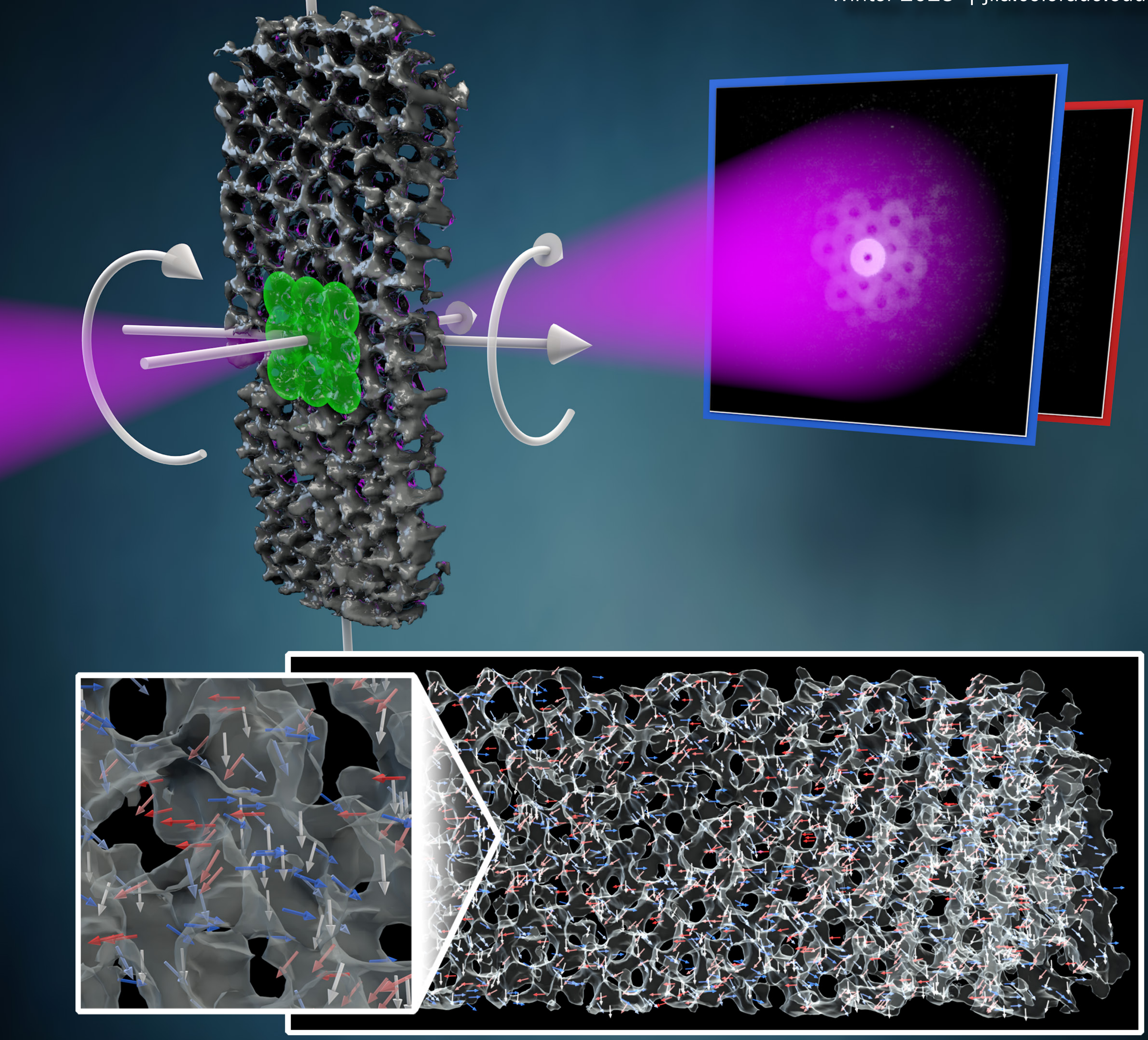
LIGHT+ MATTER

Winter 2023 | jila.colorado.edu



The Swirling Spins of Hedgehogs
pg 3.

JILA
CU Boulder and NIST

The Women in Science Panel discussion held on February 11, 2023.
(Left to Right) Panelists: Ellen Keister, the Director of Education for the STROBE Center within JILA; Ana Maria Rey, JILA and NIST Fellow; Margaret Murnane, JILA Fellow; and Kenna Hughes-Castleberry, JILA Science Communicator

Credit: Lauren Mason/JILA

JILA Light & Matter is published quarterly by the Scientific Communications Office at JILA, a joint institute of the University of Colorado and the National Institute of Standards and Technology.

The science communicators do their best to track down recently published journal articles and illuminating research photos and graphics. If you have an image or a recent paper you'd like to see featured, contact us at: sco@jila.colorado.edu

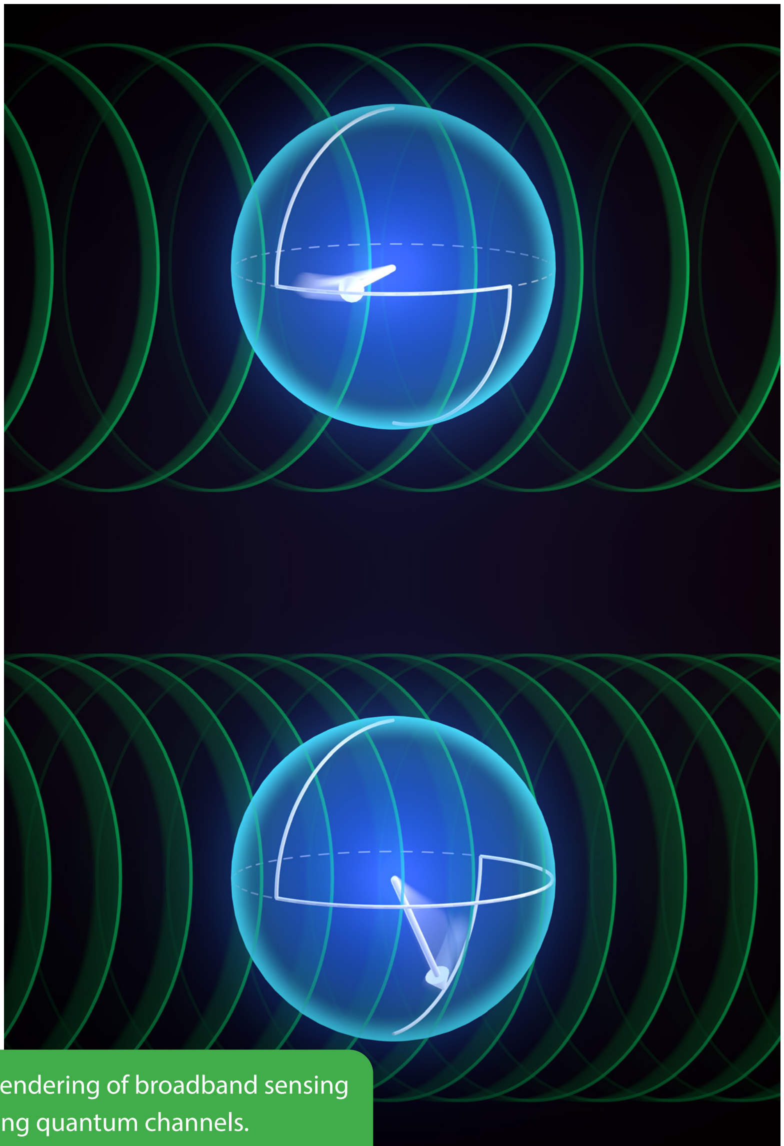
Please check out this issue of JILA Light & Matter online at https://jila.colorado.edu/publications/jila-light-matter-quarterly

Steven Burrows, Project Manager, Artwork
Kristin Conrad, Design & Production
Kenna Castleberry, Science Writing, Design, Editor-in-Chief
Gwen Dickinson, Editor

Research Highlights

Feature Articles

Defining the Limits of Quantum Sensing



A rendering of broadband sensing using quantum channels.

Credit: Steven Burrows/Anthony Polloreno

There are many methods to determine what the limits are for certain processes. Many of these methods look to reach the upper and lower bounds to identify them for making accurate measurements and calculations. In the growing field of quantum sensing, these limits have yet to be found. That may change, thanks to research done by JILA Fellow Graeme Smith and his research team, with JILA and NIST Fellow James Thompson. In a new study published in *Physical Review Applied,* the JILA and NIST researchers collaborated with scientists at the quantum company Quantinuum to try and identify the upper limits of quantum sensing.

Quantum sensors are devices that can be used to measure gravitational waves, magnetic fields, and other physical properties. They can be part of global positioning systems or even satellites. To look at the limits of quantum sensors, the researchers studied how they behave in a type of magnetic field, called an AC magnetic field, that can be created by running an AC current through a coil. To understand various measurements of the magnetic field, the researchers used a quantity called the Quantum Fisher Information (QFI). According to first author and Smith research group graduate student, Anthony Polloreno: "The Quantum Fisher Information is a measure of how much information about a parameter you can extract from a quantum state. In this case, you have a quantum state, like the spin [of a particle], which is interacting with a magnetic field. You're interested in how much information you can extract about the magnetic field." The researchers defined a new quantity, the integrated QFI (IQFI), a measurement of the upper bound, which they could then use in their mathematical calculations for the limitations of quantum sensing.

By simulating sensing experiments for various durations, the researchers found that the limitations of the quantum sensor were being affected by time. “The idea is that you have a quantum state in an AC magnetic field,” explained Polloreno. “The longer the thing sits in the field, in general, the more information you can learn about the magnetic field, which is why you would expect for instance, the IQFI to maybe increase as a function of time.” Looking at their data, the researchers developed a set of protocols for other scientists to use to test for a quantum sensor's upper bound, using the IQFI value. The researchers believe that these new protocols could be especially important, due to their narrower parameters, for a few applications, including axion detection and dynamical decoupling.

Axion Detection and Dynamic Decoupling

Axions are hypothetical particles that could be the source of dark matter. Other JILA Fellows are in the process of attempting to detect these axions using quantum sensors. “In axion detection, they do these kinds of broad frequency scans, where they're looking for a signal at many frequencies,” Polloreno stated. Having protocols that determine an upper bound for these broad frequency scans can help scientists save time and make more accurate measurements as the protocols start with narrow parameters.

The team's new protocols can also be used to understand dynamical decoupling. According to Polloreno: “Dynamical decoupling is this idea in quantum computation where you have noise that your qubits are experiencing. And you would rather there not be any noise, but of course, there is noise. So, dynamical decoupling tries to reduce some of this noise sensitivity by moving the susceptibility to the noise around to different frequency bands.” The researchers' new protocols can help to zero in on the right frequency bands for lowering noise susceptibility, thereby assisting scientists with other quantum computing experiments. “From our work we've seen that our new protocols can be applied to both axion detection and dynamical decoupling in completely different ways,” Polloreno elaborated. “One is if you're trying to build sensors to detect things, and the other is if you're trying to isolate your system to not be susceptible to noise.”

Collaboration Leads to Results

This experiment not only illustrated successful collaboration between research teams at JILA, but also illustrated further cooperation with the Colorado-based quantum computing company, Quantinuum (previously Honeywell Quantum Solutions). Quantinuum was brought in via graduate student Joshua Levin, who has recently graduated from the University of Colorado Boulder with his PhD, and who had an internship at Quantinuum at the time of this study. Communicating with colleagues at JILA, Levin and the Quantinuum team were able to help create the theoretical setting of the experiment. “One of the examples we give in the paper is using a transverse field to estimate the amplitude of an AC magnetic field,” said Polloreno. “This example was provided by Josh and the scientists at Quantinuum.” Polloreno and other JILA researchers were grateful to have the benefits of the collaboration with an industrial team. “While at JILA, I've been grateful to work on projects that have been inspired by experimental collaborations,” Polloreno added. “This project was inspired by Graeme's group, James' group, and Quantinuum. I think JILA's commitment to connecting theory and experiment helped extremely naturally.”

Anthony M. Polloreno, Jacob L. Beckey, Joshua Levin, Ariel Shlosberg, James K. Thompson, Michael Foss-Feig, David Hayes, and Graeme Smith. " Opportunities and Limitations in Broadband Sensing." Physical Review Applied. 19(1), 014029 2023.

Written by Kenna Hughes-Castleberry

The Swirling Spins of Hedgehogs

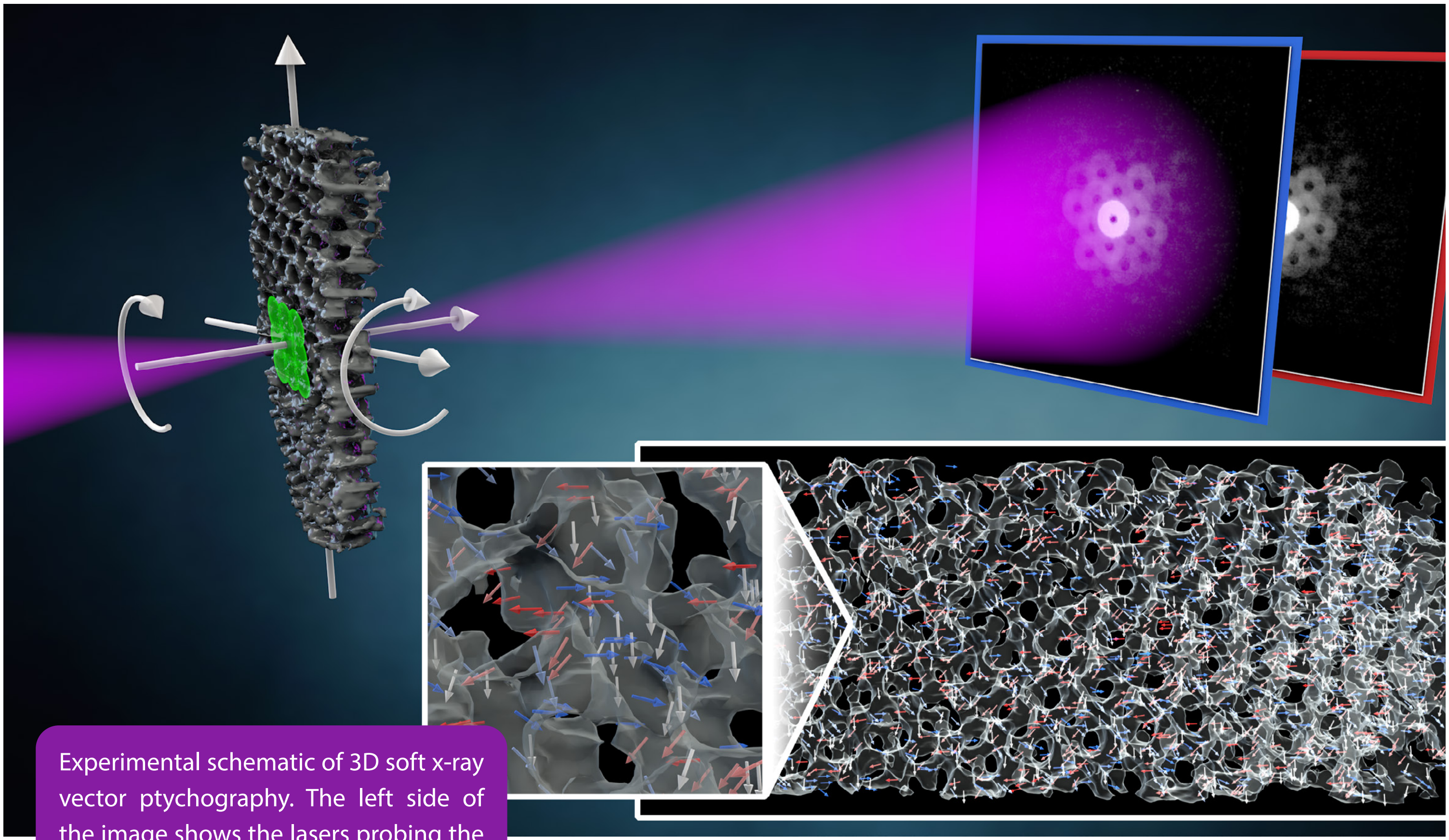
Though microscopes have been in use for centuries, there is still much that we cannot see at the smallest length scales. Current microscopies range from the simple optical microscopes used in high school science classes, to x-ray microscopes that can image through visibly-opaque objects, to electron microscopes that use electrons instead of light to capture images of vaccines and viruses. However, there is a great need to see beyond the static structure of an object—to be able capture a nano- or biosystem functioning in real time, or to visualize the magnetic field on nanometer scales. A team of researchers from the STROBE Center have been working together to overcome these challenges. STROBE is an NSF Science and Technology Center led by JILA Fellow Margaret Murnane. The large and multidisciplinary collaboration included Chen-Ting Liao and the Kapteyn-Murnane group from JILA, the Miao and Osher groups from University of California, Los Angeles, Ezio Iacocca from University of Colorado Colorado Springs, David Shapiro and collaborators at Lawrence Berkley National Laboratory, and the Badding and Crespi groups from Pennsylvania State University. They developed and implemented a new method to use x-ray beams to capture the 3D magnetic texture in a material with very high, 10-nanometer spatial resolution for the first time. They published their new technique and new scientific findings in *Nature Nanotechnology.*

Magnetic Lattices

The team investigated a nanostructured magnetic sample, consisting of tiny spheres of nickel, only ~30 nm across, connected together by slender few-nm "necks" of nickel, that together form a structure called a magnetic metalattice. This complex nanostructured magnet is expected to produce swirling magnetic fields with topological spin textures that are far more complex than in a uniform magnet. However, until recently, there was no experimental method to measure the 3D spin texture at the nanoscale.

Using the x-ray synchrotron light source at the Lawrence Berkley National Laboratory, the researchers overcame these challenges. "When we illuminate the meta-lattice sample with a coherent (i.e. ,laser-like) x-ray beam, the light scatters from the sample to produce diffraction patterns on a detector," explained co-first-author Chen-Ting Liao. "Then we scan the sample in 2D, change the polarizations of the light, and take the data again. Finally, we tilt and rotate the sample and repeat the measurements." This creates a lot of data. "We collect about 800,000 distinct diffraction patterns, corresponding to several terabytes of data," Liao added. "We then work with our collaborators to combine all these different diffraction patterns with state-of-the-art algorithms to reconstruct the full 3D vector image of the sample. This imaging technique is called 3D soft x-ray vector ptychography, and is the first general method to capture 3D spin texture at the nanoscale."

Imaging spin textures is extremely important, as it can help physicists to better understand magnetism at a fundamental level, and to design more energy-efficient data storage, memory, and nanodevices. "We have known about the existence of magnetism for thousands of years, yet we still do not understand it at a fundamental level," Murnane explained "Using electron microscopy, one can make a beautiful 2D image of a static spin-texture, but it is challenging to capture a full 3D image. Other scientists were able to capture a 3D image at a spatial resolution of about 100 nanometers, but they had to make assumptions about the sample to extract the 3D image." With this new technique, researchers do not have to make any assumptions. "The rich physics in these nanostructures is only apparent when you can see the detailed spin textures with very high spatial resolution," said Murnane. "The technique that



Experimental schematic of 3D soft x-ray vector ptychography. The left side of the image shows the lasers probing the metal superlattice

Credit: Steven Burrows/Murnane and Kapteyn Groups

STROBE developed is a real imaging science tour-de-force."

Hedgehogs and Anti-Hedgehogs

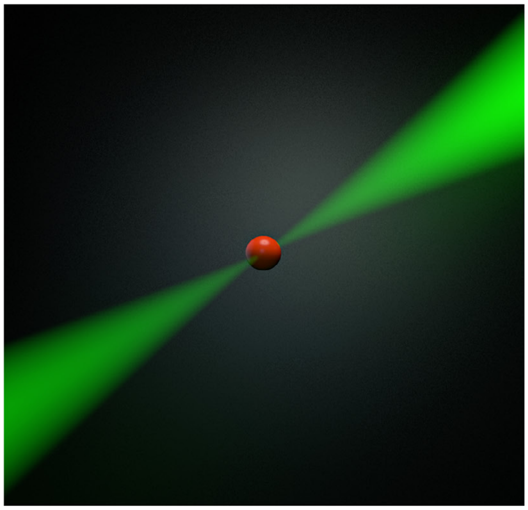
The topological magnetic spin textures that the researchers studied are called 3D magnetic skyrmions, or hedgehogs, due to their spiny shape in magnetic rotation. "We can think of magnetic hedgehogs as special 3D spin textures with a specific topology or shape," Liao said. "When the topological charge is either +1 or -1, we get the equivalent of a magnetic monopole, which is a type of emergent magnetic quasi-particle. We also see anti-hedgehogs, where the 3D shape is an inverted hedgehog." Studying hedgehogs has been difficult in the past, because this could only be done using computer simulations that had to make approximations. Thanks to the team's new technique, hedgehogs can now be visualized accurately, giving more useful data to researchers about how they interact and fluctuate within the lattice.

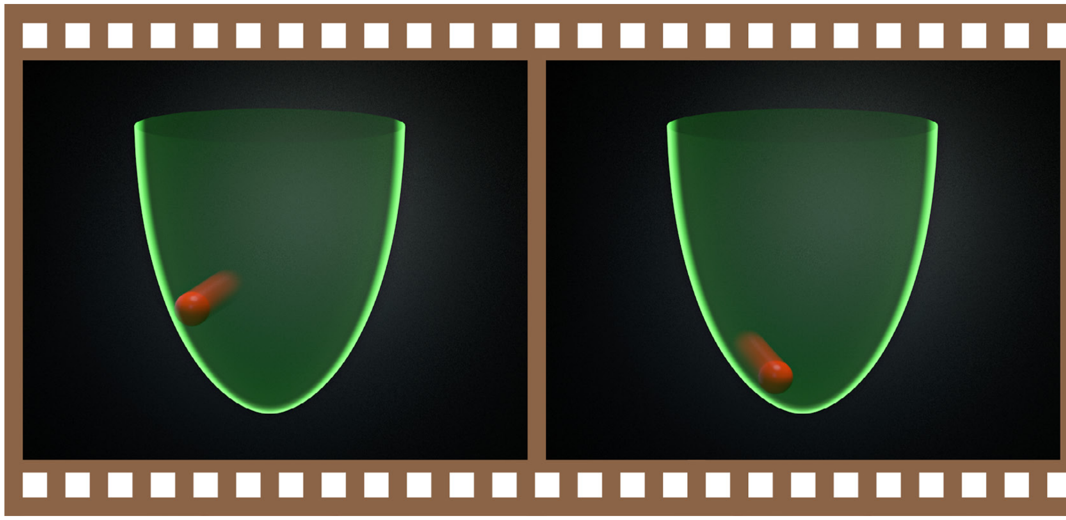
Armed with this new visualization technique, the team of researchers is excited to study spin textures further. "STROBE is developing tabletop setups and helping to commission national facilities that can capture the static and dynamic spin texture in materials," explained Murnane. All algorithms developed for this data analysis will be open-sourced soon. Liao, Murnane, Miao, and the rest of the team will continue to share their results to help the community to drive advances in materials science. In this experiment, as with others, they found that collaboration is key for moving scientific progress forward.

Arjun Rana, Chen-Ting Liao, Ezio Iacocca, Ji Zou, Minh Pham, Xingyuan Lu, Emma-Elizabeth Cating-Subramanian, Yuan Hung Lo, Sinéad A. Ryan, Charles S. Bevis, Robert M. Karl Jr, Andrew J. Glaid, Jeffrey Rable, Pratibha Mahale, Joel Hirst, Thomas Ostler, William Liu, Colum M. O'Leary, Young-Sang Yu, Karen Bustillo, Hendrik Ohldag, David A. Shapiro, Sadegh Yazdi, Thomas E. Mallouk, Stanley J. Osher, Henry C. Kapteyn, Vincent H. Crespi, John V. Badding, Yaroslav Tserkovnyak, Margaret M. Murnane, and Jianwei Miao. "Three-dimensional topological magnetic monopoles and their interactions in a ferromagnetic meta-lattice." Nature Nanotechnology (2023). https://doi.org/10.1038/s41565-022-01311-0

Written by Kenna Hughes-Castleberry

A Quantum Video Reel





When it comes to creating ever more intriguing quantum systems, a constant need is finding new ways to observe them in a wide range of physical scenarios. JILA fellows Cindy Regal and Ana Maria Rey have teamed up with Oriol Romero-Isart, a professor at the University of Innsbruck and IQOQI (Institute for Quantum Optics and Quantum Information) to show that a trapped particle in the form of an atom readily reveals its full quantum state with quite simple ingredients, opening up opportunities for studies of the quantum state of ever larger particles.

In the quantum realm an atom does not behave as point particle, instead it behaves more as a wave. Its properties (e.g., its position and velocity) are described in terms of what is referred to as the wavefunction of the atom. One way to learn about the wavefunction of a particle is to let the atom fly and then capture its location with a camera.

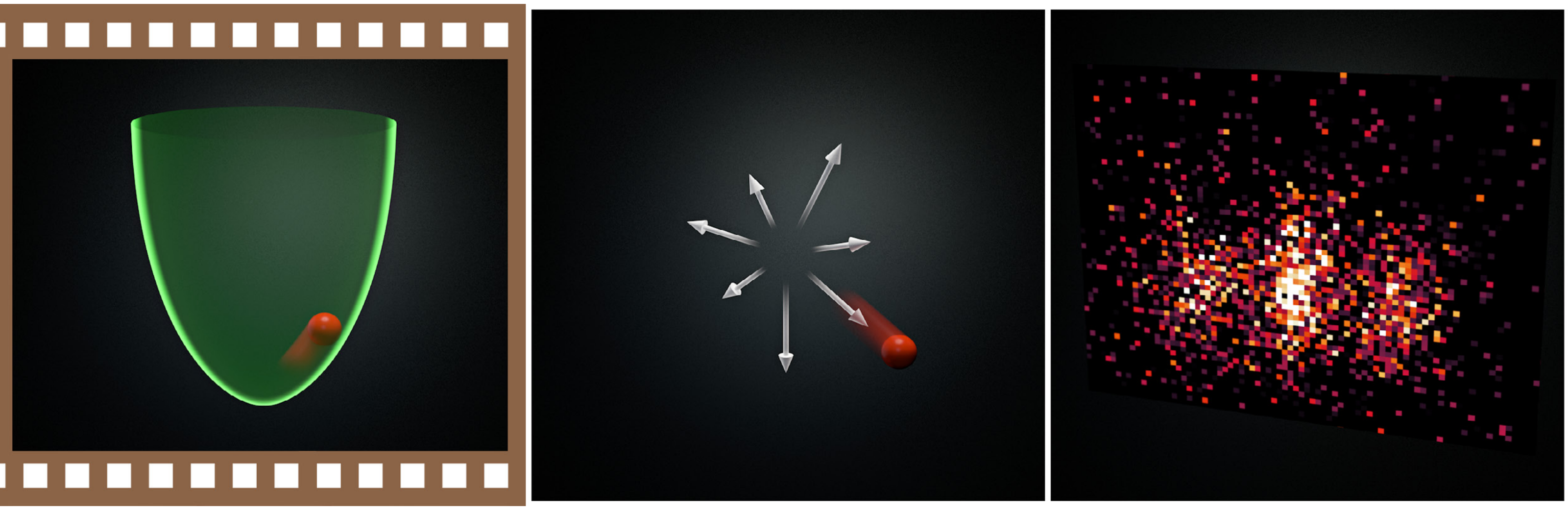
And with the right tricks, pictures can be taken of the particle's quantum state from many vantage points, resulting in what is known as quantum tomography ('tomo' being Greek for slice or section, and 'graphy' meaning describing or recording). In the work published in *Nature Physics*, the authors used a rubidium atom placed carefully in a specific state of its motion in a tightly focused laser beam, known as an optical tweezer. And they were able to observe it from many vantage points by letting it evolve in the optical tweezer in time. Like a ball rolling in a bowl, at different times the velocity and location of the particle interchange, and by snapping pictures at the right time during a video reel of the ball, many vantages of the particle's state can be revealed.

The researchers used multiple time-of-flight camera pictures as a tomography tool and reconstructed the quantum state of their trapped atom without any other aids. The quantum tomography revealed features one would not find for an atom in a classical state, but that required instead a genuine quantum description for understanding the combined measured patterns.

Flying Particles

Atoms that are trapped and behaving quantum mechanically are nothing new to JILA, and time-of-flight is a way in which experimenters often learn about the momentum spread of a collection of atoms.

One reason the researchers started thinking about this experiment with a single atom was actually because of protocols proposed for large trapped particles, where many atoms in a solid are stuck to-



An artistic film strip depicting the process of creating time-of-flight imaging using optical tweezers and a special camera

Credit: Steven Burrows/Rey, Regal and Romero-Isart Groups

gether, moving as one. “Nanoparticles are solid objects containing billions of atoms and can be used to test quantum mechanics at large scales,” Romero-Isart explained. “Some of the ideas and protocols we have theoretically devised in this context can be tested with single atoms, using the exquisite control that the team of Cindy Regal has with single atoms in their lab.”

Romero-Isart proposed in a 2011 paper that time of flight combined with letting a single particle roll coherently in a trap could result in full quantum tomography. And, in contrast to many techniques that are often used for quantum tomography, it would be applicable to any particle, as long as it could be seen on a camera. “Quantum tomography has been accomplished in many different ways for a variety of particles and systems,” explained Regal. The technique used by the researchers, however, is intriguingly simple because you just wait for the right time during the video reel, and let the atom fly. “Quantum tomography is a protocol that aims to determine the full quantum state of a system,” explained JILA and NIST Fellow Ana Maria Rey. As Romero-Isart, added: “Since in quantum mechanics a single measurement perturbs the state of the system, quantum tomography requires the ability to repeat the experiment under identical conditions.”

Regal, Rey, and Romero-Isart set out to see if an optical tweezer trap was a controlled enough platform to see a provable quantum behavior for a single particle, the single particle being an atom for these experiments, using Romero-Isart’s proposed video reel technique.

Operating the Camera

Using the optical tweezers, Regal and her team were able to record the atom's time of flight after releasing the atom from the trap. “For this experiment, we looked at rubidium atoms,” Regal added. “What we do is create many single identical atoms, around 60,000 times, each time creating the atom nominally in the same state.” In repeating this over and over, the researchers could create a type of image that reveals the velocity, or momentum, of the atom at the time when it was released from the trap. “Imagine, for example, a par-

-ticle that has very low momentum," Rey posited, "If we release it, then the particle will barely move and we will find it very close to its initial position after time evolution. On the other hand, a very energetic particle will move very fast after we release it from the trap, and we will find it very far away. So, the map of the positions of the particles after a long time of evolution allows us to determine the momentum at the time of release."

The camera used to take these images was different from what Regal used in the past to help create these informative images. "Because we had to take images of the atoms quickly during their flight, it is important to capture as many photons from the atom as possible and optimize the camera for low noise," said Regal.

A new video reel is then taken by repeating the experiment sequence again, but capturing the system at a different point in time in the optical tweezer video reel.

Imaging Quantum States

Using all of the images from the video reel, the team could then estimate the quantum states of the atom. "One key contribution of the theory was to be able to reconstruct what is called the Wigner function of the state (which connects the wave function of a quantum state to a probability distribution in position-momentum space) from experimental measurements," explained Rey.

"One key outcome of the work was to prepare the atom in a state that is fully quantum and cannot admit a classical description," Rey added. "We were able to demonstrate that even accounting for small imperfections and systematic errors unavoidable in the experiment, the state retains a negative Wigner function which can only happen for genuine quantum states." The capability to prepare and measure a single atom wavefunction featuring a negative Wigner function revealed the success of the quantum protocol implemented by the researchers. The measurement idea will be useful for benchmarking the performance of quantum state control in optical tweezers, which is increasingly important for quantum computing and metrology in neutral atom arrays.

As much of quantum physics revolves around isolating and manipulating atomic states, the results of this experiment offer promising new avenues for further explorations. "There are exciting directions ahead," Rey said. Regal, Rey, and Romero-Isart will continue their collaboration by not only drawing parallels between how one images quantum states of neutral particles, but also in creating arbitrary motional quantum states, and expanding concepts to more traps and more atoms. These explorations will further push the boundaries of quantum control afforded by optical tweezers.

M.O. Brown, S. R. Muleady, W.J. Dworschack, R.J. Lewis-Swan, A.M. Rey, O. Romero-Isart, C.A. Regal. "Time-of-flight quantum tomography of an atom in an optical tweezer." Nature Physics. (2023). https://doi.org/10.1038/s41567-022-01890-8

Written by Kenna Hughes-Castleberry

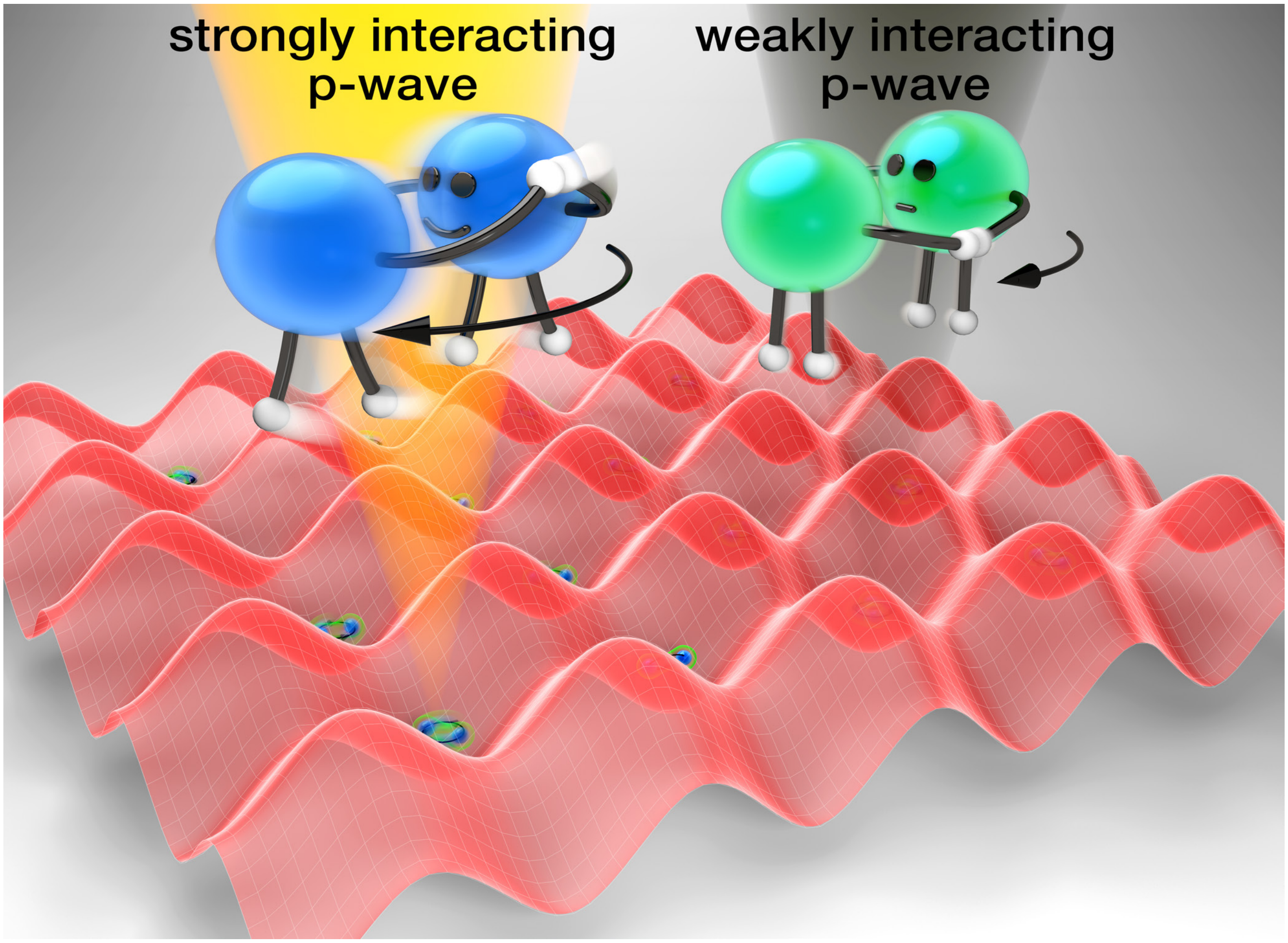
Atoms Do the Twist

At ultra-cold temperatures, quantum mechanics dictate how particles bump into each other. The collisions depend both on the quantum statistics of the colliding partners (their location within the medium) and on their collisional energy and angular momentum. The angular momentum of the particles creates an energy barrier, a field of energy that prevents two molecules from interacting, and which can also affect particle dynamics in the quantum realm. The two main types of interactions at the quantum level are s-waves and p-waves. S-wave types of collisions happen naturally between fermions when they exist together in two different internal states and happen with zero angular momenta, which creates a low energy barrier. That means that atoms can collide "head-on." S-wave collisions have been very well studied and characterized. However, quantum statistics prevents identical fermions (those having the same internal state) to collide via s-wave interactions, instead forcing them to interact via the so-called "p-wave" channel.

In contrast with s-wave interactions, p-wave interactions are penalized by the aforementioned energy barrier. In order to collide, particles need to carry a non-zero angular momentum in order to overcome that barrier—they need to spin around each other, like a pair of dancers. The net angular momentum of the partners can give rise to rich quantum behaviors and phases of matter that have been intensively sought in real materials and cold atoms, but which have not yet been found. Besides the energy barrier, the dynamics of three-body recombination, which involves interactions when three atoms are present rather than two, can make it complicated to study p-wave interactions in an isolated space. To overcome these problems, and to measure coherent p-wave interactions between two particles for the first time, JILA and NIST Fellow Ana Maria Rey and her group, together with JILA theorist Jose D'Incao, collaborated with the University of Toronto experimentalist team led by Joseph Thywissen. They devised a method to isolate pairs of atoms in an optical lattice, a web of laser light that helps isolate and control particle interactions, then gave the particles the necessary angular momentum, or twist, for the atoms to collide via p-wave using specific laser beam frequencies. This resulted in the first observation of p-wave interactions in an experiment. The researchers have published their findings in the journal *Nature.*

An Examination of the Three-Body Recombination

Three-body recombination is a process that happens in cold gases and has been a problem for many physicists in designing quantum particle experiments. In the p-wave case, the three-body collisions are so violent that they cause atoms to escape the optical lattice (trap). According to Rey: "When you have a three-atom system, the conditions for energy and momentum conservation allow two of the atoms to group together and release a lot of energy, which the third atom can soak up and use to escape from the trap. So, we can only keep them trapped for very short times in experiments. It's hard to track what is actually happening during these collisions." To overcome this issue, the researchers managed to isolate pairs of fermions. In an optical lattice, it is possible to prepare conditions at which there are exactly two atoms on a lattice site, but never three. Furthermore, the researchers were able to use a magnetic field to tune the interaction strength and check whether the predicted theoretical values matched the data. As Thywissen added: "The interaction energy cannot exceed a maximum value, which is reached at the so-called unitary point." This unitary point is a special limiting case where the



A representation of the indifferent interactions of p-waves based on their angular momentum

Credit: Steven Burrows/Rey Group and Thywissen Group

p-wave interactions are as strong as they can be in the lattice.

Researchers have long sought to generate coherent unitary p-wave interactions because of all the exciting exotic quantum phases of matter that these interactions enable. In the past, three-body recombination stopped them from getting close. Pioneering experiments carried out in a bulk gas by Deborah Jin at JILA were able to actually determine the rate at which particles are lost and provided first insights into the nature of p-wave collisions. However, since particles are lost very fast in a bulk gas it has been hard to make further progress in studying the p-wave processes.

Looking Closer at Atomic Interactions

Besides the three-body recombination, the energy barrier resulting from the mutual angular momentum of the atoms makes it harder to study isolated p-wave interactions. Vijin Venu, a graduate student in Thywissen's group said: "This means that the interacting atoms are not colliding head-on but their quantum mechanical collisions are characterized by a circular motion around each other." This circular motion can create both energy and motional problems in how the atoms collide. Rey added, "This is something that, even though it has been studied for many years, has not been clearly understood, because there have yet to be experiments to validate the various approximations used to characterize the p-wave interactions." Working to validate these approximations, Rey and her team helped Thywissen and his laboratory develop the right experimental protocols for isolating these interactions.

To quantify the strength of the p-wave collisions, the researchers looked at a value called scattering volume, which describes the intensity or strength of the collision. Systems with strong, naturally-occurring p-wave interactions are rare, as Venu added ,"The only naturally occurring system with well-established p-wave interactions is superfluid 3He." JILA has had a history of studying p-wave interactions in atoms. "Debbie Jin did a lot of progress studying p-wave interactions," Rey stated. "Her research accomplished amazing developments but faced challenges. We are now able to control the system in a much better way and we can start to overcome previous issues."

Making the Atoms Dance to a Faster Beat...with a Magnetic Field

As mentioned previously, the researchers varied the magnetic field to tune the strength of the p-wave interactions. "We control the scattering wave function with our choice of a magnetic field," explained University of Toronto graduate student Peihang Xu, who studied under Thywissen. The magnetic field affects the energy of individual atoms, which in turn adjusts the scattering volume of the collisions. By looking at the scattering volume for different magnetic fields and different lattice depths, the researchers were able to determine a universal curve in the data, suggesting an overall trend that should be followed by any kind of atoms in any lattice potential.

Laser beams were used to excite the atoms and impart the necessary angular momentum on them to twist around each other. To do this, a spectroscopic protocol first prepared atoms that were weakly interacting to increase the strength of their interaction. Twisting then occurred via laser beam stimulation, as the atoms' angular momenta began to shift. To speed up the twisting rate to the same rate enabled by the imposed magnetic field, atoms were exposed to radio-frequency pulses at a frequency tuned to cause resonance with the atoms—similar to tuning the knob of a radio to find the frequency of the desired radio station. "When the frequency is resonant [with the atoms], we can drive the transition for our pairs of atoms to go from a weakly interacting state to a strongly interacting state," stated Xu. The experiment was able to not only measure the energy, but the coherence between the atoms and molecules formed during the collision, and in the presence of an external drive," Rey said. "All the experimental observations agree with a theory description in terms of scattering volume."

While the experiment resulted in a novel method to study p-wave collisions without the effects of three-body recombination, it also resulted in long-wanted experimental corroboration of physics theory scattering volume predictions. JILA has a reputation for pairings of experimentalists and theorists for research that produce rich scientific results. As Mikhail Mamaev, co-author and graduate student in Rey's group notes, "The physics that comes out is much more complicated and interesting."

Vijin Venu, Peihang Xu, Mikhail Mamaev, Frank Corapi, Thomas Bilitewski, Jose P. D'Incao, Cora J. Fujiwara, Ana Maria Rey, Joseph H. Thywissen. "Unitary p-wave interactions between fermions in an optical lattice" Nature. 613(1), 262-267. (2023).

Written by Kenna Hughes-Castleberry

Controlling a Quantum Classroom: New Insights into the Spin-Dynamics of Molecules

Quantum gases of interacting molecules can exhibit unique dynamics. JILA and NIST Physicist Jun Ye has spent years of research to reveal, probe, and control these dynamics with potassium-rubidium molecules. In a new article published in *Nature,* Ye and his team of researchers describe having combined two threads of previous research—spin and motional dynamics—to reveal rich many-body and collisional physics that are controllable in the laboratory.

A History Lesson in Quantum Dynamics

The rotation of polar molecules can be used to encode or "program" the spin of particles, like electrons. Previous research has shown that the rotational states of molecules can be controlled using microwave pulses, allowing physicists to use molecules to study the dynamics of spin systems. Building on fruitful collaboration between former JILA Fellow Deborah Jin and Ye, together with the theory group of Ana Maria Rey, the research team has been looking at spin dynamics for about a decade. "The group was synthesizing ultra-cold potassium-rubidium molecules in three-dimensional optical interference patterns" explained postdoctoral researcher Jacob 'Jake' Higgins. "You can think of them as a three-dimensional checkerboard, and each molecule fits into one of the checkerboard sites. The molecules were stuck in zero-dimensional sites, and the group was observing these 'spin exchanges' where they can exchange rotational energy." Molecular interactions like spin exchange can affect molecular collisions and even chemical reactions. Understanding more about these dynamics could help researchers better understand and control quantum systems. The research then moved from a three-dimensional lattice where the molecules are frozen in place to two-dimensional planes or 'pancakes' through which the molecules could freely move. In recent years, they have used these pancakes, along with other instrumental capabilities such as tunable electric fields, to control the molecular collisions.

In the latest paper, the Ye group combined the molecular rotation and motion and studied the dynamics arising from this interplay. As Higgins said, "The title of our paper is 'Tunable Itinerant Spin Dynamics [with Polar Molecules].' So, it's itinerant, which means the molecules can move. And it's about spin dynamics, like the spin exchange that the group observed 10 years ago." With their new setup, the team could further study the influence of motion on the spin dynamics of the system. Furthermor e, the new experimental platform integrates precise control of electric fields and microwave pulses to control spin orientation and coherence which enabled the group to realize a highly tunable, strongly interacting many-body system.

Fighting the Noise

Even in the ultracold regime, to study quantum dynamics, scientists must find ways to mitigate noise in the system. There are fluctuations in external fields and inhomogeneous, thermal distributions in molecular energies—both of which can obscure subtle signals that arise from the coupled spin-motional dynamics. To mitigate the effects of environmental noise while letting the molecules move, the team instead used microwave pulses in ultracold conditions. As lead author and postdoctoral researcher Jun-Ru Li explained: “There is a very important technique we implemented for this work called dynamical decoupling. Basically, we used microwave pulses to repeatedly change the state of the system such that effects of the environmental noise cancel. Eventually, you can suppress the noise from the environment on average.” Using the microwave pulses, the researchers were able to reduce the effect of the noise by a factor of 70. With a quieter system, the team was able to see a clear signal of shift in the rotational energy resulting from interactions between molecules.

Entering the Quantum Classroom

The collective interaction between molecules shifts their rotational energy levels. With the noise now suppressed, “...we can see a shift in the rotational energy levels of the molecules,” explained graduate student Calder Miller. “This is because the molecules’ electric dipoles generate electric fields, so each molecule ‘senses’ the electric fields that all the other molecules are generating. That [other] electric field shifts the rotational energy of the molecule, and that's something we can measure spectroscopically.” Because the atoms were not frozen, as in a three-dimensional lattice, they could move freely and, in turn, affect nearly all their fellow molecules. “It's a bit like if you are in a classroom where everyone is sitting at different desks, and you want to talk to each other,” added Li. “There are some people sitting far from you and some people sitting close to you. You will hear the words of the people that are close to you much better than the people that are farther away. But now, if you imagine everyone is randomly moving in this classroom, you get the chance to talk to everyone, and a collective exchange might occur.”

The researchers quantified this shift, the mean field shift, and demonstrated its tunability with experimental parameters. “We change the electric field as well as the internal state of the molecules to show that we can control the strength of their interactions, that we can make the interactions attractive or repulsive, or even flip their sign in the middle of the experiment to make the dynamics evolve backward,” Higgins said. With these tunable spin dynamics, the researchers demonstrated how control of the interactions might enable exciting applications. “That's the spirit of what the experiment is. We are really trying to delve into what all these interactions are and how we can tune them. Ultimately, [we want to know] how we can use them for quantum computation and other applications.”

Thanks to this unique experimental setup, the researchers can measure more than the mean field shift of the molecules. “We also see that the system decoheres over time,” Miller added. “This means that the phase of the molecules is randomized. We have some evidence that this is because of elastic collisions between the molecules, which are enabled by the same dipole-dipole interaction that causes the energy shift.”

The creation of this experimental setup also suggests some big implications for other fields of physics. “Ultracold molecules have long been of interest to the scientific community for their potential applications to a variety of fields including quantum chemistry, quantum magnetism, and precision measurement for fundamental physics,” said Annette “Annie” Carroll, a graduate student in Ye's laboratory. “This work paves the way for future applications of polar molecules to study open questions in other areas of condensed matter physics and materials science. Our system could really deepen our understanding of fundamental science in these areas of physics and chemistry.”

Junru Li, Kyle Matsuda, Calder Miller, Annette N. Carroll, William G. Tobias, Jacob S. Higgins, and Jun Ye. " Tunable itinerant spin dynamics with polar molecules" Nature. 614(1), 70-74. (2023).

Written by Kenna Hughes-Castleberry

(Above): A 2D itinerant spin system with polar molecules interacting and colliding

Credit: Steven Burrows/Ye Group

Using Ion Crystals to Simulate Superconductors

In a conventional superconductor ('s-wave') superconductor, the two electrons in a Cooper pair (when electrons with opposite momenta bind together), must have opposite spins. But there are unconventional superconductors with p-wave symmetry, in which electrons of the same spin pair up. This pairing is penalized by an energy barrier, and in order to overcome the barrier and pair up, electrons need to carry a non-zero angular momentum, which means that they need to spin around each other. The net angular momentum of the Cooper pairs can give rise to rich quantum behaviors and phases of matter that are intensively sought in real materials and cold atoms, but have, so far, remained elusive. In particular, the dynamics of p-wave superconductors taken away from equilibrium is predicted to exhibit a variety of temporal behaviors, some of which possess interesting quantum dynamics. Observing these 'dynamical phases' in the lab would provide a window into the nature of non-equilibrium phases of matter and some of their properties, and potentially new p-wave superconductors. In cold gases, one of the biggest challenges that has prevented researchers from observing p-wave physics is three-body losses in energy that emerge when weak p-wave interactions are enhanced via external electromagnetic fields.

To overcome these challenges, JILA and NIST Fellow Ana Maria Rey collaborated with NIST (National Institute of Standards and Technology) Ion Storage Group leader John Bollinger, and researchers at the University of Innsbruck, Rutgers University and the University of Colorado Boulder, to design a trapped-ion simulator for 2D p-wave superconductors. Their work paves a way for clean observations of the predicted non-equilibrium dynamics in future experiments using the trapped-ion simulator, or Penning trap. The researchers published their findings in *PRX Quantum.*

"The natural platform to study superconductors would be solid-state systems or ultra-cold fermionic gases [to avoid three-body energy loss]," explained University of Innsbruck postdoctoral researcher Athreya Shankar. "But the problem is that p-wave interactions are rather weak, and therefore hard to control. In order to enhance these interactions, you have to manipulate the system using external fields," Shankar added, "But that can cause other unwanted problems in your experiment. This means that your gas can become unstable before you can observe the interesting dynamics."

To circumvent these problems, Shankar, Rey, and their colleagues asked a rather unconventional question: Do we need fermions at all to simulate the non-equilibrium behavior of superconductors? The motivation for this question came from the well-known observation that the non-equilibrium behavior can be described in terms of pairs of fermions with equal and opposite momenta, i.e., Cooper pairs. "The trick, then, is to map each Cooper pair onto a two-level system, or a spin, with states 'up' and 'down'," explained Shankar. "The 'up' state indicates the presence of a Cooper pair while the 'down' states indicates that it is absent. A two-level system can be naturally encoded into two electronic levels of each trapped ion, thus providing a non-traditional route to the quantum simulation of the non-equilibrium dynamics of superconductors." The tremendous level of control offered by trapped-ion simulators and the absence of fermionic particles meant that most of the challenges faced by traditional approaches could be overcome, or better still, were non-existent.

For the experiment, the researchers considered a setup using a Penning trap, in which 2D crystals of 100 to 200 trapped ions can be stored and manipulated. They proposed to encode a two-level sys-

Opposite page: A respresentation of the dynamics within the superconducting system.
Credit: Steven Burrows/Rey Group

tem in each ion, which would simulate the presence or absence of a fermionic Cooper pair. The central idea was that the momentum space of Cooper pairs was mapped on to the real space of the ion crystal. “So, if there is an ion at a certain position in the crystal plane, it would emulate a Cooper pair with a certain 2D momentum in the superconductor,” Shankar said. “The farther the ion is from the crystal center, the larger the momentum of the associated Cooper pair.” With this association, mapping became more straightforward. Rey commented, “The goal, then, is to emulate the attraction between Cooper pairs of different momenta in a p-wave superconductor. The mapping of Cooper pair momenta on to ion positions means that we need to engineer couplings between ions that depend on where each ion is located in the crystal plane. Interestingly, we discovered a clever way to accomplish that by exciting the vibrations of the crystal while simultaneously using the fact that ions in a Penning trap are rotating.”

A standout feature of the Penning trap is that the ion crystal is actually rotating when viewed from the laboratory frame. “The rotation is necessary; it’s the source of the ion confinement in a Penning trap,” explained Bollinger. However, the rotation is usually an inconvenience, since it becomes challenging to address the ions with laser fields to manipulate their electronic states. But for the researchers, this inconvenience could actually be a benefit. “This perceived disadvantage of the Penning trap actually turned out to be the crucial ingredient to engineer ion-position dependent couplings,” Shankar pointed out. By tilting the angle of the lasers used to address the ions and by suitably tuning the laser frequencies, the electronic states of the ions can be coupled to the crystal rotation. As a result, each ion is addressed by the lasers differently, depending on its position. Rey explained, “Furthermore, the laser illumination excites vibrations in the crystal and generates a force that depends on the electronic state of the ions. As a result, the motion of the crystal mediates an effective state and position dependent coupling between ions, which emulates the attraction between the Cooper pairs mediated by lattice vibrations in a real p-wave superconductor.” This allowed the mapping of interaction strength to be more closely associated with location in the crystal. “So now, if we look at the effective interactions between ions in the crystal, we find that the interaction strength depends on the ion positions in the frame rotating with the ions, where ions are static,” Shankar added.

Using their proposed design, the team illustrated that, in theory, a variety of predicted non-equilibrium dynamics could be observed in an experiment. They also showed how one could infer the topological character of the observed dynamical behavior through appropriate measurements. “Furthermore, since the number of ions is not that many (only 100 to 200), the effect of quantum noise on the non-equilibrium dynamics can potentially be observed in an experiment,” Shankar added. Rey echoed the importance of this new method by stating: “This is very exciting, since this means the experiment could be able to observe new effects not predicted before, since they are very complicated to be treated by theory.”

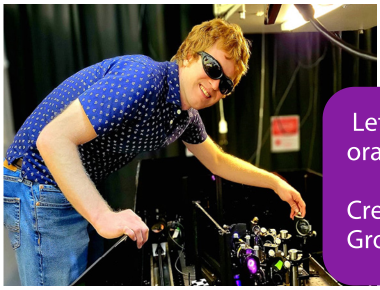
Beyond p-wave superconductors, this proposal provides a general toolbox for creating and manipulating winding spin textures known as skyrmions, which could be of broader interest, for example, in studying models of quantum magnetism and exploring better ways to build spintronics devices—a technology that exploits the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge.

Athreya Shankar, Emil A. Yuzbashyan, Victor Gurarie, Peter Zoller, John J. Bollinger, and Ana Maria Rey. " Simulating Dynamical Phases of Chiral Superconductors with a Trapped ion Magnet ." PRX Quantum 3(1), 040324 (2023).

Humans of JILA: Brendan McBennett

Surrounded by some of the world's most advanced lasers, computers, and microscopes sits Brendan McBennett, a graduate student at JILA. McBennett has been working in the laboratories of JILA Fellows Margaret Murnane and Henry Kapteyn, as part of the KM group since 2019, excited to see his research advance significantly over that time. "We use ultraviolet and extreme ultraviolet (EUV) lasers to study heat flow in nanostructured materials," McBennett states. "EUV photons have a higher photon energy that makes them insensitive to electron dynamics in most materials, combined with nanometer wavelengths. This allows them to very precisely probe surface deformations induced by heat - or thermal phonons – to capture new materials behaviors." In simple terms, McBennett is looking at heat dissipation in nanoelectronics. "Our experiments are providing a better understanding of phonon thermal transport in nanomaterials to inform the development of new predictive theories," he says. "There is a lot of technological potential, for energy efficiency, smarter design of nanoelectronics and quantum devices, and phonon-photon and phonon-electron analogs like phononic crystals and thermal diodes." McBennett's previous work at NREL (National Renewable Energy Laboratory) studied the power grid under varying renewable energy and energy efficiency scenarios, and his current research zooms in on this previous focus.

As part of the KM group in JILA, McBennett enjoys the community within his small team. "We have a close-knit team of four, with three experimentalists and a visiting theorist, and several collaborators from other universities, national labs and industry." he says. "We work very closely with theory groups all over the world, and there is a great deal of back and forth discussions to design new models based on our new experimental data." He also enjoys the time outside of the laboratory spent with fellow researchers. "We've been excited to plan more events as the team has grown," he adds. "From the Phonon Club lecture series this year to group dinners, and a hockey game. I'm grateful to my advisors Margaret and Henry for creating such an excellent work environment within the KM group. It's immensely helpful to always be able to go down the hall and work with the imaging, magnetic, and ARPES teams to solve challenges as they come up in the lab and exchange ideas."



Left; McBennett working in the laboratory

Credit: JILA/Murnane and Kapteyn Groups

As a JILA researcher, McBennett is also appreciative of the resources that JILA offers to its scientists and students, including the machine and instrument shops, the computer shops, the clean room, and more. "I can't stress enough how grateful I am to the Keck Lab and machine shop, particularly Curtis Beimborn, for making much of our research possible." McBennett explains "There are many instances from quickly checking something in the microscope to AFM and even electron beam lithography where working in the Keck lab has vastly sped up our research." Other researchers in JILA have echoed these sentiments, grateful to have the unique resources that only JILA provides. As he explains: "JILA has an excellent combination of exciting research and fantastic professors, students and staff who collaborate to make the work we do here possible. Everyone is extremely approachable, and there are many talks and events at which to meet your fellow JILAns. It is also exciting to work at an institute balanced between a university and national lab setting, with many connections to the private sector. It's possible to imagine all sorts of interesting career paths after completing your graduate work at JILA."

Written by Kenna Hughes-Castleberry

News and Awards

News

JILA Hosts Women in Science Panel to Celebrate International Women in Science Day. Some of the most important research and discoveries in science have been made by women. To celebrate these inspiring individuals and to support the next generation of female scientists, the United Nations dedicated February 11 as "International Women and Girls in Science" day. To honor this tradition, JILA hosted a panel discussion/open-forum with both JILA Fellows and JILA staff as speakers. The panelists were: Ana Maria Rey (a NIST and JILA Fellow), Margaret Murnane (JILA Fellow), Dr. Ellen Keister (Director of Education for STROBE, a science center within JILA) and Kenna Hughes-Castleberry (JILA's Science Communicator). All four panelists emphasized the need for confidence, self-care, and an empowering network for success.

Awards

JILA Fellow, NIST Physicist, and University of Colorado Physics professor Adam Kaufman and JILA Researcher Chen-Ting Liao both have been awarded a grants as part of the 2023 Young Investigator Research Program, or YIP. YIP was launched by the Air Force Office of Scientific Research, or AFOSR, the basic research arm of the Air Force Research Laboratory.

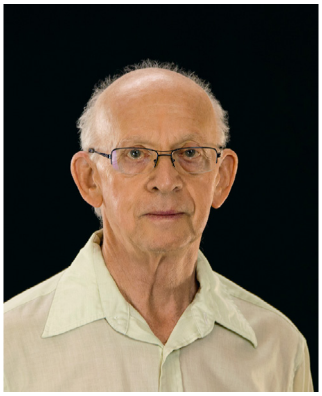
JILA and NIST Fellow as well as University of Colorado Boulder Professor Dr. Jun Ye has been awarded a 2022 Gold Medal from the U.S. Department of Commerce (DOC). The gold medal is the highest honorary award given by the DOC and "is granted by the Secretary for distinguished performance characterized by extraordinary, notable, or prestigious contributions that impact the mission of the Department and/or one or more operating units," according to the DOC.

JILA, NIST Fellow, and University of Colorado Boulder Professor Jun Ye has been appointed to the National Quantum Initiative Advisory Committee. In a recent announcement, President Biden advanced the National Quantum Initiative by appointing fifteen experts in quantum information science to the National Quantum Initiative Advisory Committee (NQIAC), with Ye being one of the members.

JILA graduate student Brendan McBennett has been announced as the 2023 recipient of the $10,000 Nick Cobb Memorial Scholarship by SPIE, the international society for optics and photonics, and Siemens EDA. McBennett was cited for this award "for his potential contributions to the field related to advanced lithography."

JILA Fellow Adjoint and the University of Colorado Boulder Astrophysical and Planetary Sciences professor Dr. Jeffrey Linksy has been selected as a Fellow for the American Astronomical Society (AAS). Linksy was cited for "decades of innovative studies of the heliosphere and the local interstellar medium; for his models of stellar chromospheres, for productive observing programs on multiple satellites and for establishing the deuterium-to-hydrogen ratio in the local disk, among other scientific contributions, and for his decades of service to the astronomical community."

Former JILA Ph.D. student Tobias Bothwell and former JILA postdoctoral researcher Colin Kennedy have been honored by NIST's (the National Institute of Standards and Technology) Physical Measurement Laboratory (PML) with the 2022 Distinguished Associate Awards.



Top: JILA Fellow Adjoint and University of Colorado Professor Dr. Jeffrey Linksy
Credit: JILA

University of Colorado Boulder

National Institute of Standards and Technology
U.S. Department of Commerce

About JILA

JILA was founded in 1962 as a joint institute of CU-Boulder and NIST. JILA is located at the base of the Rocky Mountains on the CU-Boulder campus in the Duane Physics complex.

JILA's faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey. JILA's CU members hold faculty appointments in the Departments of Physics; Astrophysical & Planetary Science; Chemistry; Biochemistry; and Molecular, Cellular, and Developmental Biology, as well as in the College of Engineering.

The wide-ranging interests of our scientists have made JILA one of the nation's leading research institutes in the physical sciences. They explore some of today's most challenging and fundamental scientific questions about quantum physics, the design of precision optical and x-ray lasers, the fundamental principles underlying the interaction of light and matter, and processes that have governed the evolution of the Universe for nearly 14 billion years. Research topics range from the small, frigid world governed by the laws of quantum mechanics through the physics of biological and chemical systems to the processes that shape the stars and galaxies. JILA science encompasses eight broad categories: Astrophysics, Atomic & Molecular Physics, Biophysics, Chemical Physics, Laser Physics, Nanoscience, Precision Measurement, and Quantum Information Science & Technology.

To learn more visit:
jila.colorado.edu