Spin Control: Modeling the Transistor of the Future

The Next Big Thing in microelectronics will be extremely small. And it probably will not be entirely electronic. As transistor dimensions continue to shrink, and computing demands continue to grow, pushing bunches of electrical charges around in semiconductors can start to look like an awfully bulky, slow and power-hungry business. So in addition to expressing digital information as the presence or absence of electric charge, researchers want to embody it in the spin of electrons -- a quantum property that conveniently has two easily discernible states, traditionally designated “up” and “down.”

Spin can be switched very fast, with low-power magnetic fields, and “spintronics” already lies at the core of today’s high-volume disk drive technology. But extending its alluring advantages to transistors has so far proven impossible.

Twenty years ago, two Purdue University scientists proposed a highly promising design. To date, however, no one has been able to build a working model. There are simply too many possible sources of error, because the desired spin effects are extremely sensitive to very tiny

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Stirring Up New Physics in Toroidal BECs

Quantum effects don’t usually intrude into daily life. That’s a fortunate state of affairs for a person who needs to know, say, the position and speed of his car at the same time.

But in the lab, macroscopic quantum systems are increasingly the subject of intense investigation, and none more so than the eerie entities called Bose-Einstein condensates (BECs). At JQI, BECs will be a focus of special attention as part of the Physics Frontier Center activities.

Researchers first created a BEC in 1995, 70 years after Satyendra Nath Bose and Albert Einstein predicted the exotic state of matter, by supercooling a cloud of trapped atoms to the point at which they all collapse into the same quantum state. In that strange condition, atoms behave in a collective fashion, as if they were a single entity or “super-atom.” But BECs can contain hundreds of thousands, or even millions, of atoms, and the resulting aggregation is big enough to see with the (very acute) naked eye, and to examine with ordinary, large-scale optical devices.

That’s one reason that, 13 years after the initial condensate was made, BECs are still revealing a host of novel phenomena and providing new insights into quantum mechanics. And JQI scientists are poised to take that research to new, ever larger dimensions.

A group headed by JQI Fellows Bill Phillips and Kris Helmerson at NIST has been exploring the characteristics of BECs created in a torus (doughnut) shape and then exposed to various forces or fields.

Usually, when atoms are trapped and chilled to around 200 billionths of a degree above absolute zero, the resulting condensate is approximately spherical or cigar-shaped.

The JQI team employs a different technique: They use an elliptical trap and shine a high-energy green laser beam through the middle of the trapped cloud, expelling atoms from the center. The result is a BEC in the shape of a torus, which has considerable advantages for certain kinds of study. For example, an ordinary BEC has a substantial density gradient, thinning out from the center to the edges. A toroidal BEC has a much more uniform density. In addition, it provides a closed loop in which atoms can move or forces can propagate, allowing a wide range of effects. That property allowed the researchers to demonstrate, in a paper published last fall, the first evidence for “persistent flow” -- frictionless, superfluid motion of atoms -- around an ultracold BEC ring.

Yet another highly intriguing advantage is that the BEC’s ring shape is the same as that of the superconducting quantum interference device, or SQUID. A SQUID is a loop of superconducting material containing one or more super-thin insulating barriers called Josephson junctions (JJ). Thanks to a quantum phenomenon called tunneling, which results from the fact that a particle’s wave function can extend across classical barriers, a current can flow across a JJ in the absence of any voltage. Applying a voltage causes the current to start alternating. Applying a magnetic field causes the current level to change.

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Stirring Up New Physics, continued

Solid state SQUIDs have enormous potential for quantum physics and the future of information processing, but have decoherence properties that are poorly understood. That’s one reason that the JQI team, which contains experts in BECs and SQUIDs, will direct some of its Physics Frontier Center work to creating and studying atomic SQUID analogues (ASA) in which moving atoms in a BEC torus play the role of electrical current.

Already JQI researchers have shown that the rotational frequency in an ASA is analogous to the magnetic field in a SQUID, with the field strength proportional to the frequency. Testing such similarities and differences is likely to provide valuable insights.

(And perhaps practical products as well: Some sort of ASA might serve an ultra-sensitive rotation detector, much as SQUIDs are now routinely used to detect extremely faint magnetic fields.)

The group has already conducted a lot of preliminary research. In particular, they developed a novel method of controlling the motion of BEC atoms by whacking them with a specially prepared laser beam, called a Laguerre-Gauss mode, that conveys orbital angular momentum to atoms it strikes. (Other teams have moved the atoms by physically stirring them.) The Laguerre-Gauss technique has many advantages, and it can produce results that are very difficult to imagine from a purely classical perspective.

For example, Helmerson and colleagues have used two carefully correlated laser pulses to generate a coherent superposition of BEC atoms rotating in two opposite directions in the torus. To confirm that half the atoms really are going one way while half are going the other, the group used another light pattern to nudge the two atomic flows so that they interfered with one another. The resulting images clearly demonstrate the expected interference patterns.

“We have the technology now to create any arbitrary rotational state -- but also any superposition of rotational states,” Helmerson says. “We’ve added another tool to the tool box of atom manipulation.” Moreover, because rotation is a topological property -- that is, one that forms a shape over an extended area and hundreds of thousands of atoms -- it tends to be more robust and less prone to external perturbation than many other atomic states, such as spin, that are often manipulated in superposition experiments. In fact, the rotation persists for 10 seconds, and does so even when the BEC atoms make up only 20 percent of the atoms in the trap.

If these and other techniques can be improved, they may lead to macroscopic quantum phenomena never before observed, such as a coherent “Schrödinger cat” state in which every atom in the torus is moving both clockwise and counterclockwise simultaneously. Preparation of an ASA might end up producing a “cat” state, while also allowing scientists to study how momentum changes and dissipates. The team also wants to see how a structure such as a vortex will behave in an ASA. They are familiar in JJ’s, but have never been observed in a BEC tunneling through a junction.

According to theory, a lone vortex (red arrow) encountering a barrier (green) may reflect off or tunnel through. In superposition, it moves clockwise and counterclockwise at the same time.
imperfections in materials, stray fields and problems with electron injection, among other factors.

Now, however, JQI Fellow Charles Clark and colleagues at NIST and at Vilnius University have devised a potential solution to the problem: creating a minutely controllable quantum analogue of the transistor action in a laboratory configuration -- in this case, an ultra-cold beam of atoms manipulated by a laser array.

One of JQI's central goals involves finding ways to simulate aspects of complex macroscopic systems, from the trillions of interacting atoms in condensed matter devices to the exotic and inaccessible physics of black holes and neutron stars, by using precision-tunable quantum models.

That approach is ideally suited to attacking the problem of the Datta-Das transistor (DDT, see illustration at right), named for the two Purdue physicists who theorized it in 1990.

“If you have a system that doesn’t work in real life,” says Jay Vaishnav, a postdoc in Clark’s group, “maybe you can understand it by building a model, introducing controlled disorder and synthetic perturbations, and then watching how it breaks down. That way you can see what kinds of imperfections it can tolerate and still work.”

The group developed a theoretical simulation in which the DDT electrons would be represented by a “source” stream of ultracold atoms (neon and rubidium could work, among others) that pass through a space in which three crossed laser beams overlap. When the atoms are struck by the first laser beam, the beam puts all the atoms in the same quantum state -- equivalent to the identical spins of the source electrons in a DDT.

But as the atoms encounter the other two laser beams in the “gate” area, they are shifted into different quantum states depending on the relative strengths of the beams.

In the DDT scheme, electrons in the gate are affected by the voltage applied to the gate electrode. It produces a field that causes the electrons’ spins to precess -- a motion akin to what happens to a spinning top as it slows down and the force of gravity causes the spin axis to start to wobble in a circular motion.

This effect arises from changes in each electron’s “spin-orbit coupling,” a phenomenon resulting from the fact that the electron experiences a constantly changing interaction between its intrinsic spin and the magnetic field it generates as it orbits.
The field generated by the DDT’s gate voltage alters the spin-orbit dynamics, shifting each electron’s spin. Only those electrons with the same spin orientation as the drain can pass through. Thus the gate voltage controls the current, just as in an ordinary all-semiconductor transistor, theoretically permitting the device to be used for information processing.

To model that action, the atomic-beam simulation uses laser light in place of the gate voltage, and the “ground” states (lowest energy conditions) of the atoms in place of spin orientation.

When the first laser beam excites the atoms, they then “decay” (that is, shed the energy by emitting a photon) into one of three ground states. Only one of those states, however, has the right quantum properties to be re-excited by the laser frequencies available, and then re-emit a photon. This is called a “bright” state, and can be disregarded for the experiment.

The other two ground states cannot absorb (and thus re-emit) the specific frequencies of any of the laser beams in use, and so they are called “dark.” The two different dark states correspond to the two possibilities for electron spin orientation -- “up” and “down” -- in the DDT. The proportion of atoms in each of the two dark states is a function of the relative intensity of the second (middle) laser beam, just as the proportion of DDT electrons in a particular spin state is a function of the device’s gate voltage.

An atomic state analyzer at the end of the process detects which of the two dark states each atom is in, corresponding to the drain of a DDT, which filters out electrons with altered spin.

Unlike the macroscopic DDT -- with its enormous number of atoms and myriad possible sources of error -- the atom-beam analogue offers the opportunity to study exceedingly small components of the device and to carefully control the behavior of the system, altering only one variable at a time. If eventually constructed, the atom-beam model should allow physicists to determine which specific factors are most critical to the performance of a DDT.


**Atom beams as a model DDT.** LEFT: A beam of atoms crosses an area in which three laser beams overlap. The first beam places each atom in the same excited state. As the atoms pass through the region where the second and third lasers cross, their states may or may not be altered. If no atomic states are changed, the entire beam passes through the analyzer -- the equivalent of maximum current in the drain of a working DDT. RIGHT: By “tuning” (changing the relative strengths of) the lasers, the state of the atoms in the beam changes in a predictable way, altering the proportion of atoms in each of the three possible ground states, two of which are dark. The quantum difference between the two dark states corresponds to the difference between spin-up and spin-down electrons in a DDT, with the laser beams acting as the gate.
New Neutron Detector Makes R&D Top 100

A new ultrasensitive, high-bandwidth neutron detector, developed by JQI Fellow Charles Clark and colleagues from the National Institute of Standards and Technology (NIST) and the University of Maryland (UMD), has won a 2008 “R&D 100 Award.”

The annual R&D 100 Award program recognizes “the 100 most technologically significant products introduced into the market” during the previous year, as selected by an independent judging panel and the editors of R&D Magazine.

Neutron detectors are important in a variety of applications, ranging from fundamental physics experiments to materials science, oil well logging, monitoring of special nuclear materials, and personal protective equipment for first responders. Present neutron detector technology is based on proportional counters, in which high-voltage electrical discharges are initiated by neutron absorption in a gas cell.

The NIST Lyman alpha neutron detector (LAND), on the other hand, detects neutrons by sensing “Lyman alpha” radiation -- in the far ultraviolet region of the optical spectrum, at a wavelength of 122 nm -- that is produced following neutron absorption by helium-3 (³He) gas.

The LAND technique offers significant advantages over proportional counters. For example, optical emissions are faster than electrical discharges, thus yielding a detector with intrinsically higher bandwidth; and LAND demonstrates single-neutron sensitivity, which has never been possible with proportional counters. In addition, LAND seems less susceptible to spurious neutron reports triggered by gamma rays.

NIST has filed a U.S. patent application on the LAND technology. A scientific paper on LAND principles was published in the peer-reviewed NIST Journal of Research in April 2008.

The LAND development team recognized by the R&D 100 Award consists of: Alan K. Thompson
and Muhammad Arif of the NIST Ionizing Radiation Division, Robert E. Vest and Charles W. Clark of the NIST Electron and Optical Physics Division, and Michael A. Coplan of UMD’s Institute for Physical Science and Technology. Critical support for this project was provided by unique NIST calibration facilities for neutron and far ultraviolet radiation, respectively the NIST Center for Neutron Research, and the SURF III Synchrotron Ultraviolet Radiation Facility.


Stirring Up New Physics, from page 3

Want to create a sizable cloud of sodium atoms, seen glowing (close-up in inset above) in JQI Fellow Kris Helmerson’s lab? You’ll need a furnace (right, top) that produces a steady stream of atoms (right, bottom). Eventually they end up trapped in an ultrahigh-vacuum enclosure (left) for detailed study.
There are nine other NSF PFCs in the United States. Selection criteria require each one to demonstrate “the potential for a profound advance in physics,” as well as “creative, substantive activities aimed at enhancing education, diversity, and public outreach [and] potential for broader impacts, e.g., impacts on other field(s) and benefits to society,” among other requirements.

The JQI PFC will meet those standards by developing a cross-disciplinary approach to fundamental understanding and control of quantum “coherence” -- the fragile condition in which objects exist in a “superposition” of multiple states at the same time -- in the context of the burgeoning field of quantum information science and quantum computing.

In particular, the PFC will emphasize work at the increasingly busy intersection of two traditionally separate areas: atomic, molecular and optical physics (AMO), and condensed-matter physics (CM).

That kind of intensely interdisciplinary effort will be necessary to explore the ways in which coherence can be produced and transferred among very different kinds of physical systems, including solid-state photon sources, individual trapped atomic ions, correlated electron gases, ultracold atomic gases in optical lattices, and superconducting quantum interference devices. At the same time, investigators will have to devise methods of forestalling “decoherence” -- the collapse of the essential coherent state.

Within that overall mission, groups of JQI scientists will focus on three major research activities:

(1) **Correlated and Topological Matter with Cold Atoms.** Tightly confined collections of cold atoms and ions, accompanied by appropriate laser beam geometries, can experience strong interactions and complex “entangled ground states” -- that is, minimum-energy conditions in which the state of one object is inextricably linked or “entangled” with another object, even though they are separated by arbitrarily large distances.
In some cases, these systems constitute a new kind of “condensed matter” that may or may not have analogues in real CM systems. Either way, they will provide valuable insights into the quantum world. Moreover, many of the systems are likely to display “topological phases” in which certain key outcomes appear as shapes extended in space. Such configurations tend to be robustly resistant to external perturbations.

(2) Supercircuits at the AMO/CM interface. The PFC will develop a hybrid device that couples a unit of magnetix flux in a superconducting circuit to the collective spin of a population of confined atoms. The arrangement will allow scientists to see how states might be exchanged between the systems, and will enable precise study of poorly-understood electric and magnetic fluctuations in superconducting devices. A second activity will involve persistent atomic currents in a toroidal (donut-shaped) trap containing a Bose-Einstein condensate. Aspects of this project are described in “Stirring Up New Physics,” starting on page 2.

(3) Quantum Optics with Hybrid Quantum Systems. Photons are natural carriers of quantum information over distance, whereas quantum states in matter -- such as semiconductor quantum dots, trapped atoms or ions -- can store coherence locally for long periods of time.

The PFC will explore various combinations and interconnections of these systems, and will examine how to interface and entangle individual atoms, degenerate gases and quantum dots with quantum states of light.

Central to this activity is the use of photons as intermediaries to entangle atomic qubits (quantum bits which can have a multitude of simultaneous values because they are in a superpositional states) and quantum dots with quantum states of light. This work will entail extensive and ambitious collaborations among several JQI laboratories.

The PFC will share space with JQI on the second floor of UMD’s Computer and Space Sciences building. Temporary contact information is available on the web at www.jqi.umd.edu/pfchome.
Entangled States

• JQI Fellow Steve Rolston wrote an article on ultracold neutral plasmas for the American Physical Society’s “Trends” feature, part of a new APS effort to highlight “the best and most interesting papers in the Physical Review journals.” The overview article, published on July 14, can be found at http://physics.aps.org/articles/v1/2.


• Thomson Reuters’ Science Watch, which tracks influential trends in research publication, named JQI Fellow Sankar Das Sarma’s paper titled “Dielectric function, screening, and plasmons in two-dimensional graphene” (Physical Review B, May 2007) as the most frequently cited paper in the area of two-dimensional graphene.

• At the Black Hat/DEFCON meetings in Las Vegas last month, JQI Fellow Charles Clark and colleagues demonstrated quantum encryption of live video streams in presentations titled “Quantum Spookshow” at Caesar’s Palace and the Riviera Hotel and Casino.

• Research by JQI Fellow Paul Lett and colleagues was highlighted in the August issue of Physics Today. The magazine’s Search & Discovery section has a three-page description of the work titled “Entangled light beams from four-wave mixing carry spatial information.” (Pages 16-18.)

On Campus, On the Web

NEW FACES: Five new postdocs recently joined JQI-related research groups. At UMD, Wes Campbell and Qudsia Quraishi will work on ultra-fast quantum gates. Le Luo, a JQI Postdoctoral Fellow, will concentrate on cavity-QED experiments with trapped ions.

At NIST, Layla Hormozi and Ludwig Mathey -- both National Research Council Postdoctoral Research Associates -- will be working with NIST’s AMO theory group.

NEWS ABOUT NEWS: In order to provide more -- and more timely -- information, subsequent news items will be posted directly to the JQI web site (www.jqi.umd.edu) as they occur, and then collected monthly in the newsletter.