Insulator with Conducting Edges

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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 Excitonmediated 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

Novel insulators with conducting edges

Physicists at the University of Zurich are researching a new class of materials: Higher-order topological insulators. The edges of these crystalline solids conduct electric current without dissipation, while the rest of the crystal remains insulating. This could be useful for applications in semiconductor technology and for building quantum computers.

Topology examines the properties of objects and solids that are protected against perturbations and deformations. Materials known so far include topological insulators, which are crystals that insulate on the inside but conduct electrical current on their surface. The conducting surfaces are topologically protected, which means that they cannot easily be brought into an insulating state.

Theoretical physicists at the University of Zurich have now predicted a new class of topological insulators with conducting properties on the edges of crystals rather than on the surface. The research team, made up of scientists from UZH, Princeton University, the Donostia International Physics Center and the Max Planck Institute of Microstructure Physics in Halle, dubbed the new material class "higher-order topological insulators." The extraordinary robustness of the conducting edges makes them particularly interesting: The current of topological electrons cannot be stopped by disorder or impurities. If an imperfection gets in the way of the current, it simply flows around the impurity.

In addition, the crystal edges do not have to be specially prepared to conduct electrical current. If the crystal breaks, the new edges automatically also conduct current. "The most exciting aspect is that electricity can at least in theory be conducted without any dissipation," says Titus Neupert, professor at the Department of Physics at UZH. "You could think of the crystal edges as a kind of highway for electrons. They can't simply make a U-turn." This property of dissipationless conductance, otherwise known from superconductors at low temperatures, is not shared with the previously known topological insulator crystals that have conducting surfaces, but is specific to the higher-order topological crystals.

The physicists' study still mostly relies on theoretical aspects. They have proposed tin telluride as the first compound to show these novel properties. "More material candidates have to be identified and probed in experiments," says Neupert. The researchers hope that in the future nanowires made of higher-order topological insulators may be used as conducting paths in electric circuits. They could be combined with magnetic and superconducting materials and used for building quantum computers. [35]

When rotated at a 'magic angle,' graphene sheets can form an insulator or a superconductor

It's hard to believe that a single material can be described by as many superlatives as graphene can. Since its discovery in 2004, scientists have found that the lacy, honeycomb-like sheet of carbon atoms - essentially the most microscopic shaving of pencil lead you can imagine - is not just the thinnest material known in the world, but also incredibly light and flexible, hundreds of times stronger than steel, and more electrically conductive than copper.

Now physicists at MIT and Harvard University have found the wonder material can exhibit even more curious electronic properties. In two papers published today in *Nature*, the team reports it can tune graphene to behave at two electrical extremes: as an insulator, in which electrons are completely blocked from flowing; and as a superconductor, in which electrical current can stream through without resistance.

Researchers in the past, including this team, have been able to synthesize graphene superconductors by placing the material in contact with other superconducting metals - an arrangement that allows graphene to inherit some superconducting behaviors. This time around, the team found a way to make graphene superconduct on its own, demonstrating that superconductivity can be an intrinsic quality in the purely carbon-based material.

The physicists accomplished this by creating a "superlattice" of two graphene sheets stacked together - not precisely on top of each other, but rotated ever so slightly, at a "magic angle" of 1.1 degrees. As a result, the overlaying, hexagonal honeycomb pattern is offset slightly, creating a precise moiré configuration that is predicted to induce strange, "strongly correlated interactions" between the electrons in the graphene sheets. In any other stacked configuration, graphene prefers to remain distinct, interacting very little, electronically or otherwise, with its neighboring layers.

The team, led by Pablo Jarillo-Herrero, an associate professor of physics at MIT, found that when rotated at the magic angle, the two sheets of graphene exhibit nonconducting behavior, similar to an exotic class of materials known as Mott insulators. When the researchers then applied voltage, adding small amounts of electrons to the graphene superlattice, they found that, at a certain level, the electrons broke out of the initial insulating state and flowed without resistance, as if through a superconductor.

"We can now use graphene as a new platform for investigating unconventional superconductivity," Jarillo-Herrero says. "One can also imagine making a superconducting transistor out of graphene, which you can switch on and off, from superconducting to insulating. That opens many possibilities for quantum devices."

A 30-year gap

A material's ability to conduct electricity is normally represented in terms of energy bands. A single band represents a range of energies that a material's electrons can have. There is an energy gap between bands, and when one band is filled, an electron must embody extra energy to overcome this gap, in order to occupy the next empty band.

A material is considered an insulator if the last occupied energy band is completely filled with electrons. Electrical conductors such as metals, on the other hand, exhibit partially filled energy bands, with empty energy states which the electrons can fill to freely move.

Mott insulators, however, are a class of materials that appear from their band structure to conduct electricity, but when measured, they behave as insulators. Specifically, their energy bands are half-filled, but because of strong electrostatic interactions between electrons (such as charges of equal sign repelling each other), the material does not conduct electricity. The half-filled band essentially splits into two miniature, almost-flat bands, with electrons completely occupying one band and leaving the other empty, and hence behaving as an insulator.

"This means all the electrons are blocked, so it's an insulator because of this strong repulsion between the electrons, so nothing can flow," Jarillo-Herrero explains. "Why are Mott insulators important? It turns out the parent compound of most high-temperature superconductors is a Mott insulator."

In other words, scientists have found ways to manipulate the electronic properties of Mott insulators to turn them into superconductors, at relatively high temperatures of about 100 Kelvin. To do this, they chemically "dope" the material with oxygen, the atoms of which attract electrons out of the Mott insulator, leaving more room for remaining electrons to flow. When enough oxygen is added, the insulator morphs into a superconductor. How exactly this transition occurs, Jarillo-Herrero says, has been a 30-year mystery.

"This is a problem that is 30 years and counting, unsolved," Jarillo-Herrero says. "These high-temperature superconductors have been studied to death, and they have many interesting behaviors. But we don't know how to explain them."

A precise rotation

Jarillo-Herrero and his colleagues looked for a simpler platform to study such unconventional physics. In studying the electronic properties in graphene, the team began to play around with simple stacks of graphene sheets. The researchers created two-sheet superlattices by first exfoliating a single flake of graphene from graphite, then carefully picking up half the flake with a glass slide coated with a sticky polymer and an insulating material of boron nitride.

They then rotated the glass slide very slightly and picked up the second half of the graphene flake, adhering it to the first half. In this way, they created a superlattice with an offset pattern that is distinct from graphene's original honeycomb lattice.

The team repeated this experiment, creating several "devices," or graphene superlattices, with various angles of rotation, between 0 and 3 degrees. They attached electrodes to each device and measured an electrical current passing through, then plotted the device's resistance, given the amount of the original current that passed through.

"If you are off in your rotation angle by 0.2 degrees, all the physics is gone," Jarillo-Herrero says. "No superconductivity or Mott insulator appears. So you have to be very precise with the alignment angle."

At 1.1 degrees - a rotation that has been predicted to be a "magic angle" - the researchers found the graphene superlattice electronically resembled a flat band structure, similar to a Mott insulator, in which all electrons carry the same energy regardless of their momentum.

"Imagine the momentum for a car is mass times velocity," Jarillo-Herrero says. "If you're driving at 30 miles per hour, you have a certain amount of kinetic energy. If you drive at 60 miles per hour, you have much higher energy, and if you crash, you could deform a much bigger object. This thing is saying, no matter if you go 30 or 60 or 100 miles per hour, they would all have the same energy."

"Current for free"

For electrons, this means that, even if they are occupying a half-filled energy band, one electron does not have any more energy than any other electron, to enable it to move around in that band. Therefore, even though such a half-filled band structure should act like a conductor, it instead behaves as an insulator - and more precisely, a Mott insulator.

This gave the team an idea: What if they could add electrons to these Mott-like superlattices, similar to how scientists doped Mott insulators with oxygen to turn them into superconductors? Would graphene assume superconducting qualities in turn?

To find out, they applied a small gate voltage to the "magic-angle graphene superlattice," adding small amounts of electrons to the structure. As a result, individual electrons bound together with other electrons in graphene, allowing them to flow where before they could not. Throughout, the researchers continued to measure the electrical resistance of the material, and found that when they added a certain, small amount of electrons, the electrical current flowed without dissipating energy - just like a superconductor.

"You can flow current for free, no energy wasted, and this is showing graphene can be a superconductor," Jarillo-Herrero says.

Perhaps more importantly, he says the researchers are able to tune graphene to behave as an insulator or a superconductor, and any phase in between, exhibiting all these diverse properties in one single device. This is in contrast to other methods, in which scientists have had to grow and manipulate hundreds of individual crystals, each of which can be made to behave in just one electronic phase.

"Usually, you have to grow different classes of materials to explore each phase," Jarillo-Herrero says. "We're doing this in-situ, in one shot, in a purely carbon device. We can explore all those physics in one device electrically, rather than having to make hundreds of devices. It couldn't get any simpler." [34]

Bringing a hidden superconducting state to light

A team of scientists has detected a hidden state of electronic order in a layered material containing lanthanum, barium, copper, and oxygen (LBCO). When cooled to a certain temperature and with certain concentrations of barium, LBCO is known to conduct electricity without resistance, but now there is evidence that a superconducting state actually occurs above this temperature too. It was just a matter of using the right tool—in this case, highintensity pulses of infrared light—to be able to see it.

Reported in a paper published in the Feb. 2 issue of *Science*, the team's finding provides further insight into the decades-long mystery of superconductivity in LBCO and similar compounds containing copper and oxygen layers sandwiched between other elements. These "cuprates" become superconducting at relatively higher temperatures than traditional superconductors, which must be frozen to near absolute zero (minus 459 degrees Fahrenheit) before their electrons can flow through them at 100-percent efficiency. Understanding why cuprates behave the way they do could help scientists design better high-temperature superconductors, eliminating the cost of expensive cooling systems and improving the efficiency of power generation, transmission, and distribution. Imagine computers that never heat up and power grids that never lose energy.

"The ultimate goal is to achieve superconductivity at room temperature," said John Tranquada, a physicist and leader of the Neutron Scatter Group in the Condensed Matter Physics and Materials Science Department at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, where he has been studying cuprates since the 1980s. "If we want to do that by design, we have to figure out which features are essential for superconductivity. Teasing out those features in such complicated materials as the cuprates is no easy task."

The copper-oxygen planes of LBCO contain "stripes" of electrical charge separated by a type of magnetism in which the electron spins alternate in opposite directions. In order for LBCO to become superconducting, the individual electrons in these stripes need to be able to pair up and move in unison throughout the material.

Previous experiments showed that, above the temperature at which LBCO becomes superconducting, resistance occurs when the electrical transport is perpendicular to the planes but is zero when the transport is parallel. Theorists proposed that this phenomenon might be the consequence of an unusual spatial modulation of the superconductivity, with the amplitude of the superconducting state oscillating from positive to negative on moving from one charge stripe to the next. The stripe pattern rotates by 90 degrees from layer to layer, and they thought that this relative orientation was blocking the superconducting electron pairs from moving coherently between the layers.

"This idea is similar to passing light through a pair of optical polarizers, such as the lenses of certain sunglasses," said Tranquada. "When the polarizers have the same orientation, they pass light, but when their relative orientation is rotated to 90 degrees, they block all light."

However, a direct experimental test of this picture had been lacking—until now.

One of the challenges is synthesizing the large, high-quality single crystals of LBCO needed to conduct experiments. "It takes two months to grow one crystal, and the process requires precise control over temperature, atmosphere, chemical composition, and other conditions," said coauthor Genda Gu, a physicist in Tranquada's group. Gu used an infrared image furnace—a machine with two bright lamps that focus infrared light onto a cylindrical rod containing the starting material, heating it to nearly 2500 degrees Fahrenheit and causing it to melt—in his crystal growth lab to grow the LBCO crystals.

Collaborators at the Max Planck Institute for the Structure and Dynamics of Matter and the University of Oxford then directed infrared light, generated from high-intensity laser pulses, at the crystals (with the light polarization in a direction perpendicular to the planes) and measured the intensity of light reflected back from the sample. Besides the usual response—the crystals reflected the same frequency of light that was sent in—the scientists detected a signal three times higher than the frequency of that incident light.

"For samples with three-dimensional superconductivity, the superconducting signature can be seen at both the fundamental frequency and at the third harmonic," said Tranquada. "For a sample in which charge stripes block the superconducting current between layers, there is no optical signature at the fundamental frequency. However, by driving the system out of equilibrium with the intense infrared light, the scientists induced a net coupling between the layers, and the superconducting signature shows up in the third harmonic. We had suspected that the electron pairing was present—it just required a stronger tool to bring this superconductivity to light."

University of Hamburg theorists supported this experimental observation with analysis and numerical simulations of the reflectivity.

This research provides a new technique to probe different types of electronic orders in hightemperature superconductors, and the new understanding may be helpful in explaining other strange behaviors in the cuprates. [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 gratly enhances the superconductivity of cuprates and may shed light on the origins of hightemperature 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 hightemperature 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 Th2N2 and FeAs2 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 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 FeAs2 layers.

The close relationship between local structure of the FeAs4 tetrahedron and the superconducting temperature, suggested TheFeAsN 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 CeRhIn5 revealed a so-called electronic nematic state, in which the material's electrons aligned in a way to reduce the symmetry of the original crystal, something that now appears to be universal among unconventional superconductors. Unconventional superconductivity develops near a phase boundary separating magnetically ordered and magnetically disordered phases of a material.

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

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

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

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

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

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

Superconductivity seen in a new light

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

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

Coexistence rather than competition

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

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

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

A new dimension to high-temperature superconductivity discovered

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

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

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

'Totally Unexpected' Physics

"This was totally unexpected, and also very exciting. This experiment has identified a new ingredient to consider in this field of study. Nobody had seen this 3-D picture before," said Jun-Sik Lee, a SLAC staff scientist and one of the leaders of the experiment conducted at SLAC's Linac Coherent Light Source (LCLS) X-ray laser. "This is an important step in understanding the physics of hightemperature superconductors."

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

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

The New Wave in Superconductivity

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

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

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

A Powerful Blend of Magnetism and Light

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

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

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

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

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

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

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

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

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

In Search of Common Links

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

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

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

Scientists Discover Hidden Magnetic Waves in High-Temperature Superconductors

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

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

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

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

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

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

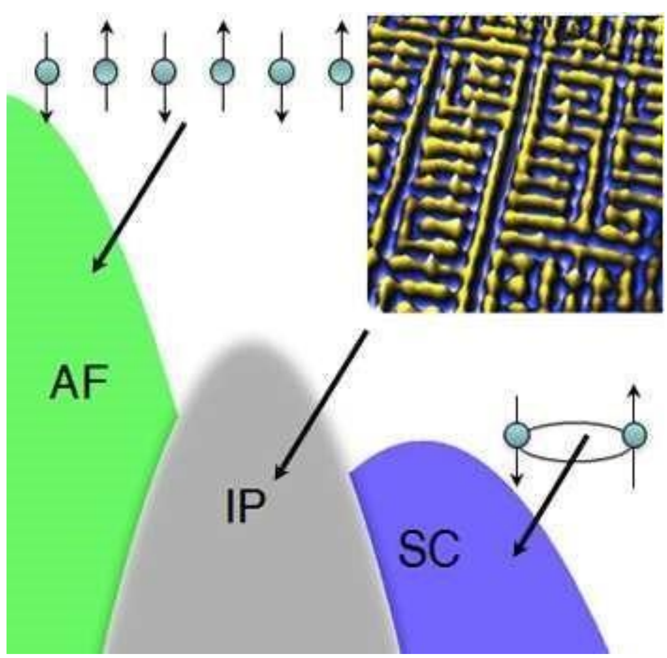
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

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

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

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

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

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

A grand unified theory of exotic superconductivity?

The role of magnetism

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

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

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

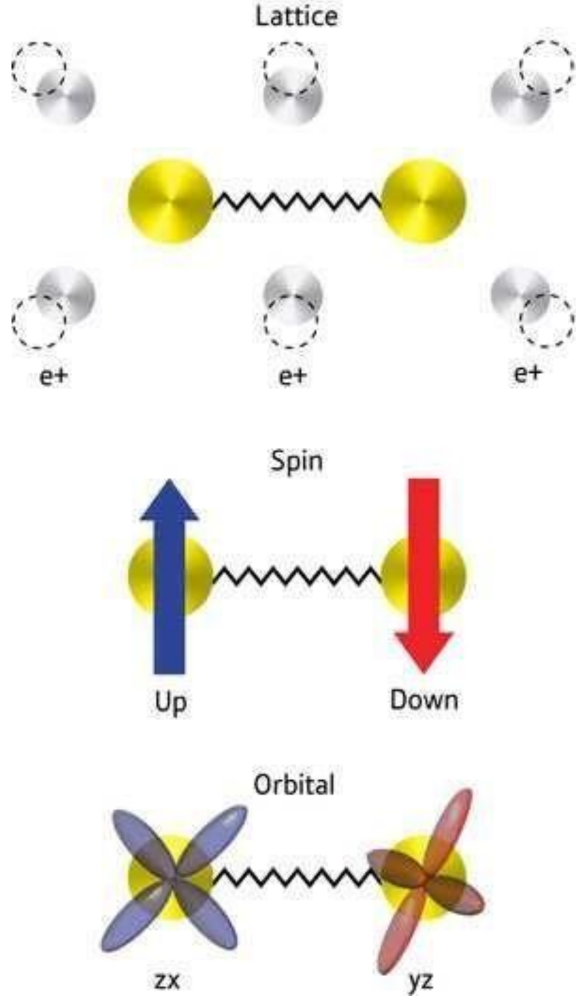
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

Significance

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

Superconductivity's third side unmasked



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

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

Strongly correlated materials

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

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

Fermions and Bosons

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

The General Weak Interaction

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

Higgs Field and Superconductivity

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

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

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

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

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

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

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

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

$$\psi \to e^{iq\phi(x)}\psi$$
$$A \to A + \nabla\phi.$$

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

The condensate wave function can be written as

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

where ρ is real amplitude, which determines the local density of the condensate. If the condensate were neutral, the flow would be along the gradients of θ, the direction in which the phase of the Schrödinger field changes. If the phase θ changes slowly, the flow is slow and has very little energy. But now θ can be made equal to zero just by making a gauge transformation to rotate the phase of the field.

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

Superconductivity and Quantum Entanglement

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

Conclusions

On the atomic scale, electron spins—a bit like tiny bar magnets pointed in specific directions—rapidly interact with each other throughout magnetic materials. When one spin rotates, this disturbance can propagate through the material as a wave, tipping and aligning the spins of neighboring electrons. Many researchers believe that this subtle excitation wave may bind electrons together to create the perfect current conveyance of HTS, which operates at slightly warmer temperatures than traditional superconductivity. [27]

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

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

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

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

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

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