paths once again overlap at the end of their spiral trajectories, they will be slightly out of phase.

Finally, the atom is irradiated with a second microwave pulse [Step 4] that causes the atom to emit light if it is in a certain spin state, and to remain “dark” (no emission) if it is in another. If the superposed spin states had not experienced any external effects, such as gravity, each atom in the trap would have a 50-percent chance of emitting or not emitting.

But if the paths of the spin states are affected by gravity, the collective output of the entire set of trapped atoms will emit more or less light – and the degree to which the light output varies is a measure of the strength of the gravitational field.

In addition to its potential practical uses, the new design “can help test the fundamental laws of nature, such as Einstein’s theory of relativity, which some believe may break down at very small time and length scales.”

“This work shows that the transition can be precisely controlled and confirms that it can be described by only two independent variables,” says lead researcher Karina Jiménez-García, a member of Ian Spielman’s group at the National Institute of Standards and Technology (NIST) and the Joint Quantum Institute (JQI). The group reports its findings in a forthcoming issue of Physical Review Letters.*

In order to understand the behavior of materials on the atomic and molecular scale, researchers often cannot experiment directly with samples. In many cases, they need model systems – analogous, at microscopic dimensions, to the physical models built by engineers to test the dynamics of a planned structure – that allow them to change one or two experimental parameters at a time while holding the rest constant. That can be prohibitively difficult, if not impossible, in bulk samples of real material.

But in recent years, quantum science has made it possible to create accurate and highly illuminating models of condensed-matter systems by using ensembles of individual atoms which are confined by electrical and magnetic forces into patterns that mimic the fundamental physics of the repeating structural pattern, or “lattice,” of a solid material.

Improving these quantum-mechanical models is an important research area at JQI, and Spielman’s group has been investigating a model for the superfluid-to-Mott insulator (SF-MI) phase transition – the point at which the atoms cease to share the same quantum properties, as if each atom were spread over the entire lattice, and change into a set of individual atoms trapped at specific locations, that do not communicate with one another.

The group’s experimental setup at NIST’s Gaithersburg, MD facility uses a cloud of about 200,000 atoms of rubidium that have been cooled to near absolute zero and confined in a combination of magnetic and optical potentials. In those conditions, a majority of the atoms forms a Bose-Einstein condensate (BEC), an exotic condition in which all the atoms coalesce into exactly the same quantum state.

Then the team loads the BEC – which is about 10 micrometers in diameter, or about one-tenth the width of a human hair – into an “optical lattice” that forms at the intersection of three laser beams placed at right angles to one another [See Figure 1, above], two horizontal and one vertical. Interference patterns in the beams’ waves cause regularly spaced areas of higher and lower energy; atoms naturally tend to settle into the lowest-energy locations like eggs in an egg carton.

continued, next page
The depth of the lattice wells (the cavities in the egg carton) is adjusted by varying the intensity of the laser beams. [See Figure 2, below] In a relatively shallow lattice, atoms can easily “tunnel” from one site to another in the condensate superfluid state, whereas deep lattice wells tend to hold each atom in place, producing the non-condensate insulator state. “We can tune the depth of all the wells in the carton by adjusting the intensity of the laser beams which create it,” Jiménez-García explains. “We can go from a flat carton to a carton with very deep wells.”

That general lab arrangement – ultracold trapped atoms suspended in an optical lattice – is the current standard worldwide for experiments on condensed-matter models. But it has a serious problem: The mathematical theory behind the model is predicated on a completely homogenous system, whereas arrays such as the JQI group uses are only homogenous on small spatial scales. Globally, they are inhomogenous because the magnetic trapping potential is not uniform across the width of the trap. As a result, the equations used to calculate expected outcomes do not accurately predict the SF-MI transition, compromising their utility.

Last year, however, an international collaboration of theorists** determined that in such configurations, where there were spatially separated SF and MI phases, the quantum state of the system could be fully specified by the relationship between only two variables: the characteristic density of the system (a composite of trapping potential, total number of trapped atoms, tunneling energy, lattice spacing and dimensionality); and the strength of the interactions between neighboring atoms.

Jiménez-García and colleagues in the JQI group set out to see if they could make an experimental system that performed according to the theorists’ specifications.

They set the depth of the vertical lattice beam such that it partitioned the roughly spherical BEC into about 60 two-dimensional, pancake-shaped segments, and then used a method similar to medical MRI scanning to select and analyze just a couple of individual 2D segments at the same time. The inhomogeneity of the originally 3D atomic sample results in the selection of 2D systems with different total number of atoms, ranging from 0 (at the edges of the system) to 4000 atoms (in the center of the system), allowing the researchers to examine a broad range of total atom numbers and lattice depths.

Because the trapping potential was not homogenous across the BEC, the group’s lattices were not completely orthogonal. “What we get instead,” Jiménez-García says, “is an array of egg cartons which have a parabolic curvature. Imagine each egg carton with the overall shape of a bowl, and the whole system as a stack of egg carton bowls.”

To determine the state of the atoms in the 2D slice, the scientists abruptly turn off the trap and let the atoms begin to fly apart. After a few thousandths of a second, they take a picture of the expanding population. If the atoms were deep into the SF state, the images will show a tightly focused bunch. If they were in the MI state, the bunch will have dispersed farther and appear more diffuse. “We detect a sharp peak in the momentum distribution which we associate with the condensate fraction,” Jiménez-García says. “Wider dispersion – that is, less condensate fraction -- would mean more MI.”

After measuring about 1300 different samples, the group was able to determine that the two-variable theory completely described the state of each slice.


I am sorry to announce the departure of Curt Suplee, the JQI Director of Communications, who has left the JQI to join the National Endowment for the Humanities where he will be overseeing their new initiative in electronic outreach.

Curt has been an integral part of our communications efforts at the JQI and has been responsible for everything you have seen: from the newsletter, to the clear exposition of complex stories, to the photography, video and podcasts. I have personally enjoyed many stimulating interactions with Curt as we developed the outreach plans for the JQI.

Curt's many years of professional science writing have been essential in our efforts to explain quantum science, and will be big shoes to fill. We are committed to continuing on the path Curt started us on, and will work to keep the momentum going. We wish Curt all the best in his new position, and expect to see some exciting new media content at the NEH in the near future.

-Steve Rolston

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**Publications**


**Papers Accepted:**


Charles Clark gave an invited talk on July 20, 2010 at the DARPA Quantum Assisted Sensing and Readout Proposers Day Workshop in Arlington, VA titled “Reducing Decoherence in Quantum Sensors.”

During the month of July, Bill Phillips taught at The Les Houches School of Physics in Les Houches, in the French Alps, on the topic “Many Body Physics with Ultracold Gases” and gave lectures on July 5-6 on the subject of “Optical Lattice and Applications to Information Processing.” Phillips also gave a public lecture on July 9 (in French if you can believe it) in the town of Les Houches, attended by people of the town and nearby, on the subject: “Le Temps et Einstein au XXI Siecle” (Time and Einstein in the 21st Century).

Charles Clark rode aboard the aircraft carrier CVN 72 USS Abraham Lincoln during the composite training unit exercise of Carrier Strike Group 9 in the Pacific Ocean, July 23-24, 2010. He was sponsored by the US Navy “Scientists to Sea” program, which places US Navy scientists aboard ships to acquaint themselves with the realities of life at sea.

Ludwig Mathey received a job offer for a faculty position at the Center for Optical Quantum Technologies at the University of Hamburg.

“Ettore Majorana and the birth of autoionization”, a paper by Ennio Arimondo (University of Pisa), Charles W. Clark (JQI) and William C. Martin (NIST), was featured on the cover of the July-September 2010 issue of Reviews of Modern Physics.


Associated with ICAP in Cairns, Australia was a school in tropical Cape Tribulation where Bill Phillips was invited over July 21-25. Phillips gave a series of lectures on “Cooling, Trapping, and Electromagnetic Manipulation of Atoms.” Even in this “dry season” it was sometimes raining so heavily lectures were suspended because they could not be heard over the rain!

ICAP 2010 Events

On July 22-24, 2010, nine graduate students from JQI attended a three-day student workshop on ultracold atoms in conjunction with the 22nd International Conference on Atomic Physics (ICAP) in Cairns, Australia. Their travel was funded by the Physics Frontier Center at the JQI.

The pre-conference workshop was at the Ferntree Rainforest Lodge in Cape Tribulation, Australia, a three-hour bus and ferry ride through the UNESCO World Heritage rainforests of northern Queensland. The students listened to daily lectures from Nobel Laureates Bill Phillips (JQI) and Wolfgang Ketterle...
Before leaving, Zhifan Zhou, a student from East China University, returned and will be a visitor in Lett’s lab for the next year. Zhou is a student of Professor Jietai Jing, a former postdoc of our own Luis Orozco. Welcome Zhifan!

Bill Phillips received the Moyal Medal on August 4 at Macquarie University. In connection with the medal, Phillips gave a lecture entitled “Quantum Information: A scientific and technological revolution for the 21st century.” The medal, named after the late Professor José Enrique Moyal of Macquarie U, is given annually by the Moyal Medal Committee.

Phillips gave a second public lecture on August 4 at the University of Sydney, as part of their “Sydney Ideas” series, with the topic: “Time, Einstein, and the Coolest Stuff in the Universe.”

Alessandro Restelli gave an invited talk at the Centre for Quantum Technologies at the National University of Singapore on August 25, 2010. The title of the talk was “Speeding-up Quantum Key Distribution.”

Ana Maria Rey visited JQI for a week in August to work on a monograph on quantum correlation functions that she is coauthoring with Indu Satija (George Mason University/NIST) and Charles Clark. Rey received her Ph.D. in Physics from the University of Maryland in 2004 and is currently an assistant professor of physics at JILA.
Fred Wellstood gave an invited talk at the Electron Glass Workshop at KITP, UC Santa Barbara, on August 23, 2010 titled, “The unusual behavior of flux noise at temperatures below 1 K.” (Video and slides of the talk are available online.)

Wellstood also chaired a poster session at the Applied Superconductivity Conference in Washington, D.C. this August. During the conference, Wellstood taught a short course titled, “Superconducting Qubits.”

Keith Burnett visited JQI during August 25-27. Burnett began his long association with NIST/JQI when he was a Fellow of JILA in the 1980s and continued as a Professor of Physics at the University of Oxford. Burnett is now strengthening his research collaborations with JQI while serving as Vice-Chancellor of the University of Sheffield (United Kingdom), a position in British parlance comparable to the President of a University. Burnett is widely known in the scientific community for his original contributions to the theory of Bose-Einstein condensation and was elected to Fellowship of the Royal Society of London in recognition of this.