THE ENTANGLEMENT TANGO
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The Cundiff group’s new 3D Fourier-transform spectroscopy technique allows researchers to peer inside the quantum world and identify quantum pathways between different states.

Credit: Hebin Li, the Cundiff group, and Brad Baylor, JILA

The PATHFINDER

The entanglement tango

Scientists think it is hard to correlate, or entangle, the quantum spin states of particles in an ultracold gas of fermions. Fermions are particles like electrons (and some atoms and molecules) whose quantum spin states prevent them from occupying the same lowest-energy state and forming a Bose-Einstein condensate. Entanglement means that two or more particles interact and retain a connection. Once particles are entangled, if something changes in one of them, all linked partners respond.

Because of this exquisite connection, entanglement is usually destroyed by messing up the state of a single particle. Thus conventional wisdom has been that it would take precise measurements or control schemes to entangle the quantum spin states of thousands of atoms in an ultracold gas. However, graduate student Michael Foss-Feig, Fellows James Thompson and Ana Maria Rey, and former Visiting Fellow Andrew Daley from the University of Pittsburgh decided to consider what happens if the state of pairs of atoms are messed up together.

Foss-Feig and his colleagues discovered that when reactive fermions are at “warm” micro-Kelvin temperatures, entanglement evolves naturally. In fact, the atomic or molecular gas has to be 10–100 times warmer than a nano-Kelvin gas to encourage entanglement. Once the temperatures are low enough for fermions to collide and react in pairs, atoms or molecules that don’t get knocked out of the experiment will be left entangled because they lose their individual identities as a result of being unable to collide. Fermions that behave this way include the atoms strontium (Sr) and ytterbium (Yb), which are used in atomic clocks, and molecules such as potassium-rubidium (KRB), which are used in JILA cold-molecule experiments.

To understand how this entanglement evolves, imagine that your quantum atomic or molecular gas is a party where the Fermion atoms or molecules—like the individuals at the party—are the dancers. They can only dance with each other when they are correlated, just as the atoms or molecules have two possible spin states, there are two kinds of tango dancers: men and women. And, at this quantum dance party, women must dance with men and vice versa. The catch is that the individual tango dancers all dance a little differently.

As the dance starts, pairs of tango dancers bump into each other. As they collide, each pair measures their mutual quantum state to discover whether they dance well together or dance poorly together. When a pair who dance well together find each other, they dance right out of the party and go home together. Soon, all the pairs who dance well have reacted with each other and left.

The only ones left at the dance are the people who don’t dance well together. It’s not that these individuals are bad or good dancers. They can’t dance together because they are correlated with each other in a way that makes it impossible to dance in pairs (i.e., collide). And, because all the remaining dancers don’t dance well together, no one can go home. Frustrated (but also slowly losing their individual identities), the party-goers check their watches to see when this boring dance will end. What they don’t realize is that they’re stuck in an unending (steady-state) party where nobody dances, but no one can escape.

The nondancing pairs have entered a quantum mechanical state called a superposition. A superposition is a state in which a particle holds two different properties—such as two different spin states—at the same time. It turns out that such a state is very useful for measuring the passage of time in an atomic clock, for reasons that can be well understood through the connection to dancers.

According to the laws of quantum mechanics, atom pairs or molecules that can’t dance well together are useless for measuring time with an atomic clock. In fact, they are oblivious to the passage of time. The pairs that dance poorly together, however, are acutely aware of the passage of time. Consequently, a steady-state tango dance party, with everyone constantly checking their watches, could be an ideal starting point for measuring time with an atomic clock.—*JILA Light & Matter*

Reference


The amazing Schrödinger equation describes the time-dependent evolution of quantum states in a physical system such as the group’s hot gas of potassium atoms (K). But, for the equation to work, someone has to figure out a key part of the equation known as the Hamiltonian. Unfortunately, Hamiltonians are really complicated for most real-life systems because they characterize a multitude of quantum states and pathways that exist inside a rolling quantum world.

For experiments involving many atoms or other particles that interact with each other and their environment, the only hope of ever figuring out the correct Hamiltonian may be to do it experimentally. And, the Cundiff group has just taken a giant step toward the goal of doing exactly that.

In a recent *Nature Communications* paper, researchers Hebin Li, former research associates Alan Bristow and Mark Siemens, graduate student Moody, and fellow Steve Cundiff report on their nifty new technique known as optical three-dimensional (3D) Fourier-transform spectroscopy. They used the technique to produce detailed spectra of a gas of hot (180 °C) K atoms. The spectra allowed them to see exactly what was happening inside the quantum world of the atoms in their experiment. Specifically, the researchers were able to disentangle all possible pathways between specific initial conditions of the K atoms (typically ground states) and final conditions (such as excited states or quantum mechanical superposition states). And, once they had identified all possible pathways, the researchers were able to make the measurements necessary for characterizing the pathways. With this information, they were able to figure out some pieces of the Hamiltonian they needed.

Li and his colleagues are excited about the many possibilities of their new technique, including the dream of coherently controlling chemical reactions. Coherent control requires an understanding of all possible quantum pathways in a particular reaction. The fact that optical 3D Fourier-transform spectroscopy made it possible to identify all of these pathways is a huge step forward in realizing this dream.

The new technique is also a huge step towards being able to experimentally determine a Hamiltonian for an even more complex system. Stay tuned.

Reference

This extra vibration is interesting because its detection indicated that the experimenters had reached an important limit on successive measurements imposed by the laws of quantum mechanics. In a recent experiment, researchers in the Regal group have gotten so good at using laser light to track the exact position of a tiny drum that they have been able to observe a limit imposed by the laws of quantum mechanics. In a recent experiment, researchers in the Regal group have gotten so good at using laser light to track the exact position of a tiny drum that they have been able to observe a limit imposed by the laws of quantum mechanics. In a recent experiment, researchers in the Regal group have gotten so good at using laser light to track the exact position of a tiny drum that they have been able to observe a limit imposed by the laws of quantum mechanics.

The Heisenberg Uncertainty Principle dictates that the closer someone comes to measuring the exact position of an object, the less that can be known about how fast it is moving at the same instant. Of course, how fast something is moving has a whole lot to do with its exact position. This paradox results in a conundrum for the experimental physicist: Do we make the best precision measurement now or obscure the motion later?

This extra vibration is interesting because its detection indicated that the experimenters had reached an important limit on successive measurements imposed by a particular law of quantum mechanics known as the Heisenberg Uncertainty Principle. The group’s detection of the Heisenberg Uncertainty Principle in action in the drum was recently reported in the journal *Science*. The Heisenberg Uncertainty Principle dictates that the closer someone comes to measuring the exact position of an object, the less that can be known about how fast it is moving at the same instant. Of course, how fast something is moving has a whole lot to do with its exact position.

Thus, when the researchers measured vibrations during the experiment, they were able to determine that quantum mechanical fluctuations of light were causing about half of them. Because the group now knows what these fluctuations look like in an experiment, the researchers’ next big step is an experimental investigation of creative ways to work around the Heisenberg Uncertainty Principle in continuous position measurements. Stay tuned.

Reference
Earlier attempts to cool molecules to ultracold temperatures failed because the molecules studied had too few “elastic” collisions with the walls of the trap, so molecules bounce off one another. Thanks to some insightful theory work by senior research associate Goulven Quéméner and Fellow John Bohn, however, the Ye group opted to cool the *OH molecule, which the theorists predicted would have elastic collisions more than 90% of the time. This collision rate meant that the molecules have enough time to exchange energy, so that there are always some molecules with more energy than average, and some with less.

The experiment had several steps: First, the researchers used a jolt of electricity through a mixture of water vapor and krypton to form the *OH molecules. Second, they used a linear decelerator equipped with an array of highly charged electrodes to slow the molecules down to a speed of 34 meters per second. The molecules were brought to a complete stop in the center of a permanent magnetic trap. These two steps have been under development for a decade. They cooled the molecules down to ~50 mK.

Finally, the researchers initiated evaporative cooling, which required a neat trick to work. The usual approach of flipping a spin in the *OH molecules was not good enough in this case to let the hotter molecules escape from the trap. So the researchers applied an electric field, which opened up some little gateways in the trap that actually let the hot molecules out.

This creative process then selectively removed the most energetic (hotter) *OH molecules from the mixture after molecule-molecule collisions. By getting rid of the hottest molecules, the temperature of the remaining gas of molecules was lowered. The process could be speeded up by applying an electric field, which opened up some little gateways in the trap that actually let the hot molecules out.

Evaporative cooling worked exceptionally well with *OH molecules. In fact, as this molecular gas got colder, evaporative cooling worked better and better.

The results were so exciting that the Ye group believes that in the future, it will be possible to evaporatively cool *OH molecules to much colder temperatures in the micro- and nano-Kelvin ranges. It’s now conceivable that the group will one day be able to cool a *OH molecular gas down to a point where every molecule in the gas enters its lowest energy state, allowing for the possibility of quantum control.

Credit: The Regal group and Brad Baxley, JILA

Single-atom trapping schematic.

After the cooling, the researchers were able to tell when the atom had reached its quantum ground state. When the atom was in the ground state, it had no additional lower-energy states. It was no longer possible for the atom to lower its energy of motion. The researchers confirmed that the atom had reached its quantum ground state when they tried one more time to lower the energy, and the atom failed to flip its spin.

Now that the Regal group has figured out how to prepare single neutral atoms in their quantum ground state, a whole new field of research is opening up. For instance, these cold atoms may be placed near complicated optical patterns near surfaces, e.g., on a chip designed for a quantum computer. This placement should be possible because neutral atoms do not usually interact with their surroundings in the same way charged ions, which were the first single particles to be cooled and trapped.

Currently, Kaufman and his colleagues are working on trapping multiple single 87Rb atoms in optical tweezers to see if it is possible to observe quantum tunneling between different tweezers after each of their single atoms is cooled to its quantum ground state. Quantum tunneling is a phenomenon where a tiny particle, such as an atom or an electron, tunnels through an energy barrier that it would not be able to surmount according to the laws of classical physics.

Reference
Ana Maria Rey’s group is devising new theoretical methods to help experimentalists use ultracold atoms, ions, and molecules to model quantum magnetism in solids. Research associate Kaden Hazzard, former research associate Salvatore Manmana, newly minted Ph.D. Michael Foss-Feig, and Fellow Rey are working on developing new tools to understand these models, which describe both solids and ultracold particles. The theorists are collaborating with three experimental teams at JILA and the National Institute of Standards and Technology (NIST). The experimental collaborations allow the theorists to test and improve their theory with precision measurements of quantum magnetism. The action occurs in novel quantum simulators based on neutral strontium atoms (Sr), beryllium ions (Be$^+$), or potassium-rubidium molecules (KRb). Each simulator uses hundreds of particles whose collective magnetic behavior is far too complex to be solved theoretically even with the most powerful supercomputers. However, experimental observations of quantum behavior in ultracold systems are expected to allow Hazzard and his colleagues to better understand the behavior of their theory. That understanding, in turn, may one day be used to describe real-world materials.

For its part, the new theory’s behavior has already yielded an innovative approach to using a quantum simulator based on ultracold KRb molecules. The new approach suggests starting a quantum simulation by zapping previously prepared quantum states in the simulator with microwave pulses. These pulses drive the quantum states far from equilibrium, resulting in a roiling mass of quantum states.

“Aiming microwaves into a quantum simulator kicks the system from its placid state,” Hazzard said. “If conventional techniques create a gently rippled pond, then this technique generates something more like a cascading waterfall.” The good news is that a cascading waterfall of quantum states makes it a lot easier for the experimentalists to assess the accuracy of their quantum simulator as well as to enhance precision spectroscopy and time measurements. Nonequilibrium simulations can be run at 200 nK instead of temperatures 10–100 times lower.

The bad news is that wildly roiling quantum states are harder to model theoretically. Fortunately, Hazzard and his colleagues were able to combine conceptual insights and mathematical skill with supercomputer calculations to come up with a new description of a quantum simulator working far out of equilibrium. As an added bonus, the new theory will be able to guide future experiments with optical atomic clocks as well as quantum simulators based on neutral Sr atoms, ultracold KRb molecules, or Be$^+$ ions. As a result of its collaboration with the John Bollinger group at NIST, for example, the Rey group has completed an important theoretical investigation of nonequilibrium dynamics in NIST’s trapped-ion quantum simulator. This work provided support to the Bollinger group in its detection of quantum magnetism inside a trapped-ion quantum simulator in 2012.

Thanks to the collaborations between JILA theorists and experimentalists from JILA and NIST, the field of quantum simulation is literally exploding!

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References

Figure p. 8: The quantum behavior of atoms (upper right) in an everyday solid (upper left) can be emulated in a quantum simulator (lower left) built by the Jin-Ye collaboration. The simulator uses ultracold KRb molecules in a lattice (lower right) in place of the atoms. A new idea from Ana Maria Rey’s group proposes running the simulator far out of equilibrium to benchmark its accuracy as well as to enhance precision spectroscopy and time measurements.

Credit: Kaden Hazzard, the Rey Group, the Jin-Ye collaboration, and Brad Baxley, JILA
are ten times more stable and precise that those with probes. Lasers used to detect the probes are shown in going for the gold that was only 70 nm when the gold had been stripped away.

The best commercial AFM probes are very thin diving-board-shaped cantilevers made of silicon or silicon nitride. Since these thin structures barely reflect the laser beams used to detect their positions, they are coated with gold to enhance reflectivity. The Perkins Group uses the technique of AFM-based force spectroscopy in liquid environments—precision measurement of piconewton-level forces—to learn about the dynamics of large biomolecules that are crucial to normal physiology and disease. Force spectroscopy requires both exquisite control of the position of the AFM tip on the atomic scale and stable force measurements.

The Perkins team previously made great advances in stabilizing AFM position. But their research on force spectroscopy was limited by substantial drifts in force measurements that plague all users of gold-coated AFM cantilevers. Although the gold coating gives a much stronger optical signal, the coating causes the cantilever to move unpredictably. So instead of the AFM cantilever moving only in response to the molecule being studied, the gold coating itself was causing cantilever motion and creating significant measurement errors.

Not surprisingly, the group decided to go after the gold that was interfering with their research. Graduate student Allison Chunside, research associates Ruby May Sullan, Duc M. Nguyen, Sara O. Case, and Matthew Bull, former research associate Gavin King, and Fellow Tom Perkins used a short chemical treatment to strip the gold off a commercial cantilever. Then, they compared this cantilever’s behavior with that of a traditional gold-coated one.

The Perkins group’s comparison showed that measurements made with the uncoated cantilever were ten times more precise in a measurement time of one second. It also showed that the gold coating was a primary source of force drift over the course of hours. Force drift is a measure of how far the probe’s starting position drifts during a series of experiments. With the normal gold-coated cantilevers, this drift was about 1,000 nm; it was only 70 nm when the gold had been stripped away.

The improvements in stability and precision were evident just 30 minutes after the uncoated probe was readied for an experiment. In contrast, gold-coated probes often require more than two hours or overnight to settle down enough to allow an experiment to proceed.

The Perkins group anticipates that the advantages of doing away with gold coatings on AFM cantilevers will benefit all sorts of experiments in biophysics and nanoscience. — Julie Phillips and Tom O’Brien

References


The Amazing Plasmon

The Nesbitt group has figured out the central role of “plasmon resonances” in light-induced emission of electrons from gold or silver nanoparticles. Plasmons are rapid-fire electron oscillations of freely moving (conduction) electrons in metals. They are caused by light of just the “right” frequency.

In metal nanoparticles, the right frequency exquisitely depends on the shape of the particle as well as its size and material. Master glass blowers actually figured this out during the Middle Ages! They learned to add tiny particles of gold and silver during glass making to produce the brilliant reds, blues, and purples of the stained glass windows in the great cathedrals of Europe. The tiny metal particles were not only responsible for the gorgeous colors, but have also prevented the hues from degrading over time, in some cases for more than a thousand years.

Today chemical physicists are working to understand the electronic responses of plasmon resonances and their relationship to the photoelectric effect, which was first explained by Albert Einstein more than a hundred years ago. In the photoelectric effect, a photon of light of sufficiently high frequency will eject an electron from a metal surface. Even if the frequency of a single photon is not high enough to dislodge an electron, intense light can also cause electron ejection when the metal surface simultaneously absorbs several photons whose collectively energy is high enough.

This multiphoton photoelectric effect is particularly amazing since it usually takes three, four, or even more photons to eject a single electron. Then, if the frequency of the light hitting the metal surface happens to resonate with the metal surface’s plasmon oscillations, billions more electrons will be ejected than would normally occur!

This plasmon-induced photoelectron emission is the subject of intense scrutiny in the Nesbitt laboratory these days. Research associate Andrej Grubisic, former research associate Volker Schweikhardt, recently minted Ph.D. Tom Baker, and Fellow David Nesbitt recently completed a study of the critical role of the intense electric field accompanying plasmon resonances in photoelectron emission. The presence of such plasmon resonances significantly increased the coherent multiphoton photoelectron yield from gold nanorods.

The researchers discovered that they could maximize electron emission from the gold nanorods if they (1) aligned the laser along the long axis of the nanorod and (2) used a laser whose frequency vibrated in sync with the plasmon oscillation. The combined effect of the laser’s frequency with the plasmon resonance created an electric field whose impact on the photoelectron emission from a gold nanorod’s surface was truly mind-boggling. The resulting light-induced emission rate of electrons increased by a factor of 10 billion!

These startling results bode well for future investigations of plasmon resonances and metallic nanoparticles in general. Such research is expected to yield such exciting new applications as ultrashort-pulsed electron sources, more efficient solar cells, light-activated anticancer agents, high-density storage drives, and ultrasensitive chemical detectors.

References


Graduate student Ben Knurr and Fellow Mathias Weber have added new insight into a catalytic reaction based on a single gold atom with an extra electron that transfers this electron into carbon dioxide molecules (CO₂). This reaction could be an important first step in future industrial processes converting waste CO₂ back into chemical fuels. As such, it could play a key role in a future carbon-neutral fuel cycle.

What the Weber group did was use vibrational spectroscopy to probe the effect of solvent CO₂ molecules as they came in contact with a gold-CO₂ complex (AuCO₂⁻). The activation reaction was most favored when all eight solvent molecular layers were in place around the complex.

Before the researchers even did the experiment, they knew that if solvent molecules of CO₂ attach themselves to the CO₂ end of the AuCO₂⁻ complex, they would enhance the chances of the CO₂ acquiring an extra electron, freeing itself from the gold atom, and completing the first step of the conversion reaction. The newly formed and highly reactive (i.e., activated) CO₂⁻ ions could then be used in a series of additional steps to make recycled liquid fuels.

Knurr and Weber found that the first eight solvent molecules of CO₂ preferentially attached themselves around the CO₂ end of the AuCO₂⁻ complex. As the number of solvent molecules increased from 1 to 8, the activation of the complex-bound CO₂ also intensified, enabling it to grab more and more of the needed excess electron.

The two key measures of atomic clock performance are stability and accuracy. A clock’s accuracy measures how well it keeps time against a mythical perfect standard. But all clocks are noisy, and averaging over hours promises to inform the design and engineering of industrial systems aimed at creating carbon-neutral fuel cycles.

The inner workings of the Sr-lattice optical atomic clock under development in the Ye labs.

**References**


When experimental physicists at Penn State were unable to observe some of the predicted behaviors of ultracold rubidium (Rb) atoms expanding inside a two-dimensional crystal of light, they turned to their theorist colleagues at the City University of New York and JILA for an explanation. Graduate student Shuming Li and Fellow Ana Maria Rey were happy to oblige.

A theoretical model of the experiment indicated that the atoms, when allowed to expand, would be clustered inside a slowly moving square-shaped fort-like barrier. This barrier would prevent the atoms inside from moving back and forth between adjacent quantum wells. Eventually, the atoms could only move vertically—doing, even though none of the atoms had a cell phone.

Rey and her collaborators figured out that as the wells formed inside the crystal of light were shallow. The atoms inside the cloud inside the fort. This simplified model only predicted the behavior observed when the energy wells forming inside the crystal of light were shallow. However, when the experimenters adjusted the intensity of the laser that creates the crystal to make the energy wells deeper, the model could not reproduce the much slower atom expansion that occurred in response.

Graduate students Justin Bohnet, Zilong Chen, Joshua M. Weiner, and Kevin Cox worked with Fellow James K. Thompson to investigate the superradiant laser’s stability in response to specific changes in its surroundings. This experiment was somewhat like investigating the stability of a bell by hitting it with a hammer and listening to it ring. But instead of hammering the superradiant laser, the researchers tickled it and used an innovative quantum-measurement technique they had previously developed to precisely determine how the atoms were responding from passing over or through other particles, especially if the atoms are confined in the same energy well. On occasion, some correlated Rb atoms can even stop acting like neighborly bosons (which can occupy the same quantum state) and start acting like fermions, which do everything they can to avoid getting close to each other.

What’s interesting about correlated atoms is that they lose their individual identities and become something altogether different from single atoms: They become a superposition of all possible characteristics of their component atoms. And the correlations themselves somehow give rise to a new type of self-trapping.

Correlated states usually appear when interactions are strong. Very strong interactions prevent the atoms from passing over or through other particles, especially if the atoms are confined in the same energy well. On occasion, some correlated Rb atoms can even stop acting like neighborly bosons (which can occupy the same quantum state) and start acting like fermions, which do everything they can to avoid getting close to each other.

The mean-field model does not capture quantum correlations and consequently predicts a much faster expansion rate than was observed when the energy wells were deeper. The mean-field theory’s assumption that there exists some kind of “average” behavior breaks down under circumstances that favor entanglement.

Clearly, a new theory is required to explain the quantum behavior of strongly interacting ultracold atoms. This theory must take account of quantum correlations and interactions. It must also map out the details of how the behavior of ultracold atoms in a lattice leads to self-trapping.

Rey and her collaborators figured out that as the wells grew deeper, it became harder for the strongly interacting atoms to move back and forth between adjacent quantum wells. Eventually, the atoms could only move vertically—even though the deeper wells themselves were not impeding their movement. Curiously (because this is the quantum world), under these “frozen” conditions, the atoms became correlated or entangled. They actually seemed to “know” what the other atoms around them were doing, even though none of the atoms had a cell phone.

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Theorists Li and Rey have their work cut out for them.

Reference
Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David J. Weiss, Shuming Li, Ana Maria Rey, and Rafael Hipolito, Physical Review Letters 110, 033001 (2013).
Fellow Mitch Begelman and colleague Marek Sikora of the Polish Academy of Sciences have proposed a solution to the long-standing puzzle of what causes black holes to launch powerful jets. Jets are extremely energetic material (plasma) traveling at close to the speed of light and spanning distances of up to hundreds of thousands of light years. The key factor in the creation of jets is the presence of a strong directional magnetic field (magnetic flux) threading the black hole. And, because magnetic flux threading a black hole is relatively rare, the new paradigm also explains why less than 10% of the “active” supermassive black holes at the center of galaxies emit jets.

Active black holes voraciously feed on relatively thin clouds of cold gas. These writhing, twisting gas clouds typically create strong magnetic fields. But, the cold gas is too turbulent to carry much of the magnetic field near the black hole. And it’s unusual for the black holes feeding on cold gas clouds to start emitting jets.

The trigger for jet emergence is the buildup of magnetic flux in a sequence of events involving a merger between an elliptical galaxy and a spiral galaxy. Elliptical galaxies contain large masses of hot gas that drag magnetic fields into the vicinity of the black hole—but not inside it. Then, when an elliptical galaxy merges with a spiral galaxy, the cold gas in the spiral galaxy pushes the magnetic field the rest of the way into the black hole. This two-step process threads the magnetic field through the black hole. At the same time, it causes the magnetic field to become organized with well-defined north and south poles. The black hole is now like a gargantuan bar magnet with a mass of millions to billions of suns. It emits powerful jets traveling close to the speed of light in opposite directions. The amount of power propelling these jets is a function of the strength of the magnetic flux running through the black hole.

Begelman and Sikora say that this mechanism explains the origin of jets from quasars. Observations have shown that quasars with jets are surrounded by thin cold disks of swirling gas. The researchers argue that these quasars must have previously encountered hot gas from an ancient elliptical galaxy before an encounter with a spiral galaxy that created the cold disk.

This work is an excellent example of the fruitful international collaborations JILA is known for throughout the world.

Reference