A New Way to Cope with Frustration

For most people, frustration is a condition to be avoided. But for scientists studying certain “frustrated” ensembles of interacting components – that is, those which cannot settle into a state that minimizes each interaction – it may be the key to understanding a host of puzzling phenomena that affect systems from neural networks and social structures to protein folding and magnetism.

Frustration has typically been extremely difficult to study because even systems with relatively few components have interactions so complex that they cannot be modeled effectively on the best conventional electronic computers.

Boxed Sets of Cooper Pairs in a Qubit

A team of researchers has produced a tenfold enhancement in the lifetime of the quantum state in a promising experimental design for a superconducting qubit, opening the possibility of further improving the exotic device for use in practical quantum information processing.

A qubit (quantum bit) is the fundamental unit of data in a quantum-information system, just as the bit (binary digit) is the fundamental unit in conventional digital computing. A bit can have one of two discrete values, 0 or 1. A qubit, however, can have either of those values – or both at once, in a condition called “quantum superposition.”
There are many systems that can be placed in a superposition of two distinct states, and thus serve as qubits, such as neutral atoms, ions, photons, electrons, quantum dots and various superconducting devices. The last category is favored by many researchers, including a group at the Laboratory for Physical Sciences headed by Ben Palmer in collaboration with JQI Fellow Fred Wellstood, because superconducting (SC) devices can be built using familiar methods from semiconductor circuit fabrication techniques.

SC qubits, however, have been plagued by notoriously short coherence time – that is, the interval during which superposition can be maintained – compared to other qubit options. As a result, extending coherence times in SC devices is an active research goal in labs around the world. “That’s the main criticism of superconducting qubits,” says Palmer. “Their lifetimes are short. Right now, there’s a lot of theories out there about what’s limiting the coherence time. That’s our goal, to try to figure out what’s limiting us.”

At present, the LPS group is investigating a qubit arrangement in which charges can “quantum tunnel” on and off a microscopic piece of superconducting aluminum, about two micrometers long.
and one-tenth of a micrometer wide. (Tunneling is a quantum-mechanical phenomenon, resulting from the Uncertainty Principle, whereby particles can cross seemingly prohibitive energy barriers.) This aluminum “island,” as it is called, is connected to two Josephson junctions [See illustration, p. 1].

The junctions consist of extremely thin insulating layers between two pieces of superconducting material across which electrons can pass in the form of pairs of electrons (called Cooper pairs) that are characteristic of superconducting current. The “Cooper pair box” qubit and surrounding apparatus are kept at a temperature around 25 thousandths of a degree above absolute zero.

The two states of the LPS qubit are a function of the number of electron pairs on the island. “One way you can think of it,” Palmer says, “is that one state has zero excess Cooper pairs on the island, and the other – the excited state – has one additional Cooper pair on the island. Those would be the two states of the system. And they’re separated in energy by a certain amount that we can actually control.”

There are two separate controls on the system that are used in tandem to manipulate its behavior. One is the strength of a magnetic field applied to the Josephson junctions. (The junctions are exquisitely sensitive to changes in magnetic flux, and devices made from such junctions are routinely used to detect very weak fields.) The other is the voltage applied to an electrode adjacent to the island. That voltage provides the energy needed to add single Cooper pairs to the island and thus change the qubit state.

The LPS team initially used a device called a single-electron transistor (SET) to read out the state of the qubit. Recently, however, they have employed a novel superconducting resonator devised by LPS scientist Zaeill Kim. [See illustration, previous page.]

“We switched the read-out for two reasons,” Palmer says. “First, it was my feeling that the SET was a noisy readout, and our lifetimes were being limited by the noise in the SET. With the resonator, the dissipation is orders of magnitude smaller. And the other thing is that the coherence times are longer.” Indeed, the lifetime of the excited state, one key component of the coherence time, has been increased from around 10 microseconds to 100 microseconds.

The new LPS design is similar to a technique pioneered by Robert Schoelkopf’s group at Yale several years ago. It relies on coupling the qubit to an attached resonating circuit that oscillates at different frequencies depending on the qubit state. “The qubit changes the resonant frequency of that resonator,” Palmer says. “It’s like it adds mass or removes mass from a system of objects connected by springs. To put the qubit in the ground state is like adding mass, and putting it in the excited state is like removing mass.”

The state of the qubit can then be determined by examining what happens to microwaves that are transmitted down a channel next to the resonator. The resonator’s frequency affects the amplitude and phase of the microwaves, which are measured at an output detector. “When we put the qubit in the ground state, the resonance will drop and the phase will change,” Palmer explains. “And then when we put the qubit in the excited state, the resonant frequency will shift over by the same amount and the phase will go the other way.”

So far, the results have been extremely promising, at least at one range of frequencies around 4 to 8 GHz. “We see a very strong frequency dependence to the lifetime,” Palmer says. “This might be a clue to what is still limiting the lifetime, and that’s something we’re trying to figure out right now. Obviously we would like to measure multiple devices as well.”
Now, however, a team of researchers has simulated frustration in the smallest possible quantum system in a precisely controllable experimental arrangement, one which can be extended to much larger systems. In addition, they have demonstrated for the first time how frustration is related to a bizarre but highly useful quantum-mechanical condition called “entanglement.” They report their findings in the June 3, 2010 issue of the journal *Nature*.

“Frustration occurs when one or more elements of a system are acted on by competing forces in a way that makes it impossible to reach one ‘ground’ state, or lowest-energy arrangement, of all individual interactions,” says research group leader Chris Monroe of the Joint Quantum Institute (JQI). “The simplest example is a system of three objects such as atoms, each of which has a spin” (the quantum-mechanical analogue of north or south magnetic poles) “that can have only one of two values – either ‘up’ or ‘down’ – and nothing in between.”

For any two such objects, the minimal-energy condition occurs when the spin of each object is the opposite of its neighbor. [See Figure 1.] So if there are only two objects, each with an opposite spin, the system naturally tends to be in this state. But add a third object and things get interesting. This third object has two neighbors, each with a different spin. It cannot line up opposite to both of them. So it is stuck between two alternatives, each of which is equally unsatisfactory and each of which requires the same amount of energy. That is the condition called frustration.

Researchers are intensely interested in that phenomenon, which can provide key insights into the way objects arrange themselves into materials such as the crystals used in electronics, or the rules that govern the way that large, complicated protein molecules coil themselves up into their distinctive shapes. Impor-
Frustration, from p. 4

Important open questions include: How do such systems evolve in time? What if the objects are quantum systems? And can the interactions among the different parts be manipulated by changing certain variables?

Monroe’s team set out to investigate those questions by creating a fully controllable version of the smallest possible frustrated magnetic network, consisting of three spins. They trapped three atoms of ytterbium, a metallic element a little lighter than gold, in a vacuum chamber and aligned them so that the atoms lined up side by side like beads on a string. [See Figure 2.]

Any three-object quantum system of this kind, in which each object can only be in one or the other of two states, will have eight possible variations. [See bottom of Figure 3, below.] For example, three coins flipped simultaneously can yield all heads, all tails or six different combinations in between. The goal of the JQI researchers was to find out what set of conditions produced each of those eight combinations on demand.

They did it by aiming two separate laser beams (traveling at right angles to one another) which intersected at the point where they hit the atoms. One beam consisted of a single frequency; the other had two additional frequencies superimposed on the laser carrier beam. Where the beams intersected, the various frequencies would alternate cancel and reinforce one another, creating a pattern of multiple “beat notes.”

These beat notes had two effects on the atoms, occurring simultaneously. One produced the equivalent of a magnetic field, which could cause the atoms’ spins to flip – that is, to switch from north pole up to south pole up. The other beat notes, in combination, gave each atom a motional “kick,” the effect of which was
different depending on each atom’s spin state. Because each atom influences its neighbors’ spins according to their proximity, the kicks provided a second set of controls on the system. [See Figure 3.]

By carefully tuning the relative strengths of the laser beams and the time intervals over which they were applied, the researchers learned how to produce any particular pattern of spins.

As a result, Monroe explains, “we have exquisite control over all aspects of this interacting system of three magnetic spins. We can make them ferromagnetic (wanting to align their ‘north’ poles the same way) or antiferromagnetic (wanting to align in opposite directions), and we can control the relative strengths of the three interactions. What’s most exciting is that we can scale this system up to many more spins – perhaps 100 or more – using almost exactly the same apparatus. By controlling these magnetic interactions with only 25 (or so) spins, we can create states that cannot be modeled with any conventional computer. What we have is a restricted type of quantum computer called a ‘quantum simulator,’ that was first proposed by Richard Feynman in the early 1980s.” [For Feynman’s proposal, see http://www.cs.princeton.edu/courses/archive/fall04/cos576/papers/feynman82/feynman82.pdf.]

In addition, the team showed for the first time how frustration is related to a quantum-mechanical condition called entanglement, in which the states of two or more objects become so inextricably connected that none of them can be described separately. So even when two entangled objects are separated by millions of miles, as soon as the state of one is measured, the state of the other is instantly known.

This condition is so unlike the way that things behave in classical physics that some of the originators of quantum mechanics – notably including Albert Einstein himself – doubted that it was true. He and two colleagues wrote a celebrated journal article in 1935 arguing that the notion of entanglement was wrong. But decades of experimental evidence since then have demonstrated its existence in objects such as pairs of photons or pairs of atoms. Indeed, generating and characterizing entanglement between two objects is now a familiar staple of quantum science. But entanglement among three or more objects is less studied and only partly understood.

Frustration, the JQI researchers determined, provides a pathway to many-object entanglement. Because frustrated systems do not have a single lowest-energy state, their components take on a variety of different arrangements, each of which is at the same energy level. Quantum theory predicts that when the objects in a system exist in a superposition of these arrangements, embodying multiple states simultaneously, they become entangled. By carefully measuring the distribution of different arrangements of the ion spins, the scientists were able to show the link between frustration and entanglement.

continued, p. 7
Their results are chiefly significant for basic science; but the work may also have practical consequences. Any eventual quantum computer will almost certainly rely on entanglement to create and transfer connections among information units during data processing.

“Entanglement is a concept that is at the heart of the strangest features of quantum mechanics,” Monroe says, “and it is easy to come up with simple examples of entanglement, say between two interacting spins. This is basically what Einstein did in 1935 in trying to show that quantum physics was just too weird to be right. But entanglement between lots of particles is a murky concept -- there's not even a unique way to quantify entanglement in big systems.

“For a huge amount of spins, like in a macroscopic magnetic material, there are very strange states where the spins form 'domains.' And even at zero temperature there can be a great deal of randomness (entropy) in the alignment of those spins. This is related to the fact that the spins can be frustrated. And with so many compromises, there are many possible spin configurations.

“In our experiment, we make a clear connection between frustration and how it leads to an extra degree of entanglement, in the smallest possible system of three spins.”
JQI at DAMOP

JQI researchers made a total of 47 presentations at the annual meeting of APS’ Division of Atomic, Molecular and Optical Physics in Houston, TX from May 25-29.

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Talking to Bill Reinhardt

“I’ll tell you how I got into Bose-Einstein condensates,” says JQI Visiting Fellow Bill Reinhardt, squinting into the past. “It was in this very room, back in 1996, while having coffee with [JQI Fellow] Charles Clark.”

A decade and a half later, the University of Washington theoretical chemist looks around the same well-worn first-floor conference room in Radiation Physics on NIST’s Gaithersburg campus. The surroundings may not have changed much, but a revolution in physics has taken place since the first BEC was created on June 5, 1995. And Reinhardt, now spending six months on site at NIST, is at the forefront of that revolution, working on exotic methods to selectively change the phase of atoms in highly rarefied BECs suspended in optical lattices.

“People would like to start doing quantum information processing (QI),” Reinhardt says. “And typically when people think of a Bose condensate for QI, they’re not thinking about a bucket of condensate,” as in the tiny atomic clouds in the first BECs.

“They’re thinking about a lot of atoms that are still coherently a condensate but in an optical lattice – a sort of egg carton configuration with all these little wells and one or a couple of atoms in each. You’d like to have all these atoms communicate with each other and arrange themselves properly. Well, one way to cause things to change their arrangement is to send a soliton through them. It changes their phases.”

Solitons are self-perpetuating single waves, perhaps most familiar in the form of tsunami waves that can travel thousands of miles with only minimal attenuation. They were first described in 1834 by Scottish naval engineer John Scotts Russell, who witnessed one propagating up a canal, “assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height.”

Of course, neither Clark nor Reinhardt was thinking about solitons in 1996. Rather, Clark asked Reinhardt to start looking at solutions to the equations that describe “possible excited, but coherent, motions of the bulk Bose condensate and how we might use the knowledge of these excited states rather than the lowest possible quantum state, which is what is found in traps following evaporative cooling. What if we could excite the whole condensate? Or, create long lasting ‘defects?’ What would those solutions look like and how would look for them in the laboratory?”

Reinhardt got busy creating analytical solutions of the Gross-Pitaevskii equation, many of which are now in the new NIST DLMF. This led to simulations, including how the systems evolved over time, and he soon discovered that if a BEC was divided by a sort of “density notch,” and the quantum phase of the condensate was different on each side, a really surprising thing happened: “All of a sudden, this density notch started moving at a constant velocity! That is a soliton. I discovered this through ignorance and experimental trial and error.”

But he was soon convinced that it was real phenomenon. Of course, a soliton couldn’t move very far through a standard BEC cloud lump, as it would hit the end of the trap. So he started thinking of “how to get a BEC to go around a toroidal (donut-shaped) trap, and how to describe the peculiar
kinds of moving defects there could be in a toroidal condensate.

“Once we discovered these solitons, Charles and I began giving seminars. But for four or five years we couldn’t convince anyone to look for one of these things. Finally the Phillips group [NIST’s Laser Cooling and Trapping Group] looked. And they actually found one. … right in the place where the theory started.”

Thereafter, progress came fast. Researchers found that if a soliton moving through a BEC collided with a barrier, it would “curl up on itself in a shape we used to call a smoke ring. That is, they rolled up and became donut-like vortices,” Reinhardt recalls.

Moreover, the solitons turned out to have truly epic longevity. “People asked me: How long will a soliton run if you just let it go? We couldn’t figure out how to set up a simple mechanism for its destruction, other that just heating it up, so maybe they don’t decay easily. Well, people built longer and longer traps, and they went farther and farther, and lasted longer and longer. Of course, if you warm up the BEC, it won’t work at all. It’s the phase coherence of the condensate that preserves the soliton.”

But in a cold BEC, the results were stunning. “At the DAMOP meeting in Houston last week,” Reinhardt says, “people reported seeing solitons in toroidal traps lasting for 15 seconds. That’s a very long time for a quantum object to maintain any kind of coherence. So these solitons are really robust.”

The physics is remarkable for its own sake. But Reinhardt believes that solitons may have various very practical uses. For one thing, “the velocity of the soliton is precisely determined by the phase difference between the left and right hand side of the condensate. So if you know how fast the soliton is going, and your trap is flat on the bottom, you have a way of measuring those phase differences very precisely. So solitons are the basis of a very novel kind of non-linear interferometry which is particularly apropos to these quantum fluids.”

In addition, they may also be exploited as a means of controlling the states of BEC atoms in an optical lattice. “It looks like you can use them to organize the phase arrangement of a quantum system by creating a network of solitons, so you get a ‘phase mesh’ you can do interesting things with,” Reinhardt says. That’s what he’s working on now, trying to reconcile and integrate insights from a host of fields ranging across condensed-matter and atomic physics to statistical mechanics and computational physics.

“All of us are speaking different languages,” he says, “and yet we’re all working basically on the same problem. Of course, you realize that these languages, if we really are honest, don’t exactly correspond. When that happens, occasionally it’s just semantics. But sometimes they’re really not saying quite the same thing. And that usually means there’s something really interesting to learn. And that’s the stage we’re at right now.”

All of that bears upon the eventual goal of “getting bosons in optical lattices and training them to do information processing. The lattice is one configuration that people want to use – to let the dynamics of these weakly interacting particles carry out your computation for you. That’s a major theme at JQI.”

Sending solitons across a lattice, perhaps by using a compressional wave at one end, or by phase engineering, may be the answer. JQI Fellow Bill Phillips has asked Reinhardt’s current NIST collaborator, Indubala Satija (who with Charles Clark initiated this new work), “what it would take to get one of these started in the lab. So that’s what I’m working on. Once I understand it, we may be able to do all kinds of tricks.”


“Adiabatic preparation of many-body states in optical lattices,” A.S. Sørensen, E. Altman, M. Gullans, J. V. Porto, M.D. Lukin, and E. Demler, accepted for publication as a rapid communication in *Physical Review A*.


According to IOP, the papers “were selected for their presentation of outstanding new research, receipt of the highest praise from our international referees and the highest number of downloads last year.”

To see the entire “Best of 2009” list, go to [http://herald.iop.org/njphighlights/m329/zea/319814/link/3357](http://herald.iop.org/njphighlights/m329/zea/319814/link/3357).


This book, over a decade in the making, derives from the NIST Digital Library of Mathematical Functions (see [http://dlmf.nist.gov](http://dlmf.nist.gov)), which was released earlier the same week.

The editors will participate in a book-signing event at Reiter’s Books in Washington, DC on June 26 from 2:00 - 6:00 PM.
**Entangled States**

**Eite Tiesinga** has won the Arthur S. Fleming award of 2009, honoring individuals for their extraordinary contributions to the federal government. (See www.gwu.edu/~flemming.) The citation notes that “Dr. Tiesinga has established a world-class research program on the theory of collisions of cold atoms. His prolific work on controlling and understanding the interactions of atoms, and using so-called Feshbach resonances to tune or control those interactions, has become crucial to cutting-edge experimental work using ultracold atoms. This includes quantum computing, quantum degenerate gases, and dipolar molecules with unusual electromagnetic quantum properties. His work enables better understanding of Bose-Einstein condensation and superfluidity associated with neutral atoms trapped in laser-generated optical lattices.”

**Bill Phillips** will address the World Science Festival in New York on June 5 on the topic: “Time, Einstein, and the Explorer’s Clock.” He will deliver a lecture titled “Quantum Information: a 20th century revolution in science and technology” at Juniata College in Huntingdon, PA, on June 12. From June 28-July 23 he will teach at a summer-school program at the École de Physique des Houches in Les Houches, France. And along with many other JQI researchers, he will attend the 22nd International Conference on Atomic Physics in Queensland, Australia from July 25-30.

**Carl Williams** has received the Physical Sciences Award from the Washington Academy of Sciences.

**Chris Monroe** gave a physics colloquium titled “Quantum Networks with Atoms and Photons” at the University of Washington in Seattle.

**Victor Yakovenko** attended the International Conference on Spectroscopies in Novel Superconductors (SNS2010) in Shanghai, China. On May 24, he delivered an invited talk, “Theories of the Time-Reversal-Symmetry Breaking and the Polar Kerr Effect in Sr2RuO4 and Underdoped Cuprates”. Part of that work was done with **Roman Lutchyn** (JQI postdoc) and **Pavel Nagornykh** (JQI graduate student).

Last month, **Garnett Bryant** gave an invited talk titled “Engineering the Optics of Quantum Dots with Nanomechanical Strain” at the ICREA Workshop on Phonon Engineering 2010, Sant Feliu de Guixols, Spain.

**Patrick Hughes** gave an invited talk titled “Far-ultraviolet signatures of the 3He (n,tp) reaction in noble gas mixtures,” at the Symposium on Radiation Measurements and Applications (SORMA XII), Ann Arbor, MI, May 27, 2010.

**Kaushik Mitra**, who defends his dissertation on June 7, has accepted an offer of employment from Intel.

**Roger Brown** was awarded a “Graduate Student Summer Research Fellowship” by the University of Maryland.

Long-term visitors to JQI this summer include **Mark Edwards** (Chair of Physics, Georgia Southern University: June-July) and JQI/NIST alumna **Jay Vaishnav** (Asst. Prof., Bucknell University: June-August).

**Charles Clark** gave an invited talk, “Phases and phase fluctuations in ultracold gases,” at the Joint Workshop on Quantum Entanglement and Dynamics in Correlated Many-Body Systems, Asia-Pacific Center for Theoretical Physics, Pohang, South Korea, on May 17, 2010.

**Left to right: Kwon Park (CMTC postdoc, 2002-2005), Krishnendu Sengupta (UMD Ph.D. 2001 -- advisor V. Yakovenko), the coffee machine and Charles Clark, at the workshop, which was jointly sponsored by the Asia Pacific Center for Theoretical Physics, and the Korea Institute for Advanced Study, where Kwon is a member of the faculty. Krishnendu is a faculty member of the Indian Association for the Cultivation of Science, Kolkata, India.**

**Photo credit: Kedar Damle**
Two JQI postdocs were among the four finalists for the 2010 American Physical Society Award for Outstanding Doctoral Thesis Research in Atomic, Molecular or Optical Physics. One is Qi Zhou, who works in Sankar Das Sarma’s group, shown in left photo with Jason Tin-Lun Ho (Ohio State University), Qi’s Ph.D. supervisor.

The other is Steve Olmschenk, now in the Laser Cooling and Trapping Group at NIST, shown at right with his supervisor, Chris Monroe.

The 2010 winner is Kang-Kuen Ni from Deborah Jin’s group at JILA. According to APS DAMOP, the award is made to “recognize doctoral thesis research of outstanding quality and achievement in atomic, molecular, or optical physics and to encourage effective written and oral presentation of research results. The award to be given annually consists of $2,500 and a certificate citing the contribution made by the recipient.

Photo credit: Bill Phillips, JQI

Entangled States, continued

New Students

Alan Migdall’s group is getting two undergraduate summer students: Mario Rusev from Lafayette College, who will work on an interferometer for a quantum measurement project; and Michelle Nadeau from American University who will work on a project to see if a photon number resolving detector can make better measurements than the standard limit.

Also joining Migdall’s group: Joffrey Peters, a graduate student transferring from Minnesota, who will work on the solid state quantum memory experiment with Elizabeth Goldschmidt.

Two undergraduates will work in Trey Porto’s UMD (ultracold mixtures) lab this summer: Edward Gan from Harvard and Esteban Castro Ruiz from Universidad Nacional Autónoma de México in Mexico City.

New graduate student in the JQI Ion Group: Shantanu Debnath.

Esteban Castro Ruiz (left) and Edward Gan of Trey Porto’s group in the Ultracold Mixtures Lab on the second floor of the Computer & Space Sciences Building at the University of Maryland.
Joshua Bienfang has been nominated for the Science and Environment Medal, which recognizes a significant contribution to the nation by a federal employee in science and environment research (including biomedicine, economics, energy, information technology, meteorology, resource conservation and space). Bienfang has used quantum physics and telecommunications technologies to demonstrate encryption services at record speeds in a system whose security is based on the properties of quantum objects, in this case, photons.

The Service to America Medals are presented annually by the nonprofit, nonpartisan Partnership for Public Service to celebrate excellence in our federal civil service. See the complete list of 2010 Service to America Medal finalists at http://servicetoamericamedals.org/SAM/finalists10/.

Note: This is the last JQI Newsletter until September 2010. For news and information updated daily, please visit the Web site at http://jqi.umd.edu as well as the site for the Physics Frontier Center, sponsored by the National Science Foundation, at http://pfc.umd.edu.