Hidden Spin for High-Temperature Superconductors

Now, researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) have unveiled a clue into the cuprates' unusual properties—and the answer lies within an unexpected source: the electron spin. [40]

This electronic super fluidity is a quantum state of matter, so it behaves in a very exotic way that is different from classical physics, Comin says. [39]

The Fermi-Hubbard model, which is believed to explain the basis for high-temperature superconductivity, is extremely simple to describe, and yet has so far proven impossible to solve, according to Zwierlein. [38]

Researchers at Karlsruhe Institute of Technology (KIT) have carried out high-resolution inelastic X-ray scattering and have found that high uniaxial pressure induces a long-range charge order competing with superconductivity. [37]

Scientists mapping out the quantum characteristics of superconductors—materials that conduct electricity with no energy loss—have entered a new regime. [36]

Now, in independent studies reported in Science and Nature, scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University report two important advances: They measured collective vibrations of electrons for the first time and showed how collective interactions of the electrons with other factors appear to boost superconductivity. [35]

At the Joint Quantum Institute (JQI), a group, led by Jimmy Williams, is working to develop new circuitry that could host such exotic states. [34]

The effect appears in compounds of lanthanum and hydrogen squeezed to extremely high pressures. [33]

University of Wisconsin-Madison engineers have added a new dimension to our understanding of why straining a particular group of materials, called Ruddlesden-Popper oxides, tampers with their superconducting properties. [32]

Nuclear techniques have played an important role in determining the crystal structure of a rare type of intermetallic alloy that exhibits superconductivity. [31]

A potential new state of matter is being reported in the journal Nature, with research showing that among superconducting materials in high magnetic fields, the phenomenon of electronic symmetry breaking is common. [30]

Researchers from the University of Geneva (UNIGE) in Switzerland and the Technical University Munich in Germany have lifted the veil on the electronic characteristics of high-temperature superconductors. Their research, published in Nature Communications, shows that the electronic densities measured in these superconductors are a combination of two separate effects. As a result, they propose a new model that suggests the existence of two coexisting states rather than competing ones postulated for the past thirty years, a small revolution in the world of superconductivity. [29]

A team led by scientists at the Department of Energy's SLAC National Accelerator Laboratory combined powerful magnetic pulses with some of the brightest X-rays on the planet to discover a surprising 3-D arrangement of a material's electrons that appears closely linked to a mysterious phenomenon known as high-temperature superconductivity. [28]

Advanced x-ray technique reveals surprising quantum excitations that persist through materials with or without superconductivity. [27]

This paper explains the magnetic effect of the superconductive current from the observed effects of the accelerating electrons, causing naturally the experienced changes of the electric field potential along the electric wire. The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories.

The changing acceleration of the electrons explains the created negative electric field of the magnetic induction, the Higgs Field, the changing Relativistic Mass and the Gravitational Force, giving a Unified Theory of the physical forces. Taking into account the Planck Distribution Law of the electromagnetic oscillators also, we can explain the electron/proton mass rate and the Weak and Strong Interactions.

Since the superconductivity is basically a quantum mechanical phenomenon and some entangled particles give this opportunity to specific matters, like Cooper Pairs or other entanglements, as strongly correlated materials and Exciton-mediated electron pairing, we can say that the secret of superconductivity is the quantum entanglement.

Contents

Author: George Rajna

The Quest of Superconductivity

Superconductivity seems to contradict the theory of accelerating charges in the static electric current, caused by the electric force as a result of the electric potential difference, since a closed circle wire no potential difference at all. [1]

On the other hand the electron in the atom also moving in a circle around the proton with a constant velocity and constant impulse momentum with a constant magnetic field. This gives the idea of the centripetal acceleration of the moving charge in the closed circle wire as this is the case in the atomic electron attracted by the proton. Because of this we can think about superconductivity as a quantum phenomenon. [2]

Experiences and Theories

Revealing hidden spin: Unlocking new paths toward high-temperature superconductors

In the 1980s, the discovery of high-temperature superconductors known as cuprates upended a widely held theory that superconductor materials carry electrical current without resistance only at very low temperatures of around 30 Kelvin (or minus 406 degrees Fahrenheit). For decades since, researchers have been mystified by the ability of some cuprates to superconduct at temperatures of more than 100 Kelvin (minus 280 degrees Fahrenheit).

Now, researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) have unveiled a clue into the cuprates' unusual properties—and the answer lies within an unexpected source: the electron spin. Their paper describing the research behind this discovery was published on Dec. 13 in the journal *Science*.

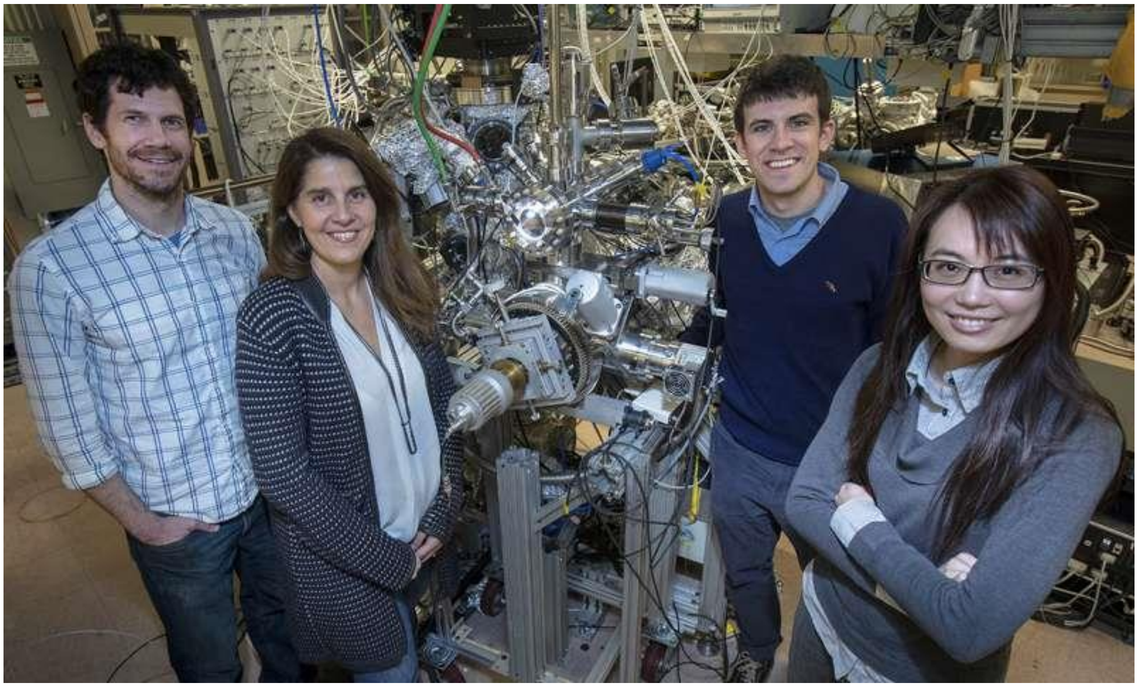
Adding electron spin to the equation

Every electron is like a tiny magnet that points in a certain direction. And electrons within most superconductor materials seem to follow their own inner compass. Rather than pointing in the same direction, their electron spins haphazardly point every which way—some up, some down, others left or right.

When scientists are developing new kinds of materials, they usually look at the materials' electron spin, or the direction in which the electrons are pointing. But when it comes to making superconductors, condensed matter physicists haven't traditionally focused on spin, because the conventionally held view was that all of the properties that make these materials unique were shaped only by the way in which two electrons interact with each other through what's known as "electron correlation."

But when a research team led by Alessandra Lanzara, a faculty scientist in Berkeley Lab's Materials Sciences Division and a Charles Kittel Professor of Physics at UC Berkeley, used a unique detector to measure samples of an exotic cuprate superconductor, Bi-2212 (bismuth strontium calcium copper oxide), with a powerful technique called SARPES (spin- and angle-resolved photoemission spectroscopy), they uncovered something that defied everything they had ever known about superconductors: a distinct pattern of electron spins within the material.

"In other words, we discovered that there was a well-defined direction in which each electron was pointing given its momentum, a property also known as spin-momentum locking," said Lanzara. "Finding it in high-temperature superconductors was a big surprise."



A research team led by Berkeley Lab's Alessandra Lanzara (second from left) used a SARPES (spin- and angle-resolved photoemission spectroscopy) detector to uncover a distinct pattern of electron spins within high-temperature cuprate …more

A new map for high-temperature superconductors

In the world of superconductors, "high temperature" means that the material can conduct electricity without resistance at temperatures higher than expected but still in extremely cold temperatures far below zero degrees Fahrenheit. That's because superconductors need to be extraordinarily cold to carry electricity without any resistance. At those low temperatures, electrons are able to move in sync with each other and not get knocked by jiggling atoms, causing electrical resistance.

And within this special class of high-temperature superconductor materials, cuprates are some of the best performers, leading some researchers to believe that they have potential use as a new material for building super-efficient electrical wires that can carry power without any loss of electron momentum, said co-lead author Kenneth Gotlieb, who was a Ph.D. student in Lanzara's lab at the time of the discovery. Understanding what makes some exotic cuprate superconductors such as Bi-2212 work at temperatures as high as 133 Kelvin (about -220 degrees Fahrenheit) could make it easier to realize a practical device.

Among the very exotic materials that condensed matter physicists study, there are two kinds of electron interactions that give rise to novel properties for new materials, including superconductors, said Gotlieb. Scientists who have been studying cuprate superconductors have focused on just one of those interactions: electron correlation.

The other kind of electron interaction found in exotic materials is "spin-orbit coupling—the way in which the electron's magnetic moment interacts with atoms in the material.

Spin-orbit coupling was often neglected in the studies of cuprate superconductors, because many assumed that this kind of electron interaction would be weak when compared to electron correlation, said co-lead author Chiu-Yun Lin, a researcher in the Lab's Materials Sciences Division and a Ph.D. student in the Department of Physics at UC Berkeley. So when they found the unusual spin pattern, Lin said that although they were pleasantly surprised by this initial finding, they still weren't sure whether it was a "true" intrinsic property of the Bi-2212 material, or an external effect caused by the way the laser light interacted with the material in the experiment.

Shining a light on electron spin with SARPES

Over the course of nearly three years, Gotlieb and Lin used the SARPES detector to thoroughly map out the spin pattern at Lanzara's lab. When they needed higher photon energies to excite a wider range of electrons within a sample, the researchers moved the detector next door to Berkeley Lab's synchrotron, the Advanced Light Source (ALS), a U.S. DOE Office of Science User Facility that specializes in lower energy, "soft" X-ray light for studying the properties of materials.

The SARPES detector was developed by Lanzara, along with co-authors Zahid Hussain, the former ALS Division Deputy, and Chris Jozwiak, an ALS staff scientist. The detector allowed the scientists to probe key electronic properties of the electrons such as valence band structure.

After tens of experiments at the ALS, where the team of researchers connected the SARPES detector to Beamline 10.0.1 so they could access this powerful light to explore the spin of the electrons moving with much higher momentum through the superconductor than those they could access in the lab, they found that Bi-2212's distinct spin pattern—called "nonzero spin—was a true result, inspiring them to ask even more questions. "There remains many unsolved questions in the field of high-temperature superconductivity," said Lin. "Our work provides new knowledge to better understand the cuprate superconductors, which can be a building block to resolve these questions."

Lanzara added that their discovery couldn't have happened without the collaborative "team science" of Berkeley Lab, a DOE national lab with historic ties to nearby UC Berkeley. "This work is a typical example of where science can go when people with expertise across the scientific disciplines come together, and how new instrumentation can push the boundaries of science," she said. [40]

Better superconductors from ceramic copper oxides

Medical magnetic resonance imaging, high-power microwave generators, superconducting magnetic energy storage units, and the solenoids in nuclear fusion reactors are very different technologies which all critically rely on the ability of superconducting materials to carry and store large electric currents in a compact space without overheating or dissipating large amounts of energy.

Despite their extraordinary properties, most superconducting materials present their own set of demands, such as the need to cool down to the temperature of liquid helium for medical MRIs. Still, superconductors are so efficient compared to everyday materials like copper that the cost of cooling them down with special cryogenic circuits is negligible compared to the energy saved from being converted—and ultimately wasted—in the form of heat, says Riccardo Comin, an assistant professor of physics.

"When you are trying to run a large current through a conventional circuit like one that's made of copper, there will be a lot of dissipation into heat because of the finite electrical resistance of the material," he says. "And that's energy that just goes lost. Because superconductors can support flow of electrons without dissipation that means that you can run very large currents, known as supercurrents, through a superconductor, without the superconductor heating up to high temperatures."

"You can inject a current in a superconductor and then just let it flow," Comin says. "Then, a superconductor can act basically like a battery, but instead of storing energy as a voltage difference, which is what you have in a lithium ion battery, you store energy in the form of a supercurrent. Then you can extract and use that current, and it's the same as pulling charge from a battery."

What sets a superconductor apart from a conventional conductor is that, in the latter, you have to apply a potential between two different points to run a current through, but in the former, you can just set in motion the current and then remove the voltage, leave the system as is, and there will be a persistent current flowing through the material.

Comin explains further: "You have initiated a motion, or flow, of electrons, that will persist forever, protected from dissipation by the laws of quantum mechanics. It's superfluid in the sense that the flow of electrons does not encounter resistance, or friction. Even if you remove the initial source that created that flow, it will continue unabated as in a frictionless electronic fluid."

This electronic super fluidity is a quantum state of matter, so it behaves in a very exotic way that is different from classical physics, Comin says. It is already being used in many high-power applications requiring large currents or large magnetic fields.

Because superconductors can sustain very large currents, they can store a lot of energy in a relatively small volume. But even superconducting materials cannot sustain limitless electrical currents, and they can lose their special properties above a critical current density, which is in excess of 10 mega-amperes per square centimeter for state-of-the-art superconducting cables. By comparison, copper can carry a maximum current density of 500 amperes per square centimeter, which is same as the current density passed through a 100-watt tungsten wire light bulb.

While these critical currents where superconductivity turns off are known, what happens at the nanoscale inside the material as its approaches that critical condition is still unknown, yet it might hold the key to engineer better superconducting cables and devices, with even higher resilience.

Comin was one of three MIT researchers to win a U.S. Air Force Young Investigator Research Program grant this fall. The three-year, $450,000 award will allow Comin to pursue research into what happens to one particular superconducting material, yttrium barium copper oxide (YBCO) when it is driven at large currents.

"Studying the electrical response of a superconductor as one drives a large current through it is essential for characterizing superconducting circuits, but there is a lot of microscopic information of what's happening inside the material that's left to reveal," he says. "The nanoscale physics of superconductors under operational conditions, namely when large currents are passed through them, is exactly what we're interested in elucidating."

"This is in a way a new direction where we're not just studying the material in its undisturbed state, let's say, just as a function of temperature, but without applying any sort of perturbation like a current or a field. Now we're moving into a direction where we're studying what happens in materials as they are driven at conditions of large currents, which are very close to those one would find inside a device or machine based on these superconducting circuits," Comin explains.

Unlike niobium-tin alloys that require liquid helium cooling (about 4 kelvins) in MRI machines, YBCO superconducts at the somewhat higher temperature of liquid nitrogen. This is significant because liquid nitrogen (about 77 kelvins, or -320.4 degrees Fahrenheit) is both more abundant and considerably cheaper to use than helium, Comin says.

But there is another price to pay. Compared to a conventional metal or conductor like copper, which is ductile and easily shaped, YBCO is a brittle ceramic that has to be cast in two-dimensional layers on a base similar to old-fashioned cassette recording tapes.

"It has a layered structure, so it forms two-dimensional atomic sheets that are weakly coupled between them, and it's very different from what a conventional metal would look like," Comin says. Comin will study the material in his lab at MIT as well as at National Laboratories while high current is applied to it around or even below liquid nitrogen temperatures.

Although superconductivity takes over at liquid nitrogen temperature, as the material is subjected to larger and larger electric fields, other electronic states, or phases, such as a charge density wave, begin to compete with superconductivity before it ceases.

"When you start to weaken superconductivity, other electronic phases start to wake up and they compete to take control over the material," he says. He plans to explore how the balance shifts between the superconducting phase and these other parasitic phases, as superconductivity weakens at high currents.

"Do these (other phases) start to take over or do they remain dormant?" Comin asks. "In one case, electrons want to flow without dissipation, and in the other case, they are stuck in place and cannot move around, like a car in a traffic jam."

Instead of being able to freely move like they do in a superconductor, without any dissipation, electrons in a charge density wave tend to sit in some regions and stay there.

"There are some regions that have more electrons, some other regions that have fewer electrons, so if you try to visualize the spatial organization of these electrons, you see that it sort of wiggles as a wave," Comin explains. "You can imagine a landscape of sand ripples on a dune. What drives the electrons to organize into a superfluid state rather than forming these static, wave-like patterns is not really known and it's what we hope to discover under those critical conditions where the superconductor starts to yield to these other competing tendencies."

The ultimate goal of this research effort is to elucidate how a persistent current, or supercurrent, flows around non-superconducting regions hosting competing phases, when the latter start to proliferate near critical conditions.

"In this project, supported by the Air Force Office for Scientific Research, we hope to gain new insights on the nanoscale physics of these superconducting devices, insights that could be transferred onto future superconductor technologies," Comin says. [39]

Atoms stand in for electrons in system for probing high-temperature superconductors

High-temperature superconductors have the potential to transform everything from electricity transmission and power generation to transportation.

The materials, in which electron pairs travel without friction—meaning no energy is lost as they move—could dramatically improve the energy efficiency of electrical systems.

Understanding how electrons move through these complex materials could ultimately help researchers design superconductors that operate at room temperature, dramatically expanding their use.

However, despite decades of research, little is known about the complex interplay between the spin and charge of electrons within superconducting materials such as cuprates, or materials containing copper.

Now, in a paper published today in the journal *Science*, researchers at MIT have unveiled a new system in which ultracold atoms are used as a model for electrons within superconducting materials.

The researchers, led by Martin Zwierlein, the Thomas A. Frank Professor of Physics at MIT, have used the system, which they describe as a "quantum emulator," to realize the Fermi-Hubbard model of particles interacting within a lattice.

The Fermi-Hubbard model, which is believed to explain the basis for high-temperature superconductivity, is extremely simple to describe, and yet has so far proven impossible to solve, according to Zwierlein.

"The model is just atoms or electrons hopping around on a lattice, and then, when they're on top of each other on the same lattice site, they can interact," he says. "But even though this is the simplest model of electrons interacting within these materials, there is no computer in the world that can solve it."

So instead, the researchers have built a physical emulator in which atoms act as stand-ins for the electrons.

To build their quantum emulator, the researchers used laser beams interfering with each other to produce a crystalline structure. They then confined around 400 atoms within this optical lattice, in a square box.

When they tilt the box by applying a magnetic field gradient, they are able to observe the atoms as they move, and measure their speed, giving them the conductivity of the material, Zwierlein says.

"It's a wonderful platform. We can look at every single atom individually as it moves around, which is unique; we cannot do that with electrons," he says. "With electrons you can only measure average quantities."

The emulator allows the researchers to measure the transport, or motion, of the atoms' spin, and how this is affected by the interaction between atoms within the material. Measuring the transport of spin has not been possible in cuprates until now, as efforts have been inhibited by impurities within the materials and other complications, Zwierlein says.

By measuring the motion of spin, the researchers were able to investigate how it differs from that of charge.

Since electrons carry both their charge and spin with them as they move through a material, the motion of the two properties should essentially be locked together, Zwierlein says.

However, the research demonstrates that this is not the case.

"We show that spins can diffuse much more slowly than charge in our system," he says.

The researchers then studied how the strength of the interactions between atoms affects how well spin can flow, according to MIT graduate student Matthew Nichols, the lead author of the paper.

"We found that large interactions can limit the available mechanisms which allow spins to move in the system, so that spin flow slows down significantly as the interactions between atoms increase," Nichols says.

When they compared their experimental measurements with state-of-the-art theoretical calculations performed on a classical computer, they found that the strong interactions present in the system made accurate numerical calculations very difficult.

"This demonstrated the strength of our ultracold atom system to simulate aspects of another quantum system, the cuprate materials, and to outperform what can be done with a classical computer," Nichols says.

Transport properties in strongly correlated materials are generally very hard to calculate using classical computers, and some of the most interesting, and practically relevant, materials like high-temperature superconductors are still poorly understood, says Zoran Hadzibabic, a professor of physics at Cambridge University, who was not involved in the research.

"(The researchers) study spin transport, which is not just hard to calculate, but also even experimentally extremely hard to study in conventional strongly-correlated materials, and thus provide a unique insight into the differences between charge and spin transport," Hadzibabic says.

Complementary to MIT's work on spin transport, the transport of charge was measured by Professor Waseem Bakr's group at Princeton University, elucidating in the same issue of *Science* how charge conductivity depends on temperature.

The MIT team hopes to carry out further experiments using the quantum emulator. For example, since the system allows the researchers to study the movement of individual atoms, they hope to investigate how the motion of each differs from that of the average, to study current "noise" on the atomic level.

"So far we have measured the average current, but what we would also like to do is look at the noise of the particles' motion; some are a little bit faster than others, so there is a whole distribution that we can learn about," Zwierlein says.

The researchers also hope to study how transport changes with dimensionality by going from a two-dimensional sheet of atoms to a one-dimensional wire. [38]

Researchers examine competing states in high-temperature superconductors

High-temperature superconductors can transport electrical energy without resistance. Researchers at Karlsruhe Institute of Technology (KIT) have carried out high-resolution inelastic X-ray scattering and have found that high uniaxial pressure induces a long-range charge order competing with superconductivity. Their study opens up new insights into the behavior of correlated electrons. The study is published in *Science*.

Superconductors transport current without losses, but only below a certain critical temperature. Conventional superconductors need to be cooled down almost to absolute zero, and even the so-called high-temperature superconductors require temperatures of around -200 degrees Celsius to transport current without resistance. Despite this, superconductors are already in widespread use. To develop superconductors that work at even higher temperatures—possibly up to room temperature—and therefore significantly contribute to an efficient energy supply, electronic states and processes involved in the formation of the superconducting condensate need to be understood at a fundamental level.

Researchers led by Professor Matthieu Le Tacon, director of the Institute of Solid-State Physics (IFP) at KIT, have now made a significant step forward. They have shown that high uniaxial pressure can be used to tune the competing states in a high-temperature superconductor. Using high-resolution inelastic X-ray scattering, the scientists examined a high-temperature cuprate superconductor, $YBa_2Cu_3O_{6.67}$. In this complex compound, copper and oxygen atoms form two-dimensional structures. Changing the charge carrier concentration in these planes yields a variety of electronic phases including superconductivity and charge orders.

In the charge ordered state, the electrons 'crystallize' into stripe-shaped nanostructures. This electronic state is usually observed in these materials when superconductivity is suppressed using very large magnetic fields, making it hard to investigate using conventional spectroscopic tools.

Inducing this state in $YBa_2Cu_3O_{6.67}$ using uniaxial pressure instead of magnetic fields allowed the researchers to study its relationship to superconductivity using X-ray scattering. They identified strong anomalies of the lattice excitation connected to the formation of the charge order. "Our results provide new insights into the behavior of electrons in correlated electron materials and into the mechanisms yielding to high-temperature superconductivity," says Professor Matthieu Le Tacon from KIT. "They also show that uniaxial pressure has the potential to control the order of the electrons in such materials." [37]

Scientists enter unexplored territory in superconductivity search

Scientists mapping out the quantum characteristics of superconductors—materials that conduct electricity with no energy loss—have entered a new regime. Using newly connected tools named OASIS at the U.S. Department of Energy's Brookhaven National Laboratory, they've uncovered previously inaccessible details of the "phase diagram" of one of the most commonly studied "high-temperature" superconductors. The newly mapped data includes signals of what happens when superconductivity vanishes.

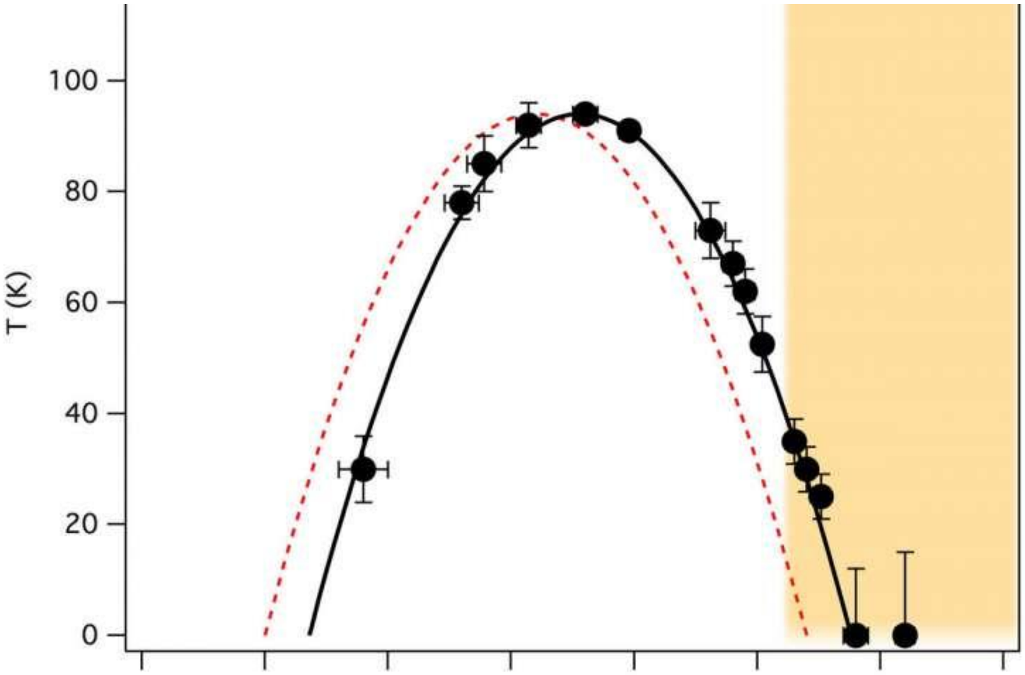
"In terms of superconductivity, this may sound bad, but if you study some phenomenon, it is always good to be able to approach it from its origin," said Brookhaven physicist Tonica Valla, who led the study just published in the journal *Nature Communications*. "If you have a chance to see how superconductivity disappears, that in turn might give insight into what causes superconductivity in the first place."

Unlocking the secrets of superconductivity holds great promise in addressing energy challenges. Materials able to carry current over long distances with no loss would revolutionize power transmission, eliminate the need for cooling computer-packed data centers, and lead to new forms of energy storage, for example. The hitch is that, at present, most known superconductors, even the "high-temperature" varieties, must themselves be kept super cold to perform their current-carrying magic. So, scientists have been trying to understand the key characteristics that cause superconductivity in these materials with the goal of discovering or creating new materials that can operate at temperatures more practical for these everyday applications.

The Brookhaven team was studying a well-known high-temperature superconductor made of layers that include bismuth-oxide, strontium-oxide, calcium, and copper-oxide (abbreviated as BSCCO). Cleaving crystals of this material creates pristine bismuth-oxide surfaces. When they analyzed the electronic structure of the pristine cleaved surface, they saw telltale signs of superconductivity at a transition temperature (Tc) of 94 Kelvin (-179 degrees Celsius)—the highest temperature at which superconductivity sets in for this well-studied material.

The team then heated samples in ozone (O3) and found that they could achieve high doping levels and explore previously unexplored portions of this material's phase diagram, which is a map-like graph showing how the material changes its properties at different temperatures under different conditions (similar to the way you can map out the temperature and pressure coordinates at which liquid water freezes when it is cooled, or changes to steam when heated). In this case, the variable the scientists were interested in was how many charge vacancies, or "holes," were added, or "doped" into the material by the exposure to ozone. Holes facilitate the flow of current by giving the charges (electrons) somewhere to go.

"For this material, if you start with the crystal of 'parent' compound, which is an insulator (meaning no conductivity), the introduction of holes results in superconductivity," Valla said. As more holes are added, the superconductivity gets stronger and at higher temperatures up to a maximum at 94 Kelvin, he explained. "Then, with more holes, the material becomes 'over-doped,' and Tc goes down—for this material, to 50 K.

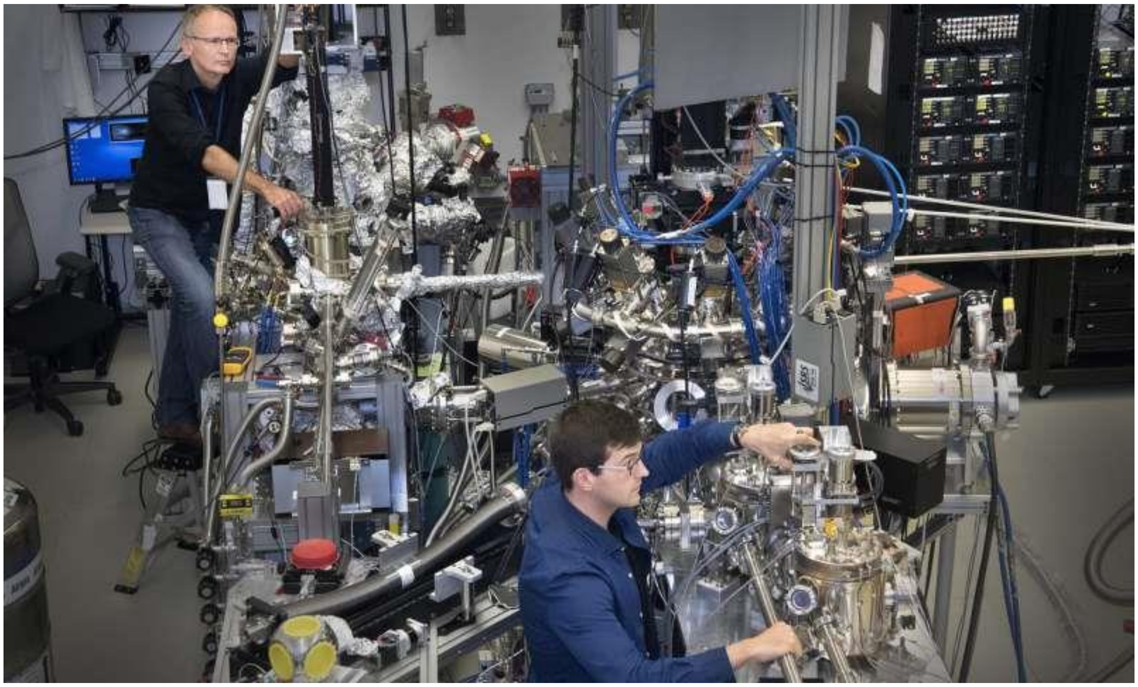


This phase diagram for BSCCO plots the temperature (T, in degrees Kelvin, on the y axis) at which superconductivity sets in as more and more charge vacancies, or "holes," are doped into the material (horizontal, x axis). On the underdoped …more"Until this study, nothing past that point was known because we couldn't get crystals doped above that level. But our new data takes us to a point of doping way beyond the previous limit, to a point where Tc is not measurable."

Said Valla, "That means we can now explore the entire dome-shaped curve of superconductivity in this material, which is something that nobody has been able to do before."

The team created samples heated in a vacuum (to produce underdoped material) and in ozone (to make overdoped samples) and plotted points along the entire superconducting dome. They discovered some interesting characteristics in the previously unexplored "far side" of the phase diagram.

"What we saw is that things become much simpler," Valla said. Some of the quirkier characteristics that exist on the well-explored side of the map and complicate scientists' understanding of high-temperature superconductivity—things like a "pseudogap" in the electronic signature, and variations in particle spin and charge densities—disappear on the overdoped far side of the dome.



Brookhaven Lab physicists Tonica Valla and Ilya Drozdov in the OASIS laboratory at Brookhaven National Laboratory. Credit: Brookhaven National Laboratory"This side of the phase diagram is somewhat like what we expect to see in more conventional superconductivity," Valla said, referring to the oldest known metal-based superconductors.

"When superconductivity is free of these other things that complicate the picture, then what is left is superconductivity that perhaps is not that unconventional," he added. "We still might not know its origin, but on this side of the phase diagram, it looks like something that theory can handle more easily, and it gives you a simpler way of looking at the problem to try to understand what is going on." [36]

Scientists make first detailed measurements of key factors related to high-temperature superconductivity

In superconducting materials, electrons pair up and condense into a quantum state that carries electrical current with no loss. This usually happens at very low temperatures. Scientists have mounted an all-out effort to develop new types of superconductors that work at close to room temperature, which would save huge amounts of energy and open a new route for designing quantum electronics. To get there, they need to figure out what triggers this high-temperature form of superconductivity and how to make it happen on demand.

Now, in independent studies reported in *Science* and *Nature*, scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University report two important advances: They measured collective vibrations of electrons for the first time and showed how collective interactions of the electrons with other factors appear to boost superconductivity.

Carried out with different copper-based materials and with different cutting-edge techniques, the experiments lay out new approaches for investigating how unconventional superconductors operate.

"Basically, what we're trying to do is understand what makes a good superconductor," said co-author Thomas Devereaux, a professor at SLAC and Stanford and director of SIMES, the Stanford Institute for Materials and Energy Sciences, whose investigators led both studies.

"What are the ingredients that could give rise to superconductivity at temperatures well above what they are today?" he said. "These and other recent studies indicate that the atomic lattice plays an important role, giving us hope that we are gaining ground in answering that question."

The high-temperature puzzle

Conventional superconductors were discovered in 1911, and scientists know how they work: Free-floating electrons are attracted to a material's lattice of atoms, which has a positive charge, in a way that lets them pair up and flow as electric current with 100 percent efficiency. Today, superconducting technology is used in MRI machines, maglev trains and particle accelerators.

But these superconductors work only when chilled to temperatures as cold as outer space. So when scientists discovered in 1986 that a family of copper-based materials known as cuprates can superconduct at much higher, although still quite chilly, temperatures, they were elated.

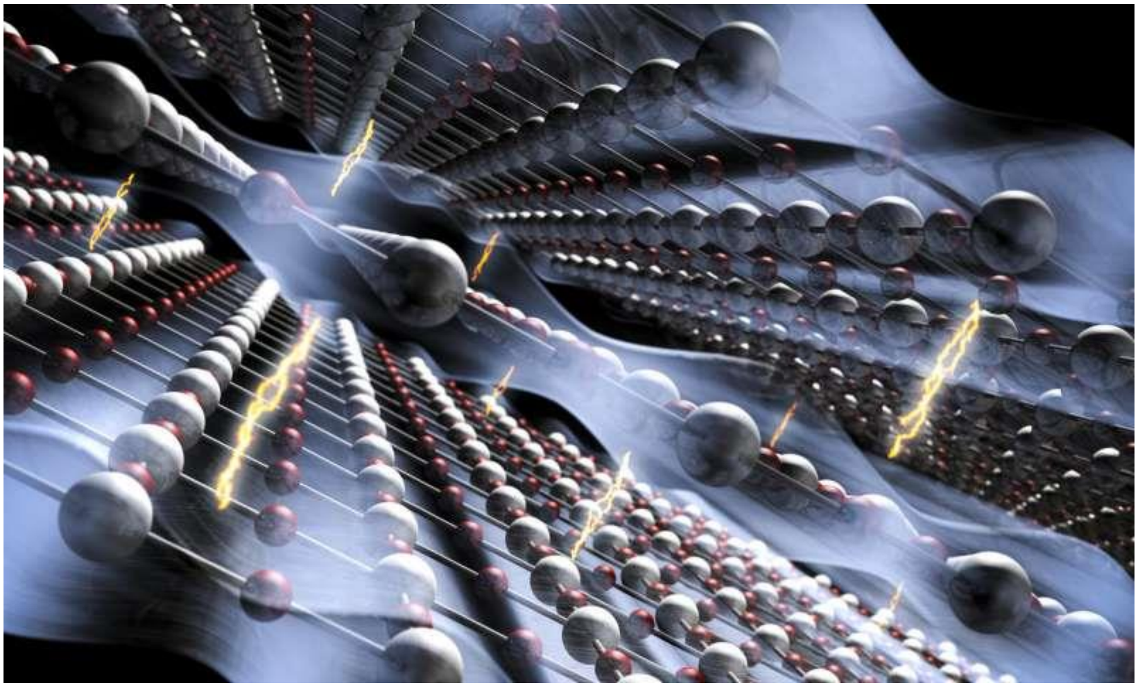
The operating temperature of cuprates has been inching up ever since – the current record is about 120 degrees Celsius below the freezing point of water – as scientists explore a number of factors that could either boost or interfere with their superconductivity. But there's still no consensus about how the cuprates function.

"The key question is how can we make all these electrons, which very much behave as individuals and do not want to cooperate with others, condense into a collective state where all the parties participate and give rise to this remarkable collective behavior?" said Zhi-Xun Shen, a SLAC/Stanford professor and SIMES investigator who participated in both studies.

Behind-the-scenes boost

One of the new studies, at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL), took a systematic look at how "doping" – adding a chemical that changes the density of electrons in a material – affects the superconductivity and other properties of a cuprate called Bi2212.

Collaborating researchers at the National Institute of Advanced Industrial Science and Technology (AIST) in Japan prepared samples of the material with slightly different levels of doping. Then a team led by SIMES researcher Yu He and SSRL staff scientist Makoto Hashimoto examined the samples at SSRL with angle-resolved photoemission spectroscopy, or ARPES. It uses a powerful beam of X-ray light to kick individual electrons out of a sample material so their momentum and energy can be measured. This reveals what the electrons in the material are doing.



An illustration depicts the repulsive energy (yellow flashes) generated by electrons in one layer of a cuprate material repelling electrons in the next layer. Theorists think this energy could play a critical role in creating the …more

In this case, as the level of doping increased, the maximum superconducting temperature of the material peaked and fell off again, He said.

The team focused in on samples with particularly robust superconducting properties. They discovered that three interwoven effects – interactions of electrons with each other, with lattice vibrations and with superconductivity itself – reinforce each other in a positive feedback loop when conditions are right, boosting superconductivity and raising the superconducting temperature of the material.

Small changes in doping produced big changes in superconductivity and in the electrons' interaction with lattice vibrations, Devereaux said. The next step is to figure out why this particular level of doping is so important.

"One popular theory has been that rather than the atomic lattice being the source of the electron pairing, as in conventional superconductors, the electrons in high-temperature superconductors form some kind of conspiracy by themselves. This is called electronic correlation," Yu He said. "For instance, if you had a room full of electrons, they would spread out. But if some of them demand more individual space, others will have to squeeze closer to accommodate them."

In this study, He said, "What we find is that the lattice has a behind-the-scenes role after all, and we may have overlooked an important ingredient for high-temperature superconductivity for the past three decades," a conclusion that ties into the results of earlier research by the SIMES group.

Electron 'Sound Waves'

The other study, performed at the European Synchrotron Radiation Facility (ESRF) in France, used a technique called resonant inelastic X-ray scattering, or RIXS, to observe the collective behavior of electrons in layered cuprates known as LCCO and NCCO.

RIXS excites electrons deep inside atoms with X-rays, and then measures the light they give off as they settle back down into their original spots.

In the past, most studies have focused only on the behavior of electrons within a single layer of cuprate material, where electrons are known to be much more mobile than they are between layers, said SIMES staff scientist Wei-Sheng Lee. He led the study with Matthias Hepting, who is now at the Max Planck Institute for Solid State Research in Germany.

But in this case, the team wanted to test an idea raised by theorists – that the energy generated by electrons in one layer repelling electrons in the next one plays a critical role in forming the superconducting state.

When excited by light, this repulsion energy leads electrons to form a distinctive sound wave known as an acoustic plasmon, which theorists predict could account for as much as 20 percent of the increase in superconducting temperature seen in cuprates.

With the latest in RIXS technology, the SIMES team was able to observe and measure those acoustic plasmons.

"Here we see for the first time how acoustic plasmons propagate through the whole lattice," Lee said. "While this doesn't settle the question of where the energy needed to form the superconducting state comes from, it does tell us that the layered structure itself affects how the electrons behave in a very profound way."

This observation sets the stage for future studies that manipulate the sound waves with light, for instance, in a way that enhances superconductivity, Lee said. The results are also relevant for developing future plasmonic technology, he said, with a range of applications from sensors to photonic and electronic devices for communications. [35]

Modified superconductor synapse reveals exotic electron behavior

Electrons tend to avoid one another as they go about their business carrying current. But certain devices, cooled to near zero temperature, can coax these loner particles out of their shells. In extreme cases, electrons will interact in unusual ways, causing strange quantum entities to emerge.

At the Joint Quantum Institute (JQI), a group, led by Jimmy Williams, is working to develop new circuitry that could host such exotic states. "In our lab, we want to combine materials in just the right way so that suddenly, the electrons don't really act like electrons at all," says Williams, a JQI Fellow and an assistant professor in the University of Maryland Department of Physics. "Instead the surface electrons move together to reveal interesting quantum states that collectively can behave like new particles."

These states have a feature that may make them useful in future quantum computers: They appear to be inherently protected from the destructive but unavoidable imperfections found in fabricated circuits. As described recently in *Physical Review Letters*, Williams and his team have reconfigured one workhorse superconductor circuit—a Josephson junction—to include a material suspected of hosting quantum states with boosted immunity.

Josephson junctions are electrical synapses comprised of two superconductors separated by a thin strip of a second material. The electron movement across the strip, which is usually made from an insulator, is sensitive to the underlying material characteristics as well as the surroundings. Scientists can use this sensitivity to detect faint signals, such as tiny magnetic fields. In this new study, the researchers replaced the insulator with a sliver of topological crystalline insulator (TCI) and detected signs of exotic quantum states lurking on the circuit's surface.

Physics graduate student Rodney Snyder, lead author on the new study, says this area of research is full of unanswered questions, down to the actual process for integrating these materials into circuits. In the case of this new device, the research team found that beyond the normal level of sophisticated material science, they needed a bit of luck.

"I'd make like 16 to 25 circuits at a time. Then, we checked a bunch of those and they would all fail, meaning they wouldn't even act like a basic Josephson junction," says Snyder. "We eventually found that the way to make them work was to heat the sample during the fabrication process. And we only discovered this critical heating step because one batch was accidentally heated on a fluke, basically when the system was broken."

Once they overcame the technical challenges, the team went hunting for the strange quantum states. They examined the current through the TCI region and saw dramatic differences when compared to an ordinary insulator. In conventional junctions, the electrons are like cars haphazardly trying to cross a single lane bridge. The TCI appeared to organize the transit by opening up directional traffic lanes between the two locations.

The experiments also indicated that the lanes were helical, meaning that the electron's quantum spin, which can be oriented either up or down, sets its travel direction. So in the TCI strip, up and down spins move in opposite directions. This is analogous to a bridge that restricts traffic according to vehicle colors—blue cars drive east and red cars head west. These kinds of lanes, when present, are indicative of exotic electron behaviors.

Just as the careful design of a bridge ensures safe passage, the TCI structure played a crucial role in electron transit. Here, the material's symmetry, a property that is determined by the underlying atom arrangement, guaranteed that the two-way traffic lanes stayed open. "The symmetry acts like a bodyguard for the surface states, meaning that the crystal can have imperfections and still the quantum states survive, as long as the overall symmetry doesn't change," says Williams.

Physicists at JQI and elsewhere have previously proposed that built-in bodyguards could shield delicate quantum information. According to Williams, implementing such protections would be a significant step forward for quantum circuits, which are susceptible to failure due to environmental interference.

In recent years, physicists have uncovered many promising materials with protected travel lanes, and researchers have begun to implement some of the theoretical proposals. TCIs are an appealing option because, unlike more conventional topological insulators where the travel lanes are often given by nature, these materials allow for some lane customization. Currently, Williams is working with materials scientists at the Army Research Laboratory to tailor the travel lanes during the manufacturing process. This may enable researchers to position and manipulate the quantum states, a step that would be necessary for building a quantum computer based on topological materials.

In addition to quantum computing, Williams is driven by the exploration of basic physics questions. "We really don't know yet what kind of quantum matter you get from collections of these more exotic states," Williams says. "And I think, quantum computation aside, there is a lot of interesting physics happening when you are dealing with these oddball states." [34]

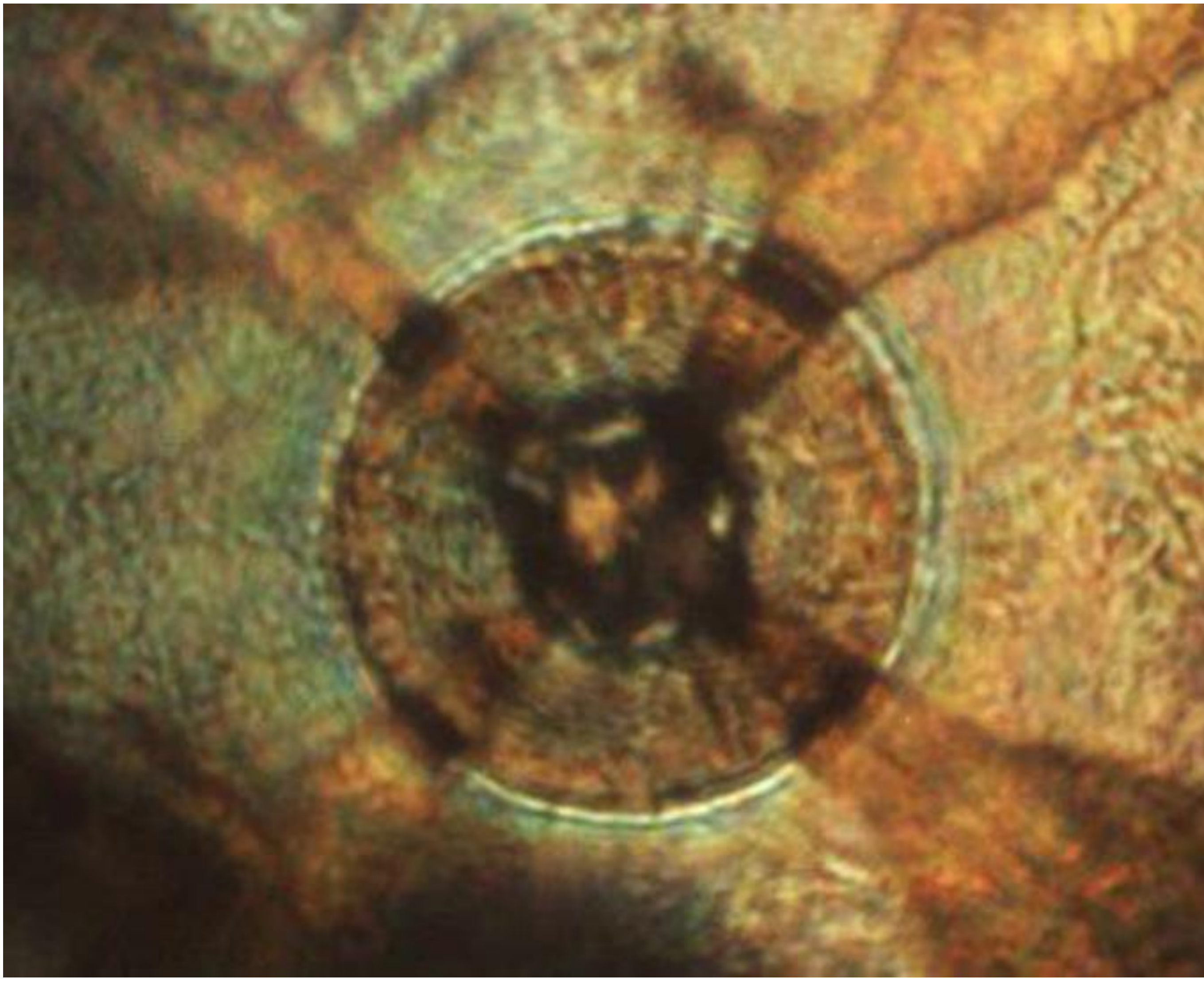
A new hydrogen-rich compound may be a record-breaking superconductor

Superconductors are heating up, and a world record-holder may have just been dethroned.

Two studies report evidence of superconductivity — the transmission of electricity without resistance — at temperatures higher than seen before. The effect appears in compounds of lanthanum and hydrogen squeezed to extremely high pressures.

All known superconductors must be chilled to function, which makes them difficult to use in real-world applications. If scientists found a superconductor that worked at room temperature, the material could be integrated into electronic devices and transmission wires, potentially saving vast amounts of energy currently lost to electrical resistance. So scientists are constantly on the lookout for higher-temperature superconductors. The current record-holder, hydrogen sulfide, which also must be compressed, works below 203 kelvins, or about −70° Celsius (*SN: 12/26/15, p. 25*).

The new evidence for superconductivity is based on a dramatic drop in the resistance of the lanthanum-hydrogen compounds when cooled below a certain temperature. One team of physicists found that their compound’s resistance plummeted at a temperature of 260 kelvins (−13° C), the temperature of a very cold winter day. The purported superconductivity occurred when the material had been crushed with almost 2 million times the pressure of Earth’s atmosphere by squeezing it between two diamonds. Some samples even showed signs of superconductivity at higher temperatures, up to 280 kelvins (about 7° C), physicist Russell Hemley of George Washington University in Washington, D.C., and colleagues report in a study posted online August 23 at arXiv.org. Hemley first reported signs of the compound’s superconductivity in May in Madrid at a symposium on superconductivity and pressure.



TAKE THE PRESSURE When crushed between two diamonds and cooled, a purported superconductor (shown here in a view through the diamonds) appears.

A.P. DROZDOV *ET AL*/ARXIV.ORG 2018

Another group found evidence of superconductivity in a lanthanum-hydrogen compound under chillier, but still record-breaking, conditions. The researchers crushed lanthanum and hydrogen in a diamond press to about 1.5 million times Earth's atmospheric pressure. When cooled to about 215 kelvins (−58° C), the compound's resistance falls sharply, physicist Mikhail Eremets of the Max Planck Institute for Chemistry in Mainz and colleagues report in a paper posted online August 21 at arXiv.org.

It's not clear what the exact structures of the chemical compounds are and whether the two groups are studying identical materials. Differences between the two teams' samples might explain the temperature discrepancy. By scattering X-rays from the compound, Hemley and colleagues showed that the material's structure was consistent with LaH_{10}, which contains 10 hydrogen atoms for every lanthanum atom. Hemley's team had previously predicted that LaH_{10} would be superconducting at a relatively high temperature.

The results are "very exciting," says theoretical chemist Eva Zurek of the University at Buffalo in New York. However, the studies are not conclusive: They have not been peer reviewed and do not yet show an essential hallmark of superconductivity called the Meissner effect, in which magnetic fields are expelled from the superconducting material (*SN: 8/8/15*, *p. 12*). But the results agree with the previous theoretical predictions made by Hemley and colleagues. So, Zurek says, "I would hope and suspect that this is indeed … correct."

The researchers are now working on bolstering their evidence for superconductivity. "Both groups should make more efforts to convince people," Eremets says.

The requirement of ultrahigh pressures makes the materials unlikely to be useful for applications, but better understanding of high-temperature superconductivity could lead scientists to other, more practical superconductors.

The potential new superconductor and the previous record-holder are both chock-full of hydrogen. Scientists are looking for superconductivity in such hydrogen-rich materials based on the prediction that pure hydrogen, when squeezed to immensely high pressures, will become a metal that is superconducting at room temperature (*SN: 8/20/16*, *p. 18*). But metallic hydrogen has proven difficult to produce, requiring pressures even higher than those needed for hydrogen-rich compounds. So scientists are looking for superconductivity in hydrogen-mimicking compounds that are easier to create.

"The picture is very bright for looking at more and more of these materials and finding these astonishingly high superconducting transition temperatures," Hemley says. [33]

Strained materials make cooler superconductors

University of Wisconsin-Madison engineers have added a new dimension to our understanding of why straining a particular group of materials, called Ruddlesden-Popper oxides, tampers with their superconducting properties.

The findings, published in the journal *Nature Communications*, could help pave the way toward new advanced electronics.

"Strain is one of the knobs we can turn to create materials with desirable properties, so it is important to learn to manipulate its effects," says Dane Morgan, the Harvey D. Spangler Professor of materials science and engineering at UW-Madison and a senior author on the paper. "These findings might also help explain some puzzling results in strained materials."

Superconducting materials could make the nation's power grid much more efficient, thanks to their ability to conduct electricity with zero resistance. The substances also enable MRI machines to see inside patients' bodies and levitate bullet trains above the tracks because of the Meissner effect.

"This work is a good example of how basic research can influence developing transformative technologies through systematic understanding of material behaviors by close interaction between theory and experiment," says Ho Nyung Lee, a distinguished scientist at the Department of Energy's Oak Ridge National Laboratory who led the research.

Most materials only become superconductors when they are very cold—below a specific point called the critical temperature. For superconductors composed of thin films of the Ruddlesden-Popper material La1.85Sr0.15CuO4, that critical temperature varies substantially depending on the conditions under which the films were grown.

"The prevailing opinion has been that strain makes it thermodynamically easier for oxygen defects that destroy the superconducting properties to form in the material, but we have shown that differences in the kinetic time scales of oxygen-defect formation between tensile and compressive strain is a key mechanism," says Ryan Jacobs, a staff scientist in Morgan's laboratory and a co-first author on the paper.

Oxygen defects are important because the amount of oxygen contained within a material can alter its critical temperature. The most obvious idea was that strain might impact properties by adjusting how much energy is needed for oxygen defects to appear.

While this effect does occur, Jacobs and colleagues at Oak Ridge National Laboratory demonstrated that strain doesn't just affect how easily defects form, but also the rate at which oxygen moves in and out of the material. These results suggest that some of the most important strain responses may be a result of changes in kinetic effects.

"Recognizing that kinetics plays a key role is very important for how you create the material," says Morgan.

The scientists created the materials they studied by growing crystalline thin films on top of two different supporting surfaces—one compressed the resulting thin films while the other stretched them out to cause tensile strain.

Strikingly, the tensile-strained materials needed much colder temperatures than the compressed films to become superconductors. Additionally, tensile strain caused the materials to lose their superconducting properties more quickly than the compressed materials.

After extensive calculations, the scientists concluded that thermodynamic effects (via the defect formation energy) alone couldn't explain the dramatic results they observed. By applying their expertise in computational simulation and the computational modeling method known as density functional theory, the researchers narrowed in on kinetics as playing a dominant role.

"This is the first window on strain altering how oxygen moves in and out of these materials," says Morgan.

Currently, the researchers are exploring other methods to optimize Ruddlesden-Popper oxides for possible use in superconducting-based devices, fuel cells, oxygen sensors and electronic devices such as memristors. They are also investigating how the findings might be applied to a closely related group of materials called perovskites, which are an active research area for the Morgan group.

The paper was also featured as a *Nature Communications* Editor's Highlight. [32]

Nuclear techniques unlock the structure of a rare type of superconducting intermetallic alloy

Nuclear techniques have played an important role in determining the crystal structure of a rare type of intermetallic alloy that exhibits superconductivity.

The research, which was recently published in the *Accounts of Chemical Research*, was a undertaking led by researchers from the Max Planck Institute for Chemical Physics of Solids, with the collaboration of the Ivan-Franko National University of Lviv, the Technical University Freiberg, the Helmholtz-Zentrum Dresden-Rossendorf, and ANSTO.

Complex metallic alloys (CMAs) have the potential to act as catalysts and serve as materials for devices that covert heat into energy (thermoelectric generators) or use magnetic refrigeration to improve the energy efficiency of cooling and temperature control systems.

Thermoelectric generators are used for low power remote applications or where bulkier but more efficient heat engines would not be possible.

The unique properties of CMAs stem from their intricate superstructure, with each repeating unit cell comprising hundreds or thousands of atoms.

The study focused on a phase of beryllium and platinum, Be21Pt5. The low X-ray scattering power of beryllium atoms had previously posed a barrier to researchers attempting to resolve the structure of beryllium-rich CMAs, such as Be21Pt5, by using X-ray powder diffraction techniques.

To locate the beryllium atoms, researchers used the ECHIDNA neutron powder diffractometer at the Australian Centre for Neutron Scattering.

Dr. Maxim Avdeev, an instrument scientist, noted that the use of neutron beams in combination with X-ray data was key to solving the structure.

"Since beryllium is a light element, it will scatter neutrons further than X-rays by a factor of approximately 20. It was not possible to locate the beryllium atoms in the crystal using X-rays, but with neutron diffraction we found them easily."

"Since beryllium is a light element, it scatters X-rays weakly. Compared to platinum, the contrast is about 1-to-20. Using neutrons changes the ratio to approximately 16-to-20 which allowed to find beryllium atoms in the crystal structure easily."

Data from X-ray and neutron powder diffraction was complemented with quantum mechanical calculations to determine electron density distribution which defines electronic properties of the material.

The diffraction data indicated that the crystal structure of Be21Pt5 was built up from four types of nested polyhedral units or clusters. Each cluster contained four shells comprising 26 atoms with a unique distribution of defects, places where an atom is missing or irregularly placed in the lattice structure.

Neutron diffraction experiments at ANSTO helped determine the crystal structure determine the structure of Be21Pt5, which consisted of four unique clusters (colour-coded above in image), each containing 26 atoms.

The collaborative nature of the study was also pivotal to solving the structure.

"The physical sample was synthesised in Germany and sent to Australia for analysis. Once we sent the diffraction data back to our collaborators, they were able to solve the structure at their home institutions."

Having resolved the crystal structure, the research team also turned their attention to the physical properties of Be21Pt5 and made an unexpected discovery. At temperatures below 2 K, Be21Pt5 was found to exhibit superconductivity.

"It's quite unusual case for this family of intermetallic compounds to undergo a superconducting phase. Further studies are necessary to understand what makes this system special and neutron scattering experiments will play an important role in the process." [31]

Superconductivity research reveals potential new state of matter

A potential new state of matter is being reported in the journal Nature, with research showing that among superconducting materials in high magnetic fields, the phenomenon of electronic symmetry breaking is common. The ability to find similarities and differences among classes of materials with phenomena such as this helps researchers establish the essential ingredients that cause novel functionalities such as superconductivity.

The high-magnetic-field state of the heavy fermion superconductor CeRhIn5 revealed a so-called electronic nematic state, in which the material's electrons aligned in a way to reduce the symmetry of the original crystal, something that now appears to be universal among unconventional superconductors. Unconventional superconductivity develops near a phase boundary separating magnetically ordered and magnetically disordered phases of a material.

"The appearance of the electronic alignment, called nematic behavior, in a prototypical heavyfermion superconductor highlights the interrelation of nematicity and unconventional superconductivity, suggesting nematicity to be common among correlated superconducting materials," said Filip Ronning of Los Alamos National Laboratory, lead author on the paper. Heavy fermions are intermetallic compounds, containing rare earth or actinide elements.

"These heavy fermion materials have a different hierarchy of energy scales than is found in transition metal and organic materials, but they often have similar complex and intertwined physics coupling spin, charge and lattice degrees of freedom," he said.

The work was reported in Nature by staff from the Los Alamos Condensed Matter and Magnet Science group and collaborators.

Using transport measurements near the field-tuned quantum critical point of CeRhIn5 at 50 Tesla, the researchers observed a fluctuating nematic-like state. A nematic state is most well known in liquid crystals, wherein the molecules of the liquid are parallel but not arranged in a periodic array. Nematic-like states have been observed in transition metal systems near magnetic and superconducting phase transitions. The occurrence of this property points to nematicity's correlation with unconventional superconductivity. The difference, however, of the new nematic state found in CeRhIn5 relative to other systems is that it can be easily rotated by the magnetic field direction.

The use of the National High Magnetic Field Laboratory's pulsed field magnet facility at Los Alamos was essential, Ronning noted, due to the large magnetic fields required to access this state. In addition, another essential contribution was the fabrication of micron-sized devices using focused ion-beam milling performed in Germany, which enabled the transport measurements in large magnetic fields.

Superconductivity is extensively used in magnetic resonance imaging (MRI) and in particle accelerators, magnetic fusion devices, and RF and microwave filters, among other uses. [30]

Superconductivity seen in a new light

Superconducting materials have the characteristic of letting an electric current flow without resistance. The study of superconductors with a high critical temperature discovered in the 1980s remains a very attractive research subject for physicists. Indeed, many experimental observations still lack an adequate theoretical description. Researchers from the University of Geneva (UNIGE) in Switzerland and the Technical University Munich in Germany have lifted the veil on the electronic characteristics of high-temperature superconductors. Their research, published in Nature Communications, shows that the electronic densities measured in these superconductors are a combination of two separate effects. As a result, they propose a new model that suggests the existence of two coexisting states rather than competing ones postulated for the past thirty years, a small revolution in the world of superconductivity.

Below a certain temperature, a superconducting material loses all electrical resistance (equal to zero). When immersed in a magnetic field, high-temperature superconductors (high-Tc) allow this field to penetrate in the form of filamentary regions, called vortices, a condition in which the material is no longer superconducting. Each vortex is a whirl of electronic currents generating their own magnetic fields and in which the electronic structure is different from the rest of the material.

Coexistence rather than competition

Some theoretical models describe high-Tc superconductors as a competition between two fundamental states, each developing its own spectral signature. The first is characterized by an ordered spatial arrangement of electrons. The second, corresponding to the superconducting phase, is characterized by electrons assembled in pairs.

"However, by measuring the density of electronic states with local tunneling spectroscopy, we discovered that the spectra that were attributed solely to the core of a vortex, where the material is not in the superconducting state, are also present elsewhere—that is to say, in areas where the superconducting state exists. This implies that these spectroscopic signatures do not originate in the vortex cores and cannot be in competition with the superconducting state," explains Christoph Renner, professor in the Department of Quantum Matter Physics of the Faculty of Science at UNIGE. "This study therefore questions the view that these two states are in competition, as largely assumed until now. Instead, they turn out to be two coexisting states that together contribute to the measured spectra," professor Renner says. Indeed, physicists from UNIGE using theoretical simulation tools have shown that the experimental spectra can be reproduced perfectly by considering the superposition of the spectroscopic signature of a superconductor and this other electronic signature, brought to light through this new research.

This discovery is a breakthrough toward understanding the nature of the high-temperature superconducting state. It challenges some theoretical models based on the competition of the two states mentioned above. It also sheds new light on the electronic nature of the vortex cores, which potentially has an impact on their dynamics. Mastery of these dynamics, and particularly of the anchoring of vortices that depend on their electronic nature, is critical for many applications such as high-field electromagnets. [29]

A new dimension to high-temperature superconductivity discovered

A team led by scientists at the Department of Energy's SLAC National Accelerator Laboratory combined powerful magnetic pulses with some of the brightest X-rays on the planet to discover a surprising 3-D arrangement of a material's electrons that appears closely linked to a mysterious phenomenon known as high-temperature superconductivity.

This unexpected twist marks an important milestone in the 30-year journey to better understand how materials known as high-temperature superconductors conduct electricity with no resistance at temperatures hundreds of degrees Fahrenheit above those of conventional metal superconductors but still hundreds of degrees below freezing. The study was published today in Science.

The study also resolves an apparent mismatch in data from previous experiments and charts a new course for fully mapping the behaviors of electrons in these exotic materials under different conditions. Researchers have an ultimate goal to aid the design and development of new superconductors that work at warmer temperatures.

'Totally Unexpected' Physics

"This was totally unexpected, and also very exciting. This experiment has identified a new ingredient to consider in this field of study. Nobody had seen this 3-D picture before," said Jun-Sik Lee, a SLAC staff scientist and one of the leaders of the experiment conducted at SLAC's Linac

Coherent Light Source (LCLS) X-ray laser. "This is an important step in understanding the physics of hightemperature superconductors."

The dream is to push the operating temperature for superconductors to room temperature, he added, which could lead to advances in computing, electronics and power grid technologies.

There are already many uses for standard superconducting technology, from MRI machines that diagnose brain tumors to a prototype levitating train, the CERN particle collider that enabled the Nobel Prize-winning discovery of the Higgs boson and ultrasensitive detectors used to hunt for dark matter, the invisible constituent believed to make up most of the mass of the universe. A planned upgrade to the LCLS, known as LCLS-II, will include a superconducting particle accelerator.

The New Wave in Superconductivity

The 3-D effect that scientists observed in the LCLS experiment, which occurs in a superconducting material known as YBCO (yttrium barium copper oxide), is a newly discovered type of 'charge density wave.' This wave does not have the oscillating motion of a light wave or a sound wave; it describes a static, ordered arrangement of clumps of electrons in a superconducting material. Its coexistence with superconductivity is perplexing to researchers because it seems to conflict with the freely moving electron pairs that define superconductivity.

The 2-D version of this wave was first seen in 2012 and has been studied extensively. The LCLS experiment revealed a separate 3-D version that appears stronger than the 2-D form and closely tied to both the 2-D behavior and the material's superconductivity.

The experiment was several years in the making and required international expertise to prepare the specialized samples and construct a powerful customized magnet that produced magnetic pulses compressed to thousandths of a second. Each pulse was 10-20 times stronger than those from the magnets in a typical medical MRI machine.

A Powerful Blend of Magnetism and Light

Those short but intense magnetic pulses suppressed the superconductivity of the YBCO samples and provided a clearer view of the charge density wave effects.

They were immediately followed at precisely timed intervals by ultrabright LCLS X-ray laser pulses, which allowed scientists to measure the wave effects.

"This experiment is a completely new way of using LCLS that opens up the door for a whole new class of future experiments," said Mike Dunne, LCLS director.

Researchers conducted many preparatory experiments at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL), which also produces X-rays for research.

LCLS and SSRL are DOE Office of Science User Facilities. Scientists from SIMES, the Stanford Institute for Materials and Energy Sciences at SLAC, and SSRL and LCLS were a part of the study.

"I've been excited about this experiment for a long time," said Steven Kivelson, a Stanford University physics professor who contributed to the study and has researched high-temperature superconductors since 1987.

Kivelson said the experiment sets very clear boundaries on the temperature and strength of the magnetic field at which the newly observed 3-D effect emerges.

"There is nothing vague about this," he said. "You can now make a definitive statement: In this material a new phase exists."

The experiment also adds weight to the growing evidence that charge density waves and superconductivity "can be thought of as two sides of the same coin," he added.

In Search of Common Links

But it is also clear that YBCO is incredibly complex, and a more complete map of all of its properties is required to reach any conclusions about what matters most to its superconductivity, said Simon Gerber of SIMES and Hoyoung Jang of SSRL, the lead authors of the study.

Follow-up experiments are needed to provide a detailed visualization of the 3-D effect, and to learn whether the effect is universal across all types of high-temperature superconductors, said SLAC staff scientist and SIMES investigator Wei-Sheng Lee, who co-led the study with Jun-Sik Lee of SSRL and Diling Zhu of LCLS. "The properties of this material are much richer than we thought," Lee said.

"We continue to make new and surprising observations as we develop new experimental tools," Zhu added. [28]

Scientists Discover Hidden Magnetic Waves in High-Temperature Superconductors

Advanced x-ray technique reveals surprising quantum excitations that persist through materials with or without superconductivity UPTON, NY—Intrinsic inefficiencies plague current systems for the generation and delivery of electricity, with significant energy lost in transit. High-temperature superconductors (HTS)—uniquely capable of transmitting electricity with zero loss when chilled to subzero temperatures—could revolutionize the planet's aging and imperfect energy infrastructure, but the remarkable materials remain fundamentally puzzling to physicists. To unlock the true potential of HTS technology, scientists must navigate a quantum-scale labyrinth and pin down the phenomenon's source.

Now, scientists at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory and other collaborating institutions have discovered a surprising twist in the magnetic properties of HTS, challenging some of the leading theories. In a new study, published online in the journal Nature Materials on August 4, 2013, scientists found that unexpected magnetic excitations—quantum waves believed by many to regulate HTS—exist in both non-superconducting and superconducting materials.

"This is a major experimental clue about which magnetic excitations are important for hightemperature superconductivity," said Mark Dean, a physicist at Brookhaven Lab and lead author on the new paper. "Cutting-edge x-ray scattering techniques allowed us to see excitations in samples previously thought to be essentially non-magnetic."

On the atomic scale, electron spins—a bit like tiny bar magnets pointed in specific directions—rapidly interact with each other throughout magnetic materials. When one spin rotates, this disturbance can propagate through the material as a wave, tipping and aligning the spins of neighboring electrons. Many researchers believe that this subtle excitation wave may bind electrons together to create the perfect current conveyance of HTS, which operates at slightly warmer temperatures than traditional superconductivity.

The research was funded through Brookhaven Lab's Center for Emergent Superconductivity, an Energy Frontier Research Center funded by the U.S. Department of Energy's Office of Science to seek understanding of the underlying nature of superconductivity in complex materials. [27]

Conventional superconductivity

Conventional superconductivity can be explained by a theory developed by Bardeen, Cooper and Schrieffer (BCS) in 1957. In BCS theory, electrons in a superconductor combine to form pairs, called Cooper pairs, which are able to move through the crystal lattice without resistance when an electric voltage is applied. Even when the voltage is removed, the current continues to flow indefinitely, the most remarkable property of superconductivity, and one that explains the keen interest in their technological potential. [3]

High-temperature superconductivity

In 1986, high-temperature superconductivity was discovered (i.e. superconductivity at temperatures considerably above the previous limit of about 30 K; up to about 130 K). It is believed that BCS theory alone cannot explain this phenomenon and that other effects are at play. These effects are still not yet fully understood; it is possible that they even control superconductivity at low temperatures for some materials. [8]

Superconductivity and magnetic fields

Superconductivity and magnetic fields are normally seen as rivals – very strong magnetic fields normally destroy the superconducting state. Physicists at the Paul Scherer Institute have now demonstrated that a novel superconducting state is only created in the material $CeCoIn_5$ when there are strong external magnetic fields. This state can then be manipulated by modifying the field direction. The material is already superconducting in weaker fields, too. In strong fields, however, an additional second superconducting state is created which means that there are two different superconducting states at the same time in the same material. The new state is coupled with an anti-ferromagnetic order that appears simultaneously with the field. The anti-ferromagnetic order from whose properties the researchers have deduced the existence of the superconducting state was detected with neutrons at PSI and at the Institute Laue-Langevin in Grenoble. [6]

Room-temperature superconductivity

After more than twenty years of intensive research the origin of high-temperature superconductivity is still not clear, but it seems that instead of *electron-phonon* attraction mechanisms, as in conventional superconductivity, one is dealing with genuine *electronic* mechanisms (e.g. by antiferromagnetic correlations), and instead of s-wave pairing, d-waves are substantial. One goal of all this research is room-temperature superconductivity. [9]

Exciton-mediated electron pairing

Theoretical work by Neil Ashcroft predicted that solid metallic hydrogen at extremely high pressure (~500 GPa) should become superconducting at approximately room-temperature because of its extremely high speed of sound and expected strong coupling between the conduction electrons and the lattice vibrations (phonons). This prediction is yet to be experimentally verified, as yet the pressure to achieve metallic hydrogen is not known but may be of the order of 500 GPa. In 1964, William A. Little proposed the possibility of high temperature superconductivity in organic polymers. This proposal is based on the exciton-mediated electron pairing, as opposed to phonon-mediated pairing in BCS theory. [9]

Resonating valence bond theory

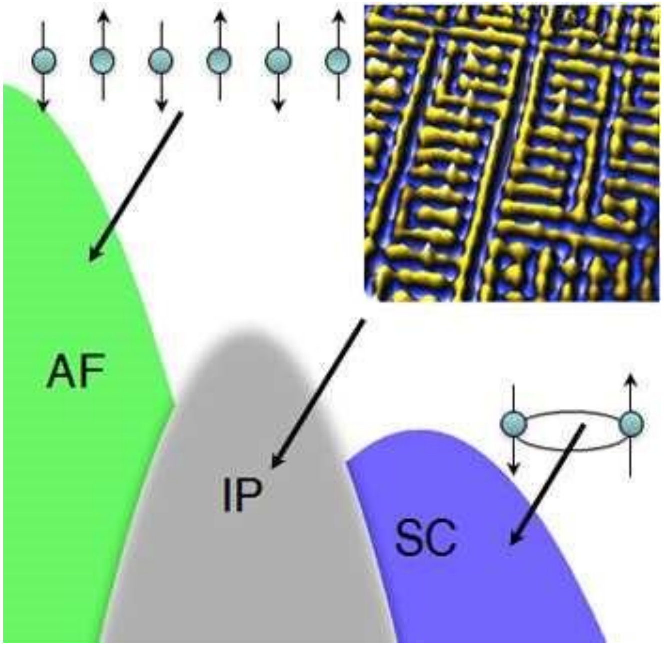
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical physicist Ganapathy Baskaran in 1987. The theory states that in copper oxide lattices, electrons from neighboring copper atoms interact to form a valence bond, which locks them in place. However, with doping, these electrons can act as mobile Cooper pairs and are able to superconduct. Anderson observed in his 1987 paper that the origins of superconductivity in doped cuprates was in the Mott insulator nature of crystalline copper oxide. RVB builds on the Hubbard and t-J models used in the study of strongly correlated materials. [10]

Strongly correlated materials

Strongly correlated materials are a wide class of electronic materials that show unusual (often technologically useful) electronic and magnetic properties, such as metal-insulator transitions or half-metallicity. The essential feature that defines these materials is that the behavior of their electrons cannot be described effectively in terms of non-interacting entities. Theoretical models of the electronic structure of strongly correlated materials must include electronic correlation to be accurate. Many transition metal oxides belong into this class which may be subdivided according to their behavior, *e.g.* high-T_c, spintronic materials, Mott insulators, spin Peierls materials, heavy fermion materials, quasi-low-dimensional materials, etc. The single most intensively studied effect is probably high-temperature superconductivity in doped cuprates, e.g. $La_{2-x}Sr_xCuO_4$. Other ordering or magnetic phenomena and temperature-induced phase transitions in many transition-metal oxides are also gathered under the term "strongly correlated materials." Typically, strongly correlated materials have incompletely filled *d*- or *f*-electron shells with narrow energy bands. One can no longer consider any electron in the material as being in a "sea" of the averaged motion of the others (also known as mean field theory). Each single electron has a complex influence on its neighbors.
[11]

New superconductor theory may revolutionize electrical engineering

High-temperature superconductors exhibit a frustratingly varied catalog of odd behavior, such as electrons that arrange themselves into stripes or refuse to arrange themselves symmetrically around atoms. Now two physicists propose that such behaviors – and superconductivity itself – can all be traced to a single starting point, and they explain why there are so many variations.



An "antiferromagnetic" state, where the magnetic moments of electrons are opposed, can lead to a variety of unexpected arrangements of electrons in a high-temperature superconductor, then finally to the formation of "Cooper pairs" that conduct without resistance, according to a new theory. [22]

Unconventional superconductivity in $Ba^{0.6}K^{0.4}Fe^{2}As^{2}$ from inelastic neutron scattering

In BCS superconductors, the energy gap between the superconducting and normal electronic states is constant, but in unconventional superconductors the gap varies with the direction the electrons are moving. In some directions, the gap may be zero. The puzzle is that the gap does not seem to vary with direction in the iron arsenides. Theorists have argued that, while the size of the gap shows no directional dependence in these new compounds, the sign of the gap is opposite for different electronic states. The standard techniques to measure the gap, such as photoemission, are not sensitive to this change in sign.

But inelastic neutron scattering is sensitive. Osborn, along with Argonne physicist Stephan Rosenkranz, led an international collaboration to perform neutron experiments using samples of the new compounds made in Argonne's Materials Science Division, and discovered a magnetic excitation in the superconducting state that can only exist if the energy gap changes sign from one electron orbital to another.

"Our results suggest that the mechanism that makes electrons pair together could be provided by antiferromagnetic fluctuations rather than lattice vibrations," Rosenkranz said. "It certainly gives direct evidence that the superconductivity is unconventional."

Inelastic neutron scattering continues to be an important tool in identifying unconventional superconductivity, not only in the iron arsenides, but also in new families of superconductors that may be discovered in the future. [23]

A grand unified theory of exotic superconductivity?

The role of magnetism

In all known types of high-Tc superconductors—copper-based (cuprate), iron-based, and so-called heavy fermion compounds—superconductivity emerges from the "extinction" of antiferromagnetism, the ordered arrangement of electrons on adjacent atoms having anti-aligned spin directions. Electrons arrayed like tiny magnets in this alternating spin pattern are at their lowest energy state, but this antiferromagnetic order is not beneficial to superconductivity.

However if the interactions between electrons that cause antiferromagnetic order can be maintained while the actual order itself is prevented, then superconductivity can appear. "In this situation, whenever one electron approaches another electron, it tries to anti-align its magnetic state," Davis said. Even if the electrons never achieve antiferromagnetic order, these antiferromagnetic interactions exert the dominant influence on the behavior of the material. "This antiferromagnetic influence is universal across all these types of materials," Davis said.

Many scientists have proposed that these antiferromagnetic interactions play a role in the ability of electrons to eventually pair up with anti-aligned spins—a condition necessary for them to carry current with no resistance. The complicating factor has been the existence of many different types of "intertwined" electronic phases that also emerge in the different types of high-Tc superconductors—sometimes appearing to compete with superconductivity and sometimes coexisting with it. [24]

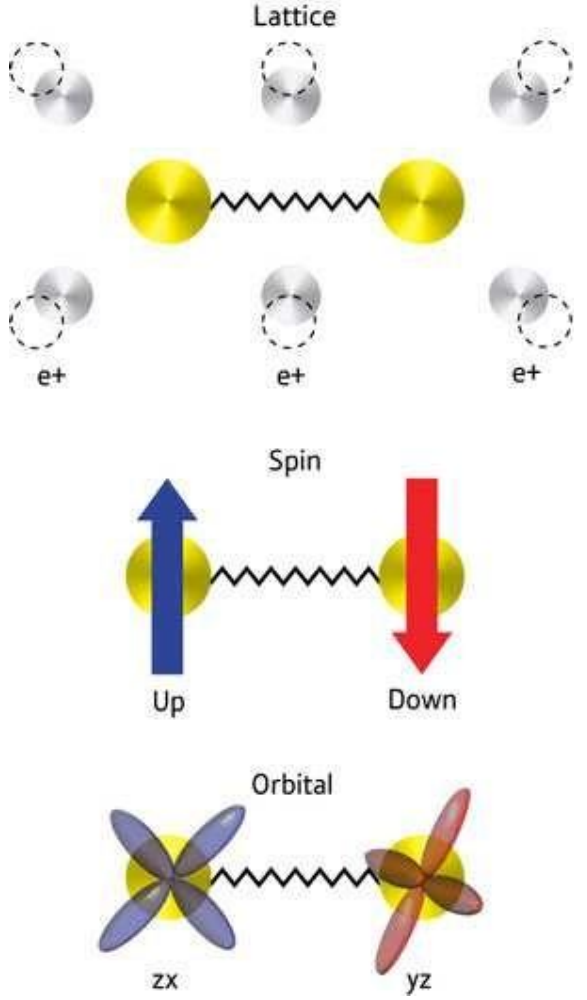
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

Unconventional superconductivity (SC) is said to occur when Cooper pair formation is dominated by repulsive electron–electron interactions, so that the symmetry of the pair wave function is other than an isotropic s-wave. The strong, on-site, repulsive electron–electron interactions that are the proximate cause of such SC are more typically drivers of commensurate magnetism. Indeed, it is the suppression of commensurate antiferromagnetism (AF) that usually allows this type of unconventional superconductivity to emerge. Importantly, however, intervening between these AF and SC phases, intertwined electronic ordered phases (IP) of an unexpected nature are frequently discovered. For this reason, it has been extremely difficult to distinguish the microscopic essence of the correlated superconductivity from the often spectacular phenomenology of the IPs. Here we introduce a model conceptual framework within which to understand the relationship between AF electron–electron interactions, IPs, and correlated SC. We demonstrate its effectiveness in simultaneously explaining the consequences of AF interactions for the copper-based, iron-based, and heavy-fermion superconductors, as well as for their quite distinct IPs.

Significance

This study describes a unified theory explaining the rich ordering phenomena, each associated with a different symmetry breaking, that often accompany high-temperature superconductivity. The essence of this theory is an ”antiferromagnetic interaction,” the interaction that favors the development of magnetic order where the magnetic moments reverse direction from one crystal unit cell to the next. We apply this theory to explain the superconductivity, as well as all observed accompanying ordering phenomena in the copper-oxide superconductors, the iron-based superconductors, and the heavy fermion superconductors. [25]

Superconductivity's third side unmasked



Shimojima and colleagues were surprised to discover that interactions between electron spins do not cause the electrons to form Cooper pairs in the pnictides. Instead, the coupling is mediated by the electron clouds surrounding the atomic cores. Some of these so-called orbitals have the same energy, which causes interactions and electron fluctuations that are sufficiently strong to mediate superconductivity.

This could spur the discovery of new superconductors based on this mechanism. “Our work establishes the electron orbitals as a third kind of pairing glue for electron pairs in superconductors, next to lattice vibrations and electron spins,” explains Shimojima. “We believe that this finding is a step towards the dream of achieving room-temperature superconductivity," he concludes. [17]

Strongly correlated materials

Strongly correlated materials give us the idea of diffraction patterns explaining the electron-proton mass rate. [13]

This explains the theories relating the superconductivity with the strong interaction. [14]

Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing. We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too.

The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. [18] One of these new matter formulas is the superconducting matter.

Higgs Field and Superconductivity

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The specific spontaneous symmetry breaking of the underlying local symmetry, which is similar to that one appearing in the theory of superconductivity, triggers conversion of the longitudinal field component to the Higgs boson, which interacts with itself and (at least of part of) the other fields in the theory, so as to produce mass terms for the above-mentioned three gauge bosons, and also to the above-mentioned fermions (see below). [16]

The Higgs mechanism occurs whenever a charged field has a vacuum expectation value. In the nonrelativistic context, this is the Landau model of a charged Bose–Einstein condensate, also known as a superconductor. In the relativistic condensate, the condensate is a scalar field, and is relativistically invariant.

The Higgs mechanism is a type of superconductivity which occurs in the vacuum. It occurs when all of space is filled with a sea of particles which are charged, or, in field language, when a charged field has a nonzero vacuum expectation value. Interaction with the quantum fluid filling the space prevents certain forces from propagating over long distances (as it does in a superconducting medium; e.g., in the Ginzburg–Landau theory).

A superconductor expels all magnetic fields from its interior, a phenomenon known as the Meissner effect. This was mysterious for a long time, because it implies that electromagnetic forces somehow become short-range inside the superconductor. Contrast this with the behavior of an ordinary metal. In a metal, the conductivity shields electric fields by rearranging charges on the surface until the total field cancels in the interior. But magnetic fields can penetrate to any distance, and if a magnetic monopole (an isolated magnetic pole) is surrounded by a metal the field can escape without collimating into a string. In a superconductor, however, electric charges move with no dissipation, and this allows for permanent surface currents, not just surface charges. When magnetic fields are introduced at the boundary of a superconductor, they produce surface currents which exactly

neutralize them. The Meissner effect is due to currents in a thin surface layer, whose thickness, the London penetration depth, can be calculated from a simple model (the Ginzburg–Landau theory).

This simple model treats superconductivity as a charged Bose–Einstein condensate. Suppose that a superconductor contains bosons with charge *q*. The wavefunction of the bosons can be described by introducing a quantum field, ψ, which obeys the Schrödinger equation as a field equation (in units where the reduced Planck constant, *ħ*, is set to 1):

$$i\frac{\partial}{\partial t}\psi = \frac{(\nabla - iqA)^2}{2m}\psi.$$

The operator ψ(*x*) annihilates a boson at the point *x*, while its adjoint $\psi^\dagger$ creates a new boson at the same point. The wavefunction of the Bose–Einstein condensate is then the expectation value ψ of ψ(*x*), which is a classical function that obeys the same equation. The interpretation of the expectation value is that it is the phase that one should give to a newly created boson so that it will coherently superpose with all the other bosons already in the condensate.

When there is a charged condensate, the electromagnetic interactions are screened. To see this, consider the effect of a gauge transformation on the field. A gauge transformation rotates the phase of the condensate by an amount which changes from point to point, and shifts the vector potential by a gradient:

$$\psi \rightarrow e^{iq\phi(x)}\psi$$

$$A \rightarrow A + \nabla\phi.$$

When there is no condensate, this transformation only changes the definition of the phase of ψ at every point. But when there is a condensate, the phase of the condensate defines a preferred choice of phase.

The condensate wave function can be written as

$$\psi(x) = \rho(x)\, e^{i\theta(x)},$$

where ρ is real amplitude, which determines the local density of the condensate. If the condensate were neutral, the flow would be along the gradients of θ, the direction in which the phase of the Schrödinger field changes. If the phase θ changes slowly, the flow is slow and has very little energy.

But now θ can be made equal to zero just by making a gauge transformation to rotate the phase of the field.

The energy of slow changes of phase can be calculated from the Schrödinger kinetic energy,

$$H = \frac{1}{2m}|(qA + \nabla)\psi|^2,$$

and taking the density of the condensate ρ to be constant,

$$H \approx \frac{\rho^2}{2m}(qA + \nabla\theta)^2.$$

Fixing the choice of gauge so that the condensate has the same phase everywhere, the electromagnetic field energy has an extra term,

$$\frac{q^2\rho^2}{2m}A^2.$$

When this term is present, electromagnetic interactions become short-ranged. Every field mode, no matter how long the wavelength, oscillates with a nonzero frequency. The lowest frequency can be read off from the energy of a long wavelength A mode,

$$E \approx \frac{\dot{A}^2}{2} + \frac{q^2\rho^2}{2m}A^2.$$

This is a harmonic oscillator with frequency

$$\sqrt{\frac{1}{m}q^2\rho^2}.$$

The quantity $|\psi|^2$ ($=\rho^2$) is the density of the condensate of superconducting particles.

In an actual superconductor, the charged particles are electrons, which are fermions not bosons. So in order to have superconductivity, the electrons need to somehow bind into Cooper pairs. [12]

The charge of the condensate *q* is therefore twice the electron charge *e*. The pairing in a normal superconductor is due to lattice vibrations, and is in fact very weak; this means that the pairs are very loosely bound. The description of a Bose–Einstein condensate of loosely bound pairs is actually more difficult than the description of a condensate of elementary particles, and was only worked out in 1957 by Bardeen, Cooper and Schrieffer in the famous BCS theory. [3]

Superconductivity and Quantum Entanglement

We have seen that the superconductivity is basically a quantum mechanical phenomenon and some entangled particles give this opportunity to specific matters, like Cooper Pairs or other entanglements, as strongly correlated materials and Exciton-mediated electron pairing. [26]

Conclusions

On the atomic scale, electron spins—a bit like tiny bar magnets pointed in specific directions—rapidly interact with each other throughout magnetic materials. When one spin rotates, this disturbance can propagate through the material as a wave, tipping and aligning the spins of neighboring electrons. Many researchers believe that this subtle excitation wave may bind electrons

together to create the perfect current conveyance of HTS, which operates at slightly warmer temperatures than traditional superconductivity. [27]

Probably in the superconductivity there is no electric current at all, but a permanent magnetic field as the result of the electron's spin in the same direction in the case of the circular wire on a low temperature. [6]

We think that there is an electric current since we measure a magnetic field. Because of this saying that the superconductivity is a quantum mechanical phenomenon.

Since the acceleration of the electrons is centripetal in a circular wire, in the atom or in the spin, there is a steady current and no electromagnetic induction. This way there is no changing in the Higgs field, since it needs a changing acceleration. [18]

The superconductivity is temperature dependent; it means that the General Weak Interaction is very relevant to create this quantum state of the matter. [19]

We have seen that the superconductivity is basically a quantum mechanical phenomenon and some entangled particles give this opportunity to specific matters, like Cooper Pairs or other entanglements. [26]

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