Photoelectron Spectroscopy

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Physicists now believe they can enhance superconductivity - the idea is to externally drive its underlying physical phenomena by changing how ions vibrating in the crystal lattice of the conductor material, called phonons, interact with electron flowing in the material. [29]

Researchers at the University of Houston have reported a new method for inducing superconductivity in non-superconducting materials, demonstrating a concept proposed decades ago but never proven. [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.

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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

Laser pulses help scientists tease apart complex electron interactions

Scientists studying high temperature superconductors-materials that carry electric current with no energy loss when cooled below a certain temperature-have been searching for ways to study in detail the electron interactions thought to drive this promising property. One big challenge is disentangling the many different types of interactions-for example, separating the effects of electrons interacting with one another from those caused by their interactions with the atoms of the material.

Now a group of scientists including physicists at the U.S. Department of Energy's Brookhaven National Laboratory has demonstrated a new laser-driven "stop-action" technique for studying complex electron interactions under dynamic conditions. As described in a paper just published in Nature Communications, they use one very fast, intense "pump" laser to give electrons a blast of energy, and a second "probe" laser to measure the electrons' energy level and direction of movement as they relax back to their normal state.

"By varying the time between the 'pump' and 'probe' laser pulses we can build up a stroboscopic record of what happens-a movie of what this material looks like from rest through the violent interaction to how it settles back down," said Brookhaven physicist Jonathan Rameau, one of the lead authors on the paper. "It's like dropping a bowling ball in a bucket of water to cause a big disruption, and then taking pictures at various times afterward," he explained.

The technique, known as time-resolved, angle-resolved photoelectron spectroscopy (tr-ARPES), combined with complex theoretical simulations and analysis, allowed the team to tease out the sequence and energy "signatures" of different types of electron interactions. They were able to pick out distinct signals of interactions among excited electrons (which happen quickly but don't dissipate much energy), as well as later-stage random interactions between electrons and the atoms that make up the crystal lattice (which generate friction and lead to gradual energy loss in the form of heat).

But they also discovered another, unexpected signal-which they say represents a distinct form of extremely efficient energy loss at a particular energy level and timescale between the other two.

"We see a very strong and peculiar interaction between the excited electrons and the lattice where the electrons are losing most of their energy very rapidly in a coherent, non-random way," Rameau said. At this special energy level, he explained, the electrons appear to be interacting with lattice atoms all vibrating at a particular frequency-like a tuning fork emitting a single note. When all of the electrons that have the energy required for this unique interaction have given up most of their energy, they start to cool down more slowly by hitting atoms more randomly without striking the "resonant" frequency, he said.

The frequency of the special lattice interaction "note" is particularly noteworthy, the scientists say, because its energy level corresponds with a "kink" in the energy signature of the same material in its superconducting state, which was first identified by Brookhaven scientists using a static form of ARPES. Following that discovery, many scientists suggested that the kink might have something to do with the material's ability to become a superconductor, because it is not readily observed above the superconducting temperature.

But the new time-resolved experiments, which were done on the material well above its superconducting temperature, were able to tease out the subtle signal. These new findings indicate that this special condition exists even when the material is not a superconductor.

"We know now that this interaction doesn't just switch on when the material becomes a superconductor; it's actually always there," Rameau said.

The scientists still believe there is something special about the energy level of the unique tuning-fork-like interaction. Other intriguing phenomena have been observed at this same energy level, which Rameau says has been studied in excruciating detail.

It's possible, he says, that the one-note lattice interaction plays a role in superconductivity, but requires some still-to-be-determined additional factor to turn the superconductivity on.

"There is clearly something special about this one note," Rameau said. [30]

When crystal vibrations' inner clock drives superconductivity

Superconductivity is like an Eldorado for electrons, as they flow without resistance through a conductor. However, it only occurs below a very low critical temperature. Physicists now believe they can enhance superconductivity - the idea is to externally drive its underlying physical phenomena by changing how ions vibrating in the crystal lattice of the conductor material, called phonons, interact with electron flowing in the material. Andreas Komnik from the University of Heidelberg and Michael Thorwart from the University of Hamburg, Germany, adapted the simplest theory of superconductivity to reflect the consequences of externally driving the occurrence of phonons. Their main result, published in EPJ B, is a simple formula explaining how it is theoretically possible to raise the critical temperature using phonon driving.

The authors studied the all-important autocorrelation function of phonons in the superconductivity BCS theory, named after John Bardeen, Leon Cooper and John Robert Schrieffer. Superconductivity is induced by phonons cooperating to bring the electrons together in the so-called Cooper pairs—against their spontaneous tendency to repel each other. In this work, the authors focused on the scenario of an X-ray light field rattling the phonons. They realized that a kind of driving, which controls the frequency of vibration of the lattice sites, can profoundly change the pairing of the electrons.

However, electrons and phonons do not follow the same internal clock. This means that change at what is perceived as a normal pace for phonons comes across as extremely slow to electrons. To eliminate this discrepancy, the author devised a solution based on bringing a clever time-averaging procedure into the BCS equations. This theoretical approach, the authors found, reveals the controlled elevation of the critical temperature. They thus managed to integrate the external phonon drive into the standard BCS theory. The advantage is that the critical temperature can be computed from this simple formula and can, in theory, be considerably elevated using the driving procedure. Surprisingly, the critical temperature was even higher up when further refinement to the equations accounted for phonon-phonon interactions. [29]

Physicists induce superconductivity in non-superconducting materials

Researchers at the University of Houston have reported a new method for inducing superconductivity in non-superconducting materials, demonstrating a concept proposed decades ago but never proven.

The technique can also be used to boost the efficiency of known superconducting materials, suggesting a new way to advance the commercial viability of superconductors, said Paul C.W. Chu, chief scientist at the Texas Center for Superconductivity at UH (TcSUH) and corresponding author of a paper describing the work, published Oct. 31 in the Proceedings of the National Academy of Sciences.

"Superconductivity is used in many things, of which MRI (magnetic resonance imaging) is perhaps the best known," said Chu, the physicist who holds the TLL Temple Chair of Science at UH. But the technology used in health care, utilities and other fields remains expensive, in part because it requires expensive cooling, which has limited widespread adoption, he said.

The research, demonstrating a new method to take advantage of assembled interfaces to induce superconductivity in the non-superconducting compound calcium iron arsenide, offers a new approach to finding superconductors that work at higher temperatures.

Superconducting materials conduct electric current without resistance, while traditional transmission materials lose as much as 10 percent of energy between the generating source and the end user. That means superconductors could allow utility companies to provide more electricity without increasing the amount of fuel used to generate electricity.

"One way that has long been proposed to achieve enhanced Tcs (critical temperature, or the temperature at which a material becomes superconducting) is to take advantage of artificially or naturally assembled interfaces," the researchers wrote. "The present work clearly demonstrates that high Tc superconductivity in the well-known non-superconducting compound CaFe2As2 (calcium iron arsenide) can be induced by antiferromagnetic/metallic layer stacking and provides the most direct evidence to date for the interface-enhanced Tc in this compound."

Chu's coauthors on the paper include lead author Kui Zhao, a recent UH graduate now at Advanced MicroFabrication Equipment Inc. in Shanghai; Liangzi Deng, Shu-Yuan Huyan and Yu-Yi Xue, both affiliated with the UH Department of Physics and TcSUH, and Bing Lv, a material physicist who recently moved to the University of Texas-Dallas.

The concept that superconductivity could be induced or enhanced at the point where two different materials come together - the interface - was first proposed in the 1970s but had never been conclusively demonstrated, Chu said. Some previous experiments showing enhanced superconducting critical temperature could not exclude other effects due to stress or chemical doping, which prevented verification, he said.

To validate the concept, researchers working in ambient pressure exposed the undoped calcium iron arsenide compound to heat - 350 degrees Centigrade, considered relatively low temperature for this procedure - in a process known as annealing. The compound formed two distinct phases, with one phase increasingly converted to the other the longer the sample was annealed. Chu said neither of the two phases was superconducting, but researchers were able to detect superconductivity at the point when the two phases coexist.

Although the superconducting critical temperature of the sample produced through the process was still relatively low, Chu said the method used to prove the concept offers a new direction in the search for more efficient, less expensive superconducting materials. [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 (CuO_2) planes, where electronic nematicity takes place, versus the crystalline distortions in between the CuO_2 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 CuO_2 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 $CeCoIn_5$ 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

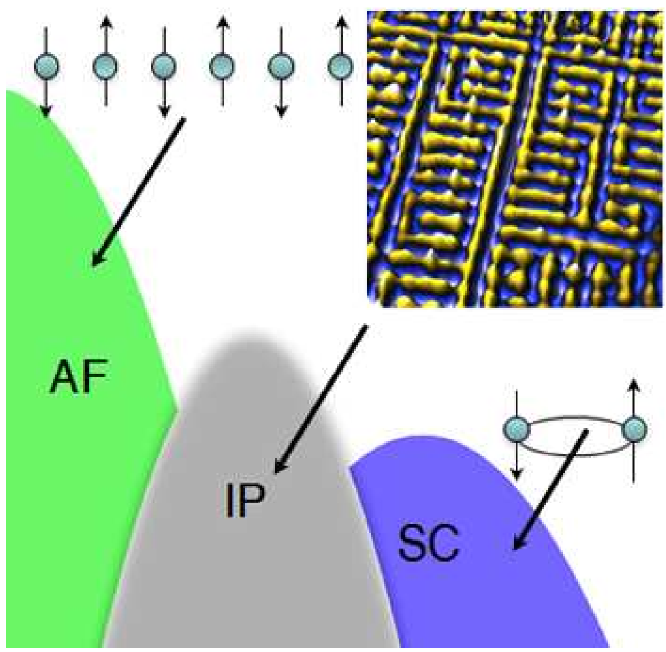
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

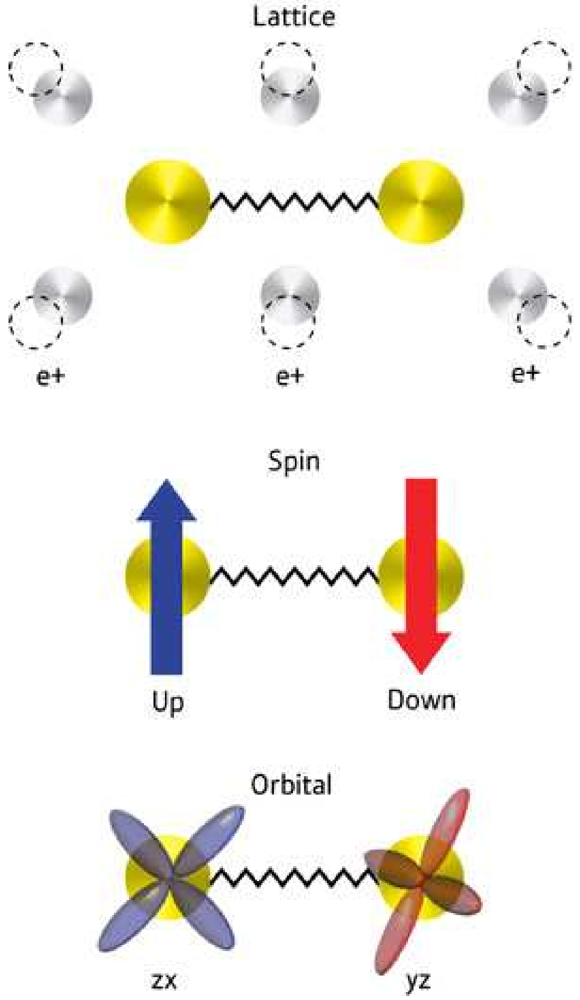
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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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