Charge Density Wave in Superconductor

An international team led by scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University has detected new features in the electronic behavior of a copper oxide material that may help explain why it becomes a perfect electrical conductor – a superconductor – at relatively high temperatures. [32]

An artistic representation of the data showing the breaking of spatial inversion and rotational symmetries in the pseudogap region of superconducting materials -- evidence that the pseudogap is a distinct phase of matter. [31]

Superconductivity is a state in a material in which there is no resistance to electric current and all magnetic fields are expelled. This behavior arises from a so-called "macroscopic quantum state" where all the electrons in a material act in concert to move cooperatively through the material without energy loss. [30]

Harvard researchers found a way to transmit spin information through superconducting materials. [29]

Researchers at the National Institute of Information and Communications Technology, in collaboration with researchers at the Nippon Telegraph and Telephone Corporation and the Qatar Environment and Energy Research Institute have discovered qualitatively new states of a superconducting artificial atom dressed with virtual photons. [28]

A group of scientists from Moscow Institute of Physics and Technology and from the Moscow State University has developed a fundamentally new type of memory cell based on superconductors – this type of memory works hundreds of times faster than the memory devices commonly used today, according to an article published in the journal Applied Physics Letters. [27]

Superconductivity is a rare physical state in which matter is able to conduct electricity—maintain a flow of electrons—without any resistance. It can only be found in certain materials, and even then it can only be achieved under controlled conditions of low temperatures and high pressures. New research from a team including Carnegie's Elissaios Stavrou, Xiao-Jia Chen, and Alexander Goncharov hones in on the structural changes underlying superconductivity in iron arsenide compounds—those containing iron and arsenic. [26]

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.

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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

Propagating "charge density wave" fluctuations are seen in superconducting copper oxides for the first time

An international team led by scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University has detected new features in the electronic behavior of a copper oxide material that may help explain why it becomes a perfect electrical conductor – a superconductor – at relatively high temperatures.

Using an ultrahigh-resolution X-ray instrument in France, the researchers for the first time saw dynamic behaviors in the material's charge density wave (CDW) – a pattern of electrons that resembles a standing wave – that lend support to the idea that these waves may play a role in high-temperature superconductivity.

Data taken at low (20 kelvins) and high (240 kelvins) temperatures showed that as the temperature increased, the CDW became more aligned with the material's atomic structure. Remarkably, at the lower temperature, the CDW also induced an unusual increase in the intensity of the oxide's atomic lattice vibrations, indicating that the dynamic CDW behaviors can propagate through the lattice.

"Previous research has shown that when the CDW is static, it competes with and diminishes superconductivity," said co-author Wei-Sheng Lee, a SLAC staff scientist and investigator with the Stanford Institute for Materials and Energy Sciences (SIMES), which led the study published June 12 in Nature Physics. "If, on the other hand, the CDW is not static but fluctuating, theory tells us they may actually help form superconductivity."

A Decades-long Search for an Explanation

The new result is the latest in a decades-long search by researchers worldwide for the factors that enable certain materials to become superconducting at relatively high temperatures.

Since the 1950s, scientists have known how certain metals and simple alloys become superconducting when chilled to within a few degrees of absolute zero: Their electrons pair up and ride waves of atomic vibrations that act like a virtual glue to hold the pairs together. Above a certain temperature, however, the glue fails as thermal vibrations increase, the electron pairs split up and superconductivity disappears.

In 1986, complex copper oxide materials were found to become superconducting at much higher – although still quite cold – temperatures. This discovery was so unexpected it caused a worldwide scientific sensation. By understanding and optimizing how these materials work, researchers hope to develop superconductors that work at room temperature and above.

At first, the most likely glue holding superconducting electron pairs together at higher temperatures seemed to be strong magnetic excitations created by interactions between electron spins. But in 2014, a theoretical simulation and experiments led by SIMES researchers concluded that these high-energy magnetic interactions are not the sole factor in copper oxide's high-temperature superconductivity. An unanticipated CDW also appeared to be important.

The latest results continue the SIMES collaboration between experiment and theory. Building upon previous theories of how electron interactions with lattice vibrations can be probed with resonant inelastic X-ray scattering, or RIXS, the signature of CDW dynamics was finally identified, providing additional support for the CDW's role in determining the electronic structure in superconducting copper oxides.

The Essential New Tool: RIXS

The new results are enabled by the development of more capable instruments employing RIXS. Now available at ultrahigh resolution at the European Synchrotron Radiation Facility (ESRF) in France, where the team performed this experiment, RIXS will also be an important feature of SLAC's upgraded Linac Coherent Light Source X-ray free-electron laser, LCLS-II. The combination of ultrahigh energy resolution and a high pulse repetition rate at LCLS-II will enable researchers to see more detailed CDW fluctuations and perform experiments aimed at revealing additional details of its behavior and links to high-temperature superconductivity. Most importantly, researchers at LCLS-II will be able to use ultrafast light-matter interactions to control CDW fluctuations and then take femtosecond-timescale snapshots of them.

RIXS involves illuminating a sample with X-rays that have just enough energy to excite some electrons deep inside the target atoms to jump up into a specific higher orbit. When the electrons relax back down into their previous positions, a tiny fraction of them emit X-rays that carry valuable atomic-scale information about the material's electronic and magnetic configuration that is thought to be important in high-temperature superconductivity.

"To date, no other technique has seen evidence of propagating CDW dynamics," Lee said.

RIXS was first demonstrated in the mid-1970s, but it could not obtain useful information to address key problems until 2007, when Giacomo Ghiringhelli, Lucio Braicovich at Milan Polytechnic in Italy and colleagues at Swiss Light Source made a fundamental change that improved its energy resolution to a level where significant details became visible – technically speaking to about 120 milli-electronvolts (meV) at the relevant X-ray wavelength, which is called a copper L edge. The new RIXS instrument at ESRF is three times better, routinely attaining an energy resolution down to 40 meV. Since 2014, the Milan group has collaborated with SLAC and Stanford scientists in their RIXS research.

"The new ultrahigh resolution RIXS makes a huge difference," Lee said. "It can show us previously invisible details." [32]

New clues emerge in 30-year-old superconductor mystery

One of the greatest mysteries of experimental physics is how so-called high-temperature superconducting materials work. Despite their name, high-temperature superconductors—materials that carry electrical current with no resistance—operate at chilly temperatures less than minus 135 degrees Celsius. They can be used to make superefficient power cables, medical MRIs, particle accelerators, and other devices. Cracking the mystery of how these materials actually work could lead to superconducting devices that operate at room temperatures—and could revolutionize electrical devices, including laptops and phones.

In a new paper in the journal Nature Physics, researchers at Caltech have at last solved one piece of this enduring puzzle. They have confirmed that a transitional phase of matter called the pseudogap—one that occurs before these materials are cooled down to become superconducting—represents a distinct state of matter, with properties very different from those of the superconducting state itself.

When matter transitions from one state, or phase, to another—say, water freezing into ice—there is a change in the ordering pattern of the materials' particles. Physicists previously had detected hints of some type of ordering of electrons inside the pseudogap state. But exactly how they were ordering—and whether that ordering constituted a new state of matter—was unclear until now.

"A peculiar property of all these high-temperature superconductors is that just before they enter the superconducting state, they invariably first enter the pseudogap state, whose origins are equally if not more mysterious than the superconducting state itself," says David Hsieh, professor of physics at

Caltech and principal investigator of the new research. "We have discovered that in the pseudogap state, electrons form a highly unusual pattern that breaks nearly all of the symmetries of space. This provides a very compelling clue to the actual origin of the pseudogap state and could lead to a new understanding of how high-temperature superconductors work."

The phenomenon of superconductivity was first discovered in 1911. When certain materials are chilled to super-cold temperatures, as low as a few degrees above absolute zero (a few degrees Kelvin), they carry electrical current with no resistance, so that no heat or energy is lost. In contrast, our laptops are not made of superconducting materials and therefore experience electrical resistance and heat up.

Chilling materials to such extremely low temperatures requires liquid helium. However, because liquid helium is rare and expensive, physicists have been searching for materials that can function as superconductors at ever-higher temperatures. The so-called high-temperature superconductors, discovered in 1986, are now known to operate at temperatures up to 138 Kelvin (minus 135 degrees Celsius) and thus can be cooled with liquid nitrogen, which is more affordable than liquid helium. The question that has eluded physicists, however—despite three Nobel Prizes to date awarded in the field of superconductivity—is exactly how high-temperatures superconductors work.

The dance of superconducting electrons

Materials become superconducting when electrons overcome their natural repulsion and form pairs. This pairing can occur under extremely cold temperatures, allowing the electrons, and the electrical currents they carry, to move unencumbered. In conventional superconductors, electron pairing is caused by natural vibrations in the crystal lattice of the superconducting material, which act like glue to hold the pairs together.

But in high-temperature superconductors, this form of "glue" is not strong enough to bind the electron pairs. Researchers think that the pseudogap, and how electrons order themselves in this phase, holds clues about what this glue may constitute for high-temperature superconductors. To study electron ordering in the pseudogap, Hsieh and his team have invented a new laser-based method called nonlinear optical rotational anisotropy. In the method, a laser is pointed at the superconducting material; in this case, crystals of ytttrium barium copper oxide (YBa2Cu3Oy). An analysis of the light reflected back at half the wavelength compared to that going in reveals any symmetry in the arrangement of the electrons in the crystals.

Broken symmetries point to new phase

Different phases of matter have distinct symmetries. For example, when water turns into ice, physicists say the symmetry has been "broken."

"In water," Hsieh explains, "the H2O molecules are pretty randomly oriented. If you were swimming in an infinite pool of water, your surroundings look the same no matter where you are. In ice, on the other hand, the H2O molecules form a regular periodic network, so if you imagine yourself submerged in an infinite block of ice, your surroundings appear different depending on whether you are sitting on an H or O atom. Therefore, we say that the translational symmetry of space is broken in going from water to ice."

With the new tool, Hsieh's team was able to show that the electrons cooled to the pseudogap phase broke a specific set of spatial symmetries called inversion and rotational symmetry. "As soon as the system entered the pseudogap region, either as a function of temperature or the amount of oxygen in the compound, there was a loss of inversion and rotational symmetries, clearly indicating a transition into a new phase of matter," says Liuyan Zhao, a postdoctoral scholar in the Hsieh lab and lead author of the new study. "It is exciting that we are using a new technology to solve an old problem."

"The discovery of broken inversion and rotational symmetries in the pseudogap drastically narrows down the set of possibilities for how the electrons are self-organizing in this phase," says Hsieh. "In some ways, this unusual phase may turn out to be the most interesting aspect of these superconducting materials."

With one piece of the puzzle solved, the researchers are on to the next. They want to know what role this ordering of electrons in the pseudogap plays in inducing high-temperature superconductivity—and how to make it happen at even higher temperatures. [31]

Manipulating quantum order

Cool a material to sufficiently low temperatures and it will seek some form of collective order. Add quantum mechanics or confine the geometry and the states of matter that emerge can be exotic, including electrons whose spins arrange themselves in spirals, pinwheels, or crystals.

In a recent pair of publications in Nature Communications, teams led by Caltech's Thomas F. Rosenbaum, professor of physics and holder of the Sonja and William Davidow Presidential Chair, report how they have combined magnetic fields and large pressures to not only induce these states at ultra-low temperatures, but also to nudge them between competing types of quantum order.

Rosenbaum is an expert on the quantum mechanical nature of materials—the physics of electronic, magnetic, and optical materials at the atomic level—that are best observed at temperatures near absolute zero. In the first of the two papers, published in June and led by Sara Haravifard, now on the faculty at Duke University, the team squeezed a collection of magnetic quantum particles in a pressure cell at temperatures near absolute zero and at magnetic fields more than 50,000 times stronger than the earth's field, and discovered the formation of new types of crystal patterns. The geometry of these crystal patterns not only reveals the underlying quantum mechanics of the interactions between the magnetic particles, but also bears on the kinds of collective states allowed for atomic systems, such as those that flow without friction.

In the work in the second paper, published in October and led by Caltech graduate student Yishu Wang and Argonne scientist Yejun Feng, Rosenbaum and colleagues also investigate how materials balance on the knife edge between different types of quantum order. In this case, however, the researchers focus on the relationship between magnetism and superconductivity—the complete disappearance of electrical resistance—and how those properties relate to one another when the material changes state under the pressures achievable in a diamond anvil cell.

The researchers used the Advanced Photon Source at Argonne National Laboratory to study the magnetic properties of the transition metal manganese phosphide (MnP) to see how it might be possible to manipulate the ordering of the spins—the intrinsic magnetic moments of the electrons—to either enhance or suppress the onset of superconductivity.

Superconductivity is a state in a material in which there is no resistance to electric current and all magnetic fields are expelled. This behavior arises from a so-called "macroscopic quantum state" where all the electrons in a material act in concert to move cooperatively through the material without energy loss.

Rosenbaum and his colleagues delineated a spiral pattern of the magnetic moments of the electrons in MnP that could be tuned by increasing pressure to induce superconductivity. Here again the particular geometry of the magnetic pattern held the key to the ultimate state that the material reached. "The experiments reveal manifest opportunities to find new low-energy states via substitutions for manganese and phosphorus with neighboring elements from the periodic table such as chromium and arsenic. The taxonomy of allowable quantum states and the ability to manipulate them unites approaches across quantum physics and technology," Rosenbaum says.

The first paper, "Crystallization of spin superlattices with pressure and field in the layered magnet SrCu2(BO3)2," was published on June 20, 2016. Coauthors include Daniel M. Silevitch, research professor of physics at Caltech. Work at Caltech was supported by the National Science Foundation. The research in the second paper, entitled "Spiral magnetic order and pressure-induced superconductivity in transition metal compounds" and published on October 6, was funded at Caltech by a U.S. Department of Energy Basic Energy Sciences award. [30]

Physicists pass spin information through a superconductor

Researchers from the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) have made a discovery that could lay the foundation for quantum superconducting devices. Their breakthrough solves one the main challenges to quantum computing: how to transmit spin information through superconducting materials.

Every electronic device—from a supercomputer to a dishwasher—works by controlling the flow of charged electrons. But electrons can carry so much more information than just charge; electrons also spin, like a gyroscope on axis.

Harnessing electron spin is really exciting for quantum information processing because not only can an electron spin up or down—one or zero—but it can also spin any direction between the two poles. Because it follows the rules of quantum mechanics, an electron can occupy all of those positions at once. Imagine the power of a computer that could calculate all of those positions simultaneously.

A whole field of applied physics, called spintronics, focuses on how to harness and measure electron spin and build spin equivalents of electronic gates and circuits.

By using superconducting materials through which electrons can move without any loss of energy, physicists hope to build quantum devices that would require significantly less power.

But there's a problem.

According to a fundamental property of superconductivity, superconductors can't transmit spin. Any electron pairs that pass through a superconductor will have the combined spin of zero.

In work published recently in Nature Physics, the Harvard researchers found a way to transmit spin information through superconducting materials.

"We now have a way to control the spin of the transmitted electrons in simple superconducting devices," said Amir Yacoby, Professor of Physics and of Applied Physics at SEAS and senior author of the paper.

A new spin on superconductivity

It's easy to think of superconductors as particle super highways but a better analogy would be a super carpool lane as only paired electrons can move through a superconductor without resistance.

These pairs are called Cooper Pairs and they interact in a very particular way. If the way they move in relation to each other (physicists call this momentum) is symmetric, then the pair's spin has to be asymmetric—for example, one negative and one positive for a combined spin of zero. When they travel through a conventional superconductor, Cooper Pairs' momentum has to be zero and their orbit perfectly symmetrical.

But if you can change the momentum to asymmetric—leaning toward one direction—then the spin can be symmetric. To do that, you need the help of some exotic (aka weird) physics.

Superconducting materials can imbue non-superconducting materials with their conductive powers simply by being in close proximity. Using this principle, the researchers built a superconducting sandwich, with superconductors on the outside and mercury telluride in the middle. The atoms in mercury telluride are so heavy and the electrons move so quickly, that the rules of relativity start to apply.

"Because the atoms are so heavy, you have electrons that occupy high-speed orbits," said Hechen Ren, coauthor of the study and graduate student at SEAS.

"When an electron is moving this fast, its electric field turns into a magnetic field which then couples with the spin of the electron. This magnetic field acts on the spin and gives one spin a higher energy than another."

So, when the Cooper Pairs hit this material, their spin begins to rotate.

"The Cooper Pairs jump into the mercury telluride and they see this strong spin orbit effect and start to couple differently," said Ren. "The homogenous breed of zero momentum and zero combined spin is still there but now there is also a breed of pairs that gains momentum, breaking the symmetry of the orbit. The most important part of that is that the spin is now free to be something other than zero."

The team could measure the spin at various points as the electron waves moved through the material. By using an external magnet, the researchers could tune the total spin of the pairs.

"This discovery opens up new possibilities for storing quantum information. Using the underlying physics behind this discovery provides also new possibilities for exploring the underlying nature of superconductivity in novel quantum materials," said Yacoby. [29]

Stable molecular state of photons and artificial atom discovered

Researchers at the National Institute of Information and Communications Technology, in collaboration with researchers at the Nippon Telegraph and Telephone Corporation and the Qatar Environment and Energy Research Institute have discovered qualitatively new states of a superconducting artificial atom dressed with virtual photons. The discovery was made using spectroscopic measurements on an artificial atom that is very strongly coupled to the light field inside a superconducting cavity. This result provides a new platform to investigate the interaction between light and matter at a fundamental level, helps understand quantum phase transitions and provides a route to applications of non-classical light such as Schrödinger cat states. It may contribute to the development of quantum technologies in areas such as quantum communication, quantum simulation and computation, or quantum metrology.

This result will be published online in the October 10 issue of the journal Nature Physics.

The indispensable technologies in modern life such as a time system measured by an atomic clock and a secure and energy-efficient communications system are based on the fundamental science of the interaction between light and matter at the single-photon level. The absorption and emission of light from any device is explained based on the interaction of light and atoms. A fundamental question in atomic physics, "How strong can the coupling of light and an atom be?" has not been answered in spite of years of research, because it is not easy to find appropriate methods to realize very strong coupling.

It was predicted over forty years ago that if the coupling is extremely strong a qualitatively new lowest energy state (the ground state) of light and an atom should be realized. A debate soon started as to whether this prediction would still apply when realistic conditions are considered. A few years ago, our collaborator at QEERI, Dr. Sahel Ashhab, performed theoretical investigations and identified desirable conditions for achieving this new state using superconducting circuits.

In the experiment, we used a microfabricated superconducting harmonic oscillator and a superconducting artificial atom (quantum bit or qubit) whose electronic states behave quantum mechanically, just like a natural atom. By carefully designing a superconducting persistent-current qubit interacting with an LC harmonic oscillator that has a large zero-point fluctuation current via a large shared Josephson inductance, we found the new ground state as predicted theoretically.

The total energy of the qubit and the oscillator is the sum of the photon energy in the oscillator, the qubit energy, and the coupling energy binding the photons to the qubit. Taking advantage of the macroscopic quantum system, we could realize circuits with coupling energy larger than both the photon energy and the qubit energy.

This situation is sometimes called 'deep strong coupling'.

In addition, we have observed that the transitions between energy levels are governed by selection rules stemming from the symmetry of the entangled energy eigenstates, including the ground state.

We plan to test whether deep strong coupling is possible or not using more than one superconducting artificial atom (qubit), which remains a question of debate.

We will also try to actively manipulate this new molecular state of photons and artificial atoms, for example, to observe and control the dynamics of photon absorption and emission, and to demonstrate new methods of entanglement generation. [28]

Scientists develop a control system for rapid superconducting memory cells

A group of scientists from Moscow Institute of Physics and Technology and from the Moscow State University has developed a fundamentally new type of memory cell based on superconductors – this type of memory works hundreds of times faster than the memory devices commonly used today, according to an article published in the journal Applied Physics Letters.

"With the operational function that we have proposed in these memory cells, there will be no need for time-consuming magnetization and demagnetization processes. This means that read and write operations will take only a few hundred picoseconds, depending on the materials and the geometry of the particular system, while conventional methods take hundreds or thousands of times longer than this," said the study author Alexander Golubov, the head of MIPT's Laboratory of Quantum Topological Phenomena in Superconducting Systems.

Golubov and his colleagues have proposed creating basic memory cells based on quantum effects in superconductor "sandwiches." Superconductors were predicted in the 1960s by the British physicist Brian Josephson. The electrons in these "sandwiches," called "Josephson junctions," are able to tunnel from one layer of a superconductor to another, passing through the dielectric like balls passing through a perforated wall.

Today, Josephson junctions are used both in quantum devices and conventional devices. For example, superconducting qubits are used to build the D-wave quantum system, which is capable of finding the minima of complex functions using the quantum annealing algorithm. There are also ultra-fast analogue-to-digital converters, devices to detect consecutive events, and other systems that do not require fast access to large amounts of memory. There have also been attempts to use the Josephson Effect to create ordinary processors. An experimental processor of this type was created in Japan in the late 1980s. In 2014, the research agency IAPRA resumed its attempts to create a prototype of a superconducting computer.

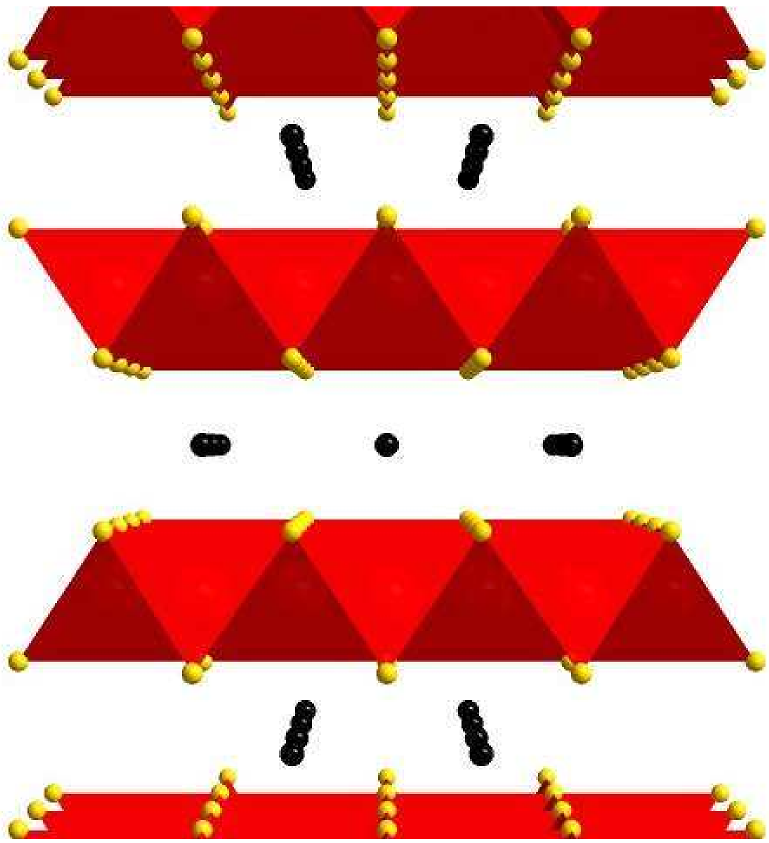
Josephson junctions with ferromagnets used as the middle of the "sandwich" are currently of greatest practical interest. In memory elements that are based on ferromagnets, information is encoded in the direction of the magnetic field vector in the ferromagnet. However, there are two fundamental flaws with this process: first, the "packaging" of the memory elements has a very low density—additional chains need to be added to provide extra charge for the cells when reading or writing data. And second, the magnetization vector cannot be changed quickly, which limits the writing speed.

The researchers proposed encoding the data in Josephson cells in the value of the superconducting current. By studying the superconductor-normal metal/ferromagnet-superconductor-insulator-superconductor junctions, the scientists discovered that in certain longitudinal and transverse dimensions, the layers of the system may have two energy minima, meaning they are in one of two different states. These two minima can be used to record data—zeros and ones.

In order to switch the system from "zero" to "one" and back again, the scientists have suggested using injection currents flowing through one of the layers of the superconductor. They propose to read the status using the current that flows through the whole structure. These operations can be performed hundreds of times faster than measuring the magnetization or magnetization reversal of a ferromagnet.

"In addition, our method requires only one ferromagnetic layer, which means that it can be adapted to so-called single flux quantum logic circuits, and this means that there will be no need to create an entirely new architecture for a processor. A computer based on single flux quantum logic can have a clock speed of hundreds of gigahertz, and its power consumption will be dozens of times lower," said Golubov. [27]

Linking superconductivity and structure



Although superconductivity has many practical applications for electronics (including scientific research instruments), medical engineering (MRI and NMR machines), and potential future applications including high-performance power transmission and storage, and very fast train travel, the difficulty of creating superconducting materials prevents it from being used to its full potential. As such, any newly discovered superconducting ability is of great interest to scientists and engineers.

Iron arsenides are relatively recently discovered superconductors. The nature of superconductivity in these particular materials remains a challenge for modern solid state physics. If the complex links between superconductivity, structure, and magnetism in these materials are unlocked, then iron arsenides could potentially be used to reveal superconductivity at much higher temperatures than previously seen, which would vastly increase the ease of practical applications for superconductivity.

When iron arsenide is combined with a metal—such as in the sodium-containing $NaFe_2As_2$ compound studied here—it was known that the ensuing compound is crystallized in a tetrahedral structure. But until now, a detailed structure of the atomic positions involved and how they change under pressure had not been determined.

The layering of arsenic and iron (As-Fe-As) in this structure is believed to be key to the compound's superconductivity. However, under pressure, this structure is thought to be partially misshapen into a so-called collapsed tetragonal lattice, which is no longer capable of superconducting, or has diminished superconducting ability.

The team used experimental evidence and modeling under pressure to actually demonstrate these previously theorized structural changes—tetragonal to collapsed tetragonal—on the atomic level. This is just the first step toward definitively determining the link between structure and superconductivity, which could potentially make higher-temperature superconductivity a real possibility.

They showed that at about 40,000 times normal atmospheric pressure (4 gigapascals), $NaFe_2As_2$ takes on the collapsed tetragonal structure. This changes the angles in the arsenic-iron-arsenic layers and is coincident with the loss in superconductivity. Moreover, they found that this transition is accompanied by a major change in bonding coordination in the formation of the interlayer arsenic-arsenic bonds. A direct consequence of this new coordination is that the system loses its two-dimensionality, and with it, superconductivity.

"Our findings are an important step in identifying the hypothesized connection between structure and superconductivity in iron-containing compounds," Goncharov said. "Understanding the loss of superconductivity on an atomic level could enhance our ease of manufacturing such compounds for practical applications, as well as improving our understanding of condensed matter physics." [26]

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

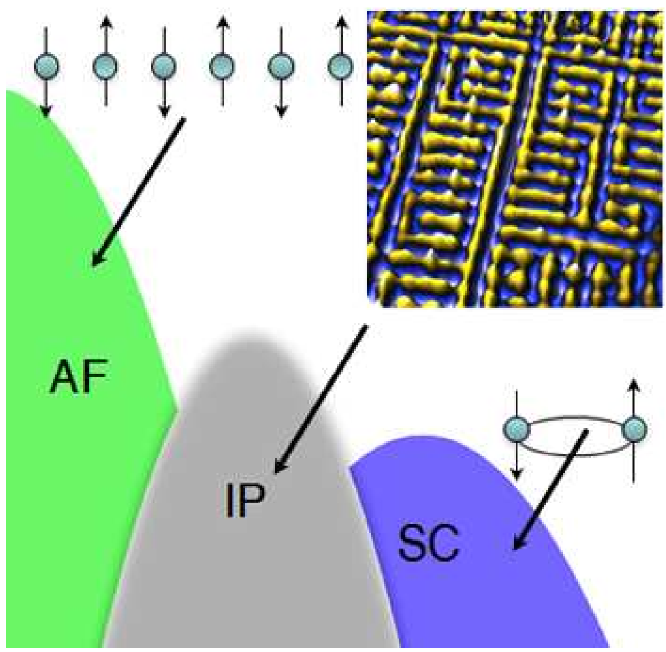
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

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

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

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

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

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

A grand unified theory of exotic superconductivity?

The role of magnetism

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

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

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

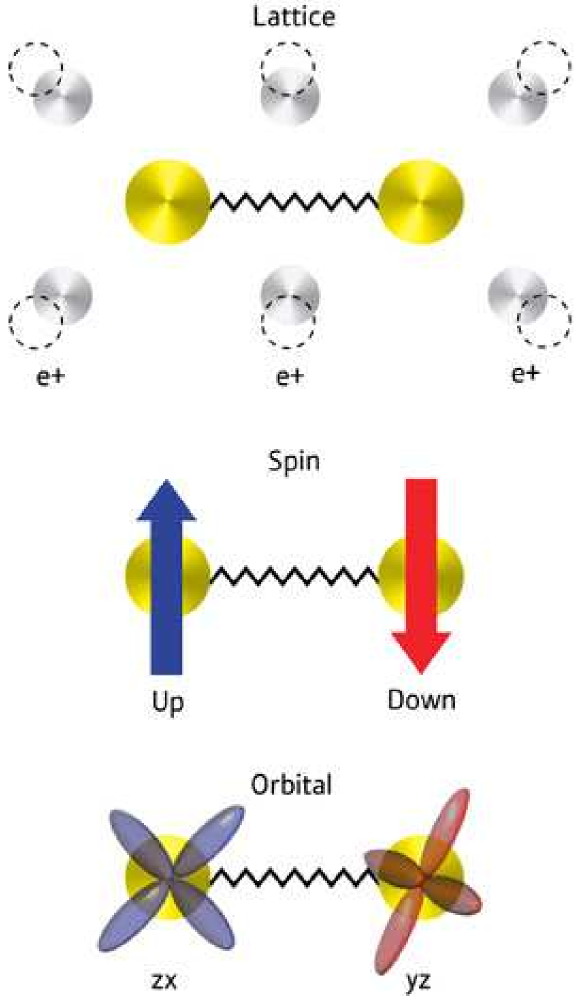
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

Significance

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

Superconductivity's third side unmasked



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

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

Strongly correlated materials

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

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

Fermions and Bosons

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

The General Weak Interaction

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

Higgs Field and Superconductivity

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

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

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

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

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

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

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

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

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

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

The condensate wave function can be written as

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

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

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

Conclusions

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]

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