

Strange Metals

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For a long time, physicists have tried to understand the relationship between a periodic pattern of conduction electrons called a charge density wave (CDW), and another quantum order, superconductivity, or zero electrical resistance, in the same material. [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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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

Strange metals become even stranger

High-temperature superconductivity was first discovered in 1986, but the physics underlying the phenomenon is still shrouded in mystery. In 1990, researchers discovered that, above their superconducting transition temperatures, the archetypal high-temperature superconductors, the cuprates, can behave as “strange” metals whose electrical resistance does not vary as expected with temperature. Now, researchers led by Arkady Shekhter of the National High Magnetic Field Laboratory in the US have shown that the same strange behaviour applies to the way their resistance varies with magnetic field. The results could have fundamental implications for our understanding of the nature of superconductivity and far beyond.

While the traditional BCS theory of superconductivity (named after its developers Bardeen, Cooper and Schrieffer) cannot explain superconductivity above about 30 K, cuprates have been shown to retain their superconducting properties at temperatures of up to 130 K. But even when the materials do finally relinquish their superconductivity, cuprates are still puzzling because of their unusual metallic behaviour.

From conventional to strange

According to Shekhter, the properties of conventional metals can be predicted from Fermi-liquid theory – an inspired, intuitive approximation of the quantum-mechanical behaviour of metallic materials. This theory, developed by the Soviet physicist Lev Landau, treats large numbers of electrons as quasiparticles. “Any material has an enormous amount of electrons, so there are no exact solutions,” explains Shekhter. “Fermi-liquid theory is not the only behaviour consistent with a material being a metal and being quantum mechanical – but it’s the one we know about and the one that works for pretty much any metal we encounter in normal life.” Apply it to the cuprates, however, and things get weird.

Fermi-liquid theory predicts that, at low temperatures, the resistance of metals should depend on the square of temperature. However, cuprates’ resistance varies linearly with temperature down to the point at which they become superconducting. A wide variety of other, similar “strange” metals, or non-Fermi liquids, have subsequently been discovered – many of them not superconductors. “There is no theoretical explanation for temperature-in-linear resistivity at the moment,” says [Louis Taillefer](#) of the University of Sherbrooke in Quebec, Canada. “It remains a baffling result.”

In the absence of such an explanation, researchers have drawn inspiration from other areas of fundamental physics. Theoretical physicist [Jan Zaanen](#) of the University of Leiden in the Netherlands has suggested that the phenomenon may result from the breakdown of the Pauli exclusion principle, so that all the particles become entangled with each other – a concept he has described as “unparticle physics”. String theorists have even drawn parallels between the physics of strange metals and the properties of charged black holes.

Superconductors in magnetic fields

In 2016, a research team led by [James Analytis](#) of the University of California, Berkeley, discovered a curious feature of the strange-metal state of an iron pnictide superconductor. At high fields, they found, [the resistance is perfectly proportional to the field](#). As with temperature, Fermi-liquid theory predicts it should be proportional to its square.

In this new research, Shekhter – a co-author of the 2016 study – worked with colleagues in the US, Columbia and Germany to ascertain whether the same “B-linear resistivity” was also seen in cuprates. They tested the resistance of thin films of strontium-doped lathanum cuprate, finding it was linearly proportional to magnetic field across a wide range of temperatures at fields up to 80 teslas – the highest they tested. Shekhter says that these results provide crucial confirmation that strange metals cannot be described by Fermi-liquid theory.



[According to Shekhter, the 100 T magnet at Los Alamos National Laboratory in the US was the “real hero” of the work. \(Courtesy: National High Magnetic Field Laboratory\)](#)

“Linear-in-temperature behaviour offers certain wiggle room to take the conventional language of metals and make it a bit more complex,” he explains. “Once you have this very unusual magnetic-field behaviour at high fields it leaves much less room for speculation. As far as I know the leading theorists are still puzzled.”

Taillefer agrees. “You cannot propose to understand anything about T-linear resistivity unless your understanding includes the cuprates, so this B-linear resistivity would not have been treated as a universal strange-metal phenomenon unless it had been seen there too,” he says.

He describes the present paper, in which he was not involved, as “a tantalizing result that’s very significant if it turns out to be true”. His caution arises from the fact that the range of fields tested is relatively small. “Superconductivity in these cuprates is very strong, so you actually need of order 60 or 70 T before you can look at the normal-state resistivity,” he explains. “So even though they went to 80 T – which is very strong – you don’t have a great range of field to see whether the relationship is linear or not.”

Jan Zaanen, meanwhile, is excited. “The present work is just part of a large development that is presently gathering steam in the experimental community,” he says. “Quite unusually, it is inspired by cutting edge developments in fundamental theoretical physics involving string theory, quantum information and many-body condensed matter physics, which went through a serendipitous convergence in recent years.”

“This is not run-of-the-mill,” Zaanen continues, “but instead potentially a ground-breaking development in fundamental physics, with ramifications for benchmarking quantum computers and even quantum gravity.”

The research is published in [Science](#). [34]

A material already known for its unique behavior is found to carry current in a way never before observed

Scientists at the Florida State University-headquartered National High Magnetic Field Laboratory have discovered a behavior in materials called cuprates that suggests they carry current in a way entirely different from conventional metals such as copper.

The research, published today in the journal *Science*, adds new meaning to the materials' moniker, "strange metals."

Cuprates are high-temperature superconductors (HTS), meaning they can carry current without any loss of energy at somewhat warmer temperatures than conventional, low-temperature superconductors (LTS). Although scientists understand the physics of LTS, they haven't yet cracked the nut of HTS materials. Exactly how the electrons travel through these materials remains the biggest mystery in the field.

For their research on one specific cuprate, lanthanum strontium copper oxide (LSCO), a team led by MagLab physicist Arkady Shekhter focused on its normal, metallic state—the state from

which superconductivity eventually emerges when the temperature dips low enough. This normal state of cuprates is known as a "strange" or "bad" metal, in part because the electrons don't conduct electricity particularly well.

Scientists have studied [conventional metals](#) for more than a century and generally agree on how electricity travels through them. They call the units that carry charge through those metals "quasiparticles," which are essentially electrons after factoring in their environment. These quasiparticles act nearly independently of each other as they carry electric charge through a conductor.

But does [quasiparticle](#) flow also explain how electric current travels in the cuprates? At the National MagLab's Pulsed Field Facility in Los Alamos, New Mexico, Shekhter and his team investigated the question. They put LSCO in a very high [magnetic field](#), applied a current to it, then measured the resistance.

The resulting data revealed that the current cannot, in fact, travel via conventional quasiparticles, as it does in copper or doped silicon. The normal metallic state of the cuprate, it appeared, was anything but normal.

"This is a new way metals can conduct electricity that is not a bunch of quasiparticles flying around, which is the only well-understood and agreed-upon language so far," Shekhter said. "Most metals work like that."



National MagLab physicist Arkady Shekhter. Credit: Stephen Bilenky/National MagLab

If not by quasiparticles, exactly how is charge being carried in the strange metal phase of LSCO? The data suggests it may be some kind of team effort by the electrons.

Scientists have known for some time about an intriguing behavior of LSCO: In its normal conducting state, resistivity changes linearly with temperature. In other words, as the temperature goes up, LSCO's resistance to electrical current goes up proportionately, which is not the case in conventional metals.

Shekhter and his colleagues decided to test LSCO's resistivity, but using magnetic field as a parameter instead of temperature. They put the material in a very powerful magnet and measured resistivity in fields up to 80 teslas. (A hospital MRI magnet, by comparison, generates a field of about 3 teslas). They discovered another case of linear resistivity: As the strength of the magnetic field increased, LSCO's resistivity went up proportionately.

The fact that the linear-in-field resistivity mirrored so elegantly the previously known linear-in-temperature resistivity of LSCO is highly significant, Shekhter said.

"Usually when you see such things, that means that it's a very simple principle behind it," he said.

The finding suggests the electrons seem to cooperate as they move through the material. Physicists have believed for some time that HTS materials exhibit such a "correlated electron behavior" in the superconducting phase, although the precise mechanism is not yet understood.

This new evidence suggests that LSCO in its normal conducting state may also carry current using something other than independent quasiparticles—although it's not superconductivity, either. What that "something" is, scientists aren't yet certain. Finding the answer may require a whole new way of looking at the problem.

"Here we have a situation where no existing language can help," Shekhter said. "We need to find a new language to think about these [materials](#)."

The new research raises plenty of questions and some tantalizing ideas, including ideas about the fundamentally different way in which resistivity could be tuned in cuprates. In conventional metals, explained Shekhter, resistivity can be tuned in multiple ways—imagine a set of dials, any of which could adjust that property.

But in cuprates, Shekhter said, "There is only one dial to adjust [resistivity](#). And both temperature and magnetic [field](#), in their own way, access that one dial."

Odd, indeed. But from strange metals, one would expect nothing less. [33]

Uncovering the interplay between two famous quantum effects

The Casimir force and superconductivity are two well-known quantum effects. These phenomena have been thoroughly studied separately, but what happens when these effects are combined in a single experiment? Now, Delft University of Technology have created a microchip on which two wires were placed in close proximity in order to measure the Casimir forces that act upon them when they become superconducting.

Is vacuum really empty? Quantum mechanics tells us that it's actually swarming with particles. In the 1940s, Dutch physicists Hendrik Casimir and Dirk Polder predicted that when two objects are placed in very close proximity, about a thousandth of the diameter of a human hair, this sea of 'vacuum particles' pushes them together – a phenomenon known as the Casimir effect. This attractive force is present between all objects and even sets fundamental limits to how closely we can place components together on microchips.

Superconductivity is another well-known [quantum](#) phenomenon, also discovered by a Dutchman, Heike Kamerlingh Onnes, in the early 20th century. It describes how certain materials, such as aluminum or lead, allow electricity to flow through them without any resistance at [cryogenic temperatures](#). Over the last 100 years, superconductors have revolutionized our understanding of physics and are responsible for magnetically levitated trains, MRI scans and even mobile phone stations.

Out of reach

While the Casimir effect and superconductivity are both widely studied quantum phenomena, almost nothing is known about the interplay between the two, and this is where some physicists think some of the next scientific breakthroughs could lie. The Casimir force has been conclusively demonstrated between various materials. However, using superconductors to measure the effect has remained out of reach due to immense technological challenges at ultra-cold temperatures.

In a new publication in *Physical Review Letters*, researchers from Delft University of Technology have introduced a novel state-of-the-art sensor that allows them to measure the forces between closely spaced superconductors for the first time. The sensor consists of a microchip on which two strings are placed in close proximity. These wires can then be cooled down to cryogenic temperatures, making them superconducting. "The strings have holes in the centre that act as an optical resonator," said group leader Simon Gröblacher. "Laser light of a certain wavelength gets trapped in there. We can use this light to measure small displacements between the two wires, which means that we can measure the forces that are acting upon them at any temperature."

Additional tests

With their unprecedented force sensitivity, the researchers are also able to probe some highly speculative theories of quantum gravity at temperatures near absolute zero—a holy grail of physics. "We could disprove one of the more unlikely and controversial quantum gravity theories, which predicted that we should see a strong Casimir-like effect due to gravitational fields bouncing off the superconductors," said Richard Norte, the first author of the paper. "We measured no such effect with our current sensitivity." If there is a gravitational Casimir effect, it is more subtle than this theory predicted.

The new microchips pave the way for further experiments in an uncharted territory of science where these two famous quantum effects collide. The researchers hope to further increase the sensitivity of their microchip sensors in the near future and potentially probe the Casimir effect between high-temperature superconductors. It remains an open question how, exactly, superconductivity works in these exotic materials, and Casimir experiments could illuminate the underlying physics. [32]

The relationship between charge density waves and superconductivity? It's complicated

For a long time, physicists have tried to understand the relationship between a periodic pattern of conduction electrons called a charge density wave (CDW), and another quantum order, superconductivity, or zero electrical resistance, in the same material. Do they compete? Co-exist? Co-operate? Do they go their separate ways?

For the first time, physicists at Ames Laboratory and their international collaborators were able to explore that relationship in the superconducting and CDW material niobium diselenide (NbSe_2), through experiments using swift electron bombardment.

"What we are doing is 'poking' the system by introducing disorder into the crystal lattice," said Ames Laboratory scientist Ruslan Prozorov. "By knocking out some of the ions, impacting electrons create defects in the material. Both quantum ordered states (CDW and superconductivity) respond in certain ways to these additional defects, which we can measure."

The research, which included resistivity measurements, London penetration depth studies, and X-ray diffraction, showed that the relationship between CDW and superconductivity is complicated—in some ways the two states compete with each other, and in others, CDW assists superconductivity.

"Charge density wave competes with superconductivity for the same conduction electrons," said Prozorov. "As CDW is suppressed or disrupted, superconductivity is grabbing the electrons needed to form Cooper's pairs, which form superconducting condensate."

But CDW also assists superconductivity through its coupling to crystal lattice vibrations, called phonons. And phonons act as a "glue" between electrons to form a Cooper pair. At some threshold level of disorder, long-range ordered CDW disappears abruptly, and superconducting transition temperature is abruptly reduced as well.

"It is very important to understand the factors that influence superconductivity, in particular its critical temperature," said Prozorov. "Room temperature superconductors of future technologies will most likely be artificially assembled from individual atoms and single atomic layers fully utilizing basic mechanisms that lead to the enhancement of useful properties. Our research is a step in that direction."

The research is further discussed in the paper, "Using controlled disorder to probe the interplay between charge order and [superconductivity](#) in NbSe₂," authored by Kyuil Cho, M. Kończykowski, S. Teknowijoyo, M.A. Tanatar, J. Guss, P.B. Gartin, J. Wilde, A. Kreyssig, R. McQueeney, A. Goldman, V. Mishra, P.J. Hirschfeld and R. Prozorov; and published in the *Nature Communications*. [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-T_c) 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_c 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 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]

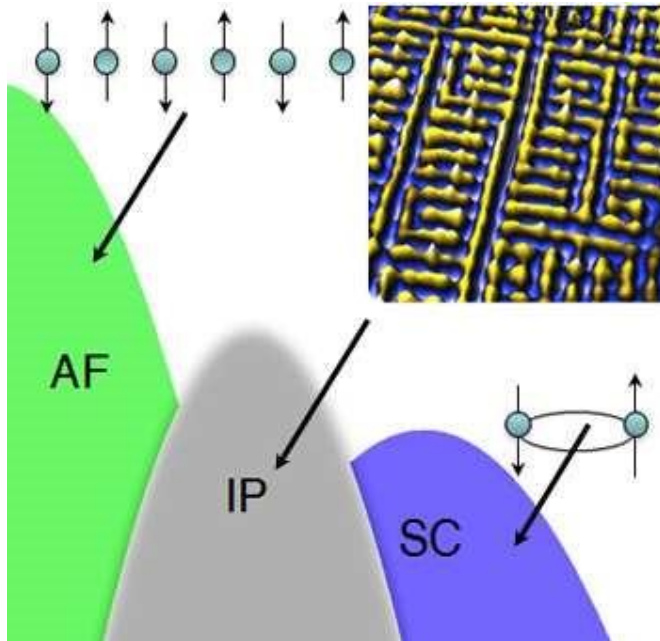
Strongly correlated materials

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. $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. 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_c 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_c superconductors—sometimes appearing to compete with superconductivity and sometimes coexisting with it. [24]

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

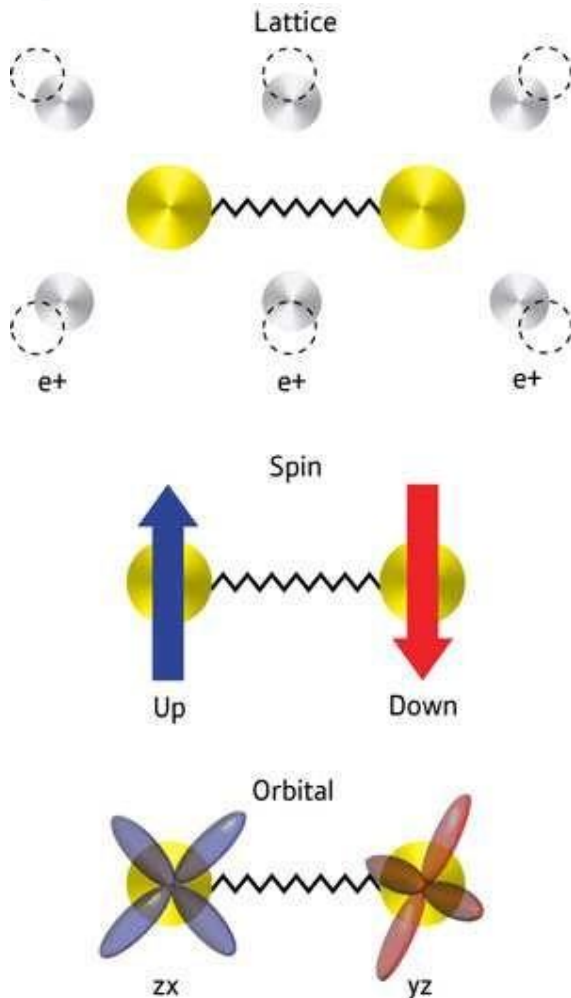
Unconventional superconductivity (SC) is said to occur when Cooper pair formation is dominated by repulsive electron–electron interactions, so that the symmetry of the pair wave function is other than an isotropic s-wave. The strong, on-site, repulsive electron–electron interactions that are the proximate 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, \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 ψ^\dagger creates a new boson at the same point. The wavefunction of the Bose–Einstein condensate is then the expectation value $\langle \psi \rangle$ 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 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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