A JQI team has devised a dramatically different kind of optical lattice -- one in which the features are smaller than the wavelength of light that created it.

Nathan Lundblad and colleagues* from JQI/NIST used a “dressing” of radio-frequency radiation to alter energy levels and re-shape cells of the lattice, producing the novel “Mexican Hat” configuration shown here instead of the more familiar “egg carton” form.

The new curvature will allow researchers to explore arrangements of atoms and degrees of freedom that are not accessible with conventional lattice patterns.

An optical lattice is formed by the intersection of multiple laser beams, producing a standing wave pattern. Within that pattern, as the beams interact with each other, there are regions with higher and lower energy intensity. As a result, an atom placed in the lattice will naturally tend to seek the minimal energy points, represented as deep wells in the figures to the right. Because lattice configurations resemble the geometrical arrangements of atoms in crystalline solids, they can be used to study atomic behaviors in a highly controlled environment.

The JQI/NIST team took a cluster of rubidium atoms, ultra-cooled it to the point at which it formed a Bose-Einstein condensate, and then nudged it into the lattice. If nothing else had been done, the energy landscape would have looked like the top figure above, and one atom would have settled into each well with only one degree of freedom -- its spin. But the researchers then gradually began applying an RF field and tuned the amplitude and frequency until the interaction of laser and RF effects created a fine, sub-wavelength structure in each well. Thus, in addition to spin, each atom in such a well would also have a positional degree of freedom in the reconfigured energy shape. That structure more closely resembles the complex symmetries of certain materials (such as high-temperature superconductors) that are of urgent interest to science. It may also make it easier to study some aspects of tunneling, the process whereby a quantum object passes through a barrier that it could not cross classically.

RF “dressing” has never been applied at these tiny dimensions before. “We’re trying to use optical lattices to gain insight into the tough problems of condensed-matter physics,” says Lundblad, “and anything we can do to take the tailored tradition of optical-lattice experiments and then increase the complexity level -- because real solids are quite complex -- is a goal to be sought after.”
An STM to Measure Phase Differences in Superconductors

Twenty years after the discovery of high-temperature superconductors, the mechanisms that cause those materials to lose electrical resistance remain unknown. To understand the phenomenon, researchers will have to determine precisely which aspects of a material’s atomic configuration contribute to superconductivity, and to measure telltale differences at the atomic scale between very slightly different arrangements in a material’s crystal lattice.

Now a JQI/UMD team is building a device to do just that: a new kind of scanning tunneling microscope (STM) that can detect the subtle difference in quantum “phase” between tiny adjacent regions on the surface of a sample.

In quantum mechanics, properties of objects are described in terms of wave functions. Just as two waves can be in or out of phase, quantum states of matter -- individual electrons or, in the case of superconductors, entire arrays of electrons that share the same phase -- vary from point to point depending on their atomic surroundings.

This can lead to distinctive effects. For example, if two pieces of the same superconducting material are separated by a very thin insulating layer, a current will flow across the barrier if there is a phase difference between the two sides. This arrangement, called a Josephson junction, is thus a sensitive detector of phase difference.

However, such a measurement only reveals an averaged phase difference across a stationary junction that is typically much larger than atomic scale.

Determining how the phase difference is related to specific atomic structure will require comparing the phase at a fixed reference point to the phase at various points on the surface. In addition, the junction itself must small enough to measure at the atomic scale.

At present, there is no device capable of making those measurements. So Bob Anderson, Chris Lobb and Fred Wellstood of JQI, and colleagues from UMD and LPS, are building a unique variation on the conventional STM.

That design involves a needle-like metal probe that moves above an atomic surface. Thanks to their wave-like quantum nature, electrons can “tunnel” across the gap between the surface and the probe; and the closer the probe, the more electrons cross the gap. Tracking the current that reaches the probe provides a detailed picture of the surface topology.

JQI’s version will use a superconducting probe that moves across a superconducting surface -- in effect, a mobile Josephson junction.

Grad student Anita Roychowdhury examines a dilution refrigerator for cooling the STM device.
As the probe reaches points at which the phase is different -- because of a defect or grain boundary in the material, a “doping” atom in the atomic lattice, the presence of a “microdomain” or pocket of different materials in a heterogenous sample, or some other cause -- the device will record a change in current.

Investigators can then look for correlations between phase and atomic structure to better understand the nature of high-temperature (high Tc) superconductors that require less expensive refrigeration to work.

For example, even within a defect-free high-Tc material, the phase changes depending on which way the lattice is oriented with respect to the detector. Take the same crystal, rotate it by 90 degrees, and the phase will be different. But no one knows exactly what aspect of the structure causes the difference.

In addition, because phase difference is a distinctive property of superconductors, the new STM will also be able to identify exactly which regions are superconducting and which are not.

The team plans to begin on well-characterized high-Tc substances such as yttrium barium copper oxide (YBCO) to calibrate and test the device. Then they will move on to target materials such as bismuth strontium calcium copper oxide (BSCCO).

First, however, they have to determine whether they can construct a superconducting STM capable of detecting the very faint signals of phase difference between two microscopic regions. To eliminate thermal noise, the system will be cooled to about 20 thousandths of a degree above absolute zero using a device called a dilution refrigerator that employs two isotopes of helium in a kind of evaporative cooling.

But low temperature alone will not be enough to do the job. Small quantum effects have an irreducible degree of uncertainty, and the signal strength is expected to be in the range of 1 billionth of an ampere. To minimize the uncertainty effects, the STM junction will be coupled to a second, larger junction that will serve to stabilize the system.

If the STM team -- which includes LPS’ Dan Sullivan, Michael Dreyer and graduate student Anita Roychowdhury -- succeeds, it will help answer one of the most urgent questions in condensed-matter physics. And their findings could prove crucial in the effort to create the next generation of high-Tc superconductors that can operate at even higher temperatures.
JQI at DAMOP: 38 and Counting

When the American Physical Society’s Division of Atomic, Molecular and Optical Physics convenes its annual meeting at Penn State (May 27-31, 2008), JQI researchers will make 38 technical presentations spanning a wide range of topics.

B1.00001 Spinning Atoms with the Orbital Angular Momentum of Light

B5.00011 Four-wave mixing in a birefringent semiconductor waveguide for correlated photon generation

C2.00008 Engineering of Quantum Entangled Dark Solitons on One-Dimensional Optical Lattices

C4.00001 A quantum defect theory of near-threshold molecular Feshbach resonance states

C4.00002 Energy structure of weakly bound molecules near Feshbach resonances

C6.00009 Ytterbium Ion Qubits for Quantum Information Processing

E1.00081 Coulomb Explosion Imaging with Shaped Pulses

E1.00086 A High Flux Cold Atomic Beam for Experiments in Strongly Coupled Cavity QED

E1.00102 Toward Creation of an Ultracold Dense Gas of Polar Molecules

I1.00004 Population dynamics in a sodium spinor condensate

J4.00006 Two-body transients in coupled atomic-molecular Bose-Einstein Condensates

J4.00011 Damped motion of one-dimensional Bose gases in an optical lattice

J5.00010 Cold Atom Cloud Evolution in Optical Tunnels

K2.00008 Bound-bound Spectroscopy of Ultracold K40-Rb87 Molecules

K5.00005 Bell inequality violation with two remote atomic qubits

K5.00007 Compact Source of Entangled Images and Squeezed Light Using Four-Wave Mixing in Rubidium Vapor

K6.00012 Attosecond dissociation of the HT molecule from the He united-atom limit

L1.00074 Single- and Multi-Mode Channels for Neutral Atom Ensembles

L1.00092 A scheme for enhanced light collection from a trapped ion

L1.00093 Simulating Quantum Spin Models with Trapped Ytterbium Ions

L1.00111 Modeling evaporative cooling of a dual-species Bose-Einstein Condensate

L1.00118 Continuous Observation of Spinor Dynamics in a Sodium Bose-Einstein Condensate

L1.00144 Experimental test of non-local realism using a fiber-based source of polarization-entangled photon pairs

P1.00001 Controlled Interaction Between Pairs of Atoms in a Double-Well Optical Lattice

P3.00007 Lifetime measurements of the rubidium 5D states

P4.00001 Generation of effective magnetic fields in Raman-dressed states

P6.00007 Rydberg Atom Population Distributions in Ultracold Plasmas

P6.00008 Using projection imaging to study ultracold plasmas

Q3.00008 Shaped-Pulse Control of CO$_2$ Bending Vibration

Q4.00002 Probing higher-order interactions with an array of double-well optical-lattice interferometers

Q4.00006 Exploring a neutral-atom SWAP gate with clock states

Q4.00008 Raman excitation of ultracold atoms to higher vibrational bands in an optical lattice

Q4.00011 Observing Zitterbewegung with Ultracold Atoms

R1.00009 Two-photon lock by ground state phase-modulation transfer in rubidium

R1.00073 Four-wave mixing in a diamond configuration: correlated photons.

U2.00006 Conditional Quantum Beats in Cavity QED

U4.00006 Collisional cooling of ultracold atom ensembles

U4.00008 State-insensitive two-color optical trapping

For information, see the DAMOP Annual Meeting program at http://meetings.aps.org/Meeting/DAMOP08/APS_epitome.
JQI/UMD researchers have increased by five orders of magnitude the distance over which a highly stringent test of a key quantum-mechanical principle can be successfully conducted. In doing so, Chris Monroe and colleagues* validated a technique that could eventually lead to final resolution of a 70-year-old debate over the nature of physical reality that pitted Albert Einstein against Niels Bohr.

Quantum mechanics allows a condition called “entanglement”: Under certain circumstances, the states of two objects are so utterly interdependent that if a measurement is made on one, the state of the other is known -- even if the objects are separated by vast distances.

Einstein believed this description of reality was incomplete, and that somehow each particle carried information along with it in a form not yet discovered. This argument remained largely philosophical until 1965, when physicist John Bell showed that, if Einstein was right, measurements made on pairs of objects during the experiment, then the results were subject to doubt. Most observers regard that issue as settled, owing to highly sophisticated experiments over the past decades.

That leaves the “detection” loophole: If the efficiency of detection of the entangled quantum states was not high enough, or if only a selected sample of all events was recorded, it was always possible that the data represented a skewed subset of results, and not necessarily the actual physical facts. The first experiment to close this loophole was done in 2000 with two beryllium ions spaced 3 micrometers apart.

Monroe’s group detected entanglement between two trapped ytterbium ions in separate enclosures a full meter apart, as heralded by entanglement of two photons, one emitted from each ion after the ions were excited by laser light. Thanks to the rules of quantum mechanics, if it is impossible to tell which ion each photon came from, they are entangled. And so, therefore, are the ions that emitted them.

Every time the detectors registered an entangled pair of photons, the experiment immediately took a reading on the state of the ions (by rotation with a microwave pulse) to verify their entanglement, eliminating the possibility of selective sampling problems. The result, after accounting for sources of error, was 81% fidelity -- more than enough to firmly close the detection loophole.

With an even larger separation between the ions, or faster detection, the group concluded, “the technique demonstrated here may ultimately allow for a loophole-free Bell inequality test.”
Twin Beams for Quantum Imaging

JQI researchers have demonstrated a specially interconnected pair of “squeezed light” beams, reduced-noise optical waves whose properties are related to each other to a degree greater than allowed by classical physics. The unusual feature of these beams is that, unlike previous such demonstrations, the beams are multi-mode, that is, they can carry multiple pixels of information in parallel. These twin squeezed-light beams may be useful for quantum imaging, a new form of optical processing that would use the rules of quantum mechanics to achieve various unprecedented feats with light. JQI/NIST’s Vincent Boyer, Alberto Marino, and Paul Lett* created the beams through a convenient and flexible technique known as four-wave mixing (4WM), in which two incoming light beams combine to generate two different outgoing light beams.

According to classical physics, any beam of light has at least a minimum level of noise, known as the “shot noise,” which consists of naturally occurring random fluctuations in all of its properties such as intensity.

The quantum-mechanical process of “squeezing” a beam can reduce the shot noise to below classical levels in a single property such as intensity, at the expense of raising the noise in a complementary property, in this case, the phase, which specifies the precise locations of the crests and valleys in the light wave.

When the researchers sent the probe and conjugate beams to two detectors and subtracted the two detector signals, they found that the noise in the intensity of the subtracted signals was about 30% of the shot noise. Therefore the fluctuations in the beams were highly interconnected or “correlated”—at levels much greater than classically possible.

Moreover, these two beams had convenient properties. Each beam was “spatially multi-mode”—in other words it contained more than one pixel of information. And even though the squeezing between the two beams was interconnected, each individual beam contained several independent modes of squeezing—so that squeezing one spatial mode
of a beam would not affect the squeezing properties of the other spatial modes in the same beam.

Such multi-spatial-mode two-mode squeezed beams of light would be useful for quantum imaging, which, for example, could allow researchers to reduce noise in one beam and pack more information in it. The squeezing properties of the other spatial modes in the same beam.

Such multi-spatial-mode two-mode squeezed beams of light would be useful for quantum imaging, which, for example, could allow researchers to reduce noise in one beam and pack more information in it. Another quantum imaging application would be to increase the sensitivity of signals by reducing intensity or phase noise and detecting smaller changes in the beam. Quantum imaging also opens the possibility of creating sharper images than allowed by classical physics, and performing simultaneous "parallel" processing of picture elements in beams that lie in two separate locations.

A rubidium vapor cell

For more information on this research, contact Ben Stein at NIST Public Affairs. E-mail address: ben.stein@nist.gov. Telephone: (301) 975 2762. Fax: (301) 926 1630.

The two-beam squeezing technique works for most types of light beams. This picture shows the intensity of an (a) input probe beam, (b) output probe beam, and (c) conjugate beam for light that has a special property known as orbital angular momentum. Subtracting the intensity of the two output beams showed squeezing of about 7.3 dB, corresponding to less than 25% of shot noise.
Maryland Shines in USN&WR Rankings

This month, U.S. News & World Report published its long-awaited annual rankings of American universities, and the University of Maryland at College Park scored high in physics, and particularly in sub-disciplines related to JQI.

Overall, UMD’s physics graduate programs ranked 13th in the nation by USN&WR’s criteria. Within specialty areas, UMD was:

- #2 in Plasma
- #5 in Atomic, Molecular and Optical
- #9 in Quantum Physics
- #10 in Nuclear Physics
- #13 in Condensed Matter Physics
- #13 in Elem. Particles/Field /String Theory

A Matter of Scale

Quantum effects do not often manifest themselves in macroscopic objects. One exception is the superconducting quantum interference device, or SQUID. Of course, it’s not exactly bulky. In fact, the version shown at left takes up only a small fraction of the surface of the chip resting in this glass dish. Alongside is a sample of the integer quantum of United States currency.

Entangled States . . .

The 17 April 2008 issue of Nature contains a three-page News Feature about topological quantum computing. (http://www.nature.com/news/2008/080416/pdf/452803a.pdf) that identifies JQI Fellow Sankar Das Sarma as a pioneer of the concept. A paper in the same issue reports detection of a quasiparticle with 1/4 the electron’s charge. “In all my talks on topological quantum computation,” Das Sarma told Nature, “I’ve said this is the one experiment that needed to be done first. And frankly I didn’t expect it this soon.”

JQI is a joint venture of the University of Maryland and the National Institute of Standards and Technology, with support from the Laboratory for Physical Sciences.