

Quantum Effects of Superconductor

The quantum behaviour of hydrogen affects the structural properties of hydrogen-rich compounds, which are possible candidates for the elusive room temperature superconductor, according to new research co-authored at the University of Cambridge. [29]

A German-French research team has constructed a new model that explains how the so-called pseudogap state forms in high-temperature superconductors. The calculations predict two coexisting electron orders. Below a certain temperature, superconductors lose their electrical resistance and can conduct electricity without loss. [28]

New findings from an international collaboration led by Canadian scientists may eventually lead to a theory of how superconductivity initiates at the atomic level, a key step in understanding how to harness the potential of materials that could provide lossless energy storage, levitating trains and ultra-fast supercomputers. [27]

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

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

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

Contents

The Quest of Superconductivity	3
Experiences and Theories	3

Quantum effects at work in the world's smelliest superconductor	3
Science & Metallurgy.	4
'Long-awaited explanation' for mysterious effects in high-temperature superconductors	5
Transition temperature much higher in ceramic than in metallic superconductors.....	5
Pseudogap: energy gap above the transition temperature	5
Two competing electron orders in the pseudogap state	5
Cuprates.....	6
Physicists discover new properties of superconductivity.....	6
Conventional superconductivity	7
Superconductivity and magnetic fields	7
Room-temperature superconductivity.....	8
Exciton-mediated electron pairing	8
Resonating valence bond theory.....	8
Strongly correlated materials	8
New superconductor theory may revolutionize electrical engineering	9
Unconventional superconductivity in $\text{Ba}^{0.6}\text{K}^{0.4}\text{Fe}^2\text{As}^2$ from inelastic neutron scattering	9
A grand unified theory of exotic superconductivity?	10
The role of magnetism.....	10
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity	11
Significance.....	11
Superconductivity's third side unmasked.....	12
Strongly correlated materials.....	12
Fermions and Bosons	13
The General Weak Interaction	13
Higgs Field and Superconductivity	13
Superconductivity and Quantum Entanglement	15
Conclusions	15
References:.....	16

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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

Quantum effects at work in the world's smelliest superconductor

New theoretical results, published online in the journal Nature, suggest that the quantum nature of hydrogen - meaning that it can behave like a particle or a wave - strongly affects the recently discovered hydrogen sulphur superconductor, a compound that when subjected to extremely high pressure, is the highest-temperature superconductor yet identified. This new step towards understanding the underlying physics of high temperature superconductivity may aid in the search for a room temperature superconductor, which could be used for applications such as levitating trains, lossless electrical grids and next-generation supercomputers.

Superconductors are materials that carry electrical current with zero electrical resistance. Low-temperature, or conventional, superconductors were first identified in the early 20th century, but they need to be cooled close to absolute zero (zero degrees on the Kelvin scale, or -273 degrees Celsius) before they start to display superconductivity. For the past century, researchers have been searching for materials that behave as superconductors at higher temperatures, which would make them more suitable for practical applications. The ultimate goal is to identify a material which behaves as a superconductor at room temperature.

Last year, German researchers identified the highest temperature superconductor yet - hydrogen sulphide, the same compound that gives rotten eggs their distinctive odour. When subjected to extreme pressure - about one million times higher than the Earth's atmospheric pressure - this stinky compound displays superconducting behaviour at temperatures as high as 203 Kelvin (-70 degrees Celsius), which is far higher than any other high temperature superconductor yet discovered.

Since this discovery, researchers have attempted to understand what it is about hydrogen sulphide that makes it capable of superconducting at such high temperatures. Now, new theoretical results suggest that the quantum behaviour of hydrogen may be the reason, as it changes the structure of the chemical bonds between atoms. The results were obtained by an international collaboration of researchers led by the University of the Basque Country and the Donostia International Physics Center, and including researchers from the University of Cambridge.

The behaviour of objects in our daily life is governed by classical, or Newtonian, physics. If an object is moving, we can measure both its position and momentum, to determine where an object is going and how long it will take to get there. The two properties are inherently linked.

However, in the strange world of quantum physics, things are different. According to a rule known as Heisenberg's uncertainty principle, in any situation in which a particle has two linked properties, only one can be measured and the other must be uncertain.

Hydrogen, being the lightest element of the periodic table, is the atom most strongly subjected to quantum behaviour. Its quantum nature affects structural and physical properties of many hydrogen compounds. An example is high-pressure ice, where quantum fluctuations of the proton lead to a change in the way that the molecules are held together, so that the chemical bonds between atoms become symmetrical.

The researchers behind the current study believe that a similar quantum hydrogen-bond symmetrisation occurs in the hydrogen sulphide superconductor.

Theoretical models that treat hydrogen atoms as classical particles predict that at extremely high pressures - even higher than those used by the German researchers for their record-breaking superconductor - the atoms sit exactly halfway between two sulphur atoms, making a fully symmetrical structure. However, at lower pressures, hydrogen atoms move to an off-centre position, forming one shorter and one longer bond.

The researchers have found that when considering the hydrogen atoms as quantum particles behaving like waves, they form symmetrical bonds at much lower pressures - around the same as those used for the German-led experiment, meaning that quantum physics, and symmetrical hydrogen bonds, were behind the record-breaking superconductivity.

"That we are able to make quantitative predictions with such a good agreement with the experiments is exciting and means that computation can be confidently used to accelerate the discovery of high temperature superconductors," said study co-author Professor Chris Pickard of Cambridge's Department of Materials

Science & Metallurgy.

According to the researcher's calculations, the quantum symmetrisation of the hydrogen bond has a tremendous impact on the vibrational and superconducting properties of hydrogen sulphide. "In order to theoretically reproduce the observed pressure dependence of the superconducting critical temperature the quantum symmetrisation needs to be taken into account," said the study's first author, Ion Errea, from the University of the Basque Country and Donostia International Physics Center.

The discovery of such a high temperature superconductor suggests that room temperature superconductivity might be possible in other hydrogen-rich compounds.

The current theoretical study shows that in all these compounds, the quantum motion of hydrogen can strongly affect the structural properties, even modifying the chemical bonding, and the electron-phonon interaction that drives the superconducting transition.

"Theory and computation have played an important role in the hunt for superconducting hydrides under extreme compression," said Pickard. "The challenges for the future are twofold - increasing

the temperature towards room temperature, but, more importantly, dramatically reducing the pressures required." [29]

'Long-awaited explanation' for mysterious effects in high-temperature superconductors

A German-French research team has constructed a new model that explains how the so-called pseudogap state forms in high-temperature superconductors. The calculations predict two coexisting electron orders. Below a certain temperature, superconductors lose their electrical resistance and can conduct electricity without loss.

"It is not to be excluded that the new pseudogap theory also provides the long-awaited explanation for why, in contrast to conventional metallic superconductors, certain ceramic copper oxide bonds lose their electrical resistance at such unusually high temperatures", say Prof. Dr. Konstantin Efetov and Dr. Hendrik Meier of the Chair of Theoretical Solid State Physics at the Ruhr-Universität Bochum. They obtained the findings in close cooperation with Dr. Catherine Pépin from the Institute for Theoretical Physics in Saclay near Paris.

The team reports in the journal Nature Physics.

Transition temperature much higher in ceramic than in metallic superconductors

Superconductivity only occurs at very low temperatures below the so-called transition temperature. In metallic superconductors, this is close to the absolute zero point of 0 Kelvin, which corresponds to about -273 degrees Celsius. However, crystalline ceramic materials can be superconductive at temperatures up to 138 Kelvin. For 25 years, researchers puzzled over the physical bases of this high-temperature superconductivity.

Pseudogap: energy gap above the transition temperature

In the superconducting state, electrons travel in so-called Cooper pairs through the crystal lattice of a material. In order to break up a Cooper pair so that two free electrons are created, a certain amount of energy is needed. This difference in the energy of the Cooper electrons and the so-called free electrons is called an energy gap. In cuprate superconductors, compounds based on copper oxide bonds, a similar energy gap also occurs under certain circumstances above the transition temperature – the pseudogap. Characteristically the pseudogap is only perceived by electrons with certain velocity directions. The model constructed by the German-French team now allows new insights into the physical inside of the pseudogap state.

Two competing electron orders in the pseudogap state

According to the model, the pseudogap state simultaneously contains two electron orders: d-wave superconductivity, in which the electrons of a Cooper pair revolve around each other in a cloverleaf shape, and a quadrupole density wave. The latter is a special electrostatic structure in which every copper atom in the two-dimensional crystal lattice has a quadrupole moment, i.e. two opposite regions of negative charge, and two opposite regions of positive charge. d-wave superconductivity and quadrupole density wave compete with each other in the pseudogap state. Due to thermal fluctuations, neither of the two systems can assert itself. However, if the system is cooled down, the thermal fluctuations become weaker and one of the two systems prevails: superconductivity. The

critical temperature at which this occurs can, in the model, be considerably higher than the transition temperature of conventional metallic superconductors. The model could thus explain why the transition temperature in the ceramic superconductors is so much higher.

Cuprates

High-temperature copper oxide superconductors are also called cuprates. In addition to copper and oxygen, they can, for example, contain the elements yttrium and barium (YBa₂Cu₃O₇). To make the material superconducting, researchers introduce "positive holes", i.e. electron holes into the crystal lattice. Through these, the electrons can "flow" in Cooper pairs. This is known as hole doping. The pseudogap state only sets in when the hole doping of the cuprate is neither too low nor too high. [28]

Physicists discover new properties of superconductivity

Professor David Hawthorn, Professor Michel Gingras, doctoral student Andrew Achkar, and post-doctoral fellow Dr. Zhihao Hao from University of Waterloo's Department of Physics and Astronomy have experimentally shown that electron clouds in superconducting materials can snap into an aligned and directional order called nematicity.

"It has become apparent in the past few years that the electrons involved in superconductivity can form patterns, stripes or checkerboards, and exhibit different symmetries - aligning preferentially along one direction," said Professor Hawthorn. "These patterns and symmetries have important consequences for superconductivity - they can compete, coexist or possibly even enhance superconductivity. "

Their results, published today in the prestigious journal Science, present the most direct experimental evidence to date of electronic nematicity as a universal feature in cuprate high-temperature superconductors.

"In this study, we identify some unexpected alignment of the electrons - a finding that is likely generic to the high temperature superconductors and in time may turn out be a key ingredient of the problem," said Professor Hawthorn.

Superconductivity, the ability of a material to conduct an electric current with zero resistance, is best described as an exotic state in high temperature superconductors - challenging to predict, let alone explain.

The scientists used a novel technique called soft x-ray scattering at the Canadian Light Source synchrotron in Saskatoon to probe electron scattering in specific layers in the cuprate crystalline structure. Specifically, the individual cuprate (CuO₂) planes, where electronic nematicity takes place, versus the crystalline distortions in between the CuO₂ planes.

Electronic nematicity happens when the electron orbitals align themselves like a series of rods - breaking their unidirectional symmetry apart from the symmetry of the crystalline structure.

The term "nematicity" commonly refers to when liquid crystals spontaneously align under an electric field in liquid crystal displays. In this case, it is the electronic orbitals that enter the nematic state as the temperature drops below a critical point.

Recent breakthroughs in high-temperature superconductivity have revealed a complex competition between the superconductive state and charge density wave order fluctuations. These periodic fluctuations in the distribution of the electrical charges create areas where electrons bunch up in high- versus low-density clouds, a phenomenon that is now recognized to be generic to the underdoped cuprates.

Results from this study show electronic nematicity also likely occurs in underdoped cuprates. Understanding the relation of nematicity to charge density wave order, superconductivity and an individual material's crystalline structure could prove important to identifying the origins of the superconducting and so-called pseudogap phases.

The authors also found the choice of doping material impacts the transition to the nematic state. Dopants, such as strontium, lanthanum, and even europium added to the cuprate lattice, create distortions in the lattice structure which can either strengthen or weaken nematicity and charge density wave order in the CuO₂ layer.

Although there is not yet an agreed upon explanation for why electronic nematicity occurs, it may ultimately present another knob to tune in the quest to achieve the ultimate goal of a room temperature superconductor.

"Future work will tackle how electronic nematicity can be tuned, possibly to advantage, by modifying the crystalline structure," says Hawthorn.

Hawthorn and Gingras are both Fellows of the Canadian Institute For Advanced Research. Gingras holds the Canada Research Chair in Condensed Matter Theory and Statistical Mechanics and spent time at the Perimeter Institute of Theoretical Physics as a visiting researcher while this work was being carried out. [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 CeCoIn₅ 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]

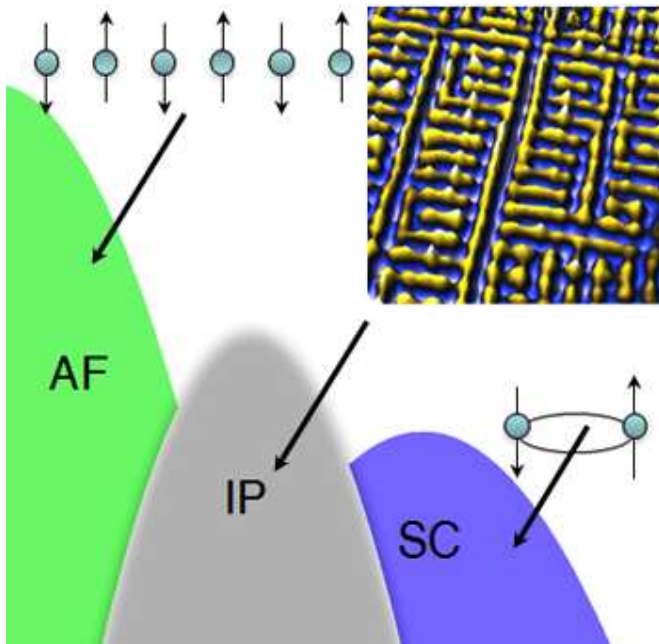
Strongly correlated materials

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. $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. 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 $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ 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-T_c 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-T_c superconductors—sometimes appearing to compete with superconductivity and sometimes coexisting with it. [24]

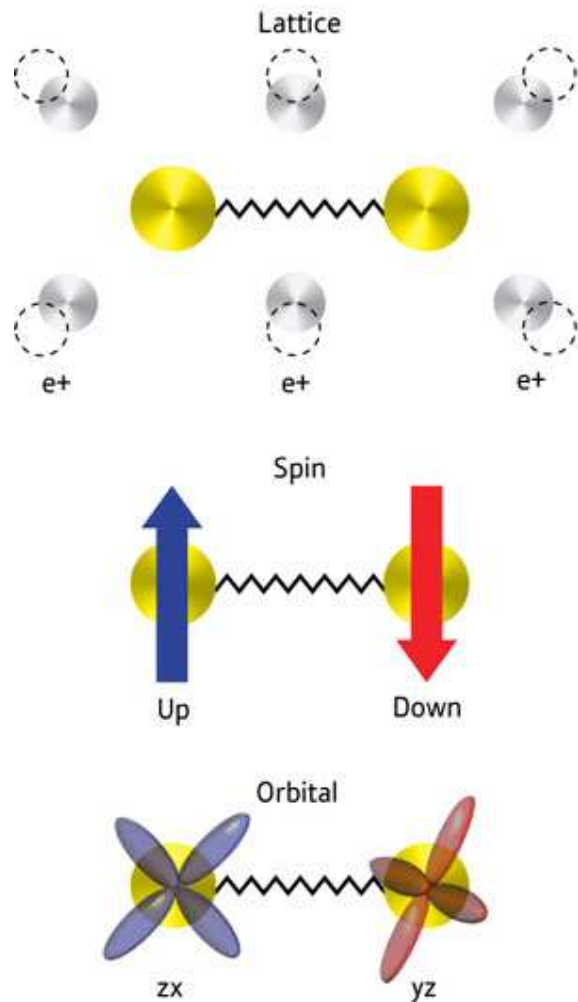
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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, \hbar , is set to 1):

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

The operator $\psi(x)$ annihilates a boson at the point x , while its adjoint ψ^\dagger creates a new boson at the same point. The wavefunction of the Bose–Einstein condensate is then the expectation value ψ of $\psi(x)$, 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:

$$\begin{aligned} \psi &\rightarrow e^{iq\phi(x)} \psi \\ A &\rightarrow A + \nabla\phi. \end{aligned}$$

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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