Quantum Fluctuations in Exotic Phases

Many fascinating phenomena with promising technological applications in areas such as superconductivity are linked to quantum phase transitions, but the role of quantum fluctuations in such transitions remains unclear. [29]

By precisely measuring the entropy of a cerium copper gold alloy with baffling electronic properties cooled to nearly absolute zero, physicists in Germany and the United States have gleaned new evidence about the possible causes of high-temperature superconductivity and similar phenomena. [28]

Physicists have theoretically shown that a superconducting current of electrons can be induced to flow by a new kind of transport mechanism: the potential flow of information. [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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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

Novel method to study quantum fluctuations in exotic phases of matter

Phase transitions include common phenomena like water freezing or boiling. Similarly, quantum systems at a temperature of absolute zero also experience phase transitions. The pressure or magnetic field applied to such systems can be adjusted so that these systems arrive at a tipping point between two phases. At this point quantum fluctuations, rather than temperature fluctuations, drive these transitions.

Many fascinating phenomena with promising technological applications in areas such as superconductivity are linked to quantum phase transitions, but the role of quantum fluctuations in such transitions remains unclear. While there have been many advances in understanding the behavior of individual particles such as protons, neutrons, and photons, the challenge of understanding systems containing many particles that strongly interact with one another has yet to be solved.

Now, an international research team led by a group at Osaka University has discovered a clear link between quantum fluctuations and the effective charge of current-carrying particles. This discovery will help researchers uncover how quantum fluctuations govern systems in which many particles interact. One example of such a system is the interaction of electrons at extremely low temperatures. While low temperatures normally cause the resistance in a metal to drop, the resistance rises again at extremely low temperatures due to small magnetic impurities—this is referred to as the Kondo effect.

"We used a magnetic field to tune the Kondo state in a carbon nanotube, ensuring that the quantum fluctuations were the only variable in the system," study coauthor Kensuke Kobayashi says. "By directly monitoring the conductance and shot noise of the carbon nanotube, we were able to demonstrate a continuous crossover between Kondo states with different symmetries."

Using this novel approach, the researchers discovered a link between quantum fluctuations and the effective charge of current-carrying particles, e^*. The discovery means that measurements of e^* can be used to quantify quantum fluctuations.

"This is very exciting, as it paves the way for future investigations into the exact role of quantum fluctuations in quantum phase transitions," explains Professor Kobayashi. Understanding quantum phase transitions has the potential to enable many interesting applications in areas such as superconductivity, Mott insulators, and the fractional quantum Hall effect. [29]

Entropy landscape sheds light on quantum mystery

By precisely measuring the entropy of a cerium copper gold alloy with baffling electronic properties cooled to nearly absolute zero, physicists in Germany and the United States have gleaned new evidence about the possible causes of high-temperature superconductivity and similar phenomena.

"This demonstration provides a foundation to better understand how novel behaviors like high-temperature superconductivity are brought about when certain kinds of materials are cooled to a quantum critical point," said Rice University physicist Qimiao Si, co-author of a new study about the research in this week's Nature Physics.

The experimental research was led by Hilbert von Löhneysen of the Karlsruhe Institute of Technology in Karlsruhe, Germany. Löhneysen's team, including study lead author Kai Grube, spent a year conducting dozens of experiments on a compound made of cerium copper and gold. By studying the effect of stress, or pressure applied in specific directions, and by making the materials very cold, the team subtly changed the spacing between the atoms in the crystalline metallic compounds and thus altered their electronic properties.

The cerium copper gold alloys are "heavy fermions," one of several of types of quantum materials that exhibit exotic electronic properties when very cold. The best-known of these are high-temperature superconductors, so named for their ability to conduct electrical current with zero resistance at temperatures well above those of traditional superconductors. Heavy fermions exhibit a different oddity: Their electrons appear to be effectively hundreds of times more massive than normal and, equally unusual, the effective electron mass seems to vary strongly as temperature changes.

These odd behaviors defy traditional physical theories. They also occur at very cold temperatures and come about when the materials are tuned to a "quantum phase transition"—a change from one state to another, like ice melting. In 2001, Si and colleagues offered a new theory: At the quantum critical point, electrons fluctuate between two entirely different quantum states, so much so that their effective mass becomes infinitely large. The theory predicted certain tell-tale signs as the quantum critical point is approached, and Si has worked with experimental physicists for the past 16 years to amass evidence to support the theory.

"Liquid water and ice are two of the classical states in which H2O can exist," said Si, director of the Rice Center for Quantum Materials. "Ice is a very ordered phase because the H2O molecules are neatly arranged in a crystal lattice. Water is less ordered compared with ice, but flowing water molecules still have underlying order. The critical point is where things are fluctuating between these two types of order. It's the point where H2O molecules sort of want to go to the pattern according to ice and sort of want to go to the pattern according to water.

"It's very similar in a quantum phase transition," he said. "Even though this transition is driven by quantum mechanics, it is still a critical point where there's maximum fluctuation between two ordered states. In this case, the fluctuations are related to the ordering of the 'spins' of electrons in the material."

Spin is an inherent property—like eye color—and every electron's spin is classified as being either "up" or "down." In magnets, like iron, spins are aligned in the same direction. But many materials exhibit the opposite behavior: Their spins alternate in a repeating up, down, up, down pattern that physicists refer to as "antiferromagnetic."

Hundreds of experiments on heavy fermions, high-temperature superconductors and other quantum materials have found that magnetic order differs on either side of a quantum critical point. Typically, experiments find antiferromagnetic order in one range of chemical composition, and a new state of order on the other side of the critical point.

"A reasonable picture is that you can have an antiferromagnetic order of spins, where the spins are quite ordered, and you can have another state in which the spins are less ordered," said Si, Rice's

Harry C. and Olga K. Wiess Professor of Physics and Astronomy. "The critical point is where fluctuations between these two states are at their maximum."

The cerium copper gold compound has become a prototype heavy fermion material for quantum criticality, largely due to the work of von Löhneysen's group.

"In 2000, we did inelastic neutron scattering experiments in the quantum critical cerium copper gold system," said von Löhneysen. "We found a spatial-temporal profile so unusual that it could not be understood in terms of the standard theory of metal."

Si said that study was one of the important factors that stimulated him and his co-authors to offer their 2001 theory, which helped explain von Löhneysen's puzzling results. In subsequent studies, Si and colleagues also predicted that entropy—a classical thermodynamic property—would increase as quantum fluctuations increased near a quantum critical point. The well-documented properties of cerium copper gold provided a unique opportunity to test the theory, Si said.

In cerium copper-six, substituting small amounts of gold for copper allows researchers to slightly increase the spacing between atoms. In the critical composition, the alloys undergo an antiferromagnetic quantum phase transition. By studying this composition and measuring the entropy numerous times under varying conditions of stress, the Karlsruhe team was able to create a 3-D map that showed how entropy at very low yet finite temperature steadily increased as the system approached the quantum critical point.

No direct measure of entropy exists, but the ratio of entropy changes to stress is directly proportional to another ratio that can be measured: the amount the sample expands or contracts due to changes in temperature. To enable the measurements at the extraordinarily low temperatures required, the Karlsruhe team developed a method for accurately measuring length changes of less than one tenth of a trillionth of a meter—approximately one-thousandth the radius of a single atom.

"We measured the entropy as a function of stress applied along all the different principal directions," said Grube, a senior researcher at Karlsruhe Institute of Technology. "We made a detailed map of the entropy landscape in the multidimensional parameter space and verified that the quantum critical point sits on top of the entropy mountain."

Von Löhneysen said the thermodynamic measurements also provide new insights into the quantum fluctuations near the critical point.

"Surprisingly, this methodology allows us to reconstruct the underlying spatial profile of quantum critical fluctuations in this quantum critical material," he said. "This is the first time that this kind of methodology has been applied."

Si said it came as a surprise that this could be done using nothing more than entropy measurements.

"It is quite remarkable that the entropy landscape can connect so well with the detailed profile of the quantum critical fluctuations determined from microscopic experiments such as inelastic neutron scattering, all the more so when both end up providing direct evidence to support the theory," he said.

More generally, the demonstration of the pronounced entropy enhancement at a quantum critical point in a multidimensional parameter space raises new insights into the way electron-electron interactions give rise to high-temperature superconductivity, Si said.

"One way to relieve the accumulated entropy of a quantum critical point is for the electrons in the system to reorganize themselves into novel phases," he said. "Among the possible phases that ensue is unconventional superconductivity, in which the electrons pair up and form a coherent macroscopic quantum state." [28]

Physicists predict supercurrent driven by potential information transfer

Physicists have theoretically shown that a superconducting current of electrons can be induced to flow by a new kind of transport mechanism: the potential flow of information. This unusual phenomena is predicted to exist in chiral channels—channels in which electrons are usually restricted to flowing in one direction only—but has never been theoretically demonstrated before now.

The physicists, Xiao-Li Huang and Yuli V. Nazarov at the Delft University of Technology in The Netherlands, have published a paper on the supercurrent induced by potential information transfer in a recent issue of Physical Review Letters.

As the scientists explain, a transport mechanism for electrons that is based on information transfer is unprecedented and has so far never been observed. Further, chiral channels are thought to be incapable of carrying a superconducting current (one with little to no resistance) at all. So it's quite surprising that a supercurrent can be induced in a chiral channel in the first place, and especially by such an exotic mechanism.

The scientists explained that, by definition, the electrons in a chiral channel can only move in one direction. To induce supercurrent, an information transfer in the direction opposite to this direction is required. However, the supercurrent, as it's not the usual electric current, can flow in either direction, depending on the phases on the superconducting leads in the proposed set-up.

The physicists also predict that the supercurrent should persist in the ground state, where, by definition, no actual information transfer can take place. The reason why this is possible is because it's not an actual information flow, but rather the potential for such a flow to occur, that drives the supercurrent.

The physicists hope that this intriguing relation between superconductivity and potential information transfer can lead to some novel capabilities. For example, as they write in their paper, supercurrent might be used to "probe the potential for information transfer without actually transferring the information." The physicists expect that it should be possible to experimentally observe the effect in graphene-based chiral channels, and they hope to further investigate this possibility in the future. [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

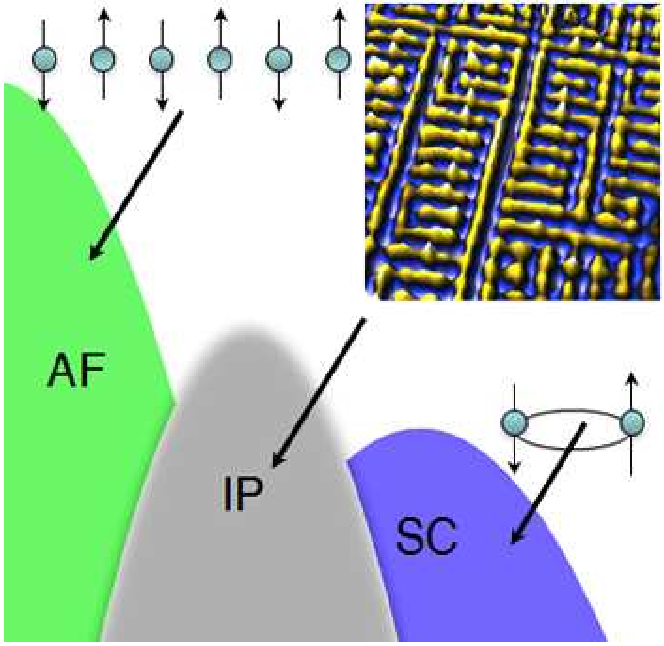
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

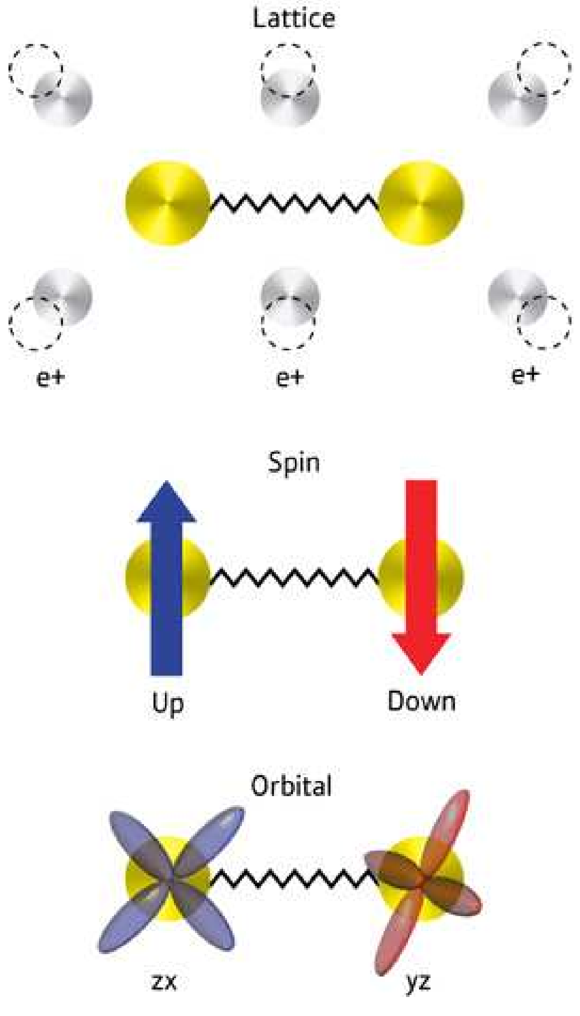
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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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