

# Superconductor Remembers

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*Using ultracold atoms, researchers at Heidelberg University have found an exotic state of matter where the constituent particles pair up when limited to two dimensions. [32]*

*Neutron diffraction at the Australian Centre for Neutron Scattering has clarified the absence of magnetic order and classified the superconductivity of a new next-generation of superconductors in a paper published in Europhysics Letters. [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.*

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## 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

### A superconductor that 'remembers' its electronic charge arrangement

In the field of superconductivity—the ability of a material to conduct electricity with virtually zero resistance—the so-called high-temperature superconductors (HTSCs) are possible candidates for a new generation of advanced technologies. One subset of these, the "cuprates," which are crystalline materials based on planes of copper oxide, are particularly promising. But scientists still need to learn much more about these materials before mainstream, room-temperature applications are possible. Currently, even the "high-temperature" superconductors must be chilled to very, very cold temperatures by everyday standards.

Working at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, researchers from Brookhaven and University College London recently discovered something new and very surprising about one type of periodic electric charge arrangement, which coexists with superconductivity in cuprates, known as a charge density wave (CDW). They found that the specific CDW order within their sample was "remembered" when the sample was repeatedly heated past the temperature where the CDW disappears. This discovery opens a new avenue of research into how these intriguing materials work, bringing scientists one step closer to a complete picture of electronic behavior in cuprates.

"It would be like melting a pile of ice cubes and then refreezing them—and discovering that they refroze into an identical pile of cubes, even down at the microscopic level," explained Brookhaven Lab physicist Claudio Mazzoli, one of the researchers involved in the study. "Nobody would expect to see that."

Mazzoli and his co-researchers describe their work in the March 29, 2019 online edition of Nature Communications.

The electronic behavior of the cuprates, as with all HTSCs, is quite complex. As the name implies, the electrons that make up a CDW form a periodic standing-wave pattern. CDWs have been observed in nearly all the cuprates, but their role in superconductivity is still not fully understood. Do they compete with superconductivity? Do they participate in it? Do they hinder superconductivity in certain ways and possibly add to it in others? Scientists are still working this out.

"In the HTSCs, any arrangement of electrons is of interest to researchers," said Brookhaven physicist Mark Dean, another of the paper's authors. "The goal is to investigate these arrangements and tune them—or perhaps remove them—so that the superconducting transition temperature of the material can approach, or maybe surpass, room temperature. To do this, we must learn as much as we can about the electrons' behavior and their structures in HTSCs."

One thing that researchers do know is that cuprates containing the same copper oxide planes—but arranged in a slightly different way—may have CDWs with dramatically different properties. It seems, then, that the part of the crystal lattice that hosts the CDW has an effect on the CDW.

Here, the group set out to learn more about the relationship between the material's lattice structure and CDW behavior. Their model system was a cuprate known as LBCO for the compounds it contains: lanthanum, barium, copper, and oxygen. LBCO has a transition temperature—the temperature below which it displays the CDW, and above which it does not—of 54 degrees Kelvin (K) (although equivalent to about -360 degrees Fahrenheit, this temperature is still relatively high in the superconductor world).

The group wanted to find out how imperfections in the LBCO crystal lattice can stabilize the CDW. They were interested in a well-known lattice distortion that occurs in the material: a tilt in the octahedral shape formed by bound copper and oxygen atoms. This tilt tends to anchor the CDW to the lattice such that it orients in a certain direction; it appears that the CDW may be sensitive to the spatial inhomogeneities, or domains, of the lattice. This relationship between the CDW and the domains, as suggested by the temperature behavior uncovered in this study, may be unique to LBCO. It will be very important to understand whether this is a general feature of the cuprates.

The group cycled their LBCO sample through a range of temperatures, repeatedly heating and cooling it, while probing it with X-rays at Brookhaven's National Synchrotron Light Source II (NSLS-II), a DOE Office of Science User Facility. At the Coherent Soft X-Ray Scattering (CSX) beamline, they used a technique known as coherent resonant X-ray diffraction, in which X-rays scatter from different domains in the CDW spatial arrangement, interfere with each other, and form a "speckle" pattern that is captured by a special camera. Analyzing this pattern yields information on the CDW's features.

This task—directly observing a CDW while tracking its changes, over a range of temperatures—is collectively very challenging, in large part due to the very short distances that characterize the features of a CDW. NSLS-II is uniquely suited to this type of investigation due to the coherent nature of the light it produces, meaning the light waves travel in unison rather than out-of-sync and jumbled. Older light sources do not have such highly coherent beams.

The speckle analysis revealed that the specific CDW order present below 54 K returned even when the sample was repeatedly cycled through much higher temperatures, up to about 240 K (about -28 °F). The researchers think that the structural changes that take place in the crystal below 240 K create a "pinning landscape" that anchors the CDW to the lattice.

"Our work opens a new route for studying the complex interplay between charge and lattice degrees of freedom in superconducting cuprates," said the paper's lead author, Xiaoqian Chen, a researcher in Brookhaven's Condensed Matter Physics and Materials Science Department at the time this study was performed (she is now working at Lawrence Berkeley National Laboratory). "It is also a great demonstration of how NSLS-II can be used to study quantum phases of materials and their spectacular, unexpected properties."

"This result emphasizes the vital importance of the role of nanoscale domains in high-temperature superconductivity. Without the domain pinning effects that have been observed, the CDW might carry current and further disrupt the superconductivity," added co-author Ian Robinson, a physicist at Brookhaven as well as at University College London. "Imaging these subtle 'phase' domain structures is still in its infancy and this work highlights the need to develop better imaging techniques so that structural details can be seen directly." [33]

### Physicists find clues to the origins of high-temperature superconductivity

Ever since cuprate (copper-containing) superconductors were first discovered in 1986, they have greatly puzzled researchers. Cuprate superconductors have critical superconducting temperatures—the point at which their electrical resistance drops to zero—of up to 138 K at ambient pressure, which far exceeds the critical temperatures of other superconductors and is even higher than what is thought possible based on theory.

Now in a new study, researchers have discovered the existence of a positive feedback loop that greatly enhances the superconductivity of cuprates and may shed light on the origins of high-temperature cuprate superconductivity—considered one of the most important open questions in physics.

The researchers, Haoxiang Li et al., at the University of Colorado at Boulder and the École Polytechnique Fédérale de Lausanne, have published a paper on their experimental ARPES (Angle Resolved Photoemission Spectroscopy) results on high-temperature cuprate superconductors in a recent issue of *Nature Communications*.

As the researchers explain, the positive feedback mechanism arises from the fact that the electrons in the non-superconducting cuprate state are correlated differently than in most other systems, including in conventional superconductors, which have strongly coherent electron correlations. In contrast, cuprates in their non-superconducting state have strongly incoherent "strange-metal" correlations, which are at least partly removed or weakened when the cuprates become superconducting.

Due to these incoherent electron correlations, it has been widely believed that the framework that describes conventional superconductivity—which is based on the notion of quasiparticles—cannot accurately describe cuprate superconductivity. In fact, some research has suggested that cuprate superconductors have such unusual electronic properties that even attempting to describe them with the notion of particles of any kind becomes useless.

This leads to the question of, what role, if any, do the strange-metal correlations play in high-temperature cuprate superconductivity?

The main result of the new paper is that these correlations don't simply disappear in the cuprate superconducting state, but instead get converted into coherent correlations that lead to an enhancement of the superconductive electron pairing. This process results in a positive feedback loop, in which the conversion of the incoherent strange-metal correlations into a coherent state increases the number of superconductive electron pairs, which in turn leads to more conversion, and so on.

The researchers found that, due to this positive feedback mechanism, the strength of the coherent electron correlations in the superconducting state is unprecedented, greatly exceeding what is possible for conventional superconductors. Such a strong electron interaction also opens up the possibility that cuprate superconductivity might occur due to a completely unconventional pairing mechanism—a purely electronic pairing mechanism that could arise solely due to quantum fluctuations.

"We experimentally discover that the incoherent electron correlations in the strange metal 'normal state' are converted to coherent correlations in the superconducting state that help strengthen the [superconductivity](#), with an ensuing positive feedback loop," coauthor Dan Dessau at the University of Colorado at Boulder told *Phys.org*. "Such a strong positive feedback loop should strengthen most conventional pairing mechanisms but could also allow for a truly unconventional (purely electronic) pairing mechanism."

Surprisingly, the researchers also found that they could describe their experimental results using a semi-conventional quasiparticle-like approach, despite the fact that cuprate superconductors behave so differently than other materials.

In the future, the researchers plan to investigate whether this positive feedback mechanism can be integrated into other materials, perhaps leading to new kinds of high-temperature superconductors.

"We can look for similar positive feedback loops in related materials, and can also use the newly developed ARPES-based techniques to probe the details of the electronic correlations in even greater detail," Li said. [33]

## Physicists find evidence of an exotic state of matter

Using ultracold atoms, researchers at Heidelberg University have found an exotic state of matter where the constituent particles pair up when limited to two dimensions. The findings from the field of quantum physics may hold important clues to intriguing phenomena of superconductivity. The results were published in *Science*.

Superconductors are materials through which electricity can flow without any resistance once they are cooled below a certain critical temperature. The technologically most relevant class of

materials, with exceptionally high critical temperatures for superconductivity, is poorly understood so far. There is evidence, however, that in order for superconductivity to occur, a certain type of particles – the [fermions](#) – must pair up. Moreover, research has shown that materials which become superconducting at relatively high temperatures have layered structures. "This means that electrons in these systems can only move in two-dimensional planes", explains Prof. Dr. Selim Jochim of Heidelberg University's Institute for Physics, who heads the project. "What we did not understand until now was how the interplay of pairing and dimensionality can lead to higher critical temperatures."

To explore this question, researchers at the Center for Quantum Dynamics performed experiments in which they confined a gas of ultracold [atoms](#) in two-dimensional traps which they created using focused laser beams. "In solid-state materials like copper oxides, there are many different effects and impurities that make these [materials](#) difficult to study. That is why we use [ultracold atoms](#) to simulate the behaviour of electrons in solids. This allows us to create very clean samples and gives us full control over the essential system parameters", says Puneet Murthy, a Ph.D. student at the Center for Quantum Dynamics at Heidelberg University and one of the lead authors of this publication.

Using a technique known as radio-frequency spectroscopy, the researchers measured the response of the atoms to a radio-wave pulse. From this response, they could tell exactly whether or not the particles were paired and in what way. These measurements were also performed for different strengths of interaction between fermions. In the course of the experiments, the researchers discovered an exotic state of matter. Theory states that fermions with a weak interaction should pair up at the temperature at which they become superconductive. However, when the scientists increased the interaction between fermions, they found that pairing occurred at temperatures several times higher than the critical [temperature](#).

"To achieve our ultimate goal of better understanding these phenomena, we will start with small systems that we put together atom by atom", says Prof. Jochim. [32]

### **Insights into atomic structure of next-generation superconductors**

Neutron diffraction at the Australian Centre for Neutron Scattering has clarified the absence of magnetic order and classified the superconductivity of a new next-generation of superconductors in a paper published in Europhysics Letters.

The iron-based nitride, ThFeAsN, which contains Th<sub>2</sub>N<sub>2</sub> and FeAs<sub>2</sub> layers, has been of considerable interest because unconventional superconductivity occurring at a temperature of 30 K. This material was of particular interest as the superconductivity was seen to arise without oxygen doping.

A large group of predominantly Chinese researchers, led by Prof Huiqian Luo from the Beijing National Laboratory for Condensed Matter Physics gathered diffraction measurements on the high intensity diffractometer WOMBAT, assisted by instrument scientists Dr Helen Maynard-Casely and Dr Guochu Deng based at the Australian Centre for Neutron Scattering. This enabled them to determine the crystal structure of the compound over a large temperature range.



In similar types of materials, the onset of a superconducting state is thought to be associated with magnetic ordering within the crystal structure. Earlier measurements had shown no magnetic ordering in the ThFeAsN material, and hence this neutron study was an opportunity to confirm this and search for other structural insights into the material's properties.

The lack of magnetic order was confirmed because no difference was found between the data sets at 6 K and 40 K. All of the observed reflections could be identified as having arisen from the atomic structure from 6K up to 300K – no magnetic reflections were identified.

Diffraction patterns over the temperature range from 300 K to 6 K also indicated there was no structural phase transition from tetragonal to orthorhombic in the crystal lattice.

The investigators reported that the lattice parameters continuously increased with temperature due to thermal expansion and a weak distortion in the tetrahedron possibly took place at 160 K. Details from the structure point to this distortion coming from the FeAs<sub>2</sub> layers.

The close relationship between local structure of the FeAs<sub>4</sub> tetrahedron and the superconducting temperature, suggested ThFeAsN is in a nearly optimised superconducting state.

This is different to many other discovered superconducting materials, which require tweaks in their chemistry to produce the highest critical temperature.

The authors also surmised that the close distance of Fe-As would favour electron hopping, reducing electron correlations and orbital order, thereby providing a reasonable explanation for the absence of magnetic order, structural transition and resistivity anomaly.

Carrier density measurements indicated that ThFeAsN could already be doped by electrons, which are probably introduced by the N deficiency or O occupancy or the reduced valence of nitrogen. The self-doping effect could be responsible for the superconductivity and suppression of magnetic order. [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 CeRhIn<sub>5</sub> 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 CeRhIn<sub>5</sub> 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 CeRhIn<sub>5</sub> 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-T<sub>c</sub>) 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-T<sub>c</sub> 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 high-temperature 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 high-temperature 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 Scherrer Institute have now demonstrated that a novel superconducting state is only created in the material  $\text{CeCoIn}_5$  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

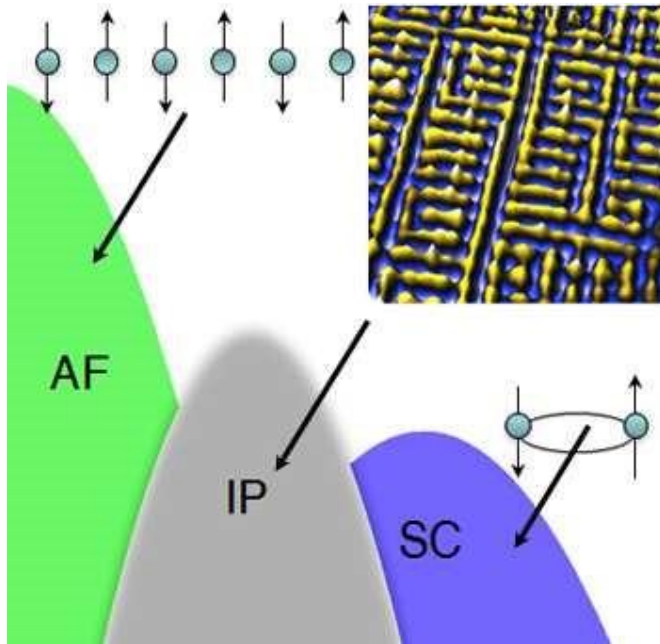
Strongly correlated materials are a wide class of electronic materials that show unusual (often technologically useful) electronic and magnetic properties, such as metal-insulator transitions or half-metallicity. The essential feature that defines these materials is that the behavior of their electrons 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.*  $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ . 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 $\text{Ba}^{0.6}\text{K}^{0.4}\text{Fe}_2\text{As}_2$ 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-T<sub>c</sub> 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-T<sub>c</sub> superconductors—sometimes appearing to compete with superconductivity and sometimes coexisting with it. [24]

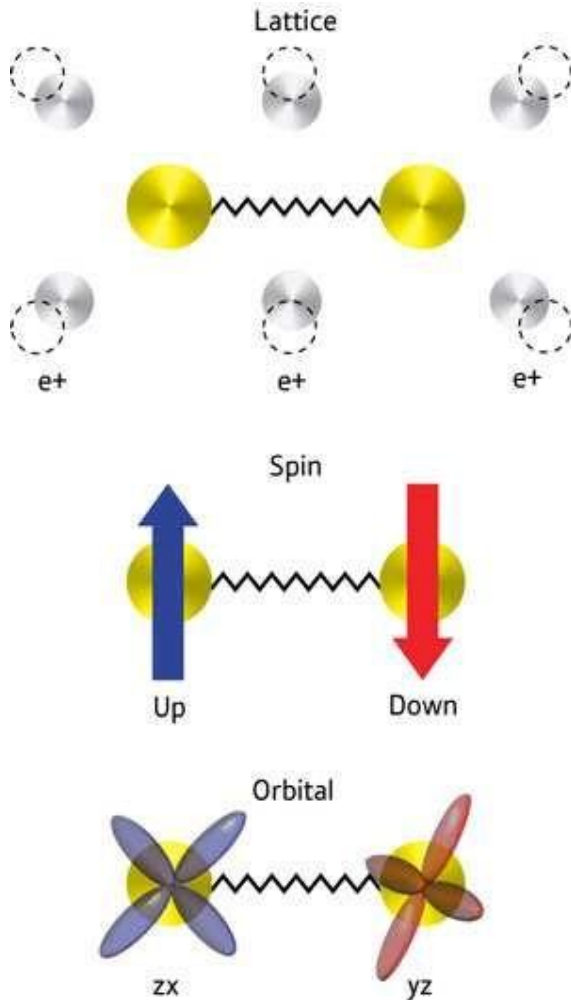
### **Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity**

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 ratio. [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,  $\psi$ , which obeys the Schrödinger equation as a field equation (in units where the reduced Planck constant,  $\hbar$ , is set to 1):

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

The operator  $\psi(x)$  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  $\psi$  of  $\psi(x)$ , 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:

$$\begin{aligned} \psi &\rightarrow e^{iq\phi(x)} \psi \\ A &\rightarrow A + \nabla\phi. \end{aligned}$$

When there is no condensate, this transformation only changes the definition of the phase of  $\psi$  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  $\rho$  is real amplitude, which determines the local density of the condensate. If the condensate were neutral, the flow would be along the gradients of  $\theta$ , the direction in which the phase of the

Schrödinger field changes. If the phase  $\theta$  changes slowly, the flow is slow and has very little energy. But now  $\theta$  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  $\rho$  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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