Paramagnetic Spins for Electrons

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Researchers at Northeast Normal University, in China, and University of the Basque Country, in Spain, have recently carried out a study investigating the superconducting transition of electrides. [29]

Superconducting quantum microwave circuits can function as qubits, the building blocks of a future quantum computer. [28]

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies. [27]

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

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

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

Contents

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

Paramagnetic spins take electrons for a ride, produce electricity from heat

An international team of researchers has observed that local thermal perturbations of spins in a solid can convert heat to energy even in a paramagnetic material—where spins weren't thought to correlate long enough to do so. This effect, which the researchers call "paramagnon drag thermopower," converts a temperature difference into an electrical voltage. This discovery could lead to more efficient thermal energy harvesting—for example, converting car exhaust heat into electric power to enhance fuel-efficiency, or powering smart clothing by body heat.

The research team includes scientists from North Carolina State University, the Department of Energy's Oak Ridge National Laboratory (ORNL), the Chinese Academy of Sciences and the Ohio State University.

In solids with magnetic ions (e.g., manganese), thermal perturbations of spins either can align with each other (ferromagnets or antiferromagnets), or not align (paramagnets). However, spins are not entirely random in paramagnets: they form short-lived, short-range, locally ordered structures—paramagnons—which exist for only a millionth of a millionth of a second and extend over only two to four atoms. In a new paper describing the work, the researchers show that despite these shortcomings, even paramagnons can move in a temperature difference and propel free electrons along with them, creating paramagnon drag thermopower.

In a proof-of-concept finding, the team observed that paramagnon drag in manganese telluride (MnTe) extends to very high temperatures and generates a thermopower that is much stronger than what electron charges alone can make.

The research team tested the concept of paramagnon drag thermopower by heating lithium-doped MnTe to approximately 250 degrees Celsius above its Néel temperature (34 degrees Celsius) - the temperature at which the spins in the material lose their long-range magnetic order and the material becomes paramagnetic.

"Above the Néel temperature, one would expect the thermopower being generated by the spin waves to drop off," says Daryoosh Vashaee, professor of electrical and computer engineering and materials science at NC State and co-corresponding author of the paper describing the work. "However, we didn't see the expected drop off, and we wanted to find out why."

At ORNL the team used neutron spectroscopy at the Spallation Neutron Source to determine what was happening within the material. "We observed that even though there were no sustained spin waves, localized clusters of ions would correlate their spins long enough to produce visible magnetic fluctuations," says Raphael Hermann, a materials scientist at ORNL and co-corresponding author of the paper. The team showed that the lifetime of these spin waves—around 30 femtoseconds—was long enough to enable the dragging of electron charges, which requires only about one femtosecond, or one quadrillionth of a second. "The short-lived spin waves, therefore, could propel the charges and create enough thermopower to prevent the predicted drop off," Hermann says.

"Before this work, it was believed that magnon drag could exist only in magnetically ordered materials, not in paramagnets," says Joseph Heremans, professor of mechanical and aerospace engineering at the Ohio State University and co-corresponding author of the paper. "Because the best thermoelectric materials are semiconductors, and because we know of no ferromagnetic semiconductor at room temperature or above, we never thought before that magnon drag could boost the thermoelectric efficiency in practical applications. This new finding changes that completely; we can now investigate paramagnetic semiconductors, of which there are a lot."

"When we observed the sudden rise of Seebeck coefficient below and near the Néel temperature, and this excess value extended to high temperatures, we suspected something fundamentally related to spins must be involved," says Huaizhou Zhao, a professor at the Chinese Academy of Science in Beijing and co-corresponding author of the paper. "So we formed a research team with complementary expertise which laid the groundwork for this discovery."

"Spins enable a new paradigm in thermoelectricity by alleviating the fundamental tradeoffs imposed by Pauli exclusion on electrons," Vashaee says. "Just as in the discovery of the spin-Seebeck effect, which led to the new area of spincaloritronics, where the spin angular momentum is transferred to the electrons, both the spin waves (i.e., magnons) and the local thermal fluctuations of magnetization in the paramagnetic state (i.e., paramagnons) can transfer their linear momentum to electrons and generate thermopower."

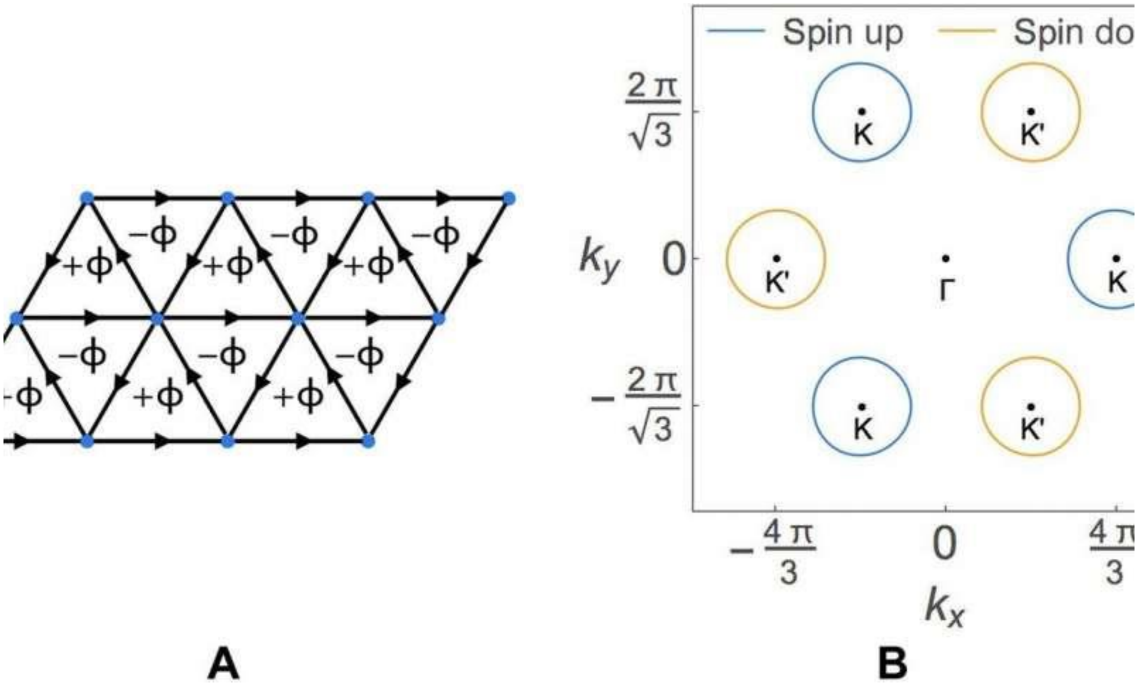
The research appears in *Science Advances*. [31]

Evidence of pair-density wave (PDW) in spin-valley locked systems

The isolation of graphene more than a decade ago transformed the landscape of condensed-matter physics, as the single-atom-thick, two-dimensional material exhibited high crystal and electronic quality to represent a conceptually new class of quantum materials. Physicists and engineers have since explored a vast family of two-dimensional crystals known as transition metal dichalcogenides (TMDs) in which electrons exist in layers with insulating, conducting or semiconducting properties, although little attention has been directed to investigate superconductivity in the 2-D crystals. Ongoing work in the field continues to provide surprisingly fertile ground for applications in low dimensional physics.

Recent discoveries in high T_c superconductors have resulted in an intense interest in a "pair-density wave" (PDW) formed in Cooper pairs (an electron pair bound together at low temperatures), although there is little theoretical understanding on the driving mechanisms of this exotic state. The complexity results from the many competing states that are in close energy in the strongly correlated region within seemingly simple models and phenomena such as the Hubbard model, frustrated magnets and high temperature superconductors. In a recent study, Jordan Venderley and Eun-Ah Kim at the Cornell University, New York, showed that inversion symmetry breaking and resulting spin-valley locking could promote PDWs to overcome the more commonly found spin and charge stripes through frustration against magnetic order. The study detailed the first robust evidence for a PDW in density matrix renormalization of a simple fermionic model via group simulation. The outcomes pointed to an intriguing possibility of the exotic state occurring in hole-doped group VI transition metal dichalcogenides (TMDs) with spin-valley locked band structure and moderate correlations. The results are now published in *Science Advances*.

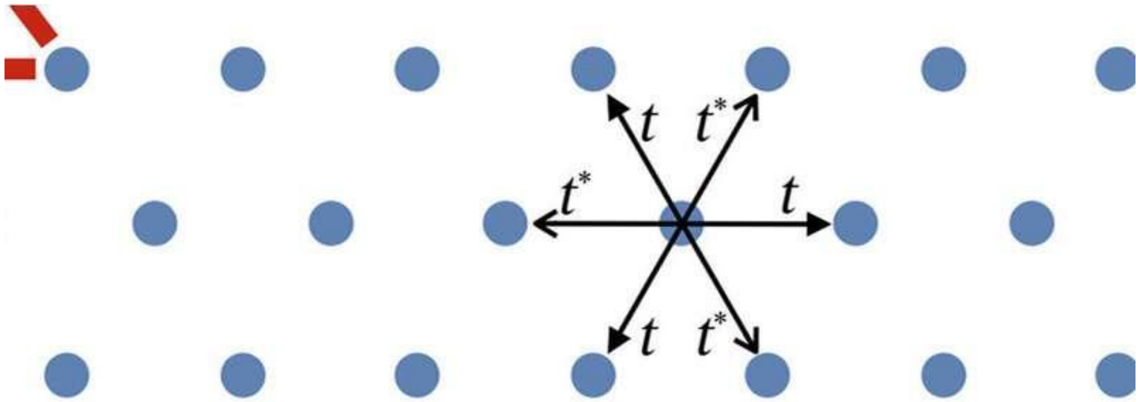
High temperature superconductors (abbreviated high-T_c) are materials that behave as superconductors at extremely high transition temperatures. The first experimental evidence of superconductors was discovered by J.G. Bednorz and K.A. Müller at IBM's Zurich Research Lab in 1986, for which they were subsequently awarded the Nobel Prize in Physics in 1987. Recent experimental and theoretical developments revived the idea of a regulated or modulated superconducting state that spontaneously breaks translational symmetry. Early efforts on regulating superconductors have closely maintained the principles in the original Fulde-Ferrell-Larkin-Ovchinnkov (FFLO) model, proposed in 1964. An alternative proposal for a modulated paired state for cuprates (materials containing copper anionic complexes) requires a strong coupling mechanism, known as a pair-density wave (PDW), which is distinct from FFLO-type superconductors.



Modelling the Fermi surface. (A) The spin-dependent staggered flux pattern for one-spin component with ± Φ flux per plaquette. An opposite flux pattern for the other spin component guarantees time-reversal symmetry. The arrows indicate the direction of positive phase hopping. (B) The Fermi surface in the tight-binding model as derived in the study. Here, the spin-valley locked, circular Fermi pockets are evident. Credit: *Science Advances*, doi: 10.1126/sciadv.aat4698.

The existing need for a strong coupling mechanism led physicists to search for the PDW state in numerical simulations. Present evidence of a PDW in the density matrix renormalization group (DMRG) was only established in the one-dimensional (1D) Kondo-Heisenberg model. Numerical evidence from the controlled approach of the DMRG is, however, lacking in simple fermionic models. A signature difficulty in realizing such a state is due to the presence of spin and charge stripe ground states instead of the PDW state on a Hubbard or t-J model in a square lattice with open-rotation symmetry. The t-J model, first derived from the Hubbard model by Josef Spalek in 1977, described strongly-correlated electron systems to calculate states of high temperature superconductivity in doped antiferromagnets (composed of a few Fe atoms on a surface exhibiting two magnetic states).

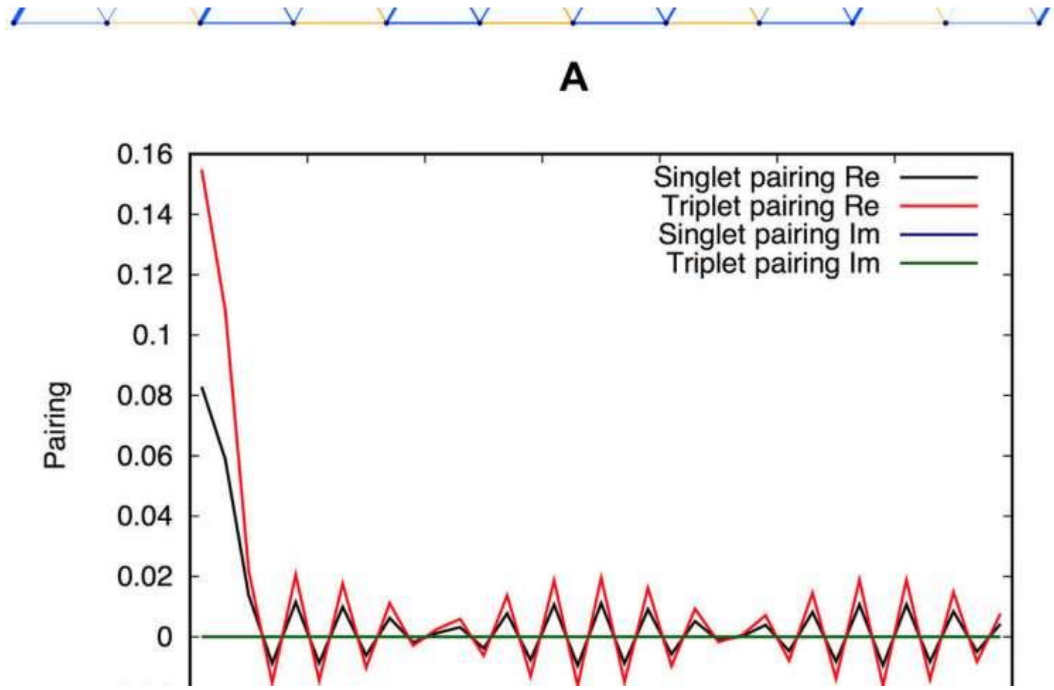
While many models exist in different branches of physics, the Hubbard model is an iconic and simple contrivance of theoretical condensed matter physics that captures the behavior of correlated electrons in solids as they hop between lattice sites. In the present study, Venderley and Kim therefore turned to a Hubbard model and expected for the frustrating magnetic spin order to nudge systems into a PDW state on a frustrated triangular lattice with broken inversion symmetry. The model captured the hole-doped monolayer group IV TMDs, used as benchmark systems to study and control intertwined electronic orders, fueled by exotic possibilities driven by spin-orbit-coupling (SOC) and a lack of centrosymmetry, alongside superconductivity as observed in preceding studies.



Lattice and edge field. A depiction of the lattice in the study. It is periodic in the short direction with three-unit cells and has open boundaries in the long direction. The ellipses on the right signify that multiple lengths are studied: L = 12, 18, 24, 36. The edge field, shown as red lines, is a pair field of the form derived in the study. The nearest-neighbor hopping structure for spin up is also shown with the spin down hopping structure being the complex conjugate of that shown above. Credit: *Science Advances*, doi: 10.1126/sciadv.aat4698.

The DMRG (density matrix renormalization group) is a powerful nonperturbative method used to study strongly interacting electronic systems and explore a diverse selection of strongly correlated, competing quantum phenomena. The DMRG technique was established in the past decade as the leading method to simulate statics and dynamics of one-dimensional quantum lattice systems, with potential for further development. To access the system's superconducting tendencies, Venderley and Kim implemented a pair-edge field motivated by the field-pinning approach, which underlay several previous studies. They biased the system to a specific superconducting state and studied the emergent symmetry of the appropriate order parameter in the bulk to deduce the model's inclination towards various instabilities.

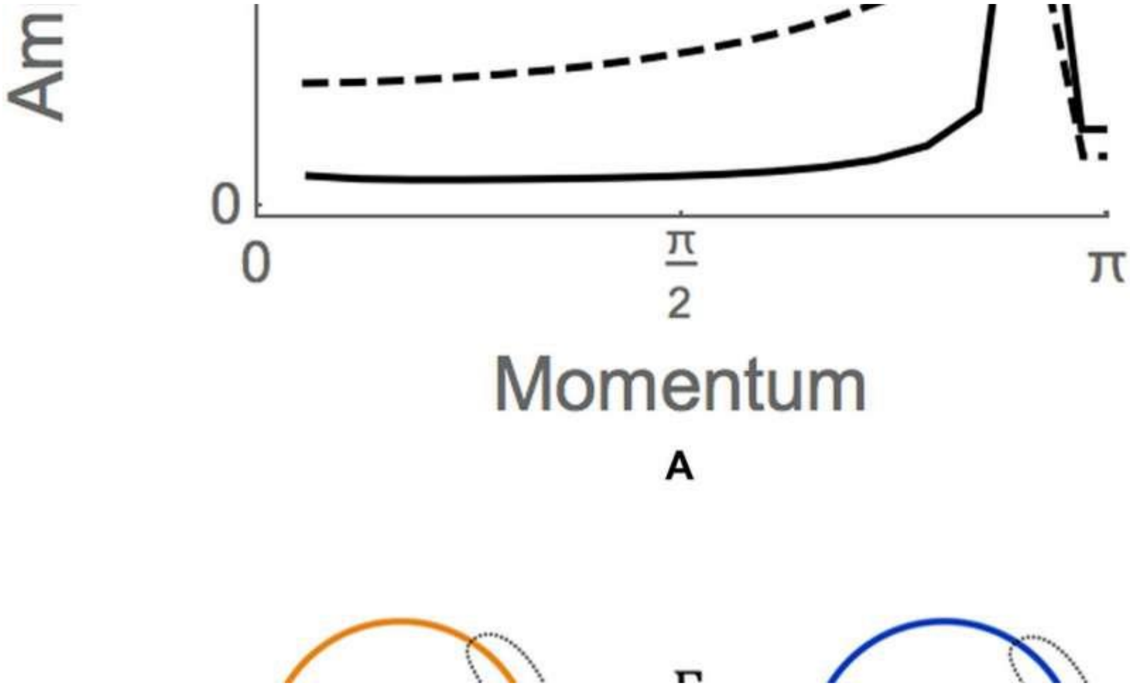
The scientists conducted the DMRG calculations and DMRG simulations in two dimensional systems using the iTensor Library developed by Stoudenmire and White. They presented the DMRG simulations in a cylinder with three-unit cells in the periodic direction and 12-, 18-, 24- and 36-unit cells in the nonperiodic direction. The width of the simulation was sufficiently large to sample the pockets in the Fermi surface but not so large as to make the DMRG prohibitively expensive for the computational resources in the lab.



Evidence of PDW oscillations. (A) Arg (Δsinglet⟨ij⟩) for all nearest-neighbors with U = +2 for the 3 by 36 lattice simulated with periodic boundary conditions along the short direction and open boundary conditions along the long direction. For visibility, the scientists truncate the plot so that only the third farthest from the edge field is shown. The line thickness is proportional to the pairing amplitude. (B) The scientists plot the real and imaginary components of Δsingletij and Δtripletij for i,j along the middle rung of the lattice to present the phase oscillations. Credit: *Science Advances*, doi: 10.1126/sciadv.aat4698.

To capture the spin-valley locked Fermi surfaces in one-band model in the valence group VI TMDs, the scientists considered a nearest-neighbor tight-binding model on the Fermi surface, where the magnetic flux introduced small amounts of anisotropy in the pockets, analogous to those observed in real semiconductor materials such as MoS_2, followed by the inclusion of on-site interactions. In the present work, the DMRG simulation unexpectedly revealed a tendency to break translational symmetry in the repulsive interaction regime to form a modulated pair state, after which the scientists observed evidence of the formation and maintenance of robust PDW oscillations, despite changes (increase) in the simulated chemical potential. This observation by Venderley and Kim was the first report of a strong coupling-driven PDW within DMRG simulations of a simple fermionic model. The phase oscillations plotted in this study, strongly resembled the PDW-type behavior reported in the earlier 1D Kondo-Heisenberg model.

Venderley and Kim then Fourier transformed these oscillations to suggest that the infinite momentum of the Cooper pairs originated from the interplay between the Fermi pockets. This view was reinforced when they probed the effect of increasing the chemical potential in the study (which decreased the pocket radius). They then captured oscillations in the singlet pairing strength and in the bond charge density to show that both orders were dominated by the same Fourier mode.



Fourier decomposition of the PDW and bond charge order. (A) Fourier transforms of the PDW and charge bond order. Zero momentum, i.e., constant contributions and decay effects have been removed. (B) Depiction of pairing in momentum space. The regions demarcated by dashed lines are the approximate pairing regions. Credit: *Science Advances*, doi: 10.1126/sciadv.aat4698.

In this way, Venderley and Kim used DMRG to study superconducting tendencies of a repulsive *U* Hubbard model on a triangular lattice with spin-valley locking. They probed the tendencies to reveal the complex superconducting phase diagram of the model with translational symmetry-breaking superconducting states; possibly in competition with a uniform state. While researchers are interested in modulating superconducting states, the observed was the first report of a strong coupling-driven PDW formed in a simple fermionic model. Venderley and Kim next aim to investigate if the observed PDW state can be found in a truly 2-D setting by using a different numerical technique such as the density matrix embedding theory that has shown high quality results in 2-D Hubbard models. [30]

Study investigates pressure-induced superconducting transition in electrides

Researchers at Northeast Normal University, in China, and University of the Basque Country, in Spain, have recently carried out a study investigating the superconducting transition of electrides. The researchers observed that a pressure-induced stable Li_6P, identified by first-principles swarm structure calculations, can become a superconductor with a considerably high superconducting transition temperature.

"Considering the wide potential applications of superconducting materials, the understanding of high-temperature superconductors is a key scientific challenge in condensed matter physics," Aitor Bergara and Guochun Yang, two of the researchers who carried out the study, told Phys.org, via email.

Electrides are ionic compounds in which most electrons reside at interstitial regions of the crystal and behave like anions. Due to their structural peculiarity, these compounds have interesting physical properties. For instance, the magnitude and distribution of their interstitial electrons can be effectively modulated, either by adjusting their chemical composition or external conditions, such as pressure.

Overall, electrides are very poor superconductors. For example, the experimentally observed superconducting transition temperature of a canonical electride $[Ca_{24}Al_{28}O_{64}]^{4+}$ $(4e^{-})_4$ is ~0.4 K. On the other hand, it is now well-known that, under high pressure, alkali metals can easily lose their outer orbital electrons and form electrides.

"Interestingly, pressure-induced lithium (Li) electride is metallic," Bergara and Yang said. "Additionally, phosphorus (P) presents a moderate electronegativity, so that they can trap some electrons in Li-rich Li-P compounds, while the remaining electrons may remain at interstitial regions. Thus, as we are predicting is this work, it would be possible to adjust the morphology of interstitial electrons by changing the ratio of Li and P and, therefore, obtain compounds with novel electronic properties. For example, according to our calculations, Li 6 P electride is predicted to have a superconducting transition temperature of 39.3 K, breaking the existing record among the electrides."

Predicting the atomic structure of materials from first principles (based only on their composition), is an extremely challenging task. It typically requires classifying a huge number of energy minima on a multidimensional energy surface lattice. In recent years, researchers have introduced several computation methods that can speed up this process, one of which is called CALYPSO.

"In our study we have used the Calypso program developed by Yanming Ma and his colleagues at Jilin University, which implements a particle swarm optimization algorithm to determine the preferred crystal structures, just fixing the Li:P ratios and pressure as the only starting inputs," Bergara and Yang explained. "Once the most stable structures are identified we have characterized their physical properties. For example, we have explored their superconducting properties within the McMillan-Allen-Dynes approximation."

In their study, Bergara, Yang and their colleagues reported that a pressure-induced stable Li_6P electride can become a superconductor with a predicted superconducting transition temperature of 39.3K; the highest predicted so far in known electrides. They found that the compound's interstitial electrons, with dumbbell-like connected electride states, play a dominant role in this superconducting transition.

"Our prediction not only breaks the superconducting transition temperature record in the electrides, but also allows a better understanding of these materials," Bergara and Yang said.

According to the researchers' predictions, other Li-rich phosphides, such as Li_5P, $Li_{11}P_2$, Li_15P_2, and Li_8P, could also be superconducting electrides, yet their T_c is expected to be lower. This recent study by Bergara, Yang and their colleagues could pave the way for further research exploring high-temperature superconductivity in similar binary compounds.

"We believe that research into superconducting electrides has just begun," Bergara and Yang said. "There is still a lot to be explored, for example, the analysis of the superconducting mechanism in novel electride compounds, especially under high pressure. As we have shown in this article, an effective way to design such superconducting materials is to explore metallic electride compounds formed between weak electronegative and strong electropositive elements." [29]

Ballistic graphene Josephson junctions enter microwave circuits

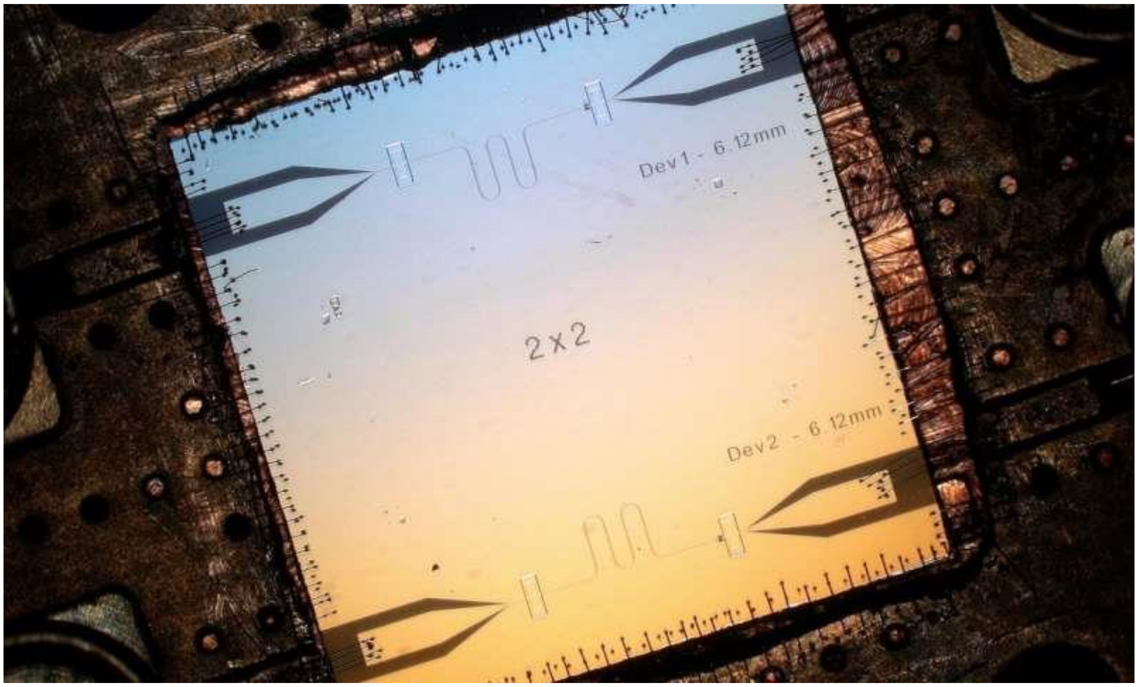
Superconducting quantum microwave circuits can function as qubits, the building blocks of a future quantum computer. A critical component of these circuits, the Josephson junction, is typically made using aluminium oxide. Researchers in the Quantum Nanoscience department at the Delft University of Technology have now successfully incorporated a graphene Josephson junction into a superconducting microwave circuit. Their work provides new insight into the interaction of superconductivity and graphene and its possibilities as a material for quantum technologies.

The essential building block of a quantum computer is the quantum bit, or qubit. Unlike regular bits, which can either be one or zero, qubits can be one, zero or a superposition of both these states. This last possibility, that bits can be in a superposition of two states at the same time, allows quantum computers to work in ways not possible with classical computers. The implications are profound: Quantum computers will be able to solve problems that will take a regular computer longer than the age of the universe to solve.

There are many ways to create qubits. One of the tried and tested methods is by using superconducting microwave circuits. These circuits can be engineered in such a way that they behave as harmonic oscillators "If we put a charge on one side, it will go through the inductor and oscillate back and forth," said Professor Gary Steele. "We make our qubits out of the different states of this charge bouncing back and forth."

An essential element of quantum microwave circuits is the so-called Josephson junction, which can, for example, consist of a non-superconducting material that separates two layers of superconducting material. Pairs of superconducting electrons can tunnel through this barrier, from one superconductor to the other, resulting in a supercurrent that can flow indefinitely long without any voltage applied.

In state-of-the art Josephson junctions for quantum circuits, the weak link is a thin layer of aluminium oxide separating two aluminium electrodes. "However, these can only be tuned with the use of a magnetic field, potentially leading to cross-talk and on-chip heating, which can complicate their use in future applications," said Steele. Graphene offers a possible solution. It has proven to host robust supercurrents over micron distances that survive in magnetic fields of up to a few Tesla. However, these devices had thus far been limited to direct current (DC) applications. Applications in microwave circuits, such as qubits or parametric amplifiers, had not been explored.



Close-up of the new a superconducting microwave circuit with a graphene Josephson junction. Credit: TU Delft

The research team at Delft University of Technology incorporated a graphene Josephson junction into a superconducting microwave circuit. By characterizing their device in the DC regime, they showed that their graphene Josephson junction exhibits ballistic supercurrent that can be tuned by the use of a gate voltage, which prevents the device from heating up. Upon exciting the circuit with microwave radiation, the researchers directly observed the Josephson inductance of the junction, which had up to this point not been directly accessible in graphene superconducting devices.

The researchers believe that graphene Josephson junctions have the potential to play an important part in future quantum computers. "It remains to be seen if they can be made into viable qubits, however," said Steele. While the graphene junctions were good enough for building qubits, they were not as coherent as traditional quantum microwave circuits based on aluminium oxide junctions, so further development of the technology is required. However, in applications that don't require high coherence, gate tunability could be useful now. One such application is in amplifiers, which are also important in quantum infrastructure. Steele: "We are quite excited about using these devices for quantum amplifier applications."

The authors have made all of the data published in the manuscript available in an open repository, including the path all the way back to the data as it was measured from the instrument. In addition, the researchers released all of the software used for measuring the data, analysing the data, and making the plots in the figures under an open-source licence.

The results of the study have been published in *Nature Communications*. [28]

Superconducting qubits can function as quantum engines

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies.

The physicists, Kewin Sachtleben, Kahio T. Mazon, and Luis G. C. Rego at the Federal University of Santa Catarina in Florianópolis, Brazil, have published a paper on their work on superconducting qubits in a recent issue of Physical Review Letters.

In their study, the physicists explain that superconducting circuits are functionally equivalent to quantum systems in which quantum particles tunnel in a double-quantum well. These wells have the ability to oscillate, meaning the width of the well changes repeatedly. When this happens, the system behaves somewhat like a piston that moves up and down in a cylinder, which changes the volume of the cylinder. This oscillatory behavior allows work to be performed on the system. The researchers show that, in the double-quantum well, part of this work comes from quantum coherent dynamics, which creates friction that decreases the work output. These results provide a better understanding of the connection between quantum and classical thermodynamic work.

"The distinction between 'classical' thermodynamic work, responsible for population transfer, and a quantum component, responsible for creating coherences, is an important result," Mazon told Phys.org. "The creation of coherences, in turn, generates a similar effect to friction, causing a notcompletely-reversible operation of the engine. In our work we have been able to calculate the reaction force caused on the quantum piston wall due to the creation of coherences. In principle this force can be measured, thus constituting the experimental possibility of observing the emergence of coherences during the operation of the quantum engine."

One of the potential benefits of viewing superconducting qubits as quantum engines is that it may allow researchers to incorporate quantum coherent dynamics into future technologies, in particular quantum computers. The physicists explain that a similar behavior can be seen in nature, where quantum coherences improve the efficiency of processes such as photosynthesis, light sensing, and other natural processes.

"Quantum machines may have applications in the field of quantum information, where the energy of quantum coherences is used to perform information manipulation in the quantum regime," Mazon said. "It is worth remembering that even photosynthesis can be described according to the working principles of a quantum machine, so unraveling the mysteries of quantum thermodynamics can help us to better understand and interpret various natural processes." [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

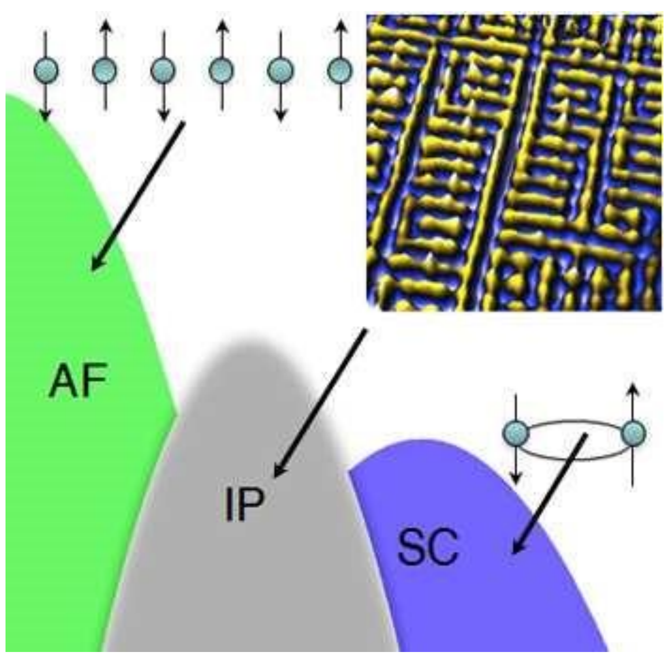
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical 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 $Ba^{0.6}K^{0.4}Fe^2As^2$ 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]

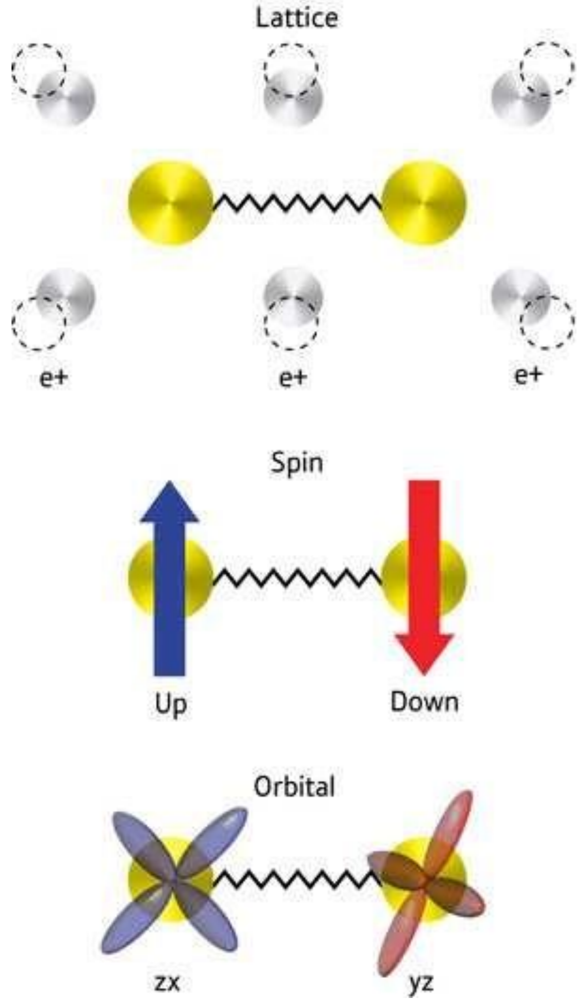
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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]

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]

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