Trapping Graphene

The idea of combining expertise of condensed matter and atomic physics to advance quantum science is at the heart of the JQI. A few years ago JQI fellow Bruce Kane, impressed by the trapping and cooling techniques of atomic physics, wondered if he could merge some of this “neat technology,” as he describes it, with a condensed matter experiment. Specifically, he observed the recent explosion in graphene research, and wanted to confine this two-dimensional array of carbon atoms (depicted right) in a quadrupole trap.

Superfluid Switch: An Atom Circuit

Over the last decade, researchers have demonstrated exquisite control and isolation of ultra-cold atoms—ingredients that together form an ideal platform for studying solid-state systems. JQI scientists plan to take this type of simulation another step, to see if they can construct circuit elements from these atomic gases where the atoms take the role of electrons, now known as the field of atomtronics.

This goal is motivated in part by successful demonstrations of superconducting circuits. The MURI atomtronics grant (Multidisciplinary University Research Initiative) supports one such experiment that not only generates persistent superfluid currents (i.e. frictionless flow): this quantum fluid can act as an atom switch.

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The experiment (Figure 1) consists of an electric quadrupole trap, similar to those used to traditionally confine single ions. Few-layer graphene flakes are suspended in a mixture of isopropyl alcohol and water and transferred to the trapping region using a technique called electrospray ionization. The liquid suspension is injected into a capillary tube that is held at a high voltage (~2000 V). This induces an electric field across the sample, which deforms the liquid into a cone at the tube opening. At a critical voltage the cone becomes unstable and a jet of partially volatile liquid carrying the flakes is emitted. The liquid evaporates and ions are dispersed into the trapping region where they become stably confined. One tricky part of the experiment is the background pressure requirements for the vacuum. For the electrospray method, the optimum performance is found at pressures of 0.5 torr, or 0.06 % of atmospheric pressure (1 atm=760 torr). Once a particle is trapped, the experimental region is pumped down to a pressure of $10^{-6}$ torr and the graphene is ready to be probed.

Graphene, which has similar optical properties to its many-layered cousin graphite, is a good light absorber, making detection with lasers straightforward. One observation that became immediately apparent in his experiments, is that depending on the light polarization, the trapped graphene would gain some angular momentum and spin at frequencies currently into the MHz (1,000,000 rotations/second). Kane’s rotating graphene holds the record for fastest spinning trapped macroscopic object. Because of that extreme tensile strength, it is estimated that the flakes can stably handle rotational frequencies almost a thousand times faster than those achieved in the current experiment, up to 1.7 GHz. Kane comes from a 2D electron-physics background and thinks that rotating graphene may open the door for experimental studies of rotating electron systems.

The results, described in Phys. Rev. B 82, 115441 (2010) as mainly a proof-of-principle experiment in the isolation of graphene, may have wide ranging implications. As Kane states in the article, “graphene has been deemed the world’s strongest material because of its large Young’s modulus and proven ability to withstand tensile strain in excess of 10 %.” What does this mean? Tensile strength is a measure of how much an object can be pulled on before it deforms irreversibly (breaks). For comparison, graphene has an impressive tensile strength about 150 times larger than stainless steel and 450 times that of human hair. Thus, continued, next page
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from a material science perspective, it might be interesting to investigate the structural integrity of graphene.

One current obstacle for graphene is isolation. The traditional technique for isolating graphene is the scotch tape method, recently recognized with a Nobel prize in physics. A drawback, which may limit the widespread use of graphene, is that the tape extraction produces jagged and irregular-sized graphene flakes. Alternatively, one can grow graphene monolayers on a substrate. Here a gas of carbon (methane) surrounds a substrate, such as copper, and is heated to temperatures above 1000 K, at which point the carbon atoms can squeeze into the spaces in the metal. The graphene layer is formed on the surface as the system is cooled and the carbon atoms leech out of the metal. Although this method results in controlled crystal growth, Kane suggests that isolation in a trap may provide a way to study high temperature properties, which is difficult to do in the presence of a substrate. Because of electrostatic tension, the trapped flakes are likely planar and so it may also be possible to modify the structure in situ or even grow crystals.

Kane, motivated in part by the success of cooling techniques that have opened the door for researching novel physics in atomic systems, wants to explore cooling graphene. Removing energy from the system may be challenging with the standard AMO toolbox because even sub-micron sized graphene flakes have countless internal degrees of freedom. However, the system may be simplified because the low temperature properties of 2D crystals, like graphene, are dominated by flexural phonons. Kane compares these vibrations, which move perpendicular to the layer of atoms, to vibrations of a drumhead. For instance, when the tension on a timpani is released, the tone shifts to lower frequencies. Similarly, if the graphene membrane tension can be reduced, the flexural phonon energies will decrease, and — assuming the membrane is thermally isolated — the temperature will drop. Kane believes that reaching low temperatures can facilitate observation of the theoretically predicted phases in the coupled electron-flexural phonon system. With all the exciting applications on the horizon, Kane is currently dedicated to building the next generation of the apparatus.

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In an interdisciplinary collaboration involving JQI fellows Gretchen Campbell, Kris Helmerson, Wendell Hill, Chris Lobb, and Bill Phillips, this work spans condensed matter, atomic physics, and specialized optics. Creating long-lived superflow in a multiple-connected Bose-Einstein condensate—in this case 40 seconds—was not easy, as defects or noise in the atom trap can artificially cause a decay in the current.

Figure 2. Intersecting laser beams (shown in red) illuminate the Bose-Einstein condensate, forming a donut-shaped all-optical trap. Additional laser light (depicted by the yellow and orange arrow) transfers orbital angular momentum to the cloud, which initializes the superflow. The team of researchers have observed persistent currents that last an impressive 40 seconds (drawing courtesy of authors).
Gretchen Campbell’s lab at NIST redesigned their atom trap to be completely made of laser light, producing an extremely smooth all-optical toroid (or donut-shaped) potential in which to study both the superflow and atomtronics (Figure 2). As Campbell explained in the May 2010 issue, demonstrating persistent currents was a necessary and challenging first step in developing the atom switch.

To manipulate the current, a classical barrier or “weak link” was created by focusing a green laser beam into the path of the superflow (depicted in Figure 1 and Figure 2). The scientists control the amplitude of the obstruction by adjusting the laser power.

The presence or absence of superflow is determined by a competition between the strength of the barrier and what is known as the chemical potential of the quantum fluid. The chemical potential, which can also be varied, is the energy required to add or remove an atom from the BEC. The barrier is analogous to a constriction in a pipe, causing the flow in the narrow region to speed-up and become turbulent.

The velocity of the superfluid around the ring can only have particular or discrete values, and in this case, it moves with the lowest allowed circulation rate. The necessary conditions for current flow cannot be maintained when the local velocity near the barrier becomes sufficiently fast. At this critical value, the weak link abruptly shuts-off the superflow, like a switch. The switch is currently not reversible and the flow, once stopped, has to be re-initialized by imparting angular momentum onto the atoms.

Campbell and Wright explain how this type of multiply-connected atom trap allows for future studies of superfluid properties such as direct measurements of the superfluid fraction. They also explain quantum fluids behave differently depending on the dimensions and type of trap, which necessarily confines them.

But first, the team will attempt a direct analog to a SQUID (superconducting quantum interference device), by dynamically moving the barrier around the toroidal BEC. SQUIDs are well-known sensors that can detect extremely small magnetic fields because of the special properties of current flow in a loop of superconducting wire containing two Josephson-junctions (June 2010 issue).

The atom-switch work is described in their manuscript, recently accepted to Physical Review Letters. In addition, this research has been highlighted during the last month in several popular science articles, listed below.
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Physics World - Ultracold atoms race around laser circuit

ScienceNews - ‘Atomtronics’ may be the new ‘electronics’

GearLog - Move Over Electronics: Atomtronics Offers New Possibilities

GeekyGadgets - Why is Atomtronics Important?

More about toroids. Campbell explains how the toroidal geometry is a good platform for building an atom-circuit because one can easily and reliably detect the presence of superflow with standard time-of-flight methods (see May 2010 issue). This is because the rotation maintains a hole which survives, even after the atoms are released from the trap. Toroids also have so-called multiply-connected geometry: imagine taking a loop of wire and placing it anywhere in an object—if the wire can be contracted until it is a point, and this process can be repeated for all coordinates in the object, then it has simply-connected geometry, as in a sphere.

Publications


Entangled States

Loudon Academy of Science high school student Ari Dyckovsky attended the International Space Olympics (ISO) in Moscow, where he took 1st place overall, including in the research portion of the competition. Ari has two academic advisors at the Loudon Academy of Science: Dan Crowe and Duke Writer. Steven Olmschenk, an NRC post-doctoral researcher at NIST, has been serving as Ari’s external research advisor. Ari’s research project was titled “Analysis of Ground-to-Satellite Entanglement-Enhanced Quantum Communication with Quantum Memories.” This topic is closely related to work done at the JQI (particularly in Chris Monroe’s group). Two of Ari’s classmates also attended the competition: Seong Bin Im (4th place overall) and Damon Rosenberg (14th place overall). The competition had about 100 participants, with delegations from Russia, Greece, Great Britain, and America.

On Dec. 4, Thomas Hanna gave an outreach talk to middle school students at ‘Journeys in Engineering, Technology and Science day’, organized by the Universities at Shady Grove. He also was invited to speak at the UConn AMO seminar Jan. 24. The title of his talk was “Making and manipulating Feshbach resonances with RF radiation.”

Ari (right) and classmates at International Space Olympics in Moscow, Russia.
The JQI participated actively at Quantum Optics V (http://www-optica.inaoep.mx/QOII/qov.html), a meeting that took place in Cozumel, Mexico from November 15 to 19, 2010. Many JQI members (Becerra, Marino, Lett, and Orozco) and former members (Gomez, Barberis) gave talks and presented posters in this prime gathering of quantum opticians from Latin America. The support from JQI and the PFC went to facilitate the travel of postdocs who wanted to present their results.


Jon Sterk, a University of Michigan graduate student in Chris Monroe’s group, completed his thesis work at UMD on Dec. 10. In late March he will begin a post-doctoral position at Sandia National Laboratories, where he will continue working with ion traps.

On Dec. 13, Matthew Beeler, a graduate student in Steve Rolston’s group, defended his thesis. In January he began working for Ian Spielman as post-doctoral researcher in the Laser Cooling and Trapping group at NIST.

Rajibul Islam, a graduate student in Chris Monroe’s group, was recently invited to discuss the group’s work on quantum simulation at two different venues. He gave the Condensed Matter Theory Seminar, UMD- titled “Phase transition in long range quantum Ising model simulated with trapped ions” (Dec 14, 2010). He then travelled to India and presented a talk titled “Adiabatic quantum simulation of spin Hamiltonians using ultracold trapped ions” at the Indian Association for the Cultivation of Science, Kolkata, India on Jan 31, 2011. Additionally, he visited his alma mater Chakdwipa High School, Haldia, India) on Jan 29, 2011 to give a popular science talk called “What do atoms look like?” to high school students.

On Feb. 4, graduate student Jeff Grover and fellow Luis Orozco visited the Thurgood Marshall Academy in Anacostia to discuss light and waves. In addition to their presentation, they donated optics kits to the students. A description of their demonstration can be found at: http://theother17hours.blogspot.com/2011/02/university-of-maryland-physics-visits.html

On Feb. 9, fellow Chris Lobb volunteered to judge a science fair at the K-8 St. Peter School on Capitol Hill. Earlier, in November, he and his wife Dr. Paola Barbara delighted students at the same school with popular demonstrations involving liquid nitrogen such as levitating a magnet above a high-Tc superconductor and making ice cream.

From Feb 17-20, Chris Monroe and Luis Orozco, with members of their research groups, attended the annual SQuInT (Southwest Quantum Information and Technology) workshop held in Boulder, CO. Kihwan Kim presented a talk and the following members contributed posters: Susan Clark, Le Luo, Andrew Manning, David Hayes, Jonathan Mizrahi, Andres Cimmarusti, Jeffrey Grover. Additionally, Steve Olmschenk presented a talk titled, “Randomized benchmarking of atomic qubits and differential light shift cancellation in an optical lattice.” Preceeding the conference, there was an Ion Trap Meeting hosted by NIST, Boulder at which Chris Monroe was an invited speaker.

Bill Phillips gave a public lecture at Bethesda-Chevy-Chase High School on Feb. 23. The lecture, titled “Time, Einstein, and the Coolest Stuff in the Universe,” was organized by the MIT club of Washington with the Walt Whitman high school science department. Lectures of this type are targeted to young students with the purpose of the fostering excitement towards STEM subject areas.
Entangled States, continued

Left: Past and present members of the Trapped Ion Quantum Information group at UMD take in the views in Boulder. Top right: Post-doctoral researcher Susan Clark presents a poster titled, “Ion-Photon Networks for Scalable Quantum Computing.” Bottom right: Post-doctoral researcher Le Luo and graduate student Andrew Manning share their research on collecting light from a trapped ion in a cavity.

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