Moving Domain Walls in Superconductor

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Scientists from Russia, China and the United States predicted and have now experimentally identified new uranium hydrides, predicting superconductivity for some of them. [34]

Russian physicists from MIPT teamed up with foreign colleagues for a groundbreaking experimental study of a material that possesses both superconducting and ferromagnetic properties. [33]

An international group of scientists, including a researcher from Skoltech, has completed an experimental and theoretical study into the properties displayed by strongly disordered superconductors at very low temperatures. [32]

The researchers found that via quick-freeze technique, the metal changed into a superconducting state for over a week. [31]

Scientists of the University of Twente and the University of Amsterdam now demonstrate a new property: the non-superconducting material bismuth shows lossless current conduction. [30]

A team of international scientists including Maia G. Vergniory, Ikerbasque researcher at DIPC and UPV/EHU associate, has discovered a new class of materials, higher-order topological insulators. [29]

A team of researchers from Japan, the U.S. and China, has identified a topological superconducting phase for possible use in an iron-based material in quantum computers. [28]

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies. [27]

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

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

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

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Author: George Rajna

The Quest of Superconductivity

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

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

Experiences and Theories

Moving domain walls induce losses in superconductor/ferromagnet hybrid systems

Physicists have shown that the motion of domain walls can be detected by monitoring voltage generated in superconducting devices. This finding can facilitate magnetic racetrack memory applications. The result was published in *Physical Review Letters*. The international research group included researchers from the University of Jyväskylä.

Recently many research groups have aimed at developing magnetic memories which are based on writing and reading magnetic information with the help of electric current. Such systems typically require such large amounts of current to switch magnetization that it can affect the thermal stability of the memory element. In order to reduce heating effects, superconducting materials which can sustain dissipationless electric current would be very useful.

Superconducting current is a flow of electrons bound in Cooper pairs, and therefore is fundamentally different from the usual current in normal metals which is carried by single electrons. Therefore, in order to develop a superconductor/ferromagnet memory element it has been necessary to understand how superconducting current can affect magnetic state.

In their paper, the research group has found answers to two fundamental questions: whether supercurrent can change magnetic states, and whether it is possible to avoid electric losses during this process.

"We have developed the theory which describes how the superconductor can lose its fundamental property of having zero resistance in a typical superconductor/ferromagnet device. This happens because of the induced magnetization dynamics in the attached ferromagnet. Although the force which drives magnetization comes from the superconducting current, the system becomes inherently dissipative and in principle cannot sustain any amount of superconducting current because of the voltage generated by the magnetization dynamics," explains Academy Research Fellow Mihail Silaev.

"We find the low-current resistance associated with the domain wall motion driven by the superconducting current. We suggest the finite slope of Shapiro steps as the characteristic feature of the regime with domain wall oscillations driven by the external current flowing through the junction," Silaev concludes. [38]

Superconductor or not? Exploring the identity crisis of this weird quantum material

Northeastern researchers have used a powerful computer model to probe a puzzling class of copper-based materials that can be turned into superconductors. Their findings offer tantalizing clues for a decades-old mystery, and a step forward for quantum computing.

The ability of a material to let electricity flow comes from the way electrons within their atoms are arranged. Depending on these arrangements, or configurations, all materials out there are either insulators or conductors of electricity.

But cuprates, a class of mysterious materials that are made from copper oxides, are famous in the scientific community for having somewhat of an identity issue that can make them both insulators and conductors.

Under normal conditions, cuprates are insulators: materials that inhibit the flow of electrons. But with tweaks to their composition, they can transform into the world's best superconductors.

The finding of this kind of superconductivity in 1986 won its discoverers a Nobel Prize in 1987, and fascinated the scientific community with a world of possibilities for improvements to supercomputing and other crucial technologies.

But with fascination came 30 years of bewilderment: Scientists have not been able to fully decipher the arrangement of electrons that encodes for superconductivity in cuprates.

Mapping the electronic configuration of these materials is arguably one of the toughest challenges in theoretical physics, says Arun Bansil, University Distinguished Professor of physics at Northeastern. And, he says, because superconductivity is a weird phenomenon that only happens at temperatures as low as -300 F (or about as cold as it gets on Uranus), figuring out the mechanisms that make it possible in the first place could help researchers make superconductors that work at room temperature.

Now, a team of researchers that includes Bansil and Robert Markiewicz, a professor of physics at Northeastern, is presenting a new way to model these strange mechanisms that lead to superconductivity in cuprates.

In a study published in *Proceedings of the National Academy of Sciences*, the team accurately predicted the behavior of electrons as they move to enable superconductivity in a group of cuprates known as yttrium barium copper oxides.

In these cuprates, the study finds, superconductivity emerges from many types of electron configurations. A whopping 26 of them, to be specific.

"During this transition phase, the material will in essence become some kind of a soup of different phases," Bansil says. "The split personalities of these wonderful materials are being now revealed for the first time."

The physics within cuprate superconductors are intrinsically weird. Markiewicz thinks of that complexity as the classical Indian myth of the blind men and the elephant, which has been a joke for decades among theoretical physicists who study cuprates.

According to the myth, blind men meet an elephant for the first time, and try to understand what the animal is by touching it. But because each of them touches only one part of its body—the trunk, tail, or legs, for example—they all have a different (and limited) concept of what an elephant is.

"In the beginning, we all looked [at cuprates] in different ways," Markiewicz says. "But we knew that, sooner or later, the right way was going to show up."

The mechanisms behind cuprates could also help explain the puzzling physics behind other materials that turn into superconductors at extreme temperatures , Markiewicz says, and revolutionize the way they can be used to enable quantum computing and other technologies that process data at ultra-fast speeds.

"We're trying to understand how they come together in the real cuprates that are used in experiments," Markiewicz says.

The challenge of modeling cuprate superconductors comes down to the weird field of quantum mechanics, which studies the behavior and movement of the tiniest bits of matter—and the strange physical rules that govern everything at the scale of atoms.

In any given material—say, the metal in your smartphone—electrons contained within just the space of a fingertip could amount to the number one followed by 22 zeros, Bansil says. Modeling the physics of such a massive number of electrons has been extremely challenging ever since the field of quantum mechanics was born.

Bansil likes to think of this complexity as butterflies inside a jar flying fast and cleverly to avoid colliding with each other. In a conducting material, electrons also move around. And because of a combination of physical forces, they also avoid each other. Those characteristics are at the core of what makes it hard to model cuprate materials.

"The problem with the cuprates is that they are at the border between being a metal and an insulator, and you need a calculation that is so good that it can systematically capture that crossover," Markiewicz says. "Our new modeling can capture this behavior."

The team includes researchers from Tulane University, Lappeenranta University of Technology in Finland, and Temple University. The researchers are the first to model the electronic states in the cuprates without adding parameters by hand to their computations, which physicists have had to do in the past.

To do that, the researchers modeled the energy of atoms of yttrium barium copper oxides at their lowest levels. Doing that allows researchers to trace electrons as they excite and move around, which in turn helps describe the mechanisms supporting the critical transition into superconductivity.

That transition, known as the pseudogap phase in the material, could be described simply as a door, Bansil says. In an insulator, the structure of the material is like a closed door that lets no one through. If the door is wide open—as it would be for a conductor—electrons pass through easily.

But in materials that experience this pseudogap phase, that door would be slightly open. The dynamics of what transforms that door into a really wide open door (or, superconductor) remains a mystery, but the new model captures 26 electron configurations that could do it.

"With our ability to now do this first-principles-parameter-free-type of modeling, we are in a position to actually go further, and hopefully begin to understand this pseudogap phase a bit better," Bansil says. [37]

Discovery of new superconducting materials using materials informatics

A NIMS-Ehime University joint research team succeeded in discovering new materials that exhibit superconductivity under high pressure using materials informatics (MI) approaches (data science-based material search techniques). This study experimentally demonstrated that MI enables efficient exploration of new superconducting materials. MI approaches may be applicable to the development of various functional materials, including superconductors.

Superconducting materials that enable long-distance electricity transmission without energy loss in the absence of electrical resistance are considered to be a key technology in solving environmental and energy issues. The conventional approach by researchers searching for new superconducting materials or other materials has been to rely on published information on material properties, such as crystalline structures and valence numbers, and their own experience and intuition. However, this approach is time-consuming, costly and very difficult because it requires extensive and exhaustive synthesis of related materials. As such, demand has been high for the development of new methods enabling more efficient exploration of new materials with desirable properties.

This joint research team took advantage of the AtomWork database, which contains more than 100,000 pieces of data on inorganic crystal structures. The team first selected approximately 1,500 candidate material groups whose electronic states could be determined through calculation. The team then narrowed this list to 27 materials with desirable superconducting properties by actually performing electronic state calculations. From these 27, two materials $SnBi_2Se_4$ and $PbBi_2Te_4$ were ultimately chosen because they were relatively easy to synthesize.

The team synthesized these two materials and confirmed that they exhibit superconductivity under high pressures using an electrical resistivity measuring device. The team also found that the superconducting transition temperatures of these materials increase with increasing pressure. This data science-based approach, which is completely different from the conventional approaches, enabled identification and efficient and precise development of superconducting materials.

Experiments revealed that these newly discovered materials may have superb thermoelectric properties in addition to superconductivity. The method we developed may be applicable to the development of various functional materials, including superconductors. In future studies, we hope to discover innovative functional materials, such as room-temperature superconducting materials, by including a wider range of materials in our studies and increasing the accuracy of the parameters relevant to desirable properties. [36]

Pushing the extra cold frontiers of superconducting science

Measuring the properties of superconducting materials in magnetic fields at close to absolute zero temperatures is difficult, but necessary to understand their quantum properties. How cold? Lower than 0.05 Kelvin (-272°C).

"For many modern (quantum) materials, to properly study the fine details of their quantum mechanical behavior you need to be cool. Cooler than was formerly thought possible," said Ruslan Prozorov, a physicist at the U.S. Department of Energy's Ames Laboratory, who specializes in developing instrumentation which measures just such things.

Prozorov and his research team have developed a method to measure magnetic properties of superconducting and magnetic materials that exhibit unusual quantum behavior at very low temperatures in high magnetic fields. The method is being used to study quantum critical behavior, mechanisms of superconductivity, magnetic frustration and phase transitions in materials, many of which were first fabricated at Ames Laboratory.

They did so by placing a tunnel diode resonator, an instrument that makes precise radio-frequency measurements of magnetic properties, in a dilution refrigerator, a cryogenic device that is able to cool samples down to milli-Kelvin temperature range. While this was already achieved before, previous works did not have the ability to apply large static magnetic fields, which is crucial for studying quantum materials.

Prozorov's group worked to overcome the technical difficulties of maintaining high-resolution magnetic measurements, while at the same time achieving ultra-cold temperatures down to 0.05 K and in magnetic fields up to 14 tesla. A similar circuit has already been used in a very high magnetic field (60 T) when the team performed the experiments at Los Alamos National Lab.

"When we first installed the dilution refrigerator, the joke was that my lab had the coldest temperatures in Iowa," said Prozorov, who conducts his research where Midwestern winters are no laughing matter. "But we were not doing this just for fun, to see how cold we could go. Many unusual quantum properties of materials can only be uncovered at these extremely low temperatures."

The group studied pairing symmetry in several unconventional superconductors, mapped a very complex phase diagram in a system with field-induced quantum critical behavior, and recently uncovered very unusual properties of a spin-ice system, "none of which would be possible without this setup," said Prozorov. [35]

Scientists discover new properties of uranium compounds

Scientists from Russia, China and the United States predicted and have now experimentally identified new uranium hydrides, predicting superconductivity for some of them. The results of their study were published in *Science Advances*.

The phenomenon of superconductivity was discovered in 1911 by a group of scientists led by Dutch physicist Heike Kamerlingh Onnes. Superconductivity means complete disappearance of electrical resistance in a material when it is cooled down to a specific temperature, forcing out the magnetic field from the material. At the start, superconductivity was discovered in a few base metals such as aluminum and mercury at temperatures of several degrees above absolute zero, which is -273° C. Of particular interest to scientists are the so-called high-temperature superconductors that exhibit superconductivity at less extreme temperatures. The highest temperature superconductors operate at -183° C, and, therefore require constant cooling. In 2015, a rare sulfur hydride (H_3S) set a new high-temperature superconductivity record of -70 °C , although at pressures as high as 1,500,000 atm.

A group of physicists led by Professor Artem R. Oganov predicted that much lower pressures of about 50,000 atmospheres can produce 14 new uranium hydrides, of which only one, UH3, has been known to date. They include compounds rich in hydrogens, such as UH7 and UH8, that the scientists also predicted to be superconducting. Many of these compounds were then obtained in the experiments conducted by the teams of Professor Alexander Goncharov at the U.S. Carnegie Institution of Washington (USA) and the Institute of Solid State Physics of the Chinese Academy of Sciences. The calculations suggest that the highest-temperature superconductor is UH7, which displays superconducting capability at -219° C – a temperature level that can be increased further by doping.

"After H_3S was discovered, scientists started eagerly searching for superconducting hydrides in other non-metals, such as selenium, phosphorus, etc. Our study showed that metal hydrides hold as much potential as non-metals in terms of high-temperature superconductivity," says the main author of the study Ivan Kruglov, a researcher in Computational Materials Discovery Laboratory at MIPT.

"The two highlights of our results are that high pressure produces an amazingly rich collection of hydrides, most of which do not fit into classical chemistry, and that these hydrides can actually be obtained and become superconducting at very low pressures, perhaps even at atmospheric pressure," says Artem Oganov. [34]

Superconductivity and ferromagnetism fight an even match

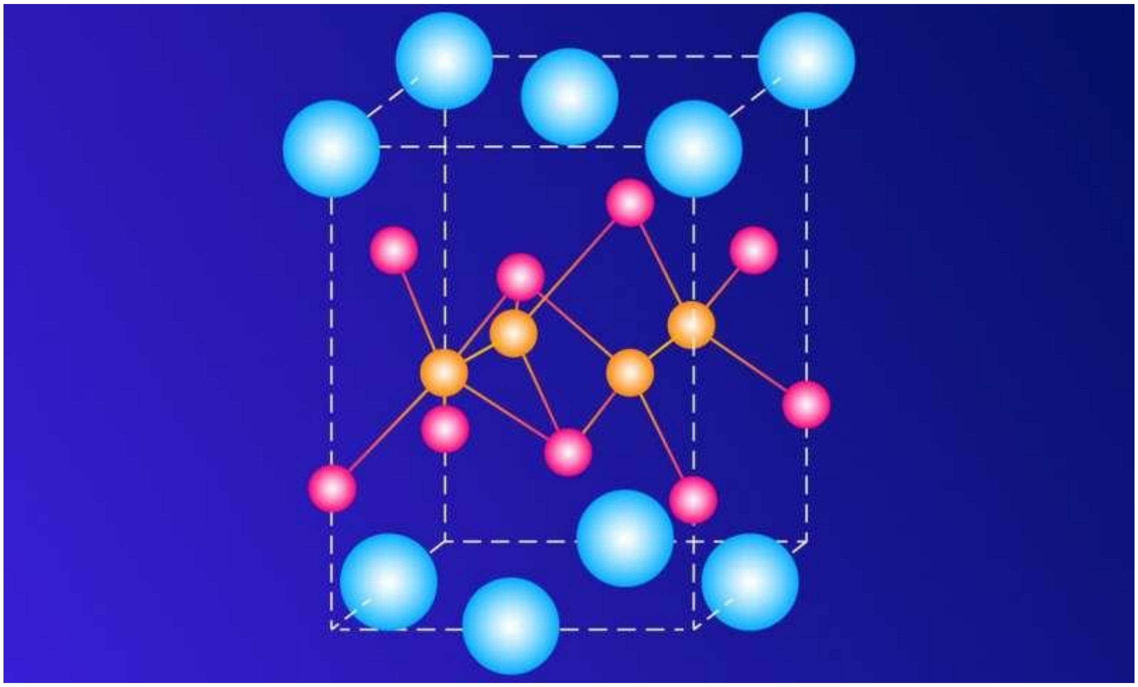
Russian physicists from MIPT teamed up with foreign colleagues for a groundbreaking experimental study of a material that possesses both superconducting and ferromagnetic properties. In their paper published in *Science Advances*, the researchers also propose an analytical solution describing the unique phase transitions in such ferromagnetic superconductors.

Ferromagnetic superconductors

The international research team studied a monocrystalline compound of europium, iron, and arsenic, doped with phosphorus with the formula $EuFe_2(As_{0.79}P_{0.21})_2$. Once cooled to 24 kelvins, or −249.15 degrees Celsius, this material exhibits zero electrical resistance, becoming a superconductor. If cooled further, below 18 K, it acquires ferromagnetic properties. In particular, it undergoes spontaneous magnetization at zero applied magnetic field, like iron, which is used to make permanent magnets.

Remarkably, ferromagnetism does not in this case destroy superconductivity. This coexistence of magnetism and superconductivity has long been an object of interest to both theoretical physicists and researchers investigating new materials with a potential for applications in conventional and high-current electronics.

From a theoretical standpoint, ferromagnetic superconductors are interesting as materials exhibiting distinct properties in different temperature ranges. Unlike them, conventional superconductors are perfect diamagnetics. That is, magnetic fields do not penetrate inside them, because an external field induces screening currents on the surface of the superconductor. These currents result in a magnetic moment that counteracts the external field.



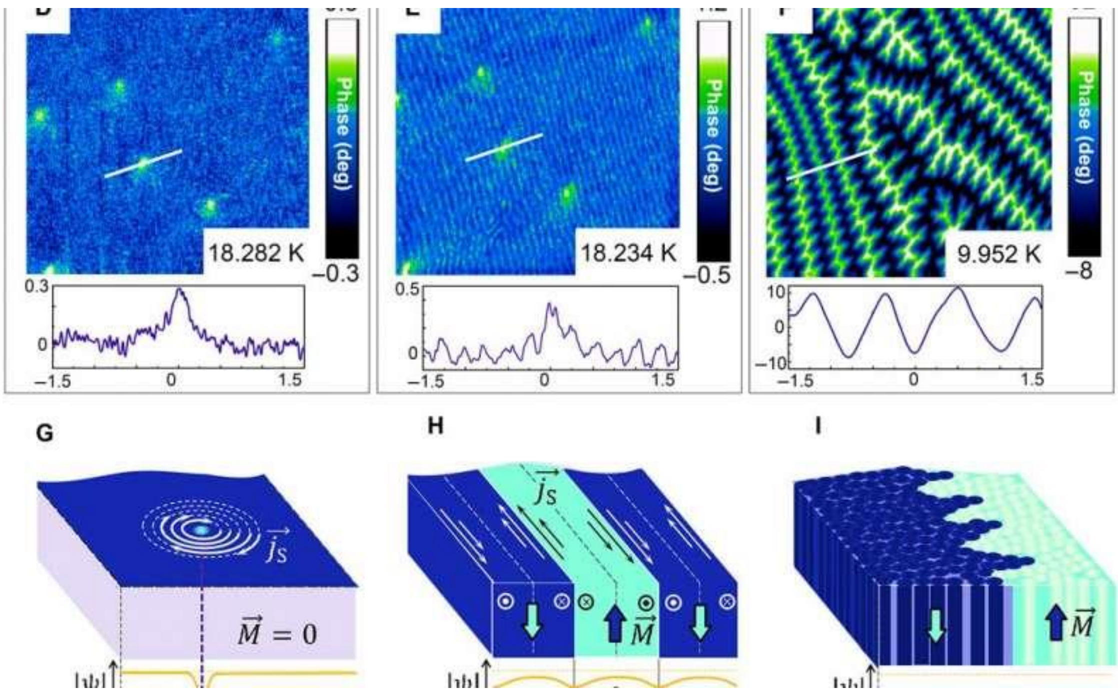
The crystal lattice of the compound examined in the study. The pink spheres represent the atoms of arsenic and phosphorus. The atoms of iron and europium are shown in orange and blue, respectively. Credit: Elena Khavina/MIPT

The magnetic and electrical properties of materials are interconnected, so the "peculiar" ferromagnetic superconductors attracted the attention of scientists. By investigating them, it is possible to better understand the nature of superconductivity as a macroscopic quantum phenomenon. Perhaps this line of research could even shed light on the prospects of superconductors that would work near room temperature, which so far seemingly fall into the realm of fantasy.

In ferromagnetic materials, the magnetizations of the constituent particles spontaneously align below a certain temperature, called the Curie point. This results in the formation of uniformly magnetized regions called domains, whose interplay determines the overall magnetic field of the material. Above the Curie temperature, the magnetic ordering is lost.

Ferromagnets are used in the industry to make various devices that store or process information encoded in magnetized media. Familiar examples of magnetic storage are hard disks, recording tape, and magnetic stripes on credit cards.

The coexistence of ferromagnetism and superconductivity could have potential from a practical standpoint. However, to develop technological applications of this combination of material properties, engineers and physicists need to understand the processes occurring in ferromagnetic superconductors in greater detail.



Magnetic force microscopy images of an 8 micron by 8 micron region on the sample at various temperatures. Image D shows a regular Abrikosov vortex state at a temperature above the ferromagnetic transition temperature but below the Curie …more

New Meissner phase

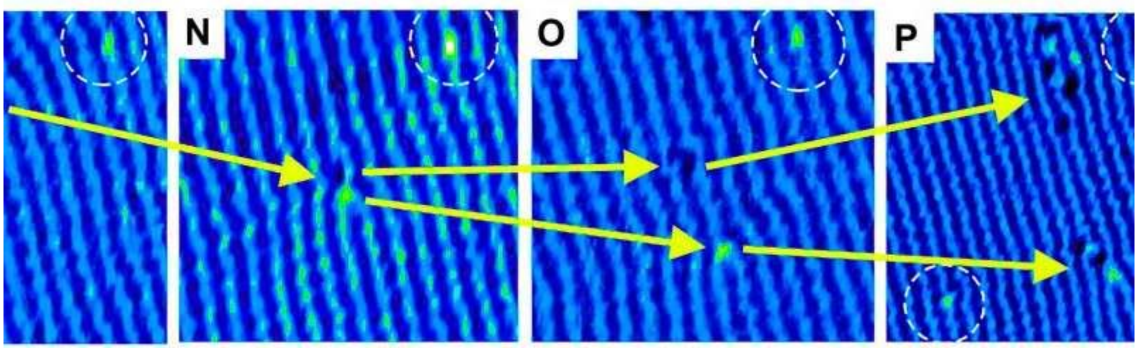
To find out what happens on the surface of the crystal investigated in the study, the researchers used a magnetic force microscope. It enabled them to create a high-resolution 3-D map showing the distribution of the magnetic field near the surface of the sample at various temperatures. Once the material was cooled below its Curie point, or about 18 K, the map revealed magnetic domains. At 19-24 K, the map shows Abrikosov vortices, which are a characteristic trait of superconductors.

Besides, the team revealed a new phase that exists slightly below the Curie point, between 17.8 and 18.25 K, and manifests itself as Meissner domains.

The Meissner-Ochsenfeld effect refers to the expulsion of a magnetic field from a superconductor during its transition into the superconducting state. The material resists being penetrated by the external magnetic field lines. As a result, the external magnetic field induces superconducting Meissner currents in a thin layer of material close to the surface of the sample.

The authors of the research reported in this story have experimentally discovered a new phase of the Meissner effect—called Meissner domains—and observed its transformation into "vortex domains." The notion of a Meissner domain refers to the periodic structure resulting from the spontaneous Meissner currents generated due to the screening of the internal magnetic subsystem of europium atoms. The transition is a consequence of the oppositely oriented spontaneous magnetic fluxons in Meissner domains being quantized once a critical magnetic field for the given superconductor has been reached.

By varying the temperature in the course of their experiment, the researchers traced the transition of the sample from one phase into another.



Cooling sample. The yellow arrows indicate the vortex-antivortex pair, as it is generated (N), separates (O), and further diverges (P). The authors note that the process is observed at domain junctions called Y dislocations (as in M) or on …more

Vasily Stolyarov, a co-author of the paper, commented on the results of the study: "For the first time ever, we have shown what happens on the surface of the recently discovered ferromagnetic superconductors. This is the first observation of so-called Meissner domains and the transition from Meissner domains to vortex domains, which occurs when vortex-antivortex pairs are spontaneously generated in Meissner domains, counteracting the screening Meissner currents in the neighboring domains. The spontaneous Abrikosov vortex-antivortex pair generation in a homogeneous superconductor has not been observed before, despite this phenomenon being predicted theoretically and indirectly inferred from research into electron transport."

"Our findings break new ground in the modern physics of superconductivity," says Stolyarov, who is deputy head of MIPT's Laboratory of Topological Quantum Phenomena in Superconducting Systems. "The results of the study lay the foundation for future fundamental theoretical and experimental research into the processes occurring in superconductors at the atomic scale. We are preparing a series of papers detailing our research into similar materials, and this publication is the first of its kind."

The physicist added that the phase transition investigated in the study could be used to control processes occurring in the superconductor. In particular, this phenomenon can help control Abrikosov vortices in the crystal and form single vortex-antivortex pairs, which is useful for developing electronics based on hybrid superconducting materials. [33]

Scientists explain the low-temperature anomaly in superconductors

An international group of scientists, including a researcher from Skoltech, has completed an experimental and theoretical study into the properties displayed by strongly disordered superconductors at very low temperatures. Following a series of experiments, the scientists developed a theory that effectively describes the previously inexplicable anomalies encountered in superconductors. The results of the study were published in *Nature Physics*.

The phenomenon of superconductivity was discovered in 1911 by a group of scientists led by Dutch physicist Heike Kamerlingh Onnes. Superconductivity means complete disappearance of electrical resistance in a material when it is cooled down to a specific temperature, resulting in the magnetic field being forced out from the material. Of particular interest to scientists are strongly disordered superconductors whose atoms do not form crystal lattices. From a practical standpoint, strongly disordered superconductors hold great potential for quantum computer development.

At very low temperatures, superconductors display an anomaly which cannot be explained in terms of the classical theory of superconductivity. This anomaly concerns the temperature dependence of the maximal magnetic field that is still consistent with the superconducting behavior of the material. This maximum field, also referred to as the "upper critical" field, always increases as the sample temperature declines, whereas in regular superconductors, it nearly stops growing at temperatures several times lower than the superconducting transition temperature. For example, in the case of amorphous indium oxide films used in this study that become superconducting at 3 K (-270 ^{o}C), one would expect the critical magnetic field to stop growing at temperatures below 0.5 K. However, the experiment indicates that the critical field keeps growing even as the temperature drops to the lowest possible values (about 0.05 K in this experiment), and its growth shows no signs of saturation.

Scientists from Skoltech, Landau Institute for Theoretical Physics, Institut Néel (France), Weizmann Institute of Science (Israel) and the University of Utah (U.S.) demonstrated that the anomaly is caused by thermal fluctuations of quantum Abrikosov vortices. The magnetic field that penetrates into the disordered superconductor has the form of vortices, i.e. tubes, each carrying magnetic flux equal to the fundamental value hc/2e, where h is the Plank constant, c is the speed of light, and e is the electron charge.

At absolute zero, these vortices are immobile and rigidly attached to the atom structure, while any nonzero temperature leads to fluctuations of the vortex tubes around home bases. The strength of these fluctuations grows with temperature, and this results in a decrease in the magnetic field that can be applied to a material without affecting its superconducting properties.

"We have developed a theory of the effect of thermal fluctuations of Abrikosov vortices upon the value of the upper critical field, which helped us to establish a relationship between two different types of measurements," says Mikhail Feigelman, principal research scientist at Skoltech and deputy director at Landau institute for Theoretical Physics.

Gaining an insight into the behavior of strongly disordered superconductors is essential for their use in superconducting quantum bits—key elements of quantum computers. It became obvious a few years ago that multiple applications in this field require very small elements with high inductance (electric inertia), and the strongly disordered superconductors are the best fit for such "super-inductance" elements. "Understanding of the behavior of these materials will help create superconducting quantum bits highly isolated from external noise," says Feigelman. [32]

Forcing a metal to be a superconductor via rapid chilling

A team of researchers with the RIKEN Center for Emergent Matter Science and The University of Tokyo, both in Japan, has found a way to force a metal to be a superconductor by cooling it very quickly. In their paper published on the open access site, *Science Advances*, the group describes their process and how well it worked.

Scientists around the world continue to seek a material that behaves as a superconductor at room temperature—such a material would be extremely valuable because it would have zero electrical resistance. Because of that, it would not increase in heat as electricity passed through it, nor lose energy. Scientists have known that cooling some materials to very cold temperatures causes them to be superconductive. They have also known that some metals fail to do so because they enter a "competing state." In this new effort, the researchers in Japan have found a way to get one such non-cooperative metal to enter a superconductive state anyway—and to stay that way for over a week.

Noting that there is a very small delay between the moment when a metal reaches a temperature cold enough to enter a superconductive state and the onset of the competing state, the researchers came up with an idea—if the metal was cooled rapidly, it might not have a chance to enter a competing state. They liken the idea to metal forgers plunging their work into cold water after fashioning to prevent it from weakening.

To find out if their idea worked, they made a metal sample out of iridium and tellurium. They connected electrodes and gave it a jolt of electricity. The jolt initially caused the metal to heat to over 27°C, but then it cooled very rapidly to -269°C, in under ten microseconds. The researchers found that via quick-freeze technique, the metal changed into a superconducting state for over a week. [31]

Topological material shows superconductivity—and not just at its surface

The special properties of topological materials typically occur at their surface. These materials, for example insulators that do conduct current at their surface, are expected to play a major role in future quantum computers. Scientists of the University of Twente and the University of Amsterdam now demonstrate a new property: the non-superconducting material bismuth shows lossless current conduction. What's even more special: it doesn't just occur at the surface but on the inside of the material as well. The scientists publish their findings in *Nature Materials*.

Topological materials have drawn increasing interest, especially after Thouless, Haldane and Kosterlitz won the Nobel Prize in Physics in 2016. These materials get their particular properties by playing with the order of energy levels. By 'twisting' these levels, a material that doesn't conduct any current under normal circumstances will suddenly become a conductor, but only at its surface. The phenomenon includes the transport of electrons and their spin – this describes the way the electron spins on its own axis and its magnetic properties.

Superconductivity

In their *Nature Materials* paper, the researchers now demonstrate a that the transport and spin of electrons are related,in a topological material. Thanks to this property, a non-superconducting material will even be able to conduct current without resistance. Majorana quasiparticles play a major role in this. Notably, this is not a property that can only be observed at the surface. Measurements show that superconduction also takes place inside the bulk of the material. This makes the properties less vulnerable to noise or pollution, for example.

Bismuth with a little antimony has become a model material for studying electronic properties. In bismuth, the number of electrons available for conduction is so low that it can hardly be called a metal. But the electrons in this 'semimetal' do move like particles at the speed of light. Applying superconducting electrodes made of niobium to a thin crystal flake of bismuth doped with antimony at a temperature of 10 milli Kelvin causes a superconducting current to flow through the material. In a superconductor, paired electrons, so-called Cooper pairs, are responsible for conduction. This is not the mechanism inside the bismuth: Here, Majorana particles are responsible. [30]

Bismuth shows novel conducting properties

A team of international scientists including Maia G. Vergniory, Ikerbasque researcher at DIPC and UPV/EHU associate, has discovered a new class of materials, higher-order topological insulators. Theoretical physicists first predicted the existence of these insulators, which have conducting properties on the edges of crystals rather than on their surfaces, and conduct electricity without dissipation. Now, these novel properties are demonstrated experimentally in bismuth.

The current flows without resistance and responds in unconventional ways to electric and magnetic fields. These unique properties have future applications in high-performance electronics and quantum computation.

Higher-order topological insulators

Recently, a new class of topological materials with novel conducting properties was predicted by a group of physicists from Donostia International Physics Center (DIPC), the University of the Basque Country (UPV/EHU), UZH, Princeton University and Max Planck Institute of Microstructure Physics. The researchers refer to it as a "higher-order topological insulator."

According to theoretical studies, the conducting edges are extraordinarily robust for higher-order topological insulators. The current of topological electrons cannot be stopped by impurities, and if the crystal breaks, the new edges automatically also conduct current. However, the most extraordinary property of these new materials is that they can theoretically conduct electricity without any dissipation, as superconductors do at low temperatures. This would be a specific property of higher-order class topological insulators.

Bismuth is topological

Now, it has been confirmed that bismuth, an element consistently described as bulk topologically trivial, follows a generalized bulk-boundary correspondence of higher-order, that is, hinges have topologically protected conducting modes instead of the surface of the crystal.

The special topological properties of this element were first identified by using symmetry arguments, topological indices, first-principles calculations, and the recently introduced framework of topological quantum chemistry.

This phenomenon was then verified experimentally. With scanning-tunneling spectroscopy, the unique signatures of the rotational symmetry of the one-dimensional states located at step edges of the crystal surface were proved. Using Josephson interferometry, scientists demonstrated their universal topological contribution to the electronic transport.

Finally, this work establishes bismuth as a higher-order topological insulator and opens the way to identify new ones. [29]

Topological superconductor phase may solve decoherence problem in quantum computers

A team of researchers from Japan, the U.S. and China, has identified a topological superconducting phase for possible use in an iron-based material in quantum computers. In their paper published in the journal *Science*, the team outlines their study of the phase, which, they claim, shows promise as a means for solving the decoherence problem in quantum computers.

As research surrounding quantum computers continues researchers confront a number of problems. One is the tendency of quantum states to degrade, resulting in computing errors—a problem known as decoherence. Experts suggest that the solution to the problem is to develop a material capable of protecting the quantum state by employing just the right topological properties. In this way, localized noise would not be able to disturb the quantum state. In this new effort, the researchers report on the identification of a topological superconducting phase that they believe could satisfy this requirement.

The researchers report that they were able to attain three key kinds of measurements believed to be necessary for analyzing the quantum phase of Fe(Te, Se) in sufficient detail, which they claim shows that the phase could prove suitable for protecting the quantum state in a system. They further report that the phase, once integrated into a suitable material, would be capable of supporting Majorana bound states (MBSs), which are quasiparticles so-named due to their discovery by Ettore Majorana. Prior research has suggested that a material capable of using Majorana properties might play a role in solving the decoherence problem.

The researchers note also that they were able to identify the helical spin polarization of the surface state and to measure the superconducting gap. They were also able to identify the surface state. Taken together, the results of their testing indicate that MBSs could be induced in a material by exerting a magnetic field to the Fe(Te, Se). If their predictions pan out, the new phase could wind up as part of the next generation of quantum computers, possibly paving the way for machines capable of manipulating more qubits than those currently in use. [28]

Superconducting qubits can function as quantum engines

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies.

The physicists, Kewin Sachtleben, Kahio T. Mazon, and Luis G. C. Rego at the Federal University of Santa Catarina in Florianópolis, Brazil, have published a paper on their work on superconducting qubits in a recent issue of Physical Review Letters.

In their study, the physicists explain that superconducting circuits are functionally equivalent to quantum systems in which quantum particles tunnel in a double-quantum well. These wells have the ability to oscillate, meaning the width of the well changes repeatedly. When this happens, the system behaves somewhat like a piston that moves up and down in a cylinder, which changes the volume of the cylinder. This oscillatory behavior allows work to be performed on the system. The researchers show that, in the double-quantum well, part of this work comes from quantum coherent dynamics, which creates friction that decreases the work output. These results provide a better understanding of the connection between quantum and classical thermodynamic work.

"The distinction between 'classical' thermodynamic work, responsible for population transfer, and a quantum component, responsible for creating coherences, is an important result," Mazon told Phys.org. "The creation of coherences, in turn, generates a similar effect to friction, causing a notcompletely-reversible operation of the engine. In our work we have been able to calculate the reaction force caused on the quantum piston wall due to the creation of coherences. In principle this force can be measured, thus constituting the experimental possibility of observing the emergence of coherences during the operation of the quantum engine."

One of the potential benefits of viewing superconducting qubits as quantum engines is that it may allow researchers to incorporate quantum coherent dynamics into future technologies, in particular quantum computers. The physicists explain that a similar behavior can be seen in nature, where quantum coherences improve the efficiency of processes such as photosynthesis, light sensing, and other natural processes.

"Quantum machines may have applications in the field of quantum information, where the energy of quantum coherences is used to perform information manipulation in the quantum regime," Mazon said. "It is worth remembering that even photosynthesis can be described according to the working principles of a quantum machine, so unraveling the mysteries of quantum thermodynamics can help us to better understand and interpret various natural processes." [27]

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

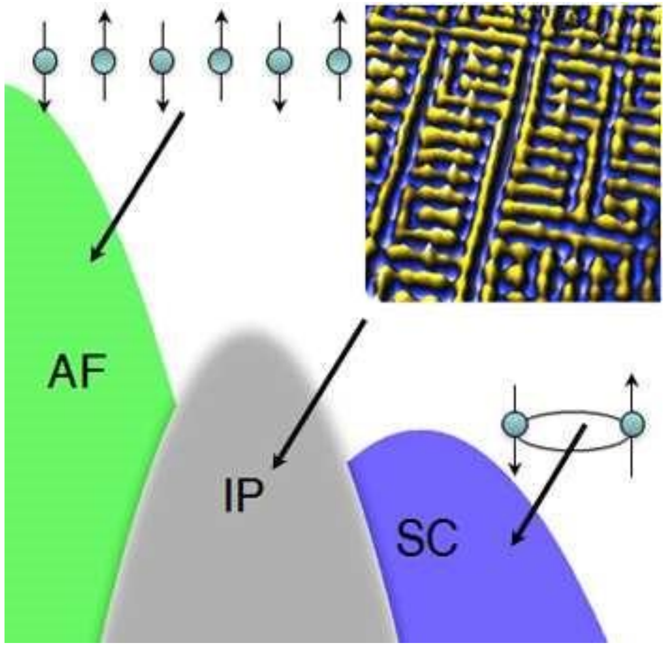
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

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

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

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

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

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

A grand unified theory of exotic superconductivity?

The role of magnetism

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

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

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

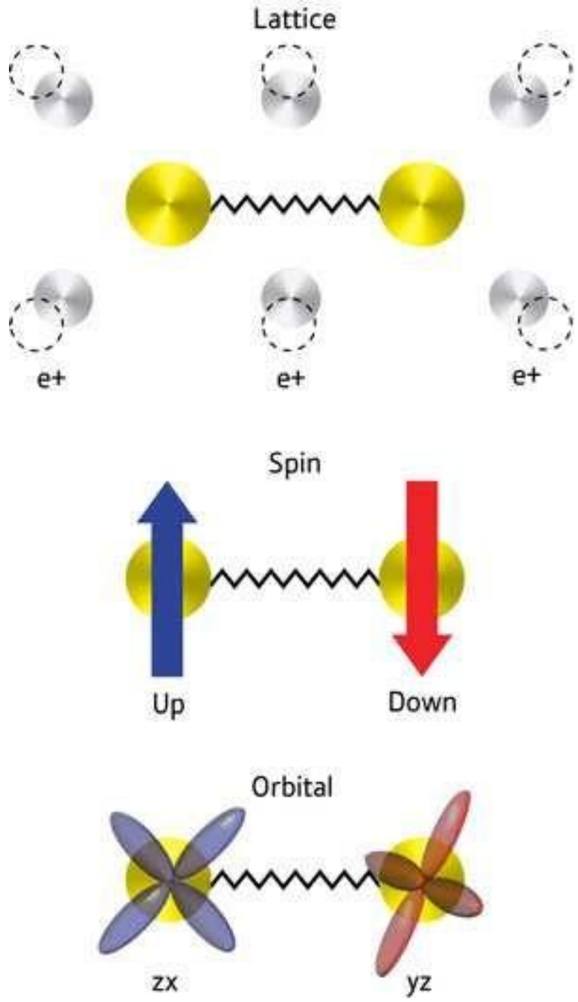
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

Significance

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

Superconductivity's third side unmasked



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

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

Strongly correlated materials

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

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

Fermions and Bosons

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

The General Weak Interaction

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

Higgs Field and Superconductivity

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

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

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

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

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

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

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

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

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

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

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

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

The condensate wave function can be written as

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

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

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

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

Superconductivity and Quantum Entanglement

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

Conclusions

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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