BECs in Lattices Get Really Perturbed

Disproportionately Large Effects From Very Small Changes in Optical Lattice Characteristics

JQI researchers have discovered a surprising phenomenon, akin to a phase transition, that occurs when atoms cooled into a Bose-Einstein condensate (BEC) are placed in an optical lattice produced by a single laser beam and then exposed to an extremely weak perturbation from one or more additional beams. The presence of the perturbing beam/s causes a dramatic change in the density distribution of the atoms in the BEC -- much more than would be expected from the small magnitude of the perturbation. The result provides a striking new insight into large changes in the ground state of a system due to a small amount of disorder.

"People are very interested in phase transitions, where the state of a system goes from one sort of behavior to another sort of behavior," says Matthew Beeler, a graduate student supervised by JQI Fellow Steve Rolston. "What we're studying [with BECs in lattices] is a transition from an extended state -- meaning that the density of the atoms is spread out -- to a localized state where the density is congregated in a few places." That transformation, Rolston's group found, is controllable.

Above right: (a) BEC atoms 20 milliseconds after release from trap and single lattice beam, V1. This and the other images are obtained by recording the light absorbed by the expanding atoms. (b) BEC atoms after release from trap and a weak beam V2, approximately 7% the power of V1. (c) The atoms after a combination of primary beam V1 and perturbing beam V2. (d) The atoms after a combination of V1, perturbing beam V2 and a second perturbing beam, V3. V2 and V3 are each about 3% the intensity of the primary lattice beam, V1. But the distribution is substantially different.
Perturbing Lattices, from page 1

by varying the characteristics of the additional weak laser beam/s superimposed on the "primary" lattice beam.*

BECs can form when a group of trapped atoms is cooled to a fraction of a degree above absolute zero.

Confined in that condition, most of the atoms "condense" into the same, minimum-energy quantum state. The JQI group starts with a cloud of about 10,000 rubidium atoms in a high-vacuum trap that uses magnetic fields and gentle nudges from light beams to quiet the atoms until they eventually condense into a space approximately 10 micrometers wide (about one-tenth the width of a human hair).

The trap is constructed such that the BEC forms about 2 mm from a mirrored surface. The researchers then shoot a single infrared laser beam through the BEC. It strikes the mirror and reflects back on itself, forming a standing wave pattern.

The atoms in the BEC "feel" the differences in potential energy created by the lattice beam, and arrange themselves into a density pattern that minimizes the energy of the BEC-lattice system. For most beam strengths, if the lattice beam is slowly turned off, the BEC returns to its initial lowest-energy, "ground-state" configuration after a few millionths of a second.

All of that was fairly well known. What was not known, or even anticipated, was the peculiar behavior that results when a second, very weak, laser beam is added to the primary beam, "perturbing" the state of the system. (See figure below.)

The second beam has basically the same wavelength as the primary. But it is projected in at an angle, so when the two beams overlap, their periods are substantially out of synch. As a result, their lattice structures are "incommensurate" -- that is, they are out of phase by an amount that cannot be expressed in a ratio of integers such as 4:3 or 10:9.

This imposed disorder prompts a drastic change in the cluster density pattern of the BEC atoms (see figure, page 1) that is far in excess of the result that would ordinarily be expected from the small extra energy in such a weak beam alone. Instead of being extended in space, the atoms become "localized" into separate clusters. Adding a second perturbing lattice changes the density distribution of the system yet again. Those

Those disproportionate effects indicate that the perturbing lattices have had a considerable impact on the wave function -- the quantum-mechanical description of the overall state of the atom-and-beam system.

That impact is reflected in the time it takes the system to return to its initial condition. In both of the multi-beam incommensurate cases, when all the beams are shut off, it can take the BEC about 100 times as long to return to its ground state as it does when the lattice is produced by the primary beam alone. (As a practical experimental matter, however, the perturbed-lattice BEC actually never returns to its ground state because the time interval is so long that interactions between the rubidium atoms set in, and begin to have a large, irreversible effect on the state of the system.)

Rolston’s group used theoretical equations to calculate the degree of alteration in the atoms’ density patterns that should occur under various scenarios. The predictions were a good match with the observations -- up to a point. But the experimental values began to diverge substantially as a second perturbing lattice was added to the original and as the power of the lattice beams was increased.

Of course, the density distribution in the tiny BEC cannot be observed directly. (A beam of light sent in to take a measurement would alter the system.) So the researchers use an indirect method: They turn off the lattice beams and the trap potential. As the atoms start to expand, a camera takes a picture of the atoms’ momentum distribution after 20 milliseconds. The distribution reflects the initial density arrangement in the trap.

The experiment illustrates the value of using arrangements of ultracold atoms to introduce controlled, reproducible degrees of disorder into a condensed matter system. Those effects are difficult to study systematically in other contexts. "There’s always some amount of disorder in condensed matter systems," Beeler says, and the sources may be hard to account for, owing to the numerous possible variables involved. Atomic systems, however -- such as the arrangement in the lattice experiment -- have much less intrinsic disorder and permit specific kinds of manipulation and adjustment of single variables.

"The bridge between atomic and condensed matter systems," he says, "is that we can model the atomic systems and put in controllable disorder. Whereas in regular condensed matter systems you can’t control your disorder."

Calculations of density distribution show how an extended single-lattice wave-function (top) may be altered so that density is localized at "beat" points (bottom) where primary and perturbing lattices interfere constructively.

LEFT: The lattice trap is suspended inside a high-vacuum chamber. The rubidium gas is cooled to near absolute zero and slowed by collision with specially tuned photons from beams of laser light that surround the atoms in six directions. The atoms are confined in the desired location with magnetic fields. The resulting near-motionless cluster forms the condensate, which is held toward the bottom of the trap.
A device invented by JQI scientists at the National Institute of Standards and Technology (NIST) to process data from multiple single-photon detectors also has a broad range of potential alternative uses, from monitoring heartbeat to tracking spikes in power or communication lines. Last month, NIST began soliciting proposals for development of a commercial prototype.

JQI Fellow Alan Migdall and JQI Research Associate Sergey Polyakov at NIST created the device to solve a data-acquisition problem in their research. "As quantum information and entanglement applications have developed," Migdall says, "the photon states created have become more complicated and involve more particles -- three or four photons or more. The typical analysis tool for measuring a pair of photons in these applications is the coincidence circuit, a two-channel device that records the time between the arrival of an electronic signal in channel one and an electronic signal in channel two. These devices typically cost on the order of $10,000."

Multiple photon channels require multiple boards, and "that gets expensive fast," Migdall explains. Moreover, there are two other problems. "The first is that the boards are often not really designed for this type of operation," and require a lot of custom modification. "In addition it is not possible to search for correlations between more than two channels on the boards. As a result, a lot of data must be moved onto your computer and processed at a latter time."

So Migdall and Polyakov started looking at processors called field programmable gate arrays (FPGAs). "These are relatively simple but very flexible chips that provide a solution to the problem of how to add more channels and process the data quickly," Migdall says. "Our platform can easily have many channels and it works by time stamping all of the input channels relative to some repetitive trigger. The platform can then filter the specific multichannel correlations before sending the results to any generic computer. The preprocessing happens in real time, and thus avoids swamping the computer with raw data."

"This has not been done before because there is a significant learning curve to get up to speed that requires familiarity with the chips, the programming of the chip at several levels, the computer drivers, and the communication link. Sergey Polyakov has worked out all of those details and created a step-by-step recipe that can be easily replicated with very inexpensive components."

Although originally designed to process binary inputs from the lab's photon detectors, the device can be coupled to an analog-to-digital converter for use with any signals "where amplitude, widths, or shapes are important," Migdall notes. For example, the system could be used to characterize single dust particles or track data from high-energy particle detectors. It could monitor changes in heartbeat or keep track of anomalies or failures in power or communication lines.

The design is freely available. Researchers can read and download instructions for building the devices at http://physics.nist.gov/Divisions/Div844/FPGA/fpga.html.

The NIST solicitation (Small Business Innovation Research Program, Solicitation Number: NIST-09-SBIR) calls for a prototype that can handle at least four channels at 2 million cycles per second (MHz), with a maximum time resolution of 4 nanoseconds or less. But with some modifications to the firmware, the device can be adjusted to operate from 10 Hz to 100 MHz or more.
Optical Tweezers Pick Up Medical Interest

JQI Fellow Co-Invented ‘Femtomolar Optical Tweezers; May Enable Sensitive Blood Tests

Cutting-edge “tweezers” are so sensitive that they can feel the tell-tale tug of tiny concentrations of pathogens in blood samples, yet don’t ever need to be sterilized—or even held—as they are ephemeral and weightless.

The National Institute of Standards and Technology (NIST) has licensed a patented “optical tweezers” technique for detecting and measuring very small concentrations of a biological substance—such as a virus on a surface.

NIST has issued a non-exclusive license for the technology to Haemonetics, a global health care company that provides blood management technologies for hospitals and blood and plasma collection agencies.

Optical tweezers are actually tightly focused laser beams. They can trap certain objects, such as latex microspheres or biological cells, and move them around in water. This occurs because the lasers' electric fields interact with electric charges on the objects.

To detect disease-causing agents, researchers can coat a microsphere with antibody particles and then touch it to a surface containing infectious particles (antigens).

The antigens then stick to the antibodies on the sphere, reminiscent of Velcro, in which loops on one strip combine with hooks on the other. By determining how much laser power is required to pull the microsphere away from the surface, one can then calculate the amount of force needed to break off the antibodies from the antigens and thus count the number of individual antigens that were bound to the sphere.

This in turn can detect and count biological antigens at extraordinarily low “femtomolar” concentrations—roughly equivalent to one antigen particle per quadrillion (1,000,000,000,000,000) water molecules.

Following up on earlier work in optical tweezers in the industrial and academic research communities in the 1970s, the licensed technology was patented in 1997 (patent #5,620,857), as a result of research conducted under the NIST BioSensor Consortium. The inventors are Howard Weetall (since retired), Kristian Helmerson, and guest researcher Rani Kishore.

For more information on these or other NIST technologies, contact Terry Lynch, NIST Office of Technology Partnerships, terry.lynch@nist.gov, (301) 975-2691.

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Entangled States

- Two more JQI Fellows have been named Fellows of the American Physical Society. **Trey Porto** was recognized for “seminal studies of ultracold atoms in optical lattices with applications to quantum information, many-body physics, and condensed matter models, and for the invention of optical lattice techniques including a super-lattice for patterned loading, and re-configurable lattice of double wells.” **Glenn Solomon** was honored for “extensive contributions to the study of quantum optics with quantum dots.”

Election to Fellowship of the APS is a competitive, peer-reviewed recognition of contributions "to the advancement of physics by independent, original research or . . . other special service to the cause of the sciences."

- **Carl Williams** has been awarded the Gold Medal, the highest honor conferred upon an employee of the Department of Commerce. The award is bestowed for “distinguished performance characterized by extraordinary, notable or prestigious contributions that impact the mission of the Department of Commerce and/or one operating unit and which reflect favorably on the Department.” Williams was recognized for "contributions to the theory and application of atomic clocks, ultra cold atomic physics and quantum information science."

- On Dec. 1, **Sankar Das Sarma** gave the inaugural invited talk, “Spin Coherence and Spin Computation in Semiconductor Nanostructures,” at the Materials Research Society’s Fall Symposium in Boston (Dec. 1-5). The next day at the same conference, **Bruce Kane** delivered a talk on “Two Dimensional Electron Systems with Mobility Exceeding 105 cm²/Vsec on Hydrogen-terminated Silicon Surfaces.”


- **Chris Monroe** organized a JQI booth for an October research open-house event celebrating the halfway point of the University of Maryland “Great Expectations” Campaign. The booth featured a live video feed from his ion trap laboratory showing a string of laser-cooled ytterbium 171 ions glowing on the screen. (See image below.)

Many highly placed administrators and university donors visited the booth. UMD President C. Dan Mote was curious as to why the central atoms in the chain were closer together than the ones on the outside. Postdocs Ming-Shien Chang and Kihwan Kim, and graduate students Simcha Korenblit and Rajibul Islam coordinated the live laboratory feed, and tag-teamed between the lab and the event hall.
On Dec. 2, Bill Phillips gave a talk titled "Time and Einstein in the 21st Century: The coolest stuff in the universe" at the Carl Friedrich von Siemens Stiftung in Munich. On Dec. 8 he gives the physics colloquium at the University of Ulm, "A Bose Condensate in an Optical Lattice: Cold Atomic Gases as Solid State Systems" This colloquium is also the Lamb Lecture, endowed at the University of Ulm by Willis Lamb. On the same European trip, Phillips will also give talks in Darmstadt, Sheffield, and Birmingham.

Charles Clark, along with J. Y. Vaishnav, Julius Ruseckas and Gediminas Juzeliunas, wrote "Ultracold atom spin field effect transistors," which has been accepted for publication in Physical Review Letters. In November, he gave a talk titled "The American Elections - What Happened?" at the Australian National University in Canberra and at the National University of Singapore.

In other activities, Clark was "adopted" by high school classes in Virginia, Florida and California as part of the American Physical Society's "Adopt-a-Physicist" program (http://www.adoptaphysicist.org). In this program, physicists volunteer to answer questions put to them by designated groups of high school students through an online forum, for a period of about two weeks. Clark wrote some 20 short essays in response to questions ranging from quantum cryptography to the optics of the rainbow to the possibility of extraterrestrial life; these were viewed over 500 times.

Finally, Clark posed with Danny Rogers (photo above: Rogers is at right), who on Oct. 31 defended his Ph.D. thesis, "New Technologies for Broadband Quantum Key Distribution: Sources, Detectors, and Systems," which was supervised by Clark and Julius Goldhar (ENEE). Rogers will receive his degree from UMD's chemical physics program. In January he joins the staff of the Johns Hopkins Applied Physics Laboratory.

Mixing It Up in OPN's Year-End Review

Paul Lett and NIST JQI colleagues Alberto Marino, Vincent Boyer and Raphael Pooser describe production of entangled images by four-wave mixing in Optics and Photonics News. The special December issue, Optics in 2008, is devoted to "the most exciting research to emerge in the preceding 12 months in the fast-paced world of optics."