# Superconductor with Topological Twist

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*Using a clever technique that causes unruly crystals of iron selenide to snap into alignment, Rice University physicists have drawn a detailed map that reveals the "rules of the road" for electrons both in normal conditions and in the critical moments just before the material transforms into a superconductor. [29]*

*Superconducting quantum microwave circuits can function as qubits, the building blocks of a future quantum computer. [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.*

## Contents

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

### Researchers detect a supercurrent at the edge of a superconductor with a topological twist

A discovery that long eluded physicists has been detected in a laboratory at Princeton. A team of physicists detected superconducting currents—the flow of electrons without wasting energy—along the exterior edge of a superconducting material. The finding was published in the May 1 issue of the journal *Science*.

The superconductor that the researchers studied is also a topological semi-metal, a material that comes with its own unusual electronic properties. The finding suggests ways to unlock a new era of "topological superconductivity" that could have value for quantum computing.

"To our knowledge, this is the first observation of an edge supercurrent in any superconductor," said Nai Phuan Ong, Princeton's Eugene Higgins Professor of Physics and the senior author on the study.

"Our motivating question was, What happens when the interior of the material is not an insulator but a superconductor?" Ong said. "What novel features arise when superconductivity occurs in a topological material?"

Although conventional superconductors already enjoy widespread usage in magnetic resonance imaging (MRI) and long-distance transmission lines, new types of superconductivity could unleash the ability to move beyond the limitations of our familiar technologies.

Researchers at Princeton and elsewhere have been exploring the connections between superconductivity and topological insulators—materials whose non-conformist electronic behaviors were the subject of the 2016 Nobel Prize in Physics for F. Duncan Haldane, Princeton's Sherman Fairchild University Professor of Physics.

Topological insulators are crystals that have an insulating interior and a conducting surface, like a brownie wrapped in tin foil. In conducting materials, electrons can hop from atom to atom, allowing electric current to flow. Insulators are materials in which the electrons are stuck and cannot move. Yet curiously, topological insulators allow the movement of electrons on their surface but not in their interior.

To explore superconductivity in topological materials, the researchers turned to a crystalline material called molybdenum ditelluride, which has topological properties and is also a superconductor once the temperature dips below a frigid 100 milliKelvin, which is -459 degrees Fahrenheit.

"Most of the experiments done so far have involved trying to 'inject' superconductivity into topological materials by putting the one material in close proximity to the other," said Stephan Kim, a graduate student in electrical engineering, who conducted many of the experiments. "What is different about our measurement is we did not inject superconductivity and yet we were able to show the signatures of edge states."

The team first grew crystals in the laboratory and then cooled them down to a temperature where superconductivity occurs. They then applied a weak magnetic field while measuring the current flow through the crystal. They observed that a quantity called the critical current displays oscillations, which appear as a saw-tooth pattern, as the magnetic field is increased.

Both the height of the oscillations and the frequency of the oscillations fit with predictions of how these fluctuations arise from the quantum behavior of electrons confined to the edges of the materials.

Researchers have long known that superconductivity arises when electrons, which normally move about randomly, bind into twos to form Cooper pairs, which in a sense dance to the same beat. "A rough analogy is a billion couples executing the same tightly scripted dance choreography," Ong said.

The script the electrons are following is called the superconductor's wave function, which may be regarded roughly as a ribbon stretched along the length of the superconducting wire, Ong said. A slight twist of the wave function compels all Cooper pairs in a long wire to move with the same velocity as a "superfluid"—in other words acting like a single collection rather than like individual particles—that flows without producing heating.

If there are no twists along the ribbon, Ong said, all Cooper pairs are stationary and no current flows. If the researchers expose the superconductor to a weak magnetic field, this adds an additional contribution to the twisting that the researchers call the magnetic flux, which, for very small particles such as electrons, follows the rules of quantum mechanics.

The researchers anticipated that these two contributors to the number of twists, the superfluid velocity and the magnetic flux, work together to maintain the number of twists as an exact integer, a whole number such as 2, 3 or 4 rather than a 3.2 or a 3.7. They predicted that as the magnetic flux increases smoothly, the superfluid velocity would increase in a saw-tooth pattern as the superfluid velocity adjusts to cancel the extra .2 or add .3 to get an exact number of twists.

The team measured the superfluid current as they varied the magnetic flux and found that indeed the saw-tooth pattern was visible.

In molybdenum ditelluride and other so-called Weyl semimetals, this Cooper-pairing of electrons in the bulk appears to induce a similar pairing on the edges.

The researchers noted that the reason why the edge supercurrent remains independent of the bulk supercurrent is currently not well understood. Ong compared the electrons moving collectively, also called condensates, to puddles of liquid.

"From classical expectations, one would expect two fluid puddles that are in direct contact to merge into one," Ong said. "Yet the experiment shows that the edge condensates remain distinct from that in the bulk of the crystal."

The research team speculates that the mechanism that keeps the two condensates from mixing is the topological protection inherited from the protected edge states in molybdenum ditelluride. The group hopes to apply the same experimental technique to search for edge supercurrents in other unconventional superconductors.

"There are probably scores of them out there," Ong said.

The study, "Evidence for an edge supercurrent in the Weyl superconductor MoTe2," by Wudi Wang, Stephan Kim, Minhao Liu, F. A. Cevallos, Robert. J. Cava and Nai Phuan Ong, was published in the journal *Science* on May 1, 2020. [31]

## Imaging nematic transitions in iron pnictide superconductors

Researchers at Stanford University have recently carried out an in-depth study of nematic transitions in iron pnictide superconductors. Their paper, published in *Nature Physics*, presents new imaging data of these transitions collected using a microscope they invented, dubbed the scanning quantum cryogenic atom microscope (SQCRAMscope).

"We invented a new type of scanning probe microscope a few years ago," Benjamin L. Lev, the researcher who led the study, told Phys.org. "One can think of it like a normal optical microscope, but instead of the lens focused on some sample slide, the focus is on a quantum gas of atoms that are levitated near the sample."

In the new microscope invented by Lev and his colleagues, atoms are levitated from an 'atom chip' trapping device using magnetic fields, until they are merely a micron above the sample slide. These atoms can transduce the magnetic fields that emanate from the sample into the light collected by the microscope's lens. As a result, SQCRAMscope can be used to image magnetic fields.

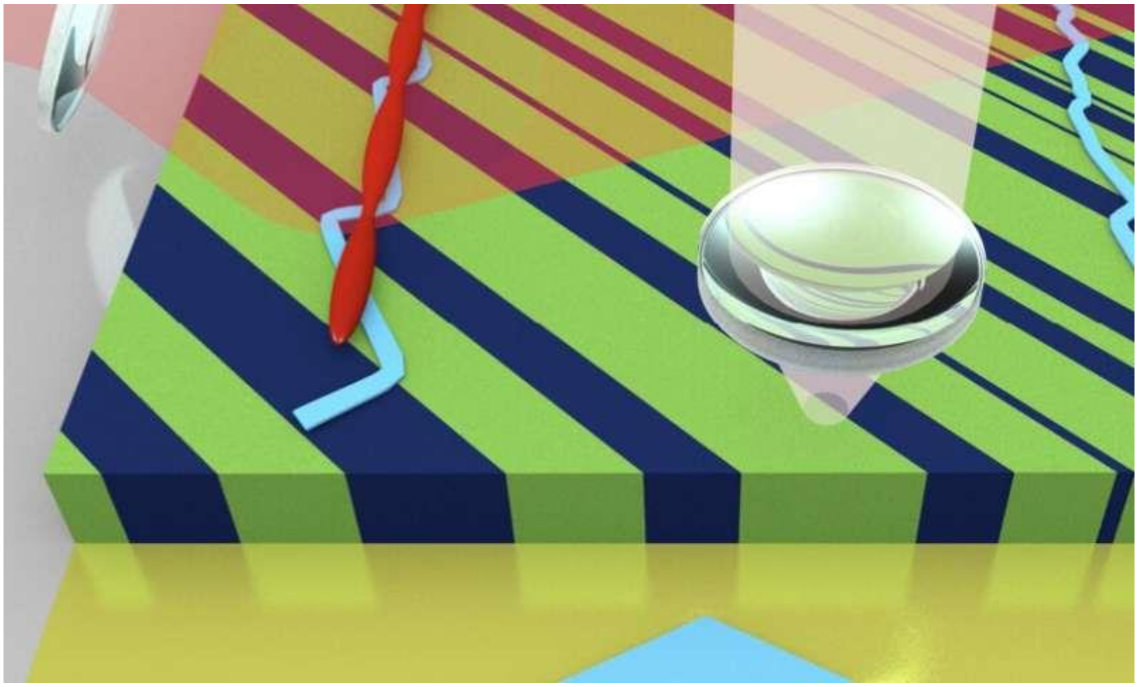
"The atoms we use are ultracold and in a quantum state: they have near absolute zero temperature and are among the coldest gases in the known universe," Lev said. "As such, they serve as the best micron-scale low-frequency magnetic field sensors. The atoms can be scanned over the material surface, allowing us to record a 2-D image of the fields nearby."

By calculating the distance between the atoms in the microscope and a material's surface, the researchers can back-out images of magnetic field sources. Magnetic field sources could, for instance, be electrons that are moving around or a general magnetization inside a material.

Imaging these sources while cooling them using a tool known as 'cryostat' could ultimately unveil new physical phenomena that occur at different phase transitions. The microscope developed by Lev and his colleagues could thus serve as a brand-new quantum sensor for imaging magnetic fields emanating from variety of materials, potentially leading to new fascinating discoveries.

"Once we demonstrated that the SQCRAMscope works, we began to search for a best first scientific use for it," Lev explained. "Iron-based (pnictide) superconductors seemed like ideal candidates, as they exhibit interesting electron transport behavior on the micron length scale at accessible temperatures."

Iron pnictide superconductors have a number of unusual and intriguing characteristics. To this day, physicists are unsure about how high-critical-temperature (high-Tc) superconductivity, such as the one observed in these materials, works. Iron-based superconductors were first uncovered around 2008. Interestingly, research revealed that they exhibited some behaviors similar to those of cuprate superconductors.



Credit: Yang et al.

"These `unconventional' superconductors (as opposed to the conventional ones like aluminum at low temperatures) famously exist in the cuprate materials, discovered in the mid 80's," Lev said. "The mechanism underlying their superconductivity remains a mystery. Researchers operating in our field hope that elucidating this mechanism will provide robust, room temperature, and ambient-pressure superconductors for use in a wide variety of technologies."

A key similarity between curprate and iron-based superconductors is that both these materials present unusual electronic phases of matter, on the warmer side of superconductivity. Two of the most renowned among these phases of matter are the 'strange metal' and the 'electron nematic' phases. The electron nematic phase is an example of a quantum liquid crystal, similar to the classic liquid crystals found in LCD displays.

"These classical crystals are nematics, meaning that the rod-like molecules all align along one direction, breaking the material's rotational symmetry," Lev said. "In other words, the molecules pick one preferred direction to point along. Condensed matter theorists in the 90's began thinking about how electrons might do the same thing. Not that electrons are anything but point-like (as far as we currently know), but that below a critical transition temperature, they would decide to preferentially flow (i.e., conduct or transport) along one particular direction in a crystal, again breaking rotational symmetry; this would show up as an anisotropy in the resistivity of the material."

While electron nematics have been consistently observed in iron-based superconductors, researchers are still unsure about the reasons why they arise and the relevance of this unique phase of matter to the lower-temperature superconducting phase. Theory has not yet definitively determined whether this phase hampers, enhances or plays little role in determining the Tc of the material's superconducting phase.

Pnictides could be ideal materials for the study of electron nematics, as electrons in them also prompt a spontaneous distortion of their crystal lattice structure. In fact, past research has found that as the electronic resistivity of these materials becomes anisotropic, their lattice distorts from a square-like to a parallelogram-like shape (i.e., from tetragonal to orthorhombic).

This transformation has two key consequences. Firstly, the resulting structural domains have a resistivity anisotropy pointing in orthogonal directions. Secondly, the fact that the lattice distortion rotates the polarization of reflected light allows one to observe these domains using optical microscopes.

"Unfortunately, the first consequence complicates transport measurements," Lev explained. "One can't just measure the resistivity anisotropy with an ohm meter because the signal averages to zero over the flipping domain structure. That's where we come in. We avoid this averaging problem by using a local probe to image the local anisotropy domain by domain by seeing the directions in which the electrons flow by detecting the magnetic field they cast."

Lev and his colleagues were the first to successfully image the local resistivity anisotropy in iron pnictide superconductors. One of the reasons they were successful is that the probe they used can operate at elevated temperatures (~130 K), such as the ones at which this unique transition occurs.

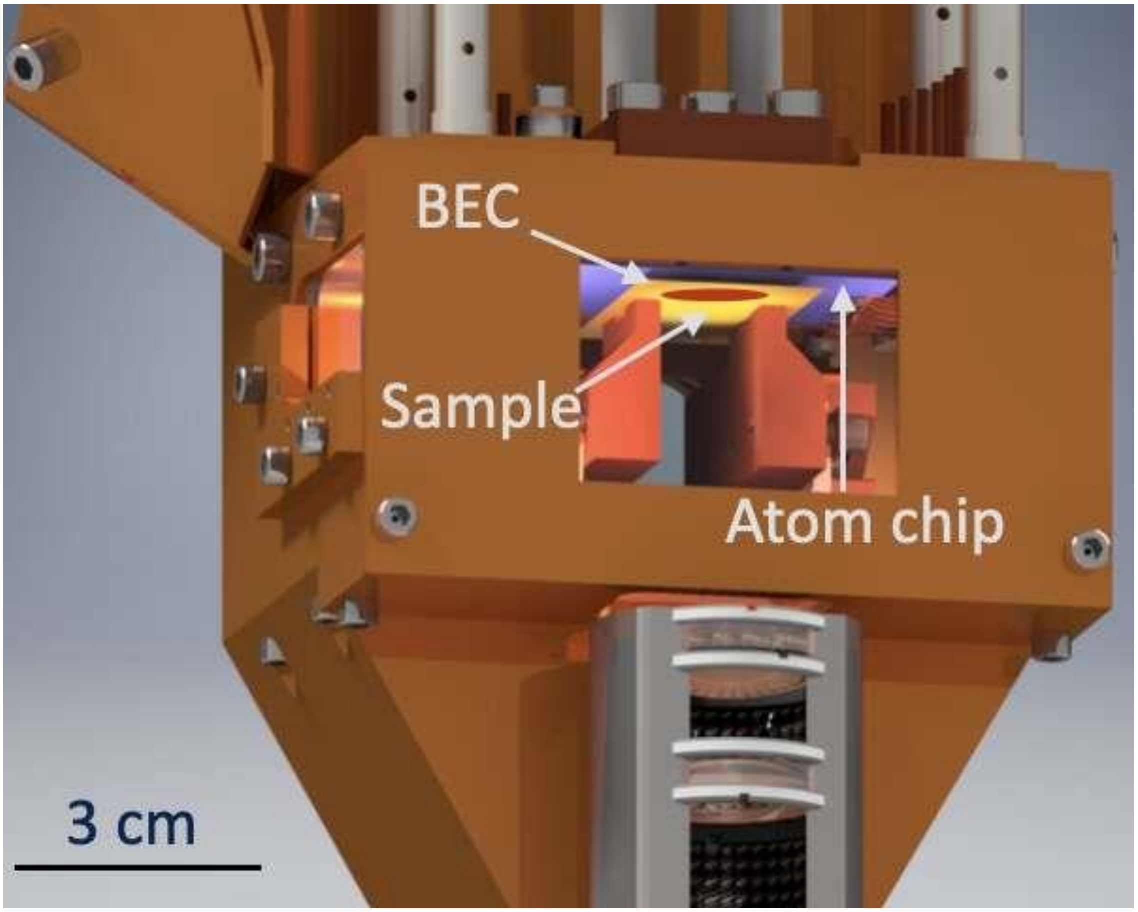


Figure explaining how the microscope developed by the researchers works. Credit: Yang et al.

"A standard probe, such as scanning SQUID magnetometry can't really image samples at these temperatures with high resolution because the device itself will get too warm and stop working with high sensitivity," Lev said. "In contrast, our probe is just a gas of atoms that do not absorb any heat from the sample. Moreover, because the atoms are transparent to most light wavelengths, we were able to shine a light onto the surface to image these domain structures at the same time as we were taking the magnetometry scans."

By imaging the domain structures and simultaneously capturing magnetometry scans, the researchers were able to identify the exact sites they were scanning within the material and determine whether the shift in lattice structures observed in iron pnictide superconductors does indeed occur at the same critical temperature as their electronic nematicity. Using this dual probe system, Lev and his colleagues could corroborate their observations, which has never been achieved when using other probing devices.

"Our device's local imaging capability allowed us to measure a sharper electron nematic transition and see that it occurred at the same temperature as the structural transition," Lev said. "The general research community often asked whether these transitions did in fact occur at the same temperature, and we showed that indeed they do, at least on the micron—to—tens-of-micron length scale."

The new microscope designed by Lev and his colleagues uses a Bose-Einstein condensate, which has a sensitivity that does not depend on the temperature of the sample that is being analyzed. In addition to its dual probe function, the microscope can thus collect highly precise measurements at anything from room to cryogenic temperatures, in a non-invasive way.

The recent study carried out by Lev and his colleagues has a number of important implications. Most notably, it demonstrates, for the very first time, the potential of the researchers' SQCRAMscope for studying physical phenomena.

Using the SQCRAMscope, the researchers were able to collect the first local images of nematic transitions in iron pnictide superconductors. These images offer new valuable insight about how and when these transitions take place. In their next studies, the researchers plan to use their quantum sensor to investigate nematicity further, as well as to explore physical phenomena in other complex quantum materials.

"We have compiled a long list of exciting materials to study now that the SQCRAMscope is fully operational," Lev said. "These either exhibit topologically protected electron transport or are strongly correlated (i.e., the electrons interact and move in a complicated dance with each other, with the consequence that at least some aspects of their physics are often still a mystery)." [30]

## Electronic map reveals 'rules of the road' in superconductor

Using a clever technique that causes unruly crystals of iron selenide to snap into alignment, Rice University physicists have drawn a detailed map that reveals the "rules of the road" for electrons both in normal conditions and in the critical moments just before the material transforms into a superconductor.

In a study online this week in the American Physical Society journal *Physical Review X* (*PRX*), physicist Ming Yi and colleagues offer up a band structure map for iron selenide, a material that has long puzzled physicists because of its structural simplicity and behavioral complexity. The map, which details the electronic states of the material, is a visual summary of data gathered from measurements of a single crystal of iron selenide as it was cooled to the point of superconductivity.

Yi began the angle-resolved photoemission spectroscopy experiments for the study during a postdoctoral stint at the University of California, Berkeley. The technically challenging experiments used powerful synchrotron light from the Stanford Synchrotron Radiation Lightsource (SSRL) to coax the crystal to emit electrons.

"In a sense, these measurements are like taking photographs of electrons that are flying out of the material," she said. "Each photograph tells the lives the electrons were living right before being kicked out of the material by photons. By analyzing all the photos, we can piece together the underlying physics that explains all of their stories."

### Red-light cameras for electrons

The electron detector tracked both the speed and direction that electrons were traveling when emitted from the crystal. That information contained important clues about the quantum mechanical laws that dictated the traffic patterns at a larger, microscopic scale, where key aspects of superconductivity are believed to arise.

These rules are encoded in a material's electronic structure, Yi said.

"They're like an electronic fingerprint of a material," she said. "Each material has its own unique fingerprint, which describes the allowed energy states electrons can occupy based on quantum mechanics. The electronic structure helps us decide, for example, whether something will be a good conductor or a good insulator or a superconductor."

### When things go sideways

Electrical resistance is what causes wires, smartphones and computers to heat up during use, and it costs billions of dollars each year in lost power on electric grids and cooling bills for data centers. Superconductivity, the zero-resistance flow of electricity, could eliminate that waste, but physicists have struggled to understand and explain the behavior of unconventional superconductors like iron selenide.

Yi was in graduate school when the first iron-based superconductors were discovered in 2008, and she's spent her career studying them. In each of these, an atom-thick layer of iron is sandwiched between other elements. At room temperature, the atoms in this iron layer are arranged in checkerboard squares. But when the materials are cooled near the point of superconductivity, the iron atoms shift and the squares become rectangular. This change brings about direction-dependent behavior, or nematicity, which is believed to play an important but undetermined role in superconductivity.

"Iron selenide is special because in all of the other iron-based materials, nematicity appears together with magnetic order," Yi said. "If you have two orders forming together, it is very difficult to tell which is more important, and how each one affects superconductivity. In iron selenide, you only have nematicity, so it gives us a unique chance to study how nematicity contributes to superconductivity by itself."

### Performing under pressure

The upshot of nematicity is that the traffic patterns of electrons—and the quantum rules that cause the patterns—may be quite different for electrons flowing right-to-left, along the long axis of the rectangles, than for the electrons flowing up-and-down along the short axis. But getting a clear look at those traffic patterns in iron selenide has been challenging because of twinning, a property of the crystals that causes the rectangles to randomly change orientation by 90 degrees. Twinning means that long-axis rectangles will run left-to-right about half of the time and up-and-down the other half.

Twinning in iron selenide made it impossible to obtain clear, whole-sample measurements of nematic order in the material until Rice physicists Pengcheng Dai and Tong Chen published a clever solution to the problem in May. Building on a detwinning technique developed by Dai and colleagues in 2014, Chen found he could detwin fragile crystals of iron selenide by gluing them atop a sturdier layer of barium iron arsenide and turning a screw to apply a bit of pressure. The technique causes all the nematic layers in the iron selenide to snap into alignment.

Dai and Chen were co-authors on the PRX paper, and Yi said the detwinning technique was key to getting clear data about the impact of nematicity on iron selenide's electronic behavior.

"This study would not have been possible without the detwinning technique that Pengcheng and Tong developed," Yi said. "It allowed us to take a peek at the arrangements of electronic states as the material system gets ready for superconductivity. We were able to make precise statements about the availability of electrons belonging to different orbitals that could participate in superconductivity when nematic rules have to be obeyed."

### A path forward

Yi said the data show that the magnitude of nematic shifts in iron selenide are comparable to the shifts measured in more complicated iron-based superconductors that also feature magnetic order. She said that suggests the nematicity that's observed in iron selenide could be a universal feature of all iron-based superconductors, regardless of the presence of long-range magnetism. And she hopes that her data allow theorists to explore that possibility and others.

"This set of measurements will provide precise guidance for theoretical models that aim to describe the nematic superconducting state in iron-based superconductors," she said. "That's important because nematicity plays a role in bringing about superconductivity in all of these materials." [29]

## Ballistic graphene Josephson junctions enter microwave circuits

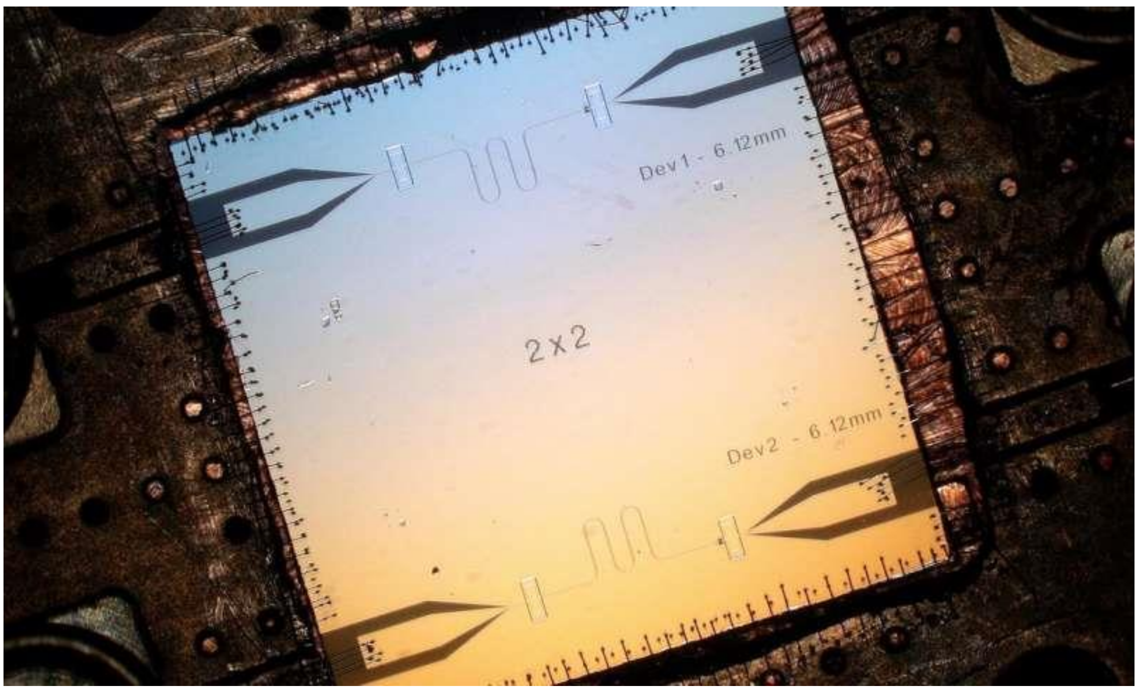
Superconducting quantum microwave circuits can function as qubits, the building blocks of a future quantum computer. A critical component of these circuits, the Josephson junction, is typically made using aluminium oxide. Researchers in the Quantum Nanoscience department at the Delft University of Technology have now successfully incorporated a graphene Josephson junction into a superconducting microwave circuit. Their work provides new insight into the interaction of superconductivity and graphene and its possibilities as a material for quantum technologies.

The essential building block of a quantum computer is the quantum bit, or qubit. Unlike regular bits, which can either be one or zero, qubits can be one, zero or a superposition of both these states. This last possibility, that bits can be in a superposition of two states at the same time, allows quantum computers to work in ways not possible with classical computers. The implications are profound: Quantum computers will be able to solve problems that will take a regular computer longer than the age of the universe to solve.

There are many ways to create qubits. One of the tried and tested methods is by using superconducting microwave circuits. These circuits can be engineered in such a way that they behave as harmonic oscillators  "If we put a charge on one side, it will go through the inductor and oscillate back and forth," said Professor Gary Steele. "We make our qubits out of the different states of this charge bouncing back and forth."

An essential element of quantum microwave circuits is the so-called Josephson junction, which can, for example, consist of a non-superconducting material that separates two layers of superconducting material. Pairs of superconducting electrons can tunnel through this barrier, from one superconductor to the other, resulting in a supercurrent that can flow indefinitely long without any voltage applied.

In state-of-the art Josephson junctions for quantum circuits, the weak link is a thin layer of aluminium oxide separating two aluminium electrodes. "However, these can only be tuned with the use of a magnetic field, potentially leading to cross-talk and on-chip heating, which can complicate their use in future applications," said Steele. Graphene offers a possible solution. It has proven to host robust supercurrents over micron distances that survive in magnetic fields of up to a few Tesla. However, these devices had thus far been limited to direct current (DC) applications. Applications in microwave circuits, such as qubits or parametric amplifiers, had not been explored.




Close-up of the new a superconducting microwave circuit with a graphene Josephson junction. Credit: TU Delft

The research team at Delft University of Technology incorporated a graphene Josephson junction into a superconducting microwave circuit. By characterizing their device in the DC regime, they showed that their graphene Josephson junction exhibits ballistic supercurrent that can be tuned by the use of a gate voltage, which prevents the device from heating up. Upon exciting the circuit with microwave radiation, the researchers directly observed the Josephson inductance of the junction, which had up to this point not been directly accessible in graphene superconducting devices.

The researchers believe that graphene Josephson junctions have the potential to play an important part in future quantum computers. "It remains to be seen if they can be made into viable qubits, however," said Steele. While the graphene junctions were good enough for building qubits, they were not as coherent as traditional quantum microwave circuits based on aluminium oxide junctions, so further development of the technology is required. However, in applications that don't require high coherence, gate tunability could be useful now. One such application is in amplifiers, which are also important in quantum infrastructure. Steele: "We are quite excited about using these devices for quantum amplifier applications."

The authors have made all of the data published in the manuscript available in an open repository, including the path all the way back to the data as it was measured from the instrument. In addition, the researchers released all of the software used for measuring the data, analysing the data, and making the plots in the figures under an open-source licence.

The results of the study have been published in *Nature Communications*. [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

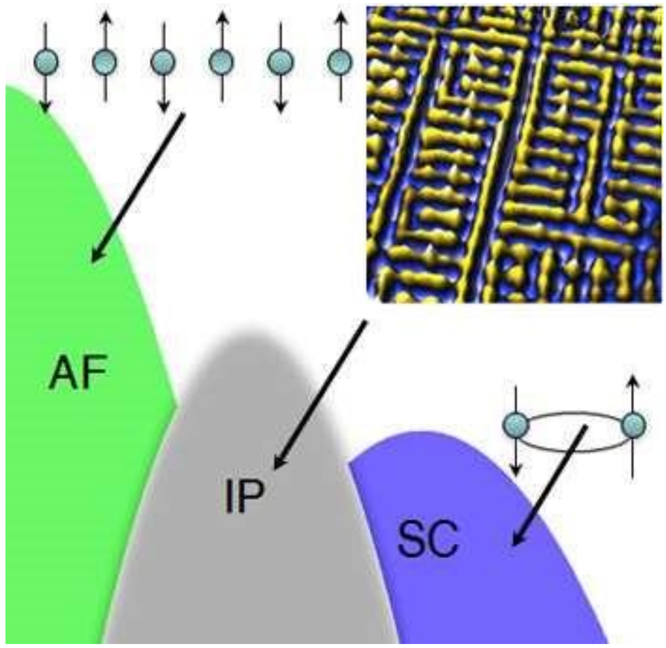
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical 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]

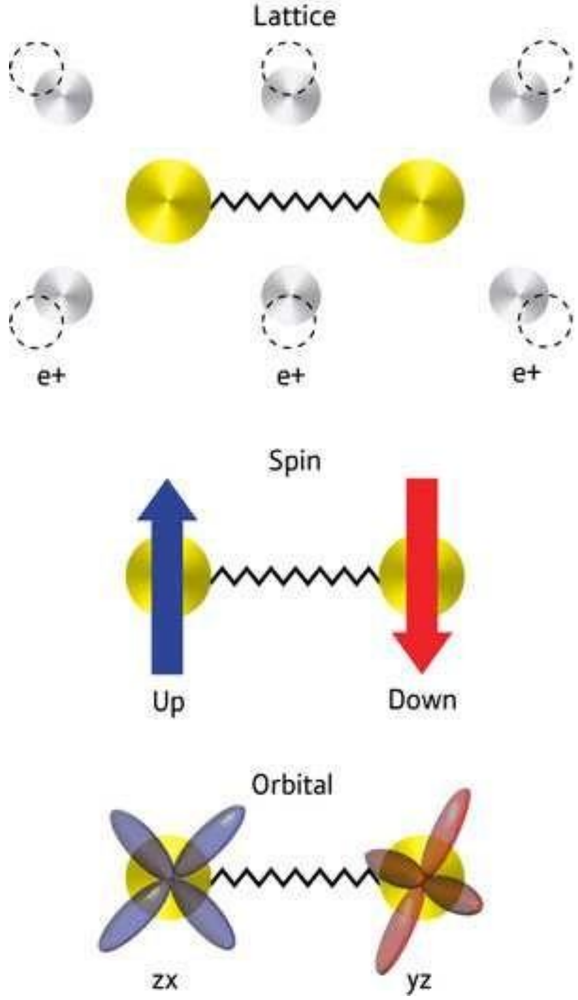
## Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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:

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

$$A \to A + \nabla\phi.$$

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

The condensate wave function can be written as

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

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

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

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

## Superconductivity and Quantum Entanglement

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

## Conclusions

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]

## References:


[1] https://www.academia.edu/3833335/The_Magnetic_field_of_the_Electric_current

[2] https://www.academia.edu/4239860/The_Bridge_between_Classical_and_Quantum_Mechanics

[3] http://en.wikipedia.org/wiki/BCS_theory

[4] http://en.wikipedia.org/wiki/Meissner_effect#cite_note-3

[5] http://en.wikipedia.org/wiki/London_equations

[6] Superconductivity switched on by magnetic field http://phys.org/news/2013-12-superconductivity-magnetic-field.html#jCp

[7] http://en.wikipedia.org/wiki/Superconductivity

[8] http://en.wikipedia.org/wiki/High-temperature_superconductivity

[9] http://en.wikipedia.org/wiki/Room-temperature_superconductor

[10] http://en.wikipedia.org/wiki/Resonating_valence_bond_theory

[11] http://en.wikipedia.org/wiki/Strongly_correlated_material

[12] http://en.wikipedia.org/wiki/Cooper_pair

[13] https://www.academia.edu/3834454/3_Dimensional_String_Theory

[14] http://en.wikipedia.org/wiki/Color_superconductivity

[15] http://en.wikipedia.org/wiki/Fermi_surface

[16] http://en.wikipedia.org/wiki/Higgs_mechanism

[17] Superconductivity's third side unmasked http://phys.org/news/2011-06-superconductivity-side-unmasked.html#nRlv

[18] https://www.academia.edu/4158863/Higgs_Field_and_Quantum_Gravity

[19] https://www.academia.edu/4221717/General_Weak_Interaction

[20] Einstein on Superconductivity http://arxiv.org/pdf/physics/0510251/

[21] Conventional Superconductivity http://phys.org/news150729937.html#jCp

[22] http://phys.org/news/2013-12-superconductor-theory-revolutionize-electrical.html#jCp

[23] http://phys.org/news150729937.html#jCp

[24] http://phys.org/news/2013-10-grand-theory-exotic-superconductivity.html#jCp

[25] http://www.pnas.org/content/early/2013/10/09/1316512110.full.pdf+html

[26] The Secret of Quantum Entanglement

https://www.academia.edu/7229968/The_Secret_of_Quantum_Entanglement

[27] Superconducting qubits can function as quantum engines https://phys.org/news/2017-10-superconducting-qubits-function-quantum.html

[28] Ballistic graphene Josephson junctions enter microwave circuits

https://phys.org/news/2018-10-ballistic-graphene-josephson-junctions-microwave.html

[29] Electronic map reveals 'rules of the road' in superconductor

https://phys.org/news/2019-12-electronic-reveals-road-superconductor.html

[30] Imaging nematic transitions in iron pnictide superconductors

https://phys.org/news/2020-04-imaging-nematic-transitions-iron-pnictide.html

[31] Researchers detect a supercurrent at the edge of a superconductor with a topological twist

https://phys.org/news/2020-04-supercurrent-edge-superconductor-topological.html