Room-Temperature Superconductivity

And they suggest that laser light might be a good way to create and explore transient states that could be stabilized for practical applications—including, potentially, room-temperature superconductivity. [32]

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Now a team led by MIT's Plasma Science and Fusion Center (PSFC) and MIT spinout company Commonwealth Fusion Systems (CFS), has developed and extensively tested an HTS cable technology that can be scaled and engineered into the high-performance magnets. [30]

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.

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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

Study raises new possibilities for triggering room-temperature superconductivity with light

Much like people can learn more about themselves by stepping outside of their comfort zones, researchers can learn more about a system by giving it a jolt that makes it a little unstable—scientists call this "out of equilibrium"—and watching what happens as it settles back down into a more stable state.

In the case of a superconducting material known as yttrium barium copper oxide, or YBCO, experiments have shown that under certain conditions, knocking it out of equilibrium with a laser pulse allows it to superconduct—conduct electrical current with no loss—at much closer to room temperature than researchers expected. This could be a big deal, given that scientists have been pursuing room-temperature superconductors for more than three decades.

But do observations of this unstable state have any bearing on how high-temperature superconductors would work in the real world, where applications like power lines, maglev trains, particle accelerators and medical equipment require them to be stable?

A study published in *Science Advances* today suggests that the answer is yes.

"People thought that even though this type of study was useful, it was not very promising for future applications," said Jun-Sik Lee, a staff scientist at the Department of Energy's SLAC National Accelerator Laboratory and leader of the international research team that carried out the study.

"But now we have shown that the fundamental physics of these unstable states are very similar to those of stable ones. So this opens up huge opportunities, including the possibility that other materials could also be nudged into a transient superconducting state with light. It's an interesting state that we can't see any other way."

What does normal look like?

YBCO is a copper oxide compound, or cuprate, a member of a family of materials that was discovered in 1986 to conduct electricity with zero resistance at much higher temperatures than scientists had thought possible.

Like conventional superconductors, which had been discovered more than 70 years earlier, YBCO switches from a normal to a superconducting state when chilled below a certain transition temperature. At that point, electrons pair up and form a condensate—a sort of electron soup—that effortlessly conducts electricity. Scientists have a solid theory of how this happens in old-style superconductors, but there's still no consensus about how it works in unconventional ones like YBCO.

One way to attack the problem is to study the normal state of YBCO, which is plenty weird in its own right. The normal state contains a number of complex, interwoven phases of matter, each with the potential to help or hinder the transition to superconductivity, that jostle for dominance and sometimes overlap. What's more, in some of those phases electrons seem to recognize each other and act collectively, as if they were dragging each other around.

It's a real tangle, and researchers hope that understanding it better will shed light on how and why these materials become superconducting at temperatures much higher than the theoretical limit predicted for conventional superconductors.

It's hard to explore these fascinating normal states at the warm temperatures where they occur, so scientists generally chill their YBCO samples to the point where they become superconducting, then switch off the superconductivity to restore the normal state.

The switching is generally done by exposing the material to a magnetic field. This is the favored approach because it leaves the material in a stable configuration—the sort you would need to create a practical device.

Superconductivity can also be switched off with a pulse of light, Lee said. This creates a normal state that's a little off balance—out of equilibrium—where interesting things can happen, from a scientific point of view. But the fact that it's unstable has made scientists wary of assuming that anything they learn there can also be applied to stable materials like the ones needed for practical applications.

Waves that stay put

In this study, Lee and his collaborators compared the two switching approaches—magnetic fields and light pulses—by focusing on how they affect a peculiar phase of matter known as charge density waves, or CDWs, that appears in superconducting materials. CDWs are wavelike patterns of higher and lower electron density, but unlike ocean waves, they don't move around.

Two-dimensional CDWs were discovered in 2012, and in 2015 Lee and his collaborators discovered a new 3D type of CDW. Both types are intimately intertwined with high-temperature superconductivity, and they can serve as markers of the transition point where superconductivity turns on or off.

To compare what CDWs look like in YBCO when its superconductivity is switched off with light versus magnetism, the research team did experiments at three X-ray light sources.

First they measured the properties of the undisturbed material, including its charge density waves, at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL).

Then samples of the material were exposed to high magnetic fields at the SACLA synchrotron facility in Japan and to laser light at the Pohang Accelerator Laboratory's X-ray free-electron laser (PAL-XFEL) in Korea, so that changes in their CDWs could be measured.

"These experiments showed that exposing the samples to magnetism or light generated similar 3D patterns of CDWs," said SLAC staff scientist and study co-author Sanghoon Song. Although how and why this happens is still not understood, he said, the results demonstrate that the states induced by either approach have the same fundamental physics. And they suggest that laser light might be a good way to create and explore transient states that could be stabilized for practical applications—including, potentially, room-temperature superconductivity. [32]

Researchers synthesize room temperature superconducting material

Compressing simple molecular solids with hydrogen at extremely high pressures, University of Rochester engineers and physicists have, for the first time, created material that is superconducting at room temperature.

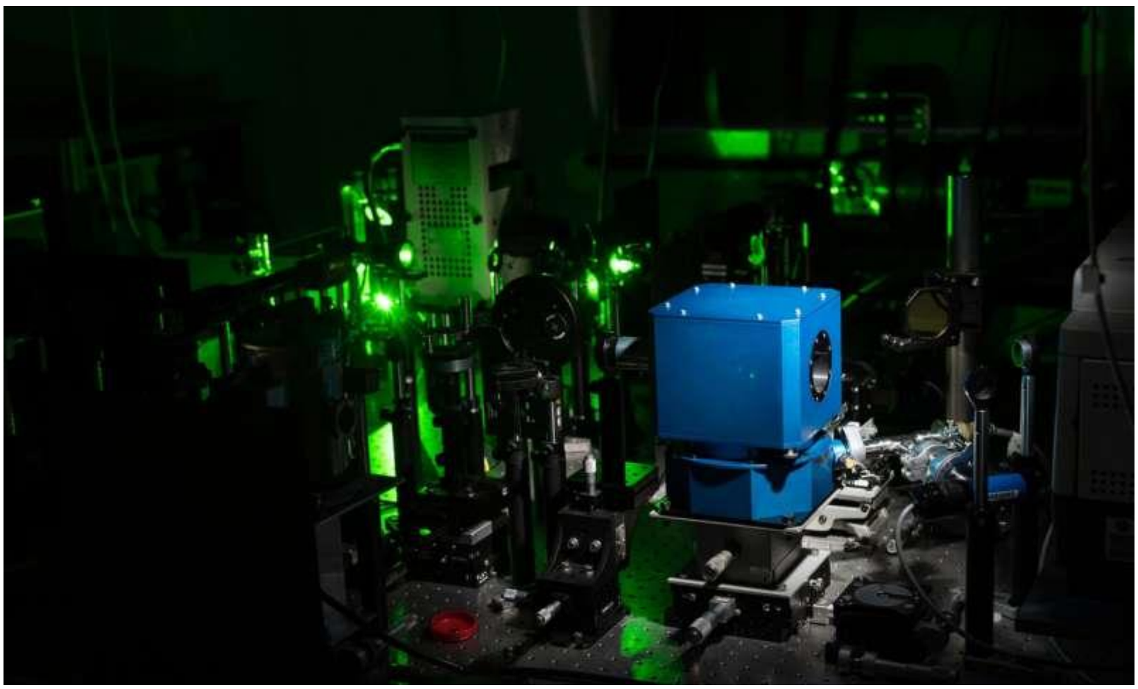
Featured as the cover story in the journal *Nature*, the work was conducted by the lab of Ranga Dias, an assistant professor of physics and mechanical engineering.

Dias says developing materials that are superconducting—without electrical resistance and expulsion of magnetic field at room temperature—is the "holy grail" of condensed matter physics. Sought for more than a century, such materials "can definitely change the world as we know it," Dias says.

In setting the new record, Dias and his research team combined hydrogen with carbon and sulfur to photochemically synthesize simple organic-derived carbonaceous sulfur hydride in a diamond anvil cell, a research device used to examine miniscule amounts of materials under extraordinarily high pressure.

The carbonaceous sulfur hydride exhibited superconductivity at about 58 degrees Fahrenheit and a pressure of about 39 million psi. This is the first time that superconducting material has been observed at room temperatures.

"Because of the limits of low temperature, materials with such extraordinary properties have not quite transformed the world in the way that many might have imagined. However, our discovery will break down these barriers and open the door to many potential applications," says Dias, who is also affiliated with the University's Materials Science and High Energy Density Physics programs.



Applications include:

Power grids that transmit electricity without the loss of up to 200 million megawatt hours (MWh) of the energy that now occurs due to resistance in the wires.

A new way to propel levitated trains and other forms of transportation.

Medical imaging and scanning techniques such as MRI and magnetocardiography

Faster, more efficient electronics for digital logic and memory device technology.

"We live in a semiconductor society, and with this kind of technology, you can take society into a superconducting society where you'll never need things like batteries again," says Ashkan Salamat of the University of Nevada Las Vegas, a coauthor of the discovery.

The amount of superconducting material created by the diamond anvil cells is measured in picoliters—about the size of a single inkjet particle.

The next challenge, Dias says, is finding ways to create the room temperature superconducting materials at lower pressures, so they will be economical to produce in greater volume. In comparison to the millions of pounds of pressure created in diamond anvil cells, the atmospheric pressure of Earth at sea level is about 15 PSI.

Why room temperature matters

First discovered in 1911, superconductivity gives materials two key properties. Electrical resistance vanishes. And any semblance of a magnetic field is expelled, due to a phenomenon called the Meissner effect. The magnetic field lines have to pass around the superconducting material, making it possible to levitate such materials, something that could be used for frictionless high-speed trains, known as maglev trains.

Powerful superconducting electromagnets are already critical components of maglav trains, magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) machines, particle accelerators and other advanced technologies, including early quantum supercomputers.

But the superconducting materials used in the devices usually work only at extremely low temperatures—lower than any natural temperatures on Earth. This restriction makes them costly to maintain—and too costly to extend to other potential applications. "The cost to keep these materials at cryogenic temperatures is so high you can't really get the full benefit of them," Dias says.

Previously, the highest temperature for a superconducting material was achieved last year in the lab of Mikhail Eremets at the Max Planck Institute for Chemistry in Mainz, Germany, and the Russell Hemley group at the University of Illinois at Chicago. That team reported superconductivity at -10 to 8 degrees Fahrenheit using lanthanum superhydride.

Researchers have also explored copper oxides and iron-based chemicals as potential candidates for high temperature superconductors in recent years. However, hydrogen—the most abundant element in the universe —also offers a promising building block.

"To have a high temperature superconductor, you want stronger bonds and light elements. Those are the two very basic criteria," Dias says. "Hydrogen is the lightest material, and the hydrogen bond is one of the strongest.

"Solid metallic hydrogen is theorized to have high Debye temperature and strong electron-phonon coupling that is necessary for room temperature superconductivity," Dias says.

However, extraordinarily high pressures are needed just to get pure hydrogen into a metallic state, which was first achieved in a lab in 2017 by Harvard University professor Isaac Silvera and Dias, then a postdoc in Silvera's lab.

A 'paradigm shift'

And so, Dias's lab at Rochester has pursued a "paradigm shift" in its approach, using as an alternative, hydrogen-rich materials that mimic the elusive superconducting phase of pure hydrogen, and can be metalized at much lower pressures.

First the lab combined yttrium and hydrogen. The resulting yttrium superhydride exhibited superconductivity at what was then a record high temperature of about 12 degrees Fahrenheit and a pressure of about 26 million pounds per square inch.

Next the lab explored covalent hydrogen-rich organic-derived materials.

This work resulted in the carbonaceous sulfur hydride. "This presence of carbon is of tantamount importance here," the researchers report. Further "compositional tuning" of this combination of elements may be the key to achieving superconductivity at even higher temperatures, they add. [31]

Superconductor technology for smaller, sooner fusion

Scientists have long sought to harness fusion as an inexhaustible and carbon-free energy source. Within the past few years, groundbreaking high-temperature superconductor technology (HTS) sparked a new vision for achieving practical fusion energy. This approach, known as the high-field pathway to fusion, aims to generate fusion in compact devices on a shorter timescale and lower cost than alternative approaches.

A key technical challenge to realizing this vision, though, has been getting HTS superconductors to work in an integrated way in the development of new, high-performance superconducting magnets, which will enable higher magnetic fields than previous generations of magnets, and are central to confining and controlling plasma reactions.

Now a team led by MIT's Plasma Science and Fusion Center (PSFC) and MIT spinout company Commonwealth Fusion Systems (CFS), has developed and extensively tested an HTS cable technology that can be scaled and engineered into the high-performance magnets. The team's research was published on Oct. 7 in *Superconductor Science and Technology*. Researchers included MIT assistant professor and principal investigator Zachary Hartwig; PSFC Deputy Head of Engineering Rui F. Vieira and other key PSFC technical and engineering staff; CFS Chief Science Officer Brandon Sorbom Ph.D. '17 and other CFS engineers; and scientists at CERN in Geneva, Switzerland, and at the Robinson Research Institute at Victoria University of Wellington, New Zealand.

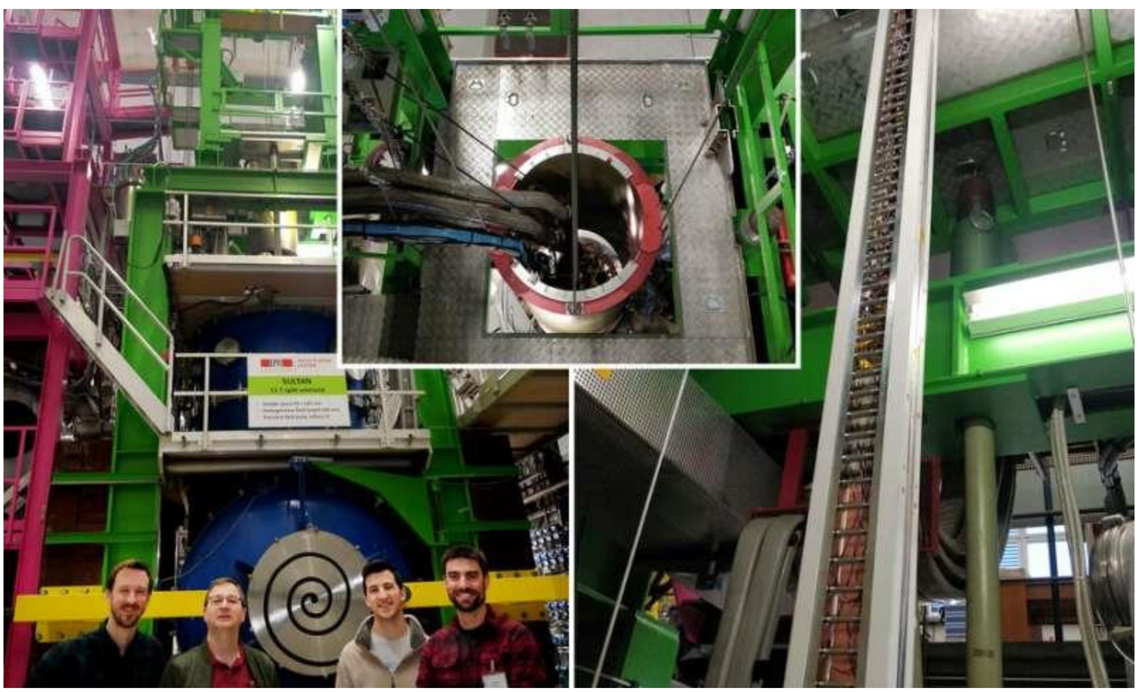
This development follows a recent boost to the high-field pathway, when 47 researchers from 12 institutions published seven papers in the Journal of Plasma Physics, showing that a high-field fusion device, called SPARC, built with such magnets would produce net energy—more energy than it consumes—something never previously demonstrated.

"The cable technology for SPARC is an important piece of the puzzle as we work to accelerate the timeline of achieving fusion energy," says Hartwig, assistant professor of nuclear science and engineering, and leader of the research team at the PSFC. "If we're successful in what we're doing and in other technologies, fusion energy will start to make a difference in mitigating climate change—not in 100 years, but in 10 years."

A super cable

The innovative technology described in the paper is a superconducting cable that conducts electricity with no resistance or heat generation and that will not degrade under extreme mechanical, electrical, and thermal conditions. Branded VIPER (an acronymic feat that stands for Vacuum Pressure Impregnated, Insulated, Partially transposed, Extruded, and Roll-formed), it consists of commercially produced thin steel tapes coated with HTS compound—yttrium-barium-copper-oxide—that are packaged into an assembly of copper and steel components to form the cable. Cryogenic coolant, such as supercritical helium, can flow easily through the cable to remove heat and keep the cable cold even under challenging conditions.

"One of our advances was figuring out a way to solder the HTS tape inside the cable, effectively making it a monolithic structure where everything is thermally connected," says Sorbom. Yet VIPER can also be fashioned into twists and turns, using joints to create "almost any type of geometry," he adds. This makes the cable an ideal building material for winding into coils capable of generating and containing magnetic fields of enormous strength, such as those required to make fusion devices substantially smaller than presently envisioned net-energy fusion devices.



Left: Cable Team members (l-r) Zach Hartwig, Phil Michael, Vinny Fry, and Brandon Sorbom stand in front of the SULTAN test facility in Villagen, Switzerland. Top-center: A view into the test well during installation of the cable into SULTAN. Right: A cable assembly contains two 3-meter VIPER HTS cables for SULTAN testing packaged within a superstructure for mechanical support. Credit: Zach Hartwig

Resilient and robust

"The key thing we can do with VIPER cable is make a magnetic field two to three times stronger at the size required than the present generation of superconducting magnet technology," Hartwig says. The magnitude of the magnetic field in tokamaks plays a strong nonlinear role in determining plasma performance. For example, fusion power density scales as magnetic field to the fourth power: Doubling the field increases fusion power by 16 times or, conversely, the same fusion output power can be achieved in a device 16 times smaller by volume.

"In the development of high field magnets for fusion, HTS cables are an essential ingredient, and they've been missing," says Soren Prestemon, director of the U.S. Magnet Development Program at the Lawrence Berkeley National Laboratory, who was not involved with this research. "VIPER is a breakthrough in the area of cable architecture—arguably the first candidate to be proven viable for fusion—and will enable the critical step forward to demonstration in a fusion reactor."

VIPER technology also presents a powerful approach to a particular problem in the superconducting magnet field, called a quench, "that has terrified engineers since they started building superconducting magnets," says Hartwig. A quench is a drastic temperature increase that occurs when the cold cables can no longer conduct electrical current without any resistance. When quench occurs, instead of generating almost zero heat in the superconducting state, the electrical current generates substantial resistive heating in the cable.

"The rapid temperature rise can cause the magnet to potentially damage or destroy itself if the electrical current is not shut off," says Hartwig. "We want to avoid this situation or, if not, at least know about it as quickly and certainly as possible."

The team incorporated two types of temperature-sensing fiber optic technology developed by collaborators at CERN and Robinson Research Institute. The fibers exhibited—for the first time on full-scale HTS cables and in representative conditions of high-magnetic field fusion magnets—sensitive and high-speed detection of temperature changes along the cable to monitor for the onset of quench.

Another key result was the successful incorporation of easily fabricated, low-electrical resistance, and mechanically robust joints between VIPER cables. Superconducting joints are often complex, challenging to make, and more likely to fail than others parts of a magnet; VIPER was designed to eliminate these issues. The VIPER joints have the additional advantage of being demountable, meaning they can be taken apart and reused with no impact on performance.

Prestemon notes that the cable's innovative architecture directly impacts real-world challenges in operating fusion reactors of the future. "In an actual commercial fusion-energy-producing facility, intense heat and radiation deep inside the reactor will require routine component replacements," he says. "Being able to take these joints apart and put them back together is a significant step towards making fusion a cost-effective proposition."

The 12 VIPER cables that Hartwig's team built, running between one and 12 meters in length, were evaluated with bending tests, thousands of sudden "on-off" mechanical cycles, multiple cryogenic thermal cycles, and dozens of quench-like events to simulate the kind of punishing conditions encountered in the magnets of a fusion device. The group successfully completed four multi-week test campaigns in four months at the SULTAN facility, a leading center for superconducting cable evaluation operated by Swiss Plasma Center, affiliated with Ecole Polytechnique Fédérale de Lausanne in Switzerland.

"This unprecedented rate of HTS cable testing at SULTAN shows the speed that technology can be advanced by an outstanding team with the mindset to go fast, the willingness to take risks, and the resources to execute," says Hartwig. It is a sentiment that serves as the foundation of the SPARC project.

The SPARC team continues to improve VIPER cable and is moving on to the next project milestone in mid-2021: "We'll be building a multi-ton model coil that will be similar to the size of a full-scale magnet for SPARC," says Sorbom. These research activities will continue to advance the foundational magnet technologies for SPARC and enable the demonstration of net energy from fusion, a key achievement that signals fusion is a viable energy technology. "That will be a watershed moment for fusion energy," says Hartwig. [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

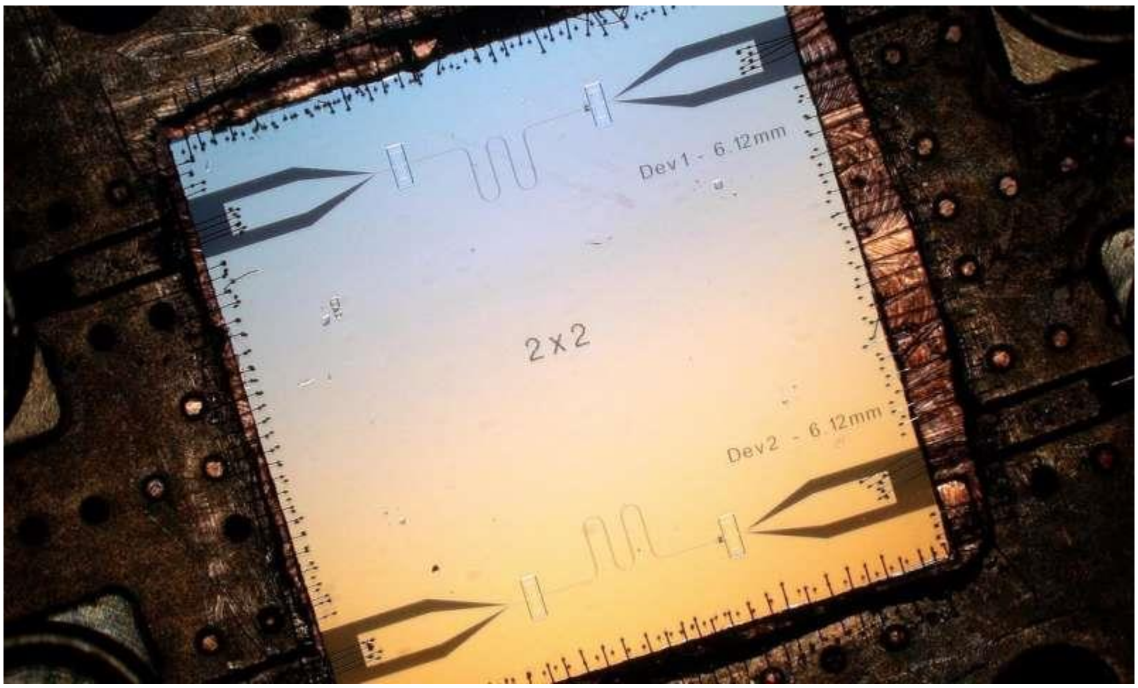
Superconducting quantum microwave circuits can function as qubits, the building blocks of a future quantum computer. A critical component of these circuits, the Josephson junction, is typically made using aluminium oxide. Researchers in the Quantum Nanoscience department at the Delft University of Technology 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

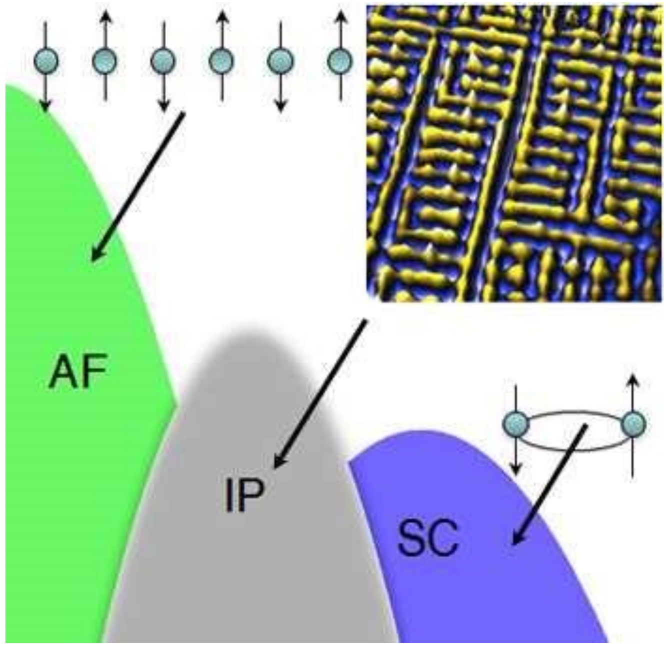
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

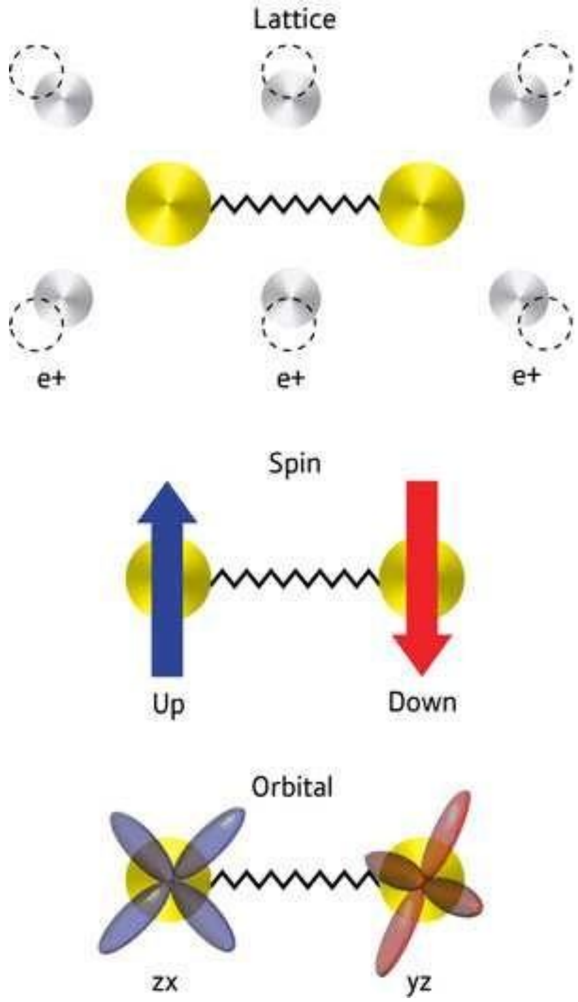
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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:

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

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

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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