Small Superconductors

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Researchers have found a way to trigger the innate, but previously hidden, ability of graphene to act as a superconductor - meaning that it can be made to carry an electrical current with zero resistance. [28]

Researchers in Japan have found a way to make the 'wonder material' graphene superconductive - which means electricity can flow through it with zero resistance. The new property adds to graphene's already impressive list of attributes, like the fact that it's stronger than steel, harder than diamond, and incredibly flexible. [27]

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

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

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

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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

How small can superconductors be?

For the first time, physicists have experimentally validated a 1959 conjecture that places limits on how small superconductors can be. Understanding superconductivity (or the lack thereof) on the nanoscale is expected to be important for designing future quantum computers, among other applications.

In 1959, physicist P.W. Anderson conjectured that superconductivity can exist only in objects that are large enough to meet certain criteria. Namely, the object's superconducting gap energy must be larger than its electronic energy level spacing—and this spacing increases as size decreases. The cutoff point (where the two values are equal) corresponds to a volume of about 100 nm3. Until now it has not been possible to experimentally test the Anderson limit due to the challenges in observing superconducting effects at this scale.

In the new study published in Nature Communications, Sergio Vlaic and coauthors at the University Paris Sciences et Lettres and French National Centre for Scientific Research (CNRS) designed a nanosystem that allowed them to experimentally investigate the Anderson limit for the first time.

The Anderson limit arises because, at very small scales, the mechanisms underlying superconductivity essentially stop working. In general, superconductivity occurs when electrons bind together to form Cooper pairs. Cooper pairs have a slightly lower energy than individual electrons, and this difference in energy is the superconducting gap energy. The Cooper pairs' lower energy inhibits electron collisions that normally create resistance. If the superconducting gap energy gets too small and vanishes—which can occur, for example, when the temperature increases—then the electron collisions resume and the object stops being a superconductor.

The Anderson limit shows that small size is another way that an object may stop being a superconductor. However, unlike the effects of increasing the temperature, this is not because smaller objects have a smaller superconducting gap energy. Instead, it arises because smaller crystals have fewer electrons, and therefore fewer electron energy levels, than larger crystals do. Since the total possible electron energy of an element stays the same, regardless of size, smaller crystals have larger spacings between their electron energy levels than larger crystals do.

According to Anderson, this large electronic energy level spacing should pose a problem, and he expected superconductivity to disappear when the spacing becomes larger than the superconducting gap energy. The reason for this, generally speaking, is that one consequence of increased spacing is a decrease in potential energy, which interferes with the competition between kinetic and potential energy that is necessary for superconductivity to occur.

To investigate what happens to the superconductivity of objects around the Anderson limit, the scientists in the new study prepared large quantities of isolated lead nanocrystals ranging in volume from 20 to 800 nm3.

Although they could not directly measure the superconductivity of such tiny objects, the researchers could measure something called the parity effect, which results from superconductivity. When an electron is added to a superconductor, the additional energy is partly affected by whether there is an even or odd number of electrons (the parity), which is due to the electrons forming Cooper pairs. If the electrons don't form Cooper pairs, there is no parity effect, indicating no superconductivity.

Although the parity effect has previously been observed in large superconductors, this study is the first time that it has been observed in small nanocrystals approaching the Anderson limit. In accordance with Anderson's predictions from more than 50 years ago, the researchers observed the parity effect for larger nanocrystals, but not for the smallest nanocrystals below approximately 100 nm3.

The results not only validate the Anderson conjecture, but also extend to a more general area, the Richardson-Gaudin models. These models are equivalent to the conventional theory of superconductivity, the Bardeen Cooper Schrieffer theory, for very small objects.

"Our experimental demonstration of the Anderson conjecture is also a demonstration of the validity of the Richardson-Gaudin models," coauthor Hervé Aubin at the University Paris Sciences et Lettres and CNRS told Phys.org. "The Richardson-Gaudin models are an important piece of theoretical works because they can be solved exactly and apply to a wide range of systems; not only to superconducting nanocrystals but also to atomic nuclei and cold fermionic atomic gas, where protons and neutrons, which are fermions like electrons, can also form Cooper pairs."

On the more practical side, the researchers expect the results to have applications in future quantum computers.

"One of the most interesting applications of superconducting islands is their use as Cooper pair boxes employed in quantum bits, the elemental unit of a hypothetical quantum computer," Aubin said. "So far, Cooper pair boxes used in qubits are much larger than the Anderson limit. Upon reducing the size of the Cooper pair box, quantum computer engineers will eventually have to cope with superconductivity at the Anderson limit." [30]

Newly discovered phenomenon accelerates electrons as they enter a viscous state

A new finding by physicists at MIT and in Israel shows that under certain specialized conditions, electrons can speed through a narrow opening in a piece of metal more easily than traditional theory says is possible.

This "superballistic" flow resembles the behavior of gases flowing through a constricted opening, however it takes place in a quantum-mechanical electron fluid, says MIT physics professor Leonid Levitov, who is the senior author of a paper describing the finding that appears this week in the Proceedings of the National Academy of Sciences.

In these constricted passageways, whether for gases passing through a tube or electrons moving through a section of metal that narrows to a point, it turns out that the more, the merrier: Big bunches of gas molecules, or big bunches of electrons, move faster than smaller numbers passing through the same bottleneck.

The behavior seems paradoxical. It's as though a mob of people trying to squeeze through a doorway all at once find that they can get through faster than one person going through alone and unobstructed. But scientists have known for nearly a century that this is exactly what happens with gases passing through a tiny opening, and the behavior can be explained through simple, basic physics, Levitov says.

In a passageway of a given size, if there are few gas molecules, they can travel unimpeded in straight lines. This means if they are moving at random, most of them will quickly hit the wall and bounce off, losing some of their energy to the wall in the process and thus slowing down every time they hit. But with a bigger batch of molecules, most of them will bump into other molecules more often than they will hit the walls. Collisions with other molecules are "lossless," since the total energy of the two particles that collide is preserved, and no overall slowdown occurs. "Molecules in a gas can achieve through 'cooperation' what they cannot accomplish individually," he says.

As the density of molecules in a passageway goes up, he explains, "You reach a point where the hydrodynamic pressure you need to push the gas through goes down, even though the particle density goes up." In short, strange as it might seem, the crowding makes the molecules speed up.

A similar phenomenon, the researchers now report, governs the behavior of electrons when they are hurtling through a narrow piece of metal, where they move in a fluid-like flow.

The result is that, through a sufficiently narrow, point-like constriction in a metal, electrons can flow at a rate that exceeds what had been considered a fundamental limit, known as Landauer's ballistic limit. Because of this, the team has dubbed the new effect "superballistic" flow. This represents a great drop in the electrical resistance of the metal—though it is much less of a drop than what would be required to produce the zero resistance in superconducting metals. However, unlike superconductivity, which requires extremely low temperatures, the new phenomenon may take place even at room temperature and thus may be far easier to implement for applications in electronic devices.

In fact, the phenomenon actually increases as the temperature rises. In contrast to superconductivity, Levitov says, superballistic flow "is assisted by temperature, rather than hindered by it."

Through this mechanism, Levitov says, "we can overcome this boundary that everyone thought was a fundamental limit on how high the conductance could be. We've shown that one can do better than that."

He says that though this particular paper is purely theoretical, other teams have already proved its basic predictions experimentally. While the speedup observed in flowing gases in the analogous case can achieve a tenfold or greater speedup, it remains to be seen whether improvements of that magnitude can be achieved for electrical conductance. But even modest reductions in resistance in some electronic circuits could be a significant improvement, he says.

"This work is careful, elegant, and surprising—all the hallmarks of very high-quality research," says David Goldhaber-Gordon, a professor of physics at Stanford University who was not involved in this research. "In science, I feel phenomena that confound our intuitions are always useful in stretching our sense of what is possible. Here, the idea that more electrons can fit through an aperture if the electrons deflect each other rather than traveling freely and independently is quite counterintuitive, in fact the opposite of what we're used to. It's especially intriguing that Levitov and co-workers find that the conductance in such systems follows such a simple rule."

While this work was theoretical, Goldhaber-Gordon adds, "Testing Levitov's simple and striking predictions experimentally will be really exciting and plausible to achieve in graphene. … Researchers have imagined building new types of electronic switches based on ballistic electron flow. Levitov's theoretical insights, if validated experimentally, would be highly relevant to this idea: Superballistic flow could allow these switches to perform better than expected (or could show that they won't work as hoped)." [29]

Graphene's sleeping superconductivity awakens

Researchers have found a way to trigger the innate, but previously hidden, ability of graphene to act as a superconductor - meaning that it can be made to carry an electrical current with zero resistance.

The finding, reported in Nature Communications, further enhances the potential of graphene, which is already widely seen as a material that could revolutionise industries such as healthcare and electronics. Graphene is a two-dimensional sheet of carbon atoms and combines several remarkable properties; for example, it is very strong, but also light and flexible, and highly conductive.

Since its discovery in 2004, scientists have speculated that graphene may also have the capacity to be a superconductor. Until now, superconductivity in graphene has only been achieved by doping it with, or by placing it on, a superconducting material - a process which can compromise some of its other properties.

But in the new study, researchers at the University of Cambridge managed to activate the dormant potential for graphene to superconduct in its own right. This was achieved by coupling it with a material called praseodymium cerium copper oxide (PCCO).

Superconductors are already used in numerous applications. Because they generate large magnetic fields they are an essential component in MRI scanners and levitating trains. They could also be used to make energy-efficient power lines and devices capable of storing energy for millions of years.

Superconducting graphene opens up yet more possibilities. The researchers suggest, for example, that graphene could now be used to create new types of superconducting quantum devices for high-speed computing. Intriguingly, it might also be used to prove the existence of a mysterious form of superconductivity known as "p-wave" superconductivity, which academics have been struggling to verify for more than 20 years.

The research was led by Dr Angelo Di Bernardo and Dr Jason Robinson, Fellows at St John's College, University of Cambridge, alongside collaborators Professor Andrea Ferrari, from the Cambridge Graphene Centre; Professor Oded Millo, from the Hebrew University of Jerusalem, and Professor Jacob Linder, at the Norwegian University of Science and Technology in Trondheim.

"It has long been postulated that, under the right conditions, graphene should undergo a superconducting transition, but can't," Robinson said. "The idea of this experiment was, if we couple graphene to a superconductor, can we switch that intrinsic superconductivity on? The question then becomes how do you know that the superconductivity you are seeing is coming from within the graphene itself, and not the underlying superconductor?"

Similar approaches have been taken in previous studies using metallic-based superconductors, but with limited success. "Placing graphene on a metal can dramatically alter the properties so it is technically no longer behaving as we would expect," Di Bernardo said. "What you see is not graphene's intrinsic superconductivity, but simply that of the underlying superconductor being passed on."

PCCO is an oxide from a wider class of superconducting materials called "cuprates". It also has well-understood electronic properties, and using a technique called scanning and tunnelling microscopy, the researchers were able to distinguish the superconductivity in PCCO from the superconductivity observed in graphene.

Superconductivity is characterised by the way the electrons interact: within a superconductor electrons form pairs, and the spin alignment between the electrons of a pair may be different depending on the type - or "symmetry" - of superconductivity involved. In PCCO, for example, the pairs' spin state is misaligned (antiparallel), in what is known as a "d-wave state".

By contrast, when graphene was coupled to superconducting PCCO in the Cambridge-led experiment, the results suggested that the electron pairs within graphene were in a p-wave state. "What we saw in the graphene was, in other words, a very different type of superconductivity than in PCCO," Robinson said. "This was a really important step because it meant that we knew the superconductivity was not coming from outside it and that the PCCO was therefore only required to unleash the intrinsic superconductivity of graphene."

It remains unclear what type of superconductivity the team activated, but their results strongly indicate that it is the elusive "p-wave" form. If so, the study could transform the ongoing debate about whether this mysterious type of superconductivity exists, and - if so - what exactly it is.

In 1994, researchers in Japan fabricated a triplet superconductor that may have a p-wave symmetry using a material called strontium ruthenate (SRO). The p-wave symmetry of SRO has never been fully verified, partly hindered by the fact that SRO is a bulky crystal, which makes it challenging to fabricate into the type of devices necessary to test theoretical predictions.

"If p-wave superconductivity is indeed being created in graphene, graphene could be used as a scaffold for the creation and exploration of a whole new spectrum of superconducting devices for fundamental and applied research areas," Robinson said. "Such experiments would necessarily lead to new science through a better understanding of p-wave superconductivity, and how it behaves in different devices and settings."

The study also has further implications. For example, it suggests that graphene could be used to make a transistor-like device in a superconducting circuit, and that its superconductivity could be incorporated into molecular electronics. "In principle, given the variety of chemical molecules that can bind to graphene's surface, this research can result in the development of molecular electronics devices with novel functionalities based on superconducting graphene," Di Bernardo added. [28]

Wonder material graphene has been turned into a superconductor

Researchers in Japan have found a way to make the 'wonder material' graphene superconductive - which means electricity can flow through it with zero resistance.

The new property adds to graphene's already impressive list of attributes, like the fact that it's stronger than steel, harder than diamond, and incredibly flexible.

But superconductivity is a big deal, even for graphene, because when electricity can flow without resistance, it can lead to significantly more efficient electronic devices, not to mention power lines. Right now, energy companies are losing about 7 percent of their energy as heat as a result of resistance in the grid.

Before you get too excited, this demonstration of superconductivity in graphene occurred at a super cold -269 degrees Celsius, so we're not going to be making power lines out of graphene any time soon.

But what is exciting, is that this research suggests that graphene could be used to build nano-sized, high-speed electronic devices. Just imagine all the electricity we could save with computers that rely on tiny graphene circuity, capable of zooming electrons around without wasting energy as heat.

For those who aren't already familiar with graphene, the material is a one-atom-thick layer of graphite (the stuff that makes up your pencils), which is made up of carbon atoms arranged in a hexagonal honeycomb patterns.

The electrons inside graphene are already pretty special, because they're able to take on a special state called Dirac-cone, where they behave as if they have no mass. That makes them very speedy, but even though graphene is a very efficient conductor, it's not a superconductor, which is a state that requires zero resistance.

Now a team from Tohoku University and the University of Tokyo have managed to achieve superconductivity by creating two graphene sheets and inserting calcium atoms between them - sort of like a calcium sandwich, with graphene acting as the bread.

These graphene sheets were grown on a silicon carbide crystal (the SiC substrate in the image above), and the team was able to show that when the temperature gets to around 4 Kelvin, or -269 degrees Celsius, the electrical conductivity of the material rapidly drops - a clear indication of superconductivity.

Superconductivity generally relies on electrons not repelling each other, as they usually do, and pairing up instead, so they can flow through materials effortlessly. As you can imagine, when that happens in a material with electrons that are already acting like they have no mass, scientists get pretty excited.

"This is significant because electrons with no mass flowing with no resistance in graphene could lead to the realisation of an ultimately high-speed nano electronic device," Tohoku University explains.

Just last year, researchers were able to make graphene superconductive by coating it in lithium, but the Japanese team has now managed to achieve the same thing while keeping the material in its original state.

They were also able to show that superconductivity didn't occur when the graphene bilayers were on their own, or when they were coated in lithium, suggesting that the calcium atoms are what's important to the process - although the researchers admit they still don't know what phenomenon is taking place in graphene to achieve superconductivity, so there's more work to be done.

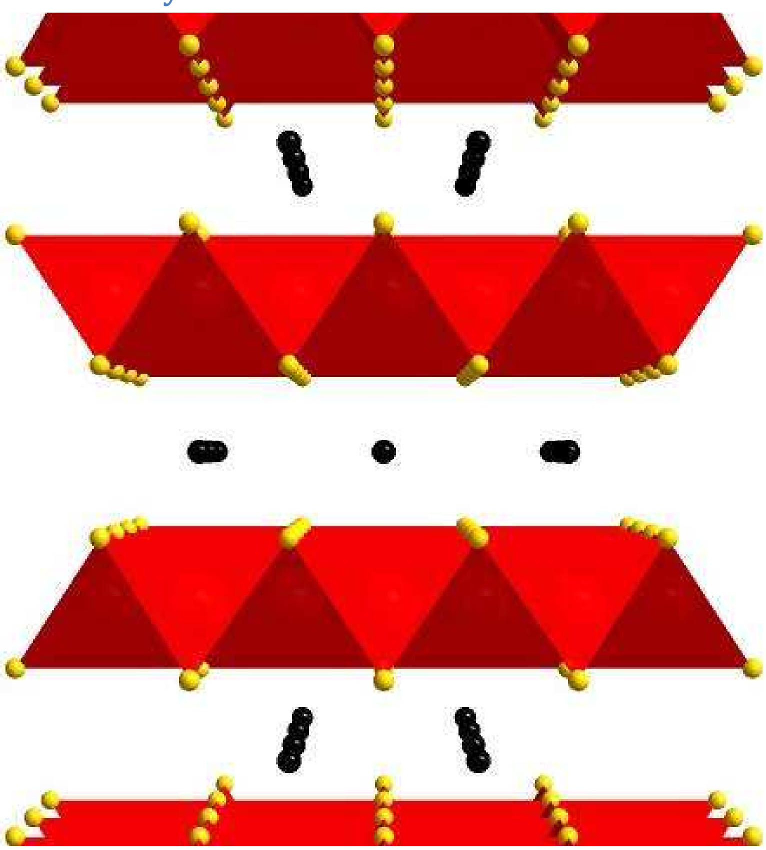
But if they can figure out what's going on, they might be able to tweak the process and find a way to achieve superconductivity in graphene at higher temperatures, and that would be huge.

As we mentioned before, graphene is unlikely to be used to build power lines - there are more promising high-temperature superconductors that would be better suited to that job - but it could revolutionise our computers.

"The latest results pave the way for the further development of ultrahigh-speed superconducting nano devices," says Tohoku University, "such as a quantum computing device, which utilises superconducting graphene in its integrated circuit."

We're looking forward to seeing what amazing thing graphene does next. [27]

Linking superconductivity and structure



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

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

When iron arsenide is combined with a metal—such as in the sodium-containing NaFe2As2 compound studied here—it was known that the ensuing compound is crystallized in a tetrahedral structure. But until now, a detailed structure of the atomic positions involved and how they change under pressure had not been determined.

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

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

They showed that at about 40,000 times normal atmospheric pressure (4 gigapascals), NaFe2As2 takes on the collapsed tetragonal structure. This changes the angles in the arsenic-iron-arsenic layers and is coincident with the loss in superconductivity. Moreover, they found that this transition is accompanied by a major change in bonding coordination in the formation of the interlayer arsenic-arsenic bonds. A direct consequence of this new coordination is that the system loses its two-dimensionality, and with it, superconductivity.

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

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

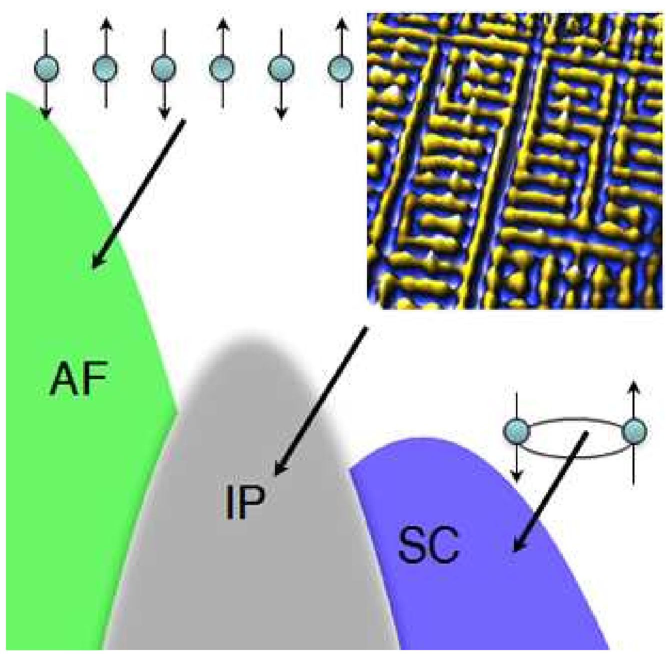
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

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

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

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

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

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

A grand unified theory of exotic superconductivity?

The role of magnetism

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

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

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

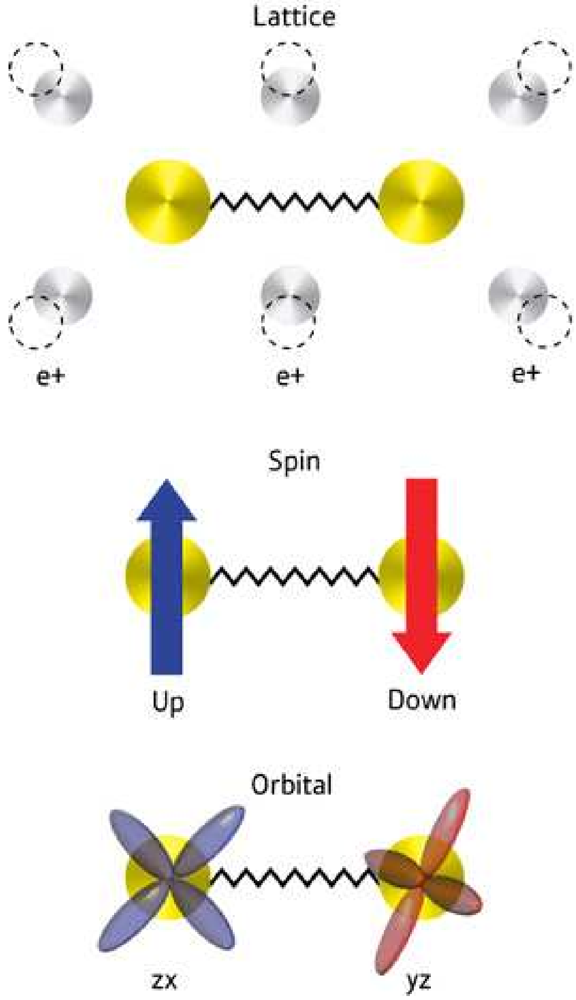
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

Significance

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

Superconductivity's third side unmasked



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

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

Strongly correlated materials

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

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

Fermions and Bosons

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

The General Weak Interaction

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

Higgs Field and Superconductivity

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

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

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

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

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

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

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

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

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

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

The condensate wave function can be written as

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

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

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

Conclusions

Probably in the superconductivity there is no electric current at all, but a permanent magnetic field as the result of the electron's spin in the same direction in the case of the circular wire on a low temperature. [6]

We think that there is an electric current since we measure a magnetic field. Because of this saying that the superconductivity is a quantum mechanical phenomenon.

Since the acceleration of the electrons is centripetal in a circular wire, in the atom or in the spin, there is a steady current and no electromagnetic induction. This way there is no changing in the Higgs field, since it needs a changing acceleration. [18]

The superconductivity is temperature dependent; it means that the General Weak Interaction is very relevant to create this quantum state of the matter. [19]

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