# Finding Magic Angle Superconductors

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*Researchers from Google and the University of California Santa Barbara have taken an important step towards the goal of building a large-scale 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

### Finding the 'magic angle' to create a new superconductor

Researchers at The Ohio State University, in collaboration with scientists around the world, have made a discovery that could provide new insights into how superconductors might move energy more efficiently to power homes, industries and vehicles.

Their work, published last week in the journal *Science Advances*, showed that graphene—a material composed of a single layer of carbon atoms—is more likely to become a superconductor than originally thought possible.

"Graphene by itself can conduct energy, as a normal metal is conductive, but it is only recently that we learned it can also be a superconductor, by making a so-called 'magic angle' – twisting a second layer of graphene on top of the first," said Jeanie Lau, a professor of physics at Ohio State and co-author of the paper. "And that opens possibilities for additional research to see if we can make this material work in the real world."

Unlike most conventional conductors, superconductors are metals that can conduct electricity without resistance, thus suffering no loss of energy.

Graphene is two-dimensional crystal—a perfectly flat piece of carbon—and, as a single layer, is not a superconductor. But earlier this year, scientists at the Massachusetts Institute of Technology published research that showed that graphene could become a superconductor if one piece of graphene were laid on top of another piece and the layers twisted to a specific angle—what they termed "the magic angle."

That magic angle, scientists thought, was between 1 degree and 1.2 degrees—a very precise angle.

"The question is, the magic angle, how magic does it have to be?" said Emilio Codecido, a graduate student in Lau's lab and a co-author on the paper.

The Ohio State team found that the magic angle appears to be less magical than originally thought. Their work found that graphene layers still superconducted at a smaller angle, around 0.9 degrees. It is a small distinction, but it could open the possibility of new experiments to investigate graphene as a potential superconductor in the real world. So far, superconducting is limited outside of scientific laboratories because in order to superconduct electricity, the electric lines must be kept at extremely low temperatures.

"This research pushed our understanding of superconductors and the magic angle a little further than the theory and prior experiments might have expected," said Marc Bockrath, a co-author of the paper and physics professor at Ohio State.

"Superconductivity could revolutionize many industries—electric transmission lines, communication lines, transportation, trains," Codecido said. "Superconductivity in twisted bilayer graphene will teach us about superconductivity at much higher temperatures, temperatures that will be useful for real-world applications. That's where future work will be focused." [34]

## Experiments explore the mysteries of 'magic' angle superconductors

In spring 2018, the surprising discovery of superconductivity in a new material set the scientific community abuzz. Built by layering one carbon sheet atop another and twisting the top one at a "magic" angle, the material enabled electrons to flow without resistance, a trait that could dramatically boost energy efficient power transmission and usher in a host of new technologies.

Now, new experiments conducted at Princeton give hints at how this material—known as magic-angle twisted graphene—gives rise to superconductivity. In this week's issue of the journal *Nature*, Princeton researchers provide firm evidence that the superconducting behavior arises from strong interactions between electrons, yielding insights into the rules that electrons follow when superconductivity emerges.

"This is one of the hottest topics in physics," said Ali Yazdani, the Class of 1909 Professor of Physics and senior author of the study. "This is a material that is incredibly simple, just two sheets of carbon that you stick one on top of the other, and it shows superconductivity."

Exactly how superconductivity arises is a mystery that laboratories around the world are racing to solve. The field even has a name, "twistronics."

Part of the excitement is that, compared to existing superconductors, the material is quite easy to study since it only has two layers and only one type of atom—carbon.

"The main thing about this new material is that it is a playground for all these kinds of physics that people have been thinking about for the last 40 years," said B. Andrei Bernevig, a professor of physics specializing in theories to explain complex materials.

The superconductivity in the new material appears to work by a fundamentally different mechanism from traditional superconductors, which today are used in powerful magnets and other limited applications. This new material has similarities to copper-based, high-temperature superconductors discovered in the 1980s called cuprates. The discovery of cuprates led to the Nobel Prize in Physics in 1987.

The new material consists of two atomically thin sheets of carbon known as graphene. Also the subject of a Nobel Prize in Physics, in 2010, graphene has a flat honeycomb pattern, like a sheet of chicken wire. In March 2018, Pablo Jarillo-Herrero and his team at the Massachusetts Institute of Technology placed a second layer of graphene atop the first, then rotated the top sheet by the "magic" angle of about 1.1 degrees. This angle had been predicted earlier by physicists to cause new electron interactions, but it came as a shock when MIT scientists demonstrated superconductivity.

Seen from above, the overlapping chicken-wire patterns give a flickering effect known as "moiré," which arises when two geometrically regular patterns overlap, and which was once popular in the fabrics and fashions of 17th and 18th century royals.

These moiré patterns give rise to profoundly new properties not seen in ordinary materials. Most ordinary materials fall into a spectrum from insulating to conducting. Insulators trap electrons in energy pockets or levels that keep them stuck in place, while metals contain energy states that permit electrons to flit from atom to atom. In both cases, electrons occupy different energy levels and do not interact or engage in collective behavior.

In twisted graphene, however, the physical structure of the moiré lattice creates energy states that prevent electrons from standing apart, forcing them to interact. "It is creating a condition where the electrons can't get out of each other's way, and instead they all have to be in similar energy levels, which is prime condition to create highly entangled states," Yazdani said.

The question the researchers addressed was whether this entanglement has any connection with its superconductivity. Many simple metals also superconduct, but all the high-temperature superconductors discovered to date, including the cuprates, show highly entangled states caused by mutual repulsion between electrons. The strong interaction between electrons appears to be a key to achieve higher temperature superconductivity.

To address this question, Princeton researchers used a scanning tunneling microscope that is so sensitive that it can image individual atoms on a surface. The team scanned samples of magic-angle twisted graphene in which they controlled the number of electrons by applying a voltage to a nearby electrode. The study provided microscopic information on electron behavior in twisted bilayer graphene, whereas most other studies to date have monitored only macroscopic electrical conduction.

By dialing the number of electrons to very low or very high concentrations, the researchers observed electrons behaving almost independently, as they would in simple metals. However, at the critical concentration of electrons where superconductivity was discovered in this system, the electrons suddenly displayed signs of strong interaction and entanglement.

At the concentration where superconductivity emerged, the team found that the electron energy levels became unexpectedly broad, signals that confirm strong interaction and entanglement. Still, Bernevig emphasized that while these experiments open the door to further study, more work needs to be done to understand in detail the type of entanglement that is occurring.

"There is still so much we don't know about these systems," he said. "We are nowhere near even scraping the surface of what can be learned through experiments and theoretical modeling."

Contributors to the study included Kenji Watanabe and Takashi Taniguchi of the National Institute for Material Science in Japan; graduate student and first author Yonglong Xie, postdoctoral research fellow Berthold Jäck, postdoctoral research associate Xiaomeng Liu, and graduate student Cheng-Li Chiu in Yazdani's research group; and Biao Lian in Bernevig's research group. [33]

## Leiden physicists image lumpy superconductor

High-temperature superconductivity is one of the big mysteries in physics. Milan Allan's research group used a Josephson Scanning Tunneling Microscope to image spatial variations of superconducting particles for the first time, and published about it in the journal *Nature*.

"One of the mysteries of high temperaturesuperconductors is the possibility of being inhomogeneous. This means that the density of the Cooper pairs causing the superconductivity changes over space," says physicist Milan Allan of LION, 'we proved that, indeed, very inhomogeneous superconductors exist, by imaging them for the first time."

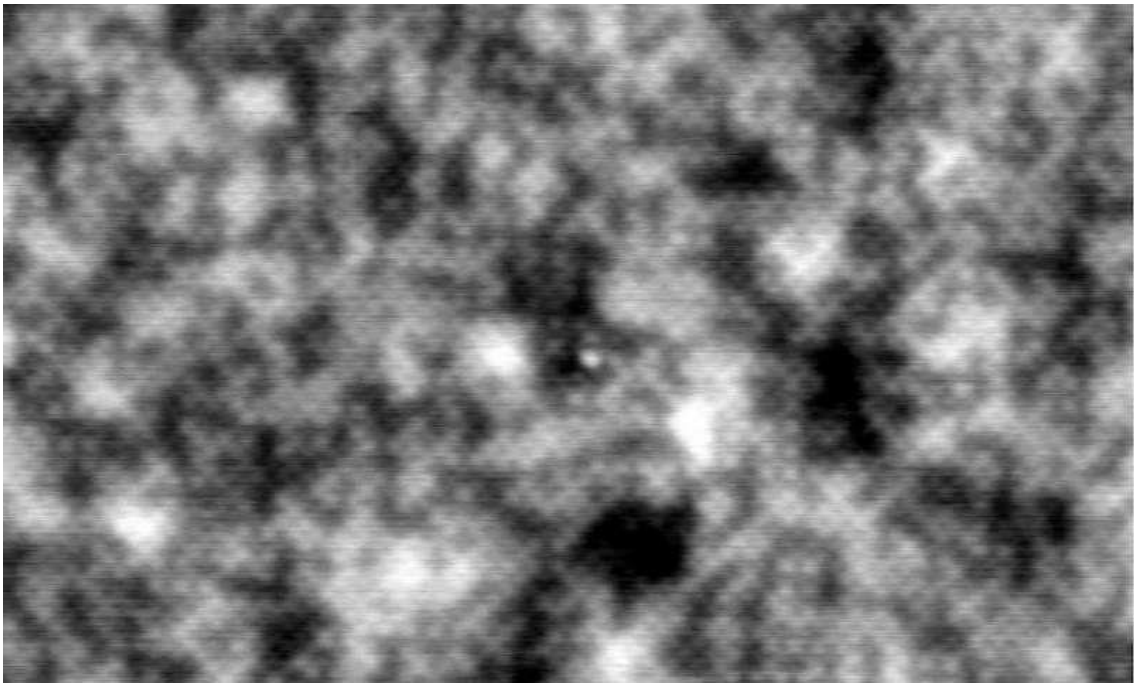
The discovery netted Doohee Cho, Koen Bastiaans, Damianos Chatzopoulos and Allan a Nature paper, and can help explain the mysterious high temperature superconductivity.

Conventional superconductivity, in which a material conducts an electrical current without any measurable resistance, was discovered in 1911. Leiden physicist Heike Kamerlingh Onnes noticed that the electrical resistance of mercury vanished at a temperature of 4.2 degrees above absolute zero.

### Sailing boats

That was strange and unexpected, because normally, electrons that flow through a metal, will bump into atoms or irregularities in the crystal structure, leading to electrical resistance.

Only in 1957, the phenomenon was explained by physicists Bardeen, Cooper and Schrieffer. They showed how electrons flowing through a crystal can sense each other at a distance, via vibrations in the crystal lattice, leading them to couple and form so called Cooper pairs.



Topography of the crystal. Credit: Leiden University

Other than electrons, Cooper pairs can merge and form one large collective, moving through the crystal. This collective is much larger than individual atoms or defects, and it will not sense them. It is a bit like the giant wave that flows through a field of sailing boats unhindered, where small waves will be stopped by individual boats.

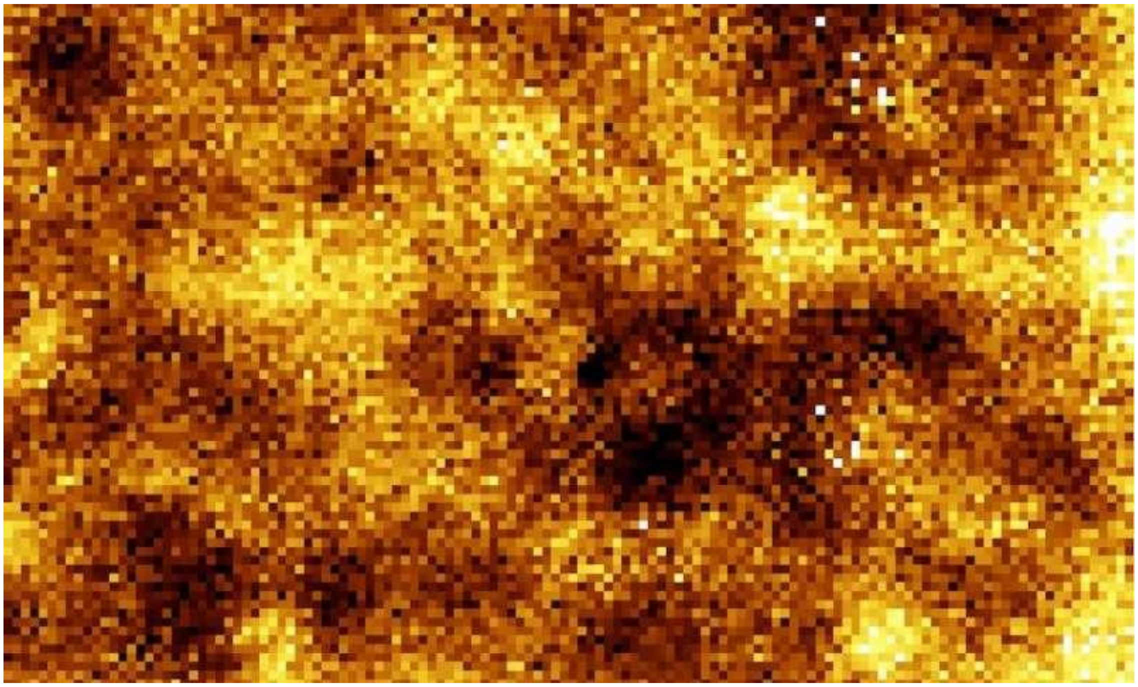
## High Temperature Superconductors

Unexpectedly, in 1986 the Swiss physicists Bednorz and Müller discovered a class of materials superconducting at unusually 'warm' temperatures up to 90 degrees above absolute zero. Warm enough to speak of High Temperature Superconductivity."

This promises a host of applications in technology, ranging from practically lossless power lines to hovering trains, if the critical temperature could be increase to room temperature.

"But the promise wasn't fulfilled," says Allan. Some applications are slowly hitting the market, but the critical temperature stalled, perhaps because to this day, theoretical physicists don't fully understand unconventional superconductivity, despite decades of experiments and theorizing.

What has been known, is that Cooper pairs in these superconductors are much smaller and sparser compared to conventional superconductors.



Density of the Cooper pairs. Credit: Leiden University

## Josephson microscope

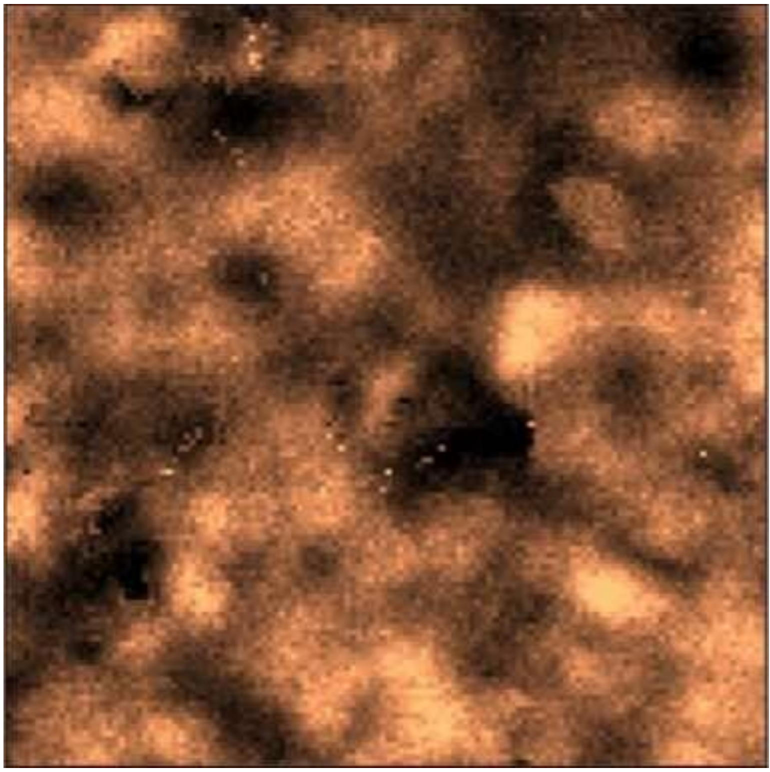
"There has been talk about this inhomogeneity for years," says Allan. To finally visualize it, Allan's group used a special kind of Scanning Tunneling-microscope (STM), which images a sample by moving a tiny needle tip above the surface. While the needle scans the surface, the local properties are measured, yielding an image at atomic resolution.

The specific type of STM is called a Josephson-STM, in which the tip is covered with superconducting lead. It uses the Josephson effect: two superconducting currents can cross a small nonconducting gap, in this case the gap between the tip and the sample. By carefully measuring this Josephson current, the density of the Cooper pairs can be measured. Using other microscopes, it can simultaneously map the coherence of the Cooper pairs, a measure of their stability.

## Lumpy Cooper pairs

The images, each taking about three days of scanning, showed that the coherence and the density were very inhomogeneous.

To exclude the possibility that this is caused by inhomogeneities in the crystal itself, the physicists imaged the atoms as well, but this yielded a completely different pattern. "This shows that the inhomogeneity is not simply a consequence of the crystal lattice but instead, it is a property of the Cooper pairs themselves," says Allan.


Coherence of the Cooper pairs. Credit: Leiden University

Josephson STM's had been built and used before, but not at the resolution and reliability that yielded these images. "It is a sum of many individual technical improvements,that allowed us to do this. And also picking the right sample." The carefully selected iron telluride selenide (FeTeSe) is an high temperature superconductor, but a relatively simple one

### A new lens

The findings can further help theorists, such as LION physicists Jan Zaanen and Koenraad Schalm, solve the mystery. With his microscope, Allan hopes to investigate other materials very soon. "It's a like a new lens, a new kind of telescope. Finally, we can look at a key property of superconductivity that previously couldn't be seen." [32]

## Unexpected properties uncovered in recently discovered superconductor

Researchers from Tokyo Metropolitan University have found that crystals of a recently discovered superconducting material, a layered bismuth chalcogenide with a four-fold symmetric structure, shows only two-fold symmetry in its superconductivity. The origin of superconductivity in these structures is not yet well understood; this finding suggests a connection with an enigmatic class of materials known as nematic superconductors and the extraordinary mechanisms by which superconductivity can emerge at easier-to-reach temperatures.

Superconductors are materials with extremely low electrical resistance. They have already seen numerous applications to powerful electromagnets, particularly in medical magnetic resonance imaging (MRI) units, where they are used to generate the strong magnetic fields required for high resolution non-invasive imaging. However, significant barriers exist which prevent more widespread usage e.g. for power transmission over long distances. The most notable is that conventional superconductivity only arises at extremely low temperatures. The first "high-temperature" superconductors were only found in the latter half of the 1980s, and the mechanisms behind how they work are still hotly debated.

In 2012, Prof Yoshikazu Mizuguchi of Tokyo Metropolitan University succeeded in engineering layered bismuth chalcogenide materials with alternating insulating and superconducting layers for the first time. (Chalcogenides are materials containing elements from group 16 of the periodic table.) Now, the same team have taken measurements on single crystals of the material and found that the rotational symmetry characteristics of the crystalline structure are not replicated in how the superconductivity changes with orientation.

Rotational symmetry breaking of magnetoresistance in $LaO_{0.5}F_{0.5}BiSSe$ under in-plane magnetic fields, possibly due to electronic nematicity. Credit: Tokyo Metropolitan University

The material the group studied consisted of superconducting layers made of bismuth, sulfur and selenium, and insulating layers made of lanthanum, fluorine and oxygen. Importantly, the chalcogenide layers had four-fold rotational (or tetragonal) symmetry i.e. the same when rotated by 90 degrees. However, when the team measured the magnetoresistance of the material at different orientations, they only found two-fold symmetry i.e. the same when rotated by 180 degrees. Further analyses at different temperatures did not suggest any changes to the structure; they concluded that this breakage of symmetry must arise from the arrangement of the electrons in the layer.

The concept of nematic phases comes from liquid crystals, in which disordered, amorphous arrays of rod-like particles can point in the same direction, breaking rotational symmetry while remaining randomly distributed over space. Very recently, it has been hypothesized that something similar in the electronic structure of materials, electronic nematicity, may be behind the emergence of superconductivity in high temperature superconductors. This finding clearly links this highly customizable system to high temperature superconductors like copper and iron-based materials. The team hope that further investigation will reveal critical insights into how otherwise widely different materials give rise to similar behavior, and how they work. [31]

## The mechanism of high-temperature superconductivity is found

Russian physicist Viktor Lakhno from Keldysh Institute of Applied Mathematics, RAS considers symmetrical bipolarons as a basis of high-temperature superconductivity. The theory explains recent experiments in which a superconductivity was reached in lanthanum hydride $LaH_{10}$ at extra-high pressure at nearly room temperature. The results of the study are published in *Physica C: Superconductivity and its Applications*.

Superconductivity implies a total absence of electric resistance in the material when it is cooled below a critical temperature. Heike Kamerlingh Onnes was the first to observe that as the mercury temperature goes down to -270°C, its resistance decreases by a factor of 10,000. Revealing how to achieve this at higher temperatures would have revolutionary technological applications.

The first theoretical explanation of superconductivity at the microscopic level was given in 1957 by Bardeed, Cooper and Schrieffer in their BCS theory. However, the this theory does not explain superconductivity above the absolute zero. By the end of 2018, two research groups discovered that lanthanum hydride $LaH_{10}$ becomes superconducting at record-high temperature. The first group asserts that the temperature of transition into the superconducting state is Tc = 215 K (-56°C). The second groups reports the temperature is Tc = 260 K (-13°C). On both accounts, the samples were under a pressure of more that one million atmospheres.

High-temperature superconductivity is found in new materials nearly at random since there is no theory that would explain the mechanism. In his new work, Viktor Lakhno suggests using bipolarons as a basis. A polaron is a quasiparticle that consists of electrons and phonons. Polarons can form pairs due to electron-phonon interaction. This interaction is so strong that they turn out to be as small as an atomic orbital and in this case are called small-radius bipolarons. The problem of this theory is that small-radius bipolarons have very large mass in comparison with an atom. Their mass is determined by a field that accompanies them in the course of motion. And the mass influences the temperature of a superconducting transition.

Viktor Lakhno constructed a new translation-invariant (TI) bipolaron theory of high-temperature superconductivity. According to his theory, the formula for determining the temperature involves not a bipolaron mass but an ordinary effective mass of a band electron, which can be either greater or less than the mass of a free electron in vacuum and about 1000 times less than the mass of an atom. The band mass changes if the crystal lattice in which an electron is squeezed. If the distance between the atoms decreases, the mass decreases, too. As a consequence, the temperature of the transition can several times exceed the relevant temperature in ordinary bipolaron theories.

"I have focused on the fact that an electron is a wave. If so, there is no preferable place in a crystal where it would be localized. It exists everywhere with equal probability. On grounds of the new bipolaron theory one can develop a new theory of superconductivity. It combines all the best features of modern conceptions," says Viktor Lakhno. [30]

## Cuprate materials have fluctuating stripes that may be linked to high-temperature superconductivity

Scientists at the Department of Energy's SLAC National Accelerator Laboratory and Stanford University have shown that copper-based superconductors, or cuprates – the first class of materials found to carry electricity with no loss at relatively high temperatures – contain fluctuating stripes of electron charge and spin that meander like rivulets over rough ground.

The stripes are zones where electrons either pile up, creating bands of negative charge, or align their spins to create bands of magnetism. They were previously known to exist in cuprate superconductors at temperatures near absolute zero, although in this deep chill the stripes did not move around and their exact role in superconductivity – do they boost or squelch it? – has been unclear.

Now the researchers have computationally demonstrated for the first time that these stripes also exist at high temperatures, but they are subtle and fluctuate in a way that could only be discovered through numerical computer simulations of a precision and scale not done before. The scientists described their study in *Science* today.

"There's reason to think that stripes of charge and spin may be intimately tied to the emergence of high-temperature superconductivity in these materials, which was discovered 30 years ago but so far is not understood or explained," said Edwin Huang, a physics graduate student at Stanford and at the Stanford Institute for Materials and Energy Sciences (SIMES) at SLAC.

"This discovery of fluctuating stripes in a realistic computer model will give us a way to test the many theories about how stripes are related to superconductivity," Huang said. "We think our results will be useful for scientists doing experimental studies of these materials, and they'll also help develop and refine the computational techniques that go hand in hand with theory and experiments to push the field forward."

The results also apply to other novel materials, said SIMES Director Thomas Devereaux. "Materials that spontaneously develop this sort of non-uniform structure are quite commonplace, including magnets and ferroelectrics," he said. "It can even be thought of as a signature of 'quantum' materials, whose surprising properties are produced by electrons that cooperate in unexpected ways. Our numerical results demonstrate that this phenomenon can generally be related to strong interactions between electron charges and spin." [29]

## A Mysterious Phenomenon

In conventional electrical conductors, current is transmitted by electrons acting individually. But in superconductors, electrons pair up to transmit current with virtually no loss.

For 75 years after their discovery, all known superconductors operated only at temperatures close to absolute zero, limiting the way they could be used.

That changed in 1986, when scientists discovered that cuprates could superconduct at much higher (although still quite chilly) temperatures. In fact, certain cuprate compounds are superconducting at temperatures higher than 100 kelvins, or minus 173 degrees Celsius, allowing development of superconducting technologies that can be chilled with liquid nitrogen.

But researchers are still far from their goal of finding superconductors that operate at close to room temperature for highly efficient power lines, maglev trains and other applications that could have a profound impact on society. Without a fundamental understanding of how high-temperature superconductors work, progress has been slow.

Computer modeling is a critical tool for achieving that understanding. Models are sets of mathematical equations based on physics that theorists create and continually refine to simulate a material's behavior using computer algorithms. They check their models against observations and experimental results to make sure they're on the right track.

In this case, the team modeled electron behavior and interactions in one of a cuprate's copper oxide layers, which is where the interesting physics happens, said SIMES staff scientist Brian Moritz. The calculations were run on Stanford's Sherlock supercomputer cluster at SLAC and at the DOE's National Energy Research Scientific Computing Center in Berkeley.

The results were in good agreement with data from neutron scattering experiments on a variety of cuprates, the scientists said, confirming that their simulations accurately capture the electronic physics of these materials.

### A More Accurate Model

This is the first time the high-temperature behavior of cuprates has been simulated with a realistic model that covers a large enough area of the material to see fluctuating stripes, Huang said. This larger scale also makes the calculations more accurate.

"There was a fine balance we needed to strike," he said. "These are extremely computationally demanding calculations. But if you simulate the behavior of smaller areas, you won't be able to see any stripes that emerge. That was the primary limitation of previous studies."

The simulations show that stripes emerge at temperatures up to 600 degrees Celsius and in a wide range of doping conditions, where compounds are added to a material to tweak its electronic behavior, and so they appear to be a universal trait of cuprate superconductors, the researchers said.

"The idea that there are fluctuating stripes in cuprates is not new, but it has been a controversial topic for many years," Huang said. "What's new here is that we can support their existence using unbiased computation on a realistic model of these materials."

One thing the study does not do, he added, is answer the question of whether or how the fluctuating stripes figure into superconductivity: "That is the direction we want to head toward."

## Superconducting qubit 3-D integration prospects bolstered by new research

Researchers from Google and the University of California Santa Barbara have taken an important step towards the goal of building a large-scale quantum computer.

Writing in the journal *Quantum Science and Technology*, they present a new process for creating superconducting interconnects, which are compatible with existing superconducting qubit technology.

The race to develop the first large-scale error-corrected quantum computer is extremely competitive, and the process itself is complex. Whereas classical computers encode data into binary digits (bits) that exist in one of two states, a quantum computer stores information in quantum bits (qubits) that may be entangled with each other and placed in a superposition of both states simultaneously.

The catch is that quantum states are extremely fragile, and any undesired interaction with the surrounding environment may destroy this quantum information. One of the biggest challenges in the creation of a large-scale quantum computer is how to physically scale up the number of qubits, while still connecting control signals to them and preserving these quantum states.

Lead author Brooks Foxen, from UC Santa Barbara, said: "There are a lot of unknowns when it comes to imagining exactly what the first large scale quantum computer will look like. In the superconducting qubit field, we're just now beginning to explore systems with 10s of qubits whereas the long-term goal is to build a computer with millions of qubits.

"Previous research has mostly involved layouts where control wires are routed on a single metal layer. More interesting circuits require the ability to route wiring in three dimensions so that wires may cross over each other. Solving this problem without introducing materials that reduce the quality of superconducting qubits is a hot topic, and several groups have recently demonstrated possible solutions. We believe that our solution, which is the first to provide fully superconducting interconnects with high critical currents, offers the most flexibility in designing other aspects of quantum circuits."

As superconducting qubit technology grows beyond one-dimensional chains of nearest neighbour coupled qubits, larger-scale two-dimensional arrays are a natural next step.

Prototypical two-dimensional arrays have been built, but the challenge of routing control wiring and readout circuitry has, so far, prevented the development of high fidelity qubit arrays of size 3x3 or larger.

Senior author Professor John M Martinis, jointly appointed at both Google and UC Santa Barbara, said: "To enable the development of larger qubit arrays, we have developed a process for fabricating fully superconducting interconnects that are materially compatible with our existing, high fidelity, aluminum on silicon qubits.

"This fabrication process opens the door to the possibility of the close integration of two superconducting circuits with each other or, as would be desirable in the case of superconducting qubits, the close integration of one high-coherence qubit device with a dense, multi-layer, signal-routing device." [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]

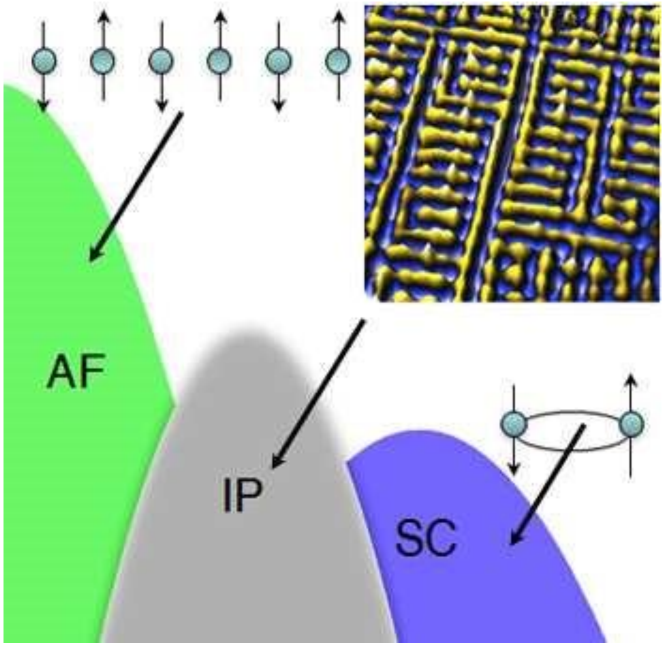
## Strongly correlated materials

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]

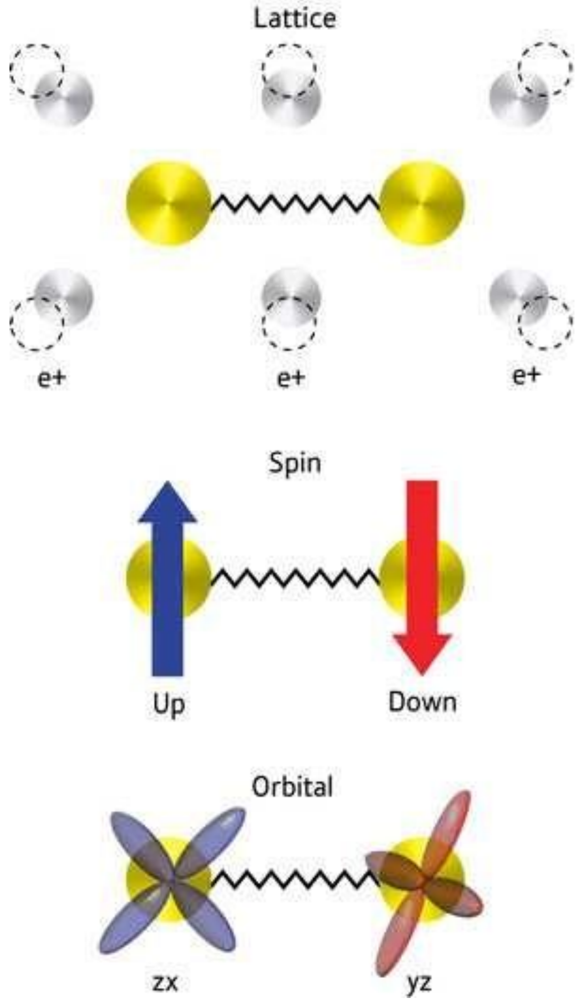
## Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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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