Magnetic Field in Superconductor

A world record for a trapped field in a superconductor, was achieved in 2014 by a team of engineers led by Professor David Cardwell. [28]

The first practical proposal was formulated 50 years ago by the American physicist Richard Garwin. He proposed that a transmission line of 1000 km, transporting 100 Gigawatt (at that time, all the energy produced in the U.S.) could be transmitted through a single underground superconductive cable, just a mere 30 cm wide, including its cooling system. The drawback was that cooling the wire down to a few degrees above absolute zero would have been too costly. [27]

Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, Cornell University, and collaborators have produced the first direct evidence of a state of electronic matter first predicted by theorists in 1964. The discovery, described in a paper published online April 13, 2016, in Nature, may provide key insights into the workings of high-temperature superconductors. [26]

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

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

Contents

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

Strongest magnetic field trapped in a superconductor is a world record

A world record for a trapped field in a superconductor, was achieved in 2014 by a team of engineers led by Professor David Cardwell.

Harnessing the equivalent of three tonnes of force inside a golf ball-sized sample of material that is normally as brittle as fine china, the team beat a record that had stood for more than a decade and the record has now been officially recognised by the Guinness World Records.

The Guinness World Records website says "A world record for a trapped field in a superconductor, was achieved in 2014 by a team of engineers led by Professor David Cardwell. The strongest magnetic field trapped in a superconductor is 17.6 tesla, achieved by researchers from the University of Cambridge (UK), the National High Magnetic Field Laboratory and the Boeing Company (both USA), as published in Superconductor Science and Technology, on 25 June 2014.

"The team used gadolinium boron carbon oxide (GdBCO) which is typically very brittle, then doped the structure with silver, and 'shrink wrapped' steel around the thumb-sized object to increase its strength. Superconductors which trap strong magnetic fields have a wide variety of applications, from Maglev trains to electricity storage."

17.6 Tesla is roughly 100 times stronger than the field generated by a typical fridge magnet - beating the previous record by 0.4 Tesla.

The research demonstrates the potential of high-temperature superconductors for applications in a range of fields, including flywheels for energy storage, 'magnetic separators', which can be used in mineral refinement and pollution control, and in high-speed levitating monorail trains. [28]

New superconductive material for long-distance energy transmission

The energy landscape in Europe is changing rapidly and the percentage of renewables is steadily increasing. For example, in Germany, solar and wind power provided an average of 33% of the total electricity production in 2015. And the phase-out of nuclear power, as part of the country's energy transition or Energiewende, will result in the expansion of the local electricity grid.

However, renewable energy depends on local weather conditions, on the possibility of electric power being shunted from one region to another, and also on the construction of a new, long-distance network of transmission lines linking countries in Europe.

With the existing technology, high-voltage DC overhead lines are currently the cheapest option. However, the rural population and environmental groups strongly oppose this solution with its unsightly pylons.

An alternative is to bury copper or aluminium high-voltage lines underground, a solution used in populated areas, but this is unlikely to be applied over long distances due to the much higher cost versus overhead lines.

Another drawback of energy transport through copper or aluminium lines is transmission losses caused by the electric resistance of these wires. This resistance causes the heating of wires, and the loss of energy. For long lines, energy loss can be as much as 10 percent of the transmitted energy. On a European level, that is the equivalent output of 3 to 5 large power plants.

In 1911, the Dutch physicist Heike Kamerling Onnes identified superconductors. He discovered that when some metals are cooled down to temperatures close to absolute zero, they lose all electrical resistance. For example, a current flowing in a closed loop of niobium held at practically absolute zero will flow forever. The scientist suggested that superconductive wires might be a good idea for energy transport.

The first practical proposal was formulated 50 years ago by the American physicist Richard Garwin. He proposed that a transmission line of 1000 km, transporting 100 Gigawatt (at that time, all the energy produced in the U.S.) could be transmitted through a single underground superconductive cable, just a mere 30 cm wide, including its cooling system. The drawback was that cooling the wire down to a few degrees above absolute zero would have been too costly.

During the 1980s, scientists discovered new ceramic materials that become superconductive at much higher temperatures, up to 70 degrees above absolute zero.

Although cooling would be much cheaper, these high-temperature superconductors are difficult to manufacture and too expensive for use over long distances.

Because of the high cost, utility companies have remained skeptical about their use in energy transport.

But in 2001, researchers in Japan discovered that a quite simple compound, magnesium diboride (MgB2), becomes superconductive at a temperature of 39 degrees above absolute zero (39 K). In 2011, at the Institute for Advanced Sustainability Studies (IASS) in Potsdam, Germany, the physics Nobel Laureate Carlo Rubbia initiated a research cluster investigating the application of superconductive lines for energy transport.

Magnesium diboride is only available in powder form, but researchers at Columbus Superconductors in Genoa, Italy, found the material could be manufactured in long strands by filling copper or nickel tubes with the powder and sintering them. "High costs barred the way for the energy transportation over long distances with superconductors. MgB2 really changed the game," says Giovanni Grasso, director general and co-founder of the company.

In 2014, a first test of the MgB2 wire at CERN confirmed that the material would be a good choice. "The MgB2 wire was tested with a very high current, up to 20,000 amperes, and this experiment confirmed the potential of MgB2 as the superconductor of choice for long-distance energy transport," says Adela Marian, a physicist at the IASS.

The institute is taking part in a study on superconductors under the European project Best Paths, with CERN, Columbus and other research groups. They are now planning a demonstration that will test a MgB2cable at conditions matching those of future energy transmission systems.

At a voltage of 200-320 kV, and a DC current of up to 10,000 amperes, the experiment will demonstrate the transmission of 3.2 gigawatts, the equivalent output of three large power stations, through a superconductive cable 12.5 mm across. This cable will be housed in a tube along with its cooling system that will keep it at an optimal temperature of 20 K.

The future design of the cooling system is still under investigation. It will work in two stages: First, an outer cooling system operating with nitrogen will bring the temperature down to 70 K, and then the temperature of the cable itself will be lowered to 20 K. The coolant will be either liquid hydrogen or helium gas.

"The cryogenic system, on which we still have to work, is the main aspect still limiting this application," says Christian Eric Bruzec, project leader at Nexans, a France-based company also part of the European project which assembled the strands produced by Columbus.

The jury is still out. Ultimately, though, underground MgB2 cables are expected to compete even with overhead transmission lines, says Marian. [27]

Elusive state of superconducting matter discovered after 50 years

Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, Cornell University, and collaborators have produced the first direct evidence of a state of electronic matter first predicted by theorists in 1964. The discovery, described in a paper published online April 13, 2016, in Nature, may provide key insights into the workings of high-temperature superconductors.

The prediction was that "Cooper pairs" of electrons in a superconductor could exist in two possible states. They could form a "superfluid" where all the particles are in the same quantum state and all move as a single entity, carrying current with zero resistance—what we usually call a superconductor. Or the Cooper pairs could periodically vary in density across space, a so-called "Cooper pair density wave." For decades, this novel state has been elusive, possibly because no instrument capable of observing it existed.

Now a research team led by J.C. Séamus Davis, a physicist at Brookhaven Lab and the James Gilbert White Distinguished Professor in the Physical Sciences at Cornell, and Andrew P. Mackenzie, Director of the Max-Planck Institute CPMS in Dresden, Germany, has developed a new way to use a scanning tunneling microscope (STM) to image Cooper pairs directly.

The studies were carried out by research associate Mohammed Hamidian (now at Harvard) and graduate student Stephen Edkins (St. Andrews University in Scotland), working as members of Davis' research group at Cornell and with Kazuhiro Fujita, a physicist in Brookhaven Lab's Condensed Matter Physics and Materials Science Department.

Superconductivity was first discovered in metals cooled almost to absolute zero (-273.15 degrees Celsius or -459.67 Fahrenheit). Recently developed materials called cuprates - copper oxides laced with other atoms - superconduct at temperatures as "high" as 148 degrees above absolute zero (-125 Celsius). In superconductors, electrons join in pairs that are magnetically neutral so they do not interact with atoms and can move without resistance.

Hamidian and Edkins studied a cuprate incorporating bismuth, strontium, and calcium (Bi2Sr2CaCu2O8) using an incredibly sensitive STM that scans a surface with sub-nanometer resolution, on a sample that is refrigerated to within a few thousandths of a degree above absolute zero.

At these temperatures, Cooper pairs can hop across short distances from one superconductor to another, a phenomenon known as Josephson tunneling. To observe Cooper pairs, the researchers briefly lowered the tip of the probe to touch the surface and pick up a flake of the cuprate material. Cooper pairs could then tunnel between the superconductor surface and the superconducting tip. The instrument became, Davis said, "the world's first scanning Josephson tunneling microscope." [26]

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

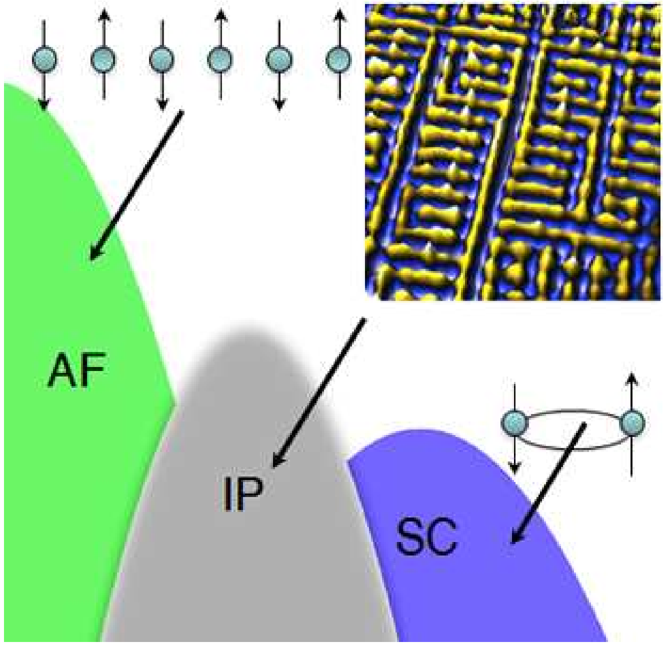
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

Unconventional superconductivity in $Ba^{0.6}K^{0.4}Fe^2As^2$ 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]

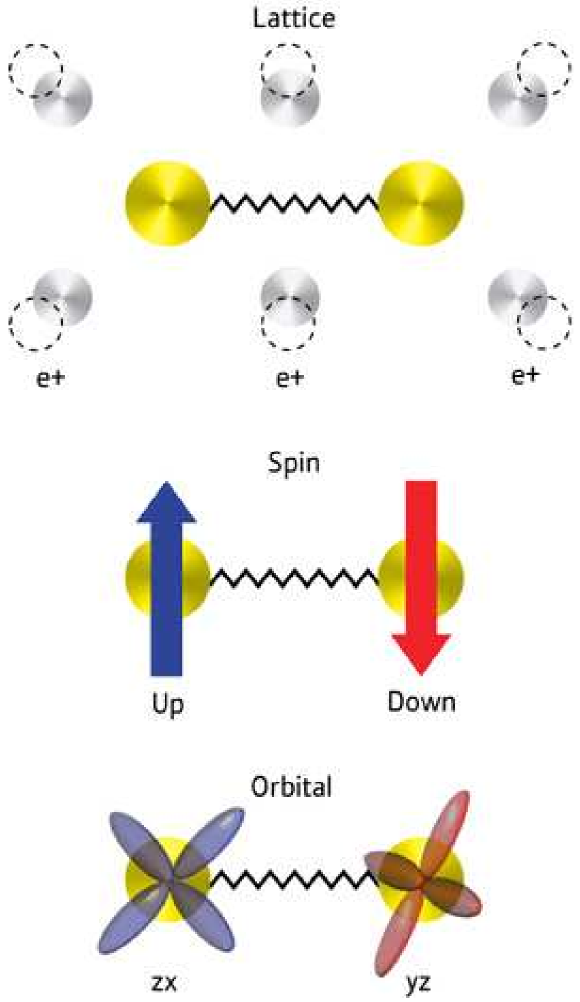
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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]

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]

References:

[1] https://www.academia.edu/3833335/The_Magnetic_field_of_the_Electric_current

[2] https://www.academia.edu/4239860/The_Bridge_between_Classical_and_Quantum_Mechanics

[3] http://en.wikipedia.org/wiki/BCS_theory

[4] http://en.wikipedia.org/wiki/Meissner_effect#cite_note-3

[5] http://en.wikipedia.org/wiki/London_equations

[6] Superconductivity switched on by magnetic field

http://phys.org/news/2013-12-superconductivity-magnetic-field.html#jCp

[7] http://en.wikipedia.org/wiki/Superconductivity

[8] http://en.wikipedia.org/wiki/High-temperature_superconductivity

[9] http://en.wikipedia.org/wiki/Room-temperature_superconductor

[10] http://en.wikipedia.org/wiki/Resonating_valence_bond_theory

[11] http://en.wikipedia.org/wiki/Strongly_correlated_material

[12] http://en.wikipedia.org/wiki/Cooper_pair

[13] https://www.academia.edu/3834454/3_Dimensional_String_Theory

[14] http://en.wikipedia.org/wiki/Color_superconductivity

[15] http://en.wikipedia.org/wiki/Fermi_surface

[16] http://en.wikipedia.org/wiki/Higgs_mechanism

[17] Superconductivity's third side unmasked

http://phys.org/news/2011-06-superconductivity-side-unmasked.html#nRlv

[18] https://www.academia.edu/4158863/Higgs_Field_and_Quantum_Gravity

[19] https://www.academia.edu/4221717/General_Weak_Interaction

[20] Einstein on Superconductivity http://arxiv.org/pdf/physics/0510251/

[21] Conventional Superconductivity http://phys.org/news150729937.html#jCp

[22] http://phys.org/news/2013-12-superconductor-theory-revolutionize-electrical.html#jCp

[23] http://phys.org/news150729937.html#jCp

[24] http://phys.org/news/2013-10-grand-theory-exotic-superconductivity.html#jCp

[25] http://www.pnas.org/content/early/2013/10/09/1316512110.full.pdf+html

[26] Elusive state of superconducting matter discovered after 50 years

http://phys.org/news/2016-04-elusive-state-superconducting-years.html

[27] New superconductive material for long-distance energy transmission

http://phys.org/news/2016-09-superconductive-material-long-distance-energy-transmission.html

[28] Strongest magnetic field trapped in a superconductor is a world record

http://phys.org/news/2016-09-strongest-magnetic-field-superconductor-world.html