Vibrations in Superconducting Crystals

Manipulating the flow of energy through superconductors could radically transform technology, perhaps leading to applications such as ultra-fast, highly efficient quantum computers. [33]

University of Wisconsin-Madison engineers have added a new dimension to our understanding of why straining a particular group of materials, called Ruddlesden-Popper oxides, tampers with their superconducting properties. [32]

Nuclear techniques have played an important role in determining the crystal structure of a rare type of intermetallic alloy that exhibits superconductivity. [31]

A potential new state of matter is being reported in the journal Nature, with research showing that among superconducting materials in high magnetic fields, the phenomenon of electronic symmetry breaking is common. [30]

Researchers from the University of Geneva (UNIGE) in Switzerland and the Technical University Munich in Germany have lifted the veil on the electronic characteristics of high-temperature superconductors. Their research, published in Nature Communications, shows that the electronic densities measured in these superconductors are a combination of two separate effects. As a result, they propose a new model that suggests the existence of two coexisting states rather than competing ones postulated for the past thirty years, a small revolution in the world of superconductivity. [29]

A team led by scientists at the Department of Energy's SLAC National Accelerator Laboratory combined powerful magnetic pulses with some of the brightest X-rays on the planet to discover a surprising 3-D arrangement of a material's electrons that appears closely linked to a mysterious phenomenon known as high-temperature superconductivity. [28]

Advanced x-ray technique reveals surprising quantum excitations that persist through materials with or without superconductivity. [27]

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

The changing acceleration of the electrons explains the created negative electric field of the magnetic induction, the Higgs Field, the changing Relativistic Mass and the

Gravitational Force, giving a Unified Theory of the physical forces. Taking into account the Planck Distribution Law of the electromagnetic oscillators also, we can explain the electron/proton mass rate and the Weak and Strong Interactions.

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

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Author: George Rajna

The Quest of Superconductivity

Superconductivity seems to contradict the theory of accelerating charges in the static electric current, caused by the electric force as a result of the electric potential difference, since a closed circle wire no potential difference at all. [1]

On the other hand the electron in the atom also moving in a circle around the proton with a constant velocity and constant impulse momentum with a constant magnetic field. This gives the idea of the centripetal acceleration of the moving charge in the closed circle wire as this is the case in the atomic electron attracted by the proton. Because of this we can think about superconductivity as a quantum phenomenon. [2]

Experiences and Theories

Scientists pinpoint energy flowing through vibrations in superconducting crystals

Manipulating the flow of energy through superconductors could radically transform technology, perhaps leading to applications such as ultra-fast, highly efficient quantum computers. But these subtle dynamics—including heat dispersion—play out with absurd speed across dizzying subatomic structures.

Now, scientists have tracked never-before-seen interactions between electrons and the crystal lattice structure of copper-oxide superconductors. The collaboration, led by scientists at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory, achieved measurement precision faster than one trillionth of one second through a groundbreaking combination of experimental techniques.

"This breakthrough offers direct, fundamental insight into the puzzling characteristics of these remarkable materials," said Brookhaven Lab scientist Yimei Zhu, who led the research. "We already had evidence of how lattice vibrations impact electron activity and disperse heat, but it was all through deduction. Now, finally, we can see it directly."

The results, published April 27 in the journal *Science Advances*, could advance research into powerful, fleeting phenomena found in copper oxides—including high-temperature superconductivity—and help scientists engineer new, better-performing materials.

"We found a nuanced atomic landscape, where certain high-frequency, 'hot' vibrations within the superconductor rapidly absorb energy from electrons and increase in intensity," said first author Tatiana Konstantinova, a Ph.D. student at Stony Brook University doing her thesis work at Brookhaven Lab. "Other sections of the lattice, however, were slow to react. Seeing this kind of tiered interaction transforms our understanding of copper oxides."

Scientists used ultra-fast electron diffraction and photoemission spectroscopy to observe changes in electron energy and momentum as well as fluctuations in the atomic structure.

Other collaborating institutions include SLAC National Accelerator Laboratory, North Carolina State University, Georgetown University, and the University of Duisburg-Essen in Germany.

Vibrations through a crystalline tree

The team chose $Bi_2Sr_2CaCu_2O_8$, a well-known superconducting copper oxide that exhibits the strong interactions central to the study. Even at temperatures close to absolute zero, the crystalline atomic lattice vibrates and very slight pulses of energy can cause the vibrations to increase in amplitude.

"These atomic vibrations are regimented and discrete, meaning they divide across specific frequencies," Zhu said. "We call vibrations with specific frequencies 'phonons,' and their interactions with flowing electrons were our target."

This system of interactions is a bit like the distribution of water through a tree, Konstantinova explained. Exposed to rain, only the roots can absorb the water before spreading it through the trunk and into the branches.

"Here, the water is like energy, raining down on the branching structure of the superconductor, and the soil is like our electrons," Konstantinova said. "But those electrons will only interact with certain phonons, which, in turn, redistribute the energy. Those phonons are like the hidden, highly interactive 'roots' that we needed to detect."

Beam-driven atomic snapshots

The atoms flex and shift on extremely fast timescales—think 100 femtoseconds, or million billionths of a second—and those motions must be pinpointed to understand their effect. And, ideally, dissect and manipulate those interactions.

The team used a custom-grown, layered bismuth-based compound, which can be cleaved into 100 nanometer samples through the relatively simple application of Scotch tape.

The material was then tested using the so-called "pump-probe" technique of million-electron-volt ultrafast electron diffraction (MeV-UED). As in similar time-resolved experiments, a fast light pulse (pump) struck the sample, lasting for just 100 femtoseconds and depositing energy. An electron beam followed, bounced off the crystal lattice, and a detector measured its diffraction pattern. Repeating this process—like a series of atomic snapshots—revealed the rapid, subtle shifting of atomic vibrations over time.

After the initial MeV-UED experiments at Brookhaven Lab, the data collection proceeded at SLAC National Accelerator Laboratory's UED facility during the relocation of the Brookhaven instrument to another building. Colleagues at the SLAC UED facility, led by Xijie Wang, assisted on the experiment.

The electron diffraction, however, only provided half the picture. Using time- and angle-resolved photoemission spectroscopy (tr-ARPES), the team tracked the changes in electrons within the material. An initial laser hit the sample and a second quickly followed—again with 100-femtosecond precision—to kick electrons off the surface. Detecting those flying electrons revealed changes over time in both energy and momentum.

The tr-ARPES experiments were conducted at the facility in University Duisburg-Essen by Brookhaven Lab scientists Jonathan Rameau and Peter Johnson and their German colleagues. Scientists from North Carolina State University and Georgetown University provided theoretical support.

"Both experimental techniques are rather sophisticated and require efforts of experts across multiple disciplines, from laser optics to accelerators and condensed matter physics," Konstantinova said. "The caliber of the instruments and the quality of the sample allowed us to distinguish between different types of lattice vibrations."

The team showed that the atomic vibrations evident in the electron-lattice interactions are varied and, in some ways, counter-intuitive.

When the lattice takes up energy from electrons, the amplitude of high-frequency phonons increases first while the lowest-frequency vibrations increase last. The different rates of energy flow between vibrations means that the sample, when subjected to a burst of photons, moves through novel stages that would be bypassed if simply exposed to heat.

"Our data guides the new quantitative descriptions of nonequilibrium behavior in complex systems," Konstantinova said. "The experimental approach readily applies to other exciting materials where electron-lattice interactions are of major interest." [33]

Strained materials make cooler superconductors

University of Wisconsin-Madison engineers have added a new dimension to our understanding of why straining a particular group of materials, called Ruddlesden-Popper oxides, tampers with their superconducting properties.

The findings, published in the journal *Nature Communications*, could help pave the way toward new advanced electronics.

"Strain is one of the knobs we can turn to create materials with desirable properties, so it is important to learn to manipulate its effects," says Dane Morgan, the Harvey D. Spangler Professor of materials science and engineering at UW-Madison and a senior author on the paper. "These findings might also help explain some puzzling results in strained materials."

Superconducting materials could make the nation's power grid much more efficient, thanks to their ability to conduct electricity with zero resistance. The substances also enable MRI machines to see inside patients' bodies and levitate bullet trains above the tracks because of the Meissner effect.

"This work is a good example of how basic research can influence developing transformative technologies through systematic understanding of material behaviors by close interaction between theory and experiment," says Ho Nyung Lee, a distinguished scientist at the Department of Energy's Oak Ridge National Laboratory who led the research.

Most materials only become superconductors when they are very cold—below a specific point called the critical temperature. For superconductors composed of thin films of the Ruddlesden-Popper material La1.85Sr0.15CuO4, that critical temperature varies substantially depending on the conditions under which the films were grown.

"The prevailing opinion has been that strain makes it thermodynamically easier for oxygen defects that destroy the superconducting properties to form in the material, but we have shown that differences in the kinetic time scales of oxygen-defect formation between tensile and compressive strain is a key mechanism," says Ryan Jacobs, a staff scientist in Morgan's laboratory and a co-first author on the paper.

Oxygen defects are important because the amount of oxygen contained within a material can alter its critical temperature. The most obvious idea was that strain might impact properties by adjusting how much energy is needed for oxygen defects to appear.

While this effect does occur, Jacobs and colleagues at Oak Ridge National Laboratory demonstrated that strain doesn't just affect how easily defects form, but also the rate at which oxygen moves in and out of the material. These results suggest that some of the most important strain responses may be a result of changes in kinetic effects.

"Recognizing that kinetics plays a key role is very important for how you create the material," says Morgan.

The scientists created the materials they studied by growing crystalline thin films on top of two different supporting surfaces—one compressed the resulting thin films while the other stretched them out to cause tensile strain.

Strikingly, the tensile-strained materials needed much colder temperatures than the compressed films to become superconductors. Additionally, tensile strain caused the materials to lose their superconducting properties more quickly than the compressed materials.

After extensive calculations, the scientists concluded that thermodynamic effects (via the defect formation energy) alone couldn't explain the dramatic results they observed. By applying their expertise in computational simulation and the computational modeling method known as density functional theory, the researchers narrowed in on kinetics as playing a dominant role.

"This is the first window on strain altering how oxygen moves in and out of these materials," says Morgan.

Currently, the researchers are exploring other methods to optimize Ruddlesden-Popper oxides for possible use in superconducting-based devices, fuel cells, oxygen sensors and electronic devices such as memristors. They are also investigating how the findings might be applied to a closely related group of materials called perovskites, which are an active research area for the Morgan group.

The paper was also featured as a *Nature Communications* Editor's Highlight. [32]

Nuclear techniques unlock the structure of a rare type of superconducting intermetallic alloy

Nuclear techniques have played an important role in determining the crystal structure of a rare type of intermetallic alloy that exhibits superconductivity.

The research, which was recently published in the *Accounts of Chemical Research*, was a undertaking led by researchers from the Max Planck Institute for Chemical Physics of Solids, with the collaboration of the Ivan-Franko National University of Lviv, the Technical University Freiberg, the Helmholtz-Zentrum Dresden-Rossendorf, and ANSTO.

Complex metallic alloys (CMAs) have the potential to act as catalysts and serve as materials for devices that covert heat into energy (thermoelectric generators) or use magnetic refrigeration to improve the energy efficiency of cooling and temperature control systems.

Thermoelectric generators are used for low power remote applications or where bulkier but more efficient heat engines would not be possible.

The unique properties of CMAs stem from their intricate superstructure, with each repeating unit cell comprising hundreds or thousands of atoms.

The study focused on a phase of beryllium and platinum, Be21Pt5. The low X-ray scattering power of beryllium atoms had previously posed a barrier to researchers attempting to resolve the structure of beryllium-rich CMAs, such as Be21Pt5, by using X-ray powder diffraction techniques.

To locate the beryllium atoms, researchers used the ECHIDNA neutron powder diffractometer at the Australian Centre for Neutron Scattering.

Dr. Maxim Avdeev, an instrument scientist, noted that the use of neutron beams in combination with X-ray data was key to solving the structure.

"Since beryllium is a light element, it will scatter neutrons further than X-rays by a factor of approximately 20. It was not possible to locate the beryllium atoms in the crystal using X-rays, but with neutron diffraction we found them easily."

"Since beryllium is a light element, it scatters X-rays weakly. Compared to platinum, the contrast is about 1-to-20. Using neutrons changes the ratio to approximately 16-to-20 which allowed to find beryllium atoms in the crystal structure easily."

Data from X-ray and neutron powder diffraction was complemented with quantum mechanical calculations to determine electron density distribution which defines electronic properties of the material.

The diffraction data indicated that the crystal structure of Be21Pt5 was built up from four types of nested polyhedral units or clusters. Each cluster contained four shells comprising 26 atoms with a unique distribution of defects, places where an atom is missing or irregularly placed in the lattice structure.

Neutron diffraction experiments at ANSTO helped determine the crystal structure determine the structure of Be21Pt5, which consisted of four unique clusters (colour-coded above in image), each containing 26 atoms.

The collaborative nature of the study was also pivotal to solving the structure.

"The physical sample was synthesised in Germany and sent to Australia for analysis. Once we sent the diffraction data back to our collaborators, they were able to solve the structure at their home institutions."

Having resolved the crystal structure, the research team also turned their attention to the physical properties of $Be_{21}Pt_5$ and made an unexpected discovery. At temperatures below 2 K, $Be_{21}Pt_5$ was found to exhibit superconductivity.

"It's quite unusual case for this family of intermetallic compounds to undergo a superconducting phase. Further studies are necessary to understand what makes this system special and neutron scattering experiments will play an important role in the process." [31]

Superconductivity research reveals potential new state of matter

A potential new state of matter is being reported in the journal Nature, with research showing that among superconducting materials in high magnetic fields, the phenomenon of electronic symmetry breaking is common. The ability to find similarities and differences among classes of materials with phenomena such as this helps researchers establish the essential ingredients that cause novel functionalities such as superconductivity.

The high-magnetic-field state of the heavy fermion superconductor $CeRhIn_5$ revealed a so-called electronic nematic state, in which the material's electrons aligned in a way to reduce the symmetry of the original crystal, something that now appears to be universal among unconventional superconductors. Unconventional superconductivity develops near a phase boundary separating magnetically ordered and magnetically disordered phases of a material.

"The appearance of the electronic alignment, called nematic behavior, in a prototypical heavyfermion superconductor highlights the interrelation of nematicity and unconventional superconductivity, suggesting nematicity to be common among correlated superconducting materials," said Filip Ronning of Los Alamos National Laboratory, lead author on the paper. Heavy fermions are intermetallic compounds, containing rare earth or actinide elements.

"These heavy fermion materials have a different hierarchy of energy scales than is found in transition metal and organic materials, but they often have similar complex and intertwined physics coupling spin, charge and lattice degrees of freedom," he said.

The work was reported in Nature by staff from the Los Alamos Condensed Matter and Magnet Science group and collaborators.

Using transport measurements near the field-tuned quantum critical point of $CeRhIn_5$ at 50 Tesla, the researchers observed a fluctuating nematic-like state. A nematic state is most well known in liquid crystals, wherein the molecules of the liquid are parallel but not arranged in a periodic array. Nematic-like states have been observed in transition metal systems near magnetic and superconducting phase transitions. The occurrence of this property points to nematicity's correlation with unconventional superconductivity. The difference, however, of the new nematic state found in CeRhIn5 relative to other systems is that it can be easily rotated by the magnetic field direction.

The use of the National High Magnetic Field Laboratory's pulsed field magnet facility at Los Alamos was essential, Ronning noted, due to the large magnetic fields required to access this state. In addition, another essential contribution was the fabrication of micron-sized devices using focused ion-beam milling performed in Germany, which enabled the transport measurements in large magnetic fields.

Superconductivity is extensively used in magnetic resonance imaging (MRI) and in particle accelerators, magnetic fusion devices, and RF and microwave filters, among other uses. [30]

Superconductivity seen in a new light

Superconducting materials have the characteristic of letting an electric current flow without resistance. The study of superconductors with a high critical temperature discovered in the 1980s remains a very attractive research subject for physicists. Indeed, many experimental observations still lack an adequate theoretical description. Researchers from the University of Geneva (UNIGE) in Switzerland and the Technical University Munich in Germany have lifted the veil on the electronic characteristics of high-temperature superconductors. Their research, published in Nature Communications, shows that the electronic densities measured in these superconductors are a combination of two separate effects. As a result, they propose a new model that suggests the existence of two coexisting states rather than competing ones postulated for the past thirty years, a small revolution in the world of superconductivity.

Below a certain temperature, a superconducting material loses all electrical resistance (equal to zero). When immersed in a magnetic field, high-temperature superconductors (high-Tc) allow this field to penetrate in the form of filamentary regions, called vortices, a condition in which the material is no longer superconducting. Each vortex is a whirl of electronic currents generating their own magnetic fields and in which the electronic structure is different from the rest of the material.

Coexistence rather than competition

Some theoretical models describe high-Tc superconductors as a competition between two fundamental states, each developing its own spectral signature. The first is characterized by an ordered spatial arrangement of electrons. The second, corresponding to the superconducting phase, is characterized by electrons assembled in pairs.

"However, by measuring the density of electronic states with local tunneling spectroscopy, we discovered that the spectra that were attributed solely to the core of a vortex, where the material is not in the superconducting state, are also present elsewhere—that is to say, in areas where the superconducting state exists. This implies that these spectroscopic signatures do not originate in the vortex cores and cannot be in competition with the superconducting state," explains Christoph Renner, professor in the Department of Quantum Matter Physics of the Faculty of Science at UNIGE. "This study therefore questions the view that these two states are in competition, as largely assumed until now. Instead, they turn out to be two coexisting states that together contribute to the measured spectra," professor Renner says. Indeed, physicists from UNIGE using theoretical simulation tools have shown that the experimental spectra can be reproduced perfectly by considering the superposition of the spectroscopic signature of a superconductor and this other electronic signature, brought to light through this new research.

This discovery is a breakthrough toward understanding the nature of the high-temperature superconducting state. It challenges some theoretical models based on the competition of the two states mentioned above. It also sheds new light on the electronic nature of the vortex cores, which potentially has an impact on their dynamics. Mastery of these dynamics, and particularly of the anchoring of vortices that depend on their electronic nature, is critical for many applications such as high-field electromagnets. [29]

A new dimension to high-temperature superconductivity discovered

A team led by scientists at the Department of Energy's SLAC National Accelerator Laboratory combined powerful magnetic pulses with some of the brightest X-rays on the planet to discover a surprising 3-D arrangement of a material's electrons that appears closely linked to a mysterious phenomenon known as high-temperature superconductivity.

This unexpected twist marks an important milestone in the 30-year journey to better understand how materials known as high-temperature superconductors conduct electricity with no resistance at temperatures hundreds of degrees Fahrenheit above those of conventional metal superconductors but still hundreds of degrees below freezing. The study was published today in Science.

The study also resolves an apparent mismatch in data from previous experiments and charts a new course for fully mapping the behaviors of electrons in these exotic materials under different conditions. Researchers have an ultimate goal to aid the design and development of new superconductors that work at warmer temperatures.

'Totally Unexpected' Physics

"This was totally unexpected, and also very exciting. This experiment has identified a new ingredient to consider in this field of study. Nobody had seen this 3-D picture before," said Jun-Sik Lee, a SLAC staff scientist and one of the leaders of the experiment conducted at SLAC's Linac Coherent Light Source (LCLS) X-ray laser. "This is an important step in understanding the physics of hightemperature superconductors."

The dream is to push the operating temperature for superconductors to room temperature, he added, which could lead to advances in computing, electronics and power grid technologies.

There are already many uses for standard superconducting technology, from MRI machines that diagnose brain tumors to a prototype levitating train, the CERN particle collider that enabled the Nobel Prize-winning discovery of the Higgs boson and ultrasensitive detectors used to hunt for dark matter, the invisible constituent believed to make up most of the mass of the universe. A planned upgrade to the LCLS, known as LCLS-II, will include a superconducting particle accelerator.

The New Wave in Superconductivity

The 3-D effect that scientists observed in the LCLS experiment, which occurs in a superconducting material known as YBCO (yttrium barium copper oxide), is a newly discovered type of 'charge density wave.' This wave does not have the oscillating motion of a light wave or a sound wave; it describes a static, ordered arrangement of clumps of electrons in a superconducting material. Its coexistence with superconductivity is perplexing to researchers because it seems to conflict with the freely moving electron pairs that define superconductivity.

The 2-D version of this wave was first seen in 2012 and has been studied extensively. The LCLS experiment revealed a separate 3-D version that appears stronger than the 2-D form and closely tied to both the 2-D behavior and the material's superconductivity.

The experiment was several years in the making and required international expertise to prepare the specialized samples and construct a powerful customized magnet that produced magnetic pulses compressed to thousandths of a second. Each pulse was 10-20 times stronger than those from the magnets in a typical medical MRI machine.

A Powerful Blend of Magnetism and Light

Those short but intense magnetic pulses suppressed the superconductivity of the YBCO samples and provided a clearer view of the charge density wave effects.

They were immediately followed at precisely timed intervals by ultrabright LCLS X-ray laser pulses, which allowed scientists to measure the wave effects.

"This experiment is a completely new way of using LCLS that opens up the door for a whole new class of future experiments," said Mike Dunne, LCLS director.

Researchers conducted many preparatory experiments at SLAC's Stanford Synchrotron Radiation Lightsource (SSRL), which also produces X-rays for research.

LCLS and SSRL are DOE Office of Science User Facilities. Scientists from SIMES, the Stanford Institute for Materials and Energy Sciences at SLAC, and SSRL and LCLS were a part of the study.

"I've been excited about this experiment for a long time," said Steven Kivelson, a Stanford University physics professor who contributed to the study and has researched high-temperature superconductors since 1987.

Kivelson said the experiment sets very clear boundaries on the temperature and strength of the magnetic field at which the newly observed 3-D effect emerges.

"There is nothing vague about this," he said. "You can now make a definitive statement: In this material a new phase exists."

The experiment also adds weight to the growing evidence that charge density waves and superconductivity "can be thought of as two sides of the same coin," he added.

In Search of Common Links

But it is also clear that YBCO is incredibly complex, and a more complete map of all of its properties is required to reach any conclusions about what matters most to its superconductivity, said Simon Gerber of SIMES and Hoyoung Jang of SSRL, the lead authors of the study.

Follow-up experiments are needed to provide a detailed visualization of the 3-D effect, and to learn whether the effect is universal across all types of high-temperature superconductors, said SLAC staff scientist and SIMES investigator Wei-Sheng Lee, who co-led the study with Jun-Sik Lee of SSRL and Diling Zhu of LCLS. "The properties of this material are much richer than we thought," Lee said.

"We continue to make new and surprising observations as we develop new experimental tools," Zhu added. [28]

Scientists Discover Hidden Magnetic Waves in High-Temperature Superconductors

Advanced x-ray technique reveals surprising quantum excitations that persist through materials with or without superconductivity UPTON, NY—Intrinsic inefficiencies plague current systems for the generation and delivery of electricity, with significant energy lost in transit. High-temperature superconductors (HTS)—uniquely capable of transmitting electricity with zero loss when chilled to subzero temperatures—could revolutionize the planet's aging and imperfect energy infrastructure, but the remarkable materials remain fundamentally puzzling to physicists. To unlock the true potential of HTS technology, scientists must navigate a quantum-scale labyrinth and pin down the phenomenon's source.

Now, scientists at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory and other collaborating institutions have discovered a surprising twist in the magnetic properties of HTS, challenging some of the leading theories. In a new study, published online in the journal Nature Materials on August 4, 2013, scientists found that unexpected magnetic excitations—quantum waves believed by many to regulate HTS—exist in both non-superconducting and superconducting materials.

"This is a major experimental clue about which magnetic excitations are important for hightemperature superconductivity," said Mark Dean, a physicist at Brookhaven Lab and lead author on the new paper. "Cutting-edge x-ray scattering techniques allowed us to see excitations in samples previously thought to be essentially non-magnetic."

On the atomic scale, electron spins—a bit like tiny bar magnets pointed in specific directions—rapidly interact with each other throughout magnetic materials. When one spin rotates, this disturbance can propagate through the material as a wave, tipping and aligning the spins of neighboring electrons. Many researchers believe that this subtle excitation wave may bind electrons together to create the perfect current conveyance of HTS, which operates at slightly warmer temperatures than traditional superconductivity.

The research was funded through Brookhaven Lab's Center for Emergent Superconductivity, an Energy Frontier Research Center funded by the U.S. Department of Energy's Office of Science to seek understanding of the underlying nature of superconductivity in complex materials. [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

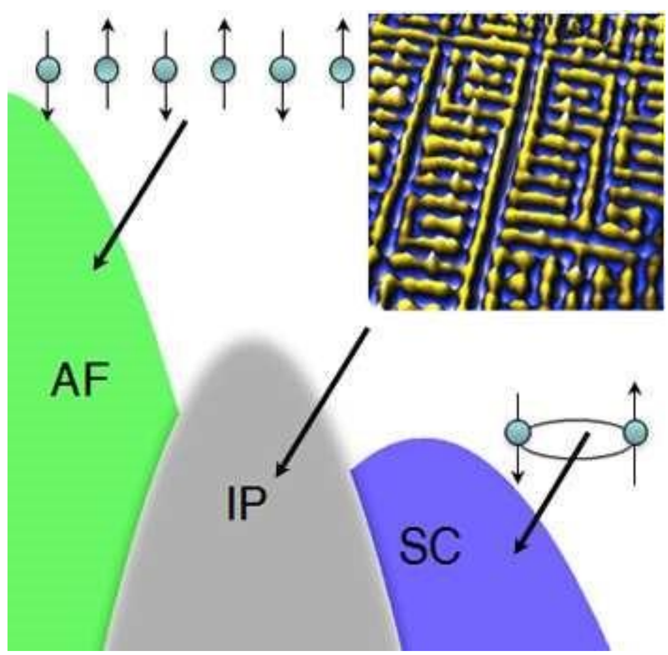
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

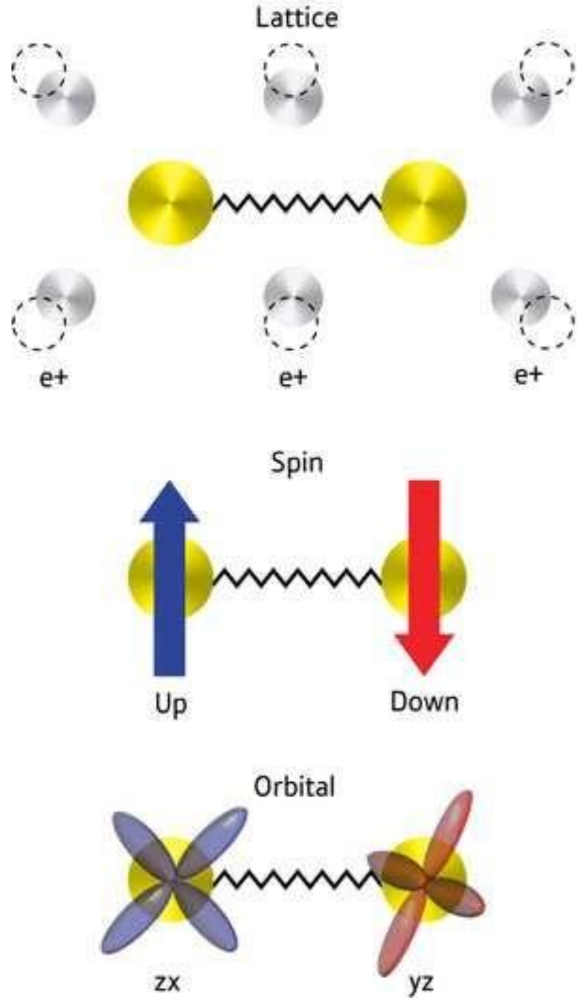
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

On the atomic scale, electron spins—a bit like tiny bar magnets pointed in specific directions—rapidly interact with each other throughout magnetic materials. When one spin rotates, this disturbance can propagate through the material as a wave, tipping and aligning the spins of neighboring electrons. Many researchers believe that this subtle excitation wave may bind electrons

together to create the perfect current conveyance of HTS, which operates at slightly warmer temperatures than traditional superconductivity. [27]

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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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] The Secret of Quantum Entanglement https://www.academia.edu/7229968/The_Secret_of_Quantum_Entanglement [27] Scientists Discover Hidden Magnetic Waves in High-Temperature Superconductors http://www.bnl.gov/newsroom/news.php?a=11564

[28] A new dimension to high-temperature superconductivity discovered http://phys.org/news/2015-11-dimension-high-temperature-superconductivity.html

[29] Superconductivity seen in a new light http://phys.org/news/2016-03-superconductivity.html

[30] Superconductivity research reveals potential new state of matter https://phys.org/news/2017-08-superconductivity-reveals-potential-state.html

[31] Nuclear techniques unlock the structure of a rare type of superconducting intermetallic alloy

https://phys.org/news/2018-04-nuclear-techniques-rare-superconducting-intermetallic.html

[32] Strained materials make cooler superconductors

https://phys.org/news/2018-04-strained-materials-cooler-superconductors.html

[33] Scientists pinpoint energy flowing through vibrations in superconducting crystals

https://phys.org/news/2018-04-scientists-energy-vibrations-superconducting-crystals.html