Nonmetallic Half-Metallicity

The microscopic mechanism proposed by the researchers differs significantly from the usual half-metal model based on a strong electron-electron interaction. [35]

Now an international team by Nagoya University has developed a new way of controlling the domain structure of ferroelectric materials, which could accelerate development of future electronic and electro-mechanical devices. [34]

The unusual crystal structures of these materials have regions in their lattices, called domains, that behave like molecular switches. [33]

A new way of operating the powerful X-ray laser at the Department of Energy's SLAC National Accelerator Laboratory has enabled researchers to detect and measure fluctuations in magnetic structures being considered for new data storage and computing technologies. [32]

Measurements at the Australian Centre for Neutron Scattering have helped clarify the arrangement of magnetic vortices, known as skyrmions, in manganese silicide (MnSi). [31]

Skyrmions are swirling spin structures with spiral shapes described in 2009. They have attracted attention in academia as representing a possible basic unit of ultra-high-density next-generation memory devices due to their unique topological stability, small size, and efficient movement. [30]

That could lead to new devices such as polariton transistors, Fei said. And that could one day lead to breakthroughs in photonic and quantum technologies. [29]

The future of nano-electronics is here. A team of researchers from the Air Force Research Laboratory, Colorado School of Mines, and the Argonne National Laboratory in Illinois have developed a novel method for the synthesis of a composite material that has the potential of vastly improving the electronics used by the Air Force. [28]

Physicists have theoretically shown that a superconducting current of electrons can be induced to flow by a new kind of transport mechanism: the potential flow of information. [27]

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

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

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

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Author: George Rajna

Physicists predict nonmetallic half-metallicity

A team of researchers of the Russian Academy of Sciences (RAS), in collaboration with a colleague from RIKEN (Institute for Physical and Chemical Research in Japan), has provided theoretical proof of the existence of a new class of materials, spin-valley half-metals. Their paper was published in the journal Physical Review Letters. The discovery has potential applications in implantable electronics and devices based on graphene, nanotubes, and a number of other promising materials.

The microscopic mechanism proposed by the researchers differs significantly from the usual half-metal model based on a strong electron-electron interaction. This might give rise to a new direction in search for "nonmetallic" half-metals, i.e., those that do not contain atoms of transition metals such as nickel, manganese and lanthanum. Such materials would be useful in implantable devices and systems. The authors use the term "spin-valley-tronics" to refer to this possible alternative to traditional electronics.

As electronics become smaller and more densely organized, it is highly challenging to continue increasing the number of transistors or the microprocessor clock rate. So researchers around the globe are exploring new possibilities. One of them is spintronics, which makes use of electron spins and already has some important practical applications. Around the turn of the century, the use of giant magnetoresistance materials in magnetic field sensors (used to read data in hard disk drives) has enabled the storage of much larger amounts of data on HDDs.

Half-metals are believed to have great potential in spintronics. They were first predicted based on computer simulations and later proved to exist experimentally. In a half-metallic material, electrons of only one spin orientation—e.g., spin up—participate in the electric current. The energy of spin-down electrons is too high, and therefore they cannot carry charge current. This means that when the current is passed through a half-metal, a spin-polarized current is generated, as well. But spin-valley-tronics seeks to manipulate not only a spin-polarized population of electrons in the current but also the so-called valley index.

The term "valley" is borrowed from semiconductor physics. Mathematically, the excitation energy in a solid is expressed by E (k, n), where k is the momentum of the electron and n is the zone index, i.e., a discrete quantum property of the state of the electron. This function may look rather odd, and in the case of several minimums with comparable excitation energies, there are multiple "valleys." Essentially, electrons whose states correspond to one of the valleys do not interact with electrons from another valley. Such an ensemble of electrons can carry not only spin and charge, but also a distinct value called the valley index.

The valley index can be used to transfer information with the help of valley currents—in this regard, the valley index is quite similar to spin. Research in this direction is currently being carried out by several groups. The researchers have now theoretically proved the existence of a novel class of materials for use in spin-valley-tronics.

The half-metals available to the researchers all contain atoms of transition metals: nickel, manganese, lanthanum, etc. The researchers demonstrated a theoretical mechanism for achieving half-metallicity that requires no transition metal atoms. This has a number of useful applications, including in implantable devices.

The physicists suggest that such nonmetallic half-metals be obtained from a special class of dielectric materials called charge- or spin-density wave insulators. The term refers to a state with periodic microscopic regions with nonzero average charge (spin) in the material. Theorists describe such systems as a quantum condensate of electron-hole pairs. For a pair of this kind to form, two valleys are required: One provides electrons, the other provides holes. It is the presence of two valleys in the original system that gives rise to spin-valley half-metallicity. In semiconductor physics, a "hole" is a quasiparticle that is considered to have a positive charge.

For a material with a density wave to become a half-metal, it requires a special treatment known as doping. This involves the incorporation of electrons or holes into the insulator. Alexander Rozhkov, a co-author of the paper and a researcher at MIPT's Department of Problems of Physics and Energetics, explains that a system can be doped by subjecting it to an external electric field or chemical modifications of bulk or surface: "For each system, a suitable type of doping atom—such as nitrogen, phosphorus, or some other element—needs to be selected. By replacing atoms of the host system with impurities donating or accepting conduction electrons, a change in the properties of the original material is induced."

The possibility of doping materials with density waves has been discussed in the literature for a long time. The systems dealt with by the researchers have various phases, including spatially inhomogeneous—for example, states with the so-called electronic phase separation, and the phases with domain walls, often called "stripes." Now, the researchers have made the unexpected discovery of two new phases—regular and spin-valley half-metallicity.

Artem Sboychakov, one of the authors of the paper and a senior researcher at ITAE RAS, said, "In a way, our discovery proved to be a surprise even to ourselves. The physical model that, we found, has a spin-valley half-metallic phase is a classical one—it has been studied for decades. It is now up to the experimenters. There are plenty of materials adequately described by the model we dealt with. I am therefore convinced that the phase we predicted will eventually be discovered, either in a material that is available today or in one that is yet to be synthesized." [35]

High-speed switching for ultrafast electromechanical switches and sensors

Many next-generation electronic and electro-mechanical device technologies hinge on the development of ferroelectric materials. The unusual crystal structures of these materials have regions in their lattices, called domains, that behave like molecular switches. The alignment of a domain can be toggled by an electric field, which changes the position of atoms in the crystal and switches the polarization direction. These crystals are typically grown on supporting substrates that help to define and organize the behavior of domains. Control over the switching of domains when making crystals of ferroelectric materials is essential for future applications.

Now an international team by Nagoya University has developed a new way of controlling the domain structure of ferroelectric materials, which could accelerate development of future electronic and electro-mechanical devices.

"We grew lead zirconate titanate films on different substrate types to induce different kinds of physical strain, and then selectively etched parts of the films to create nanorods," says lead author Tomoaki Yamada. "The domain structure of the nanorods was almost completely flipped compared with [that of] the thin film."

Lead zirconate titanate is a common type of ferroelectric material, which switches based on the movement of trapped lead atoms between two stable positions in the crystal lattice. Parts of the film were deliberately removed to leave freestanding rods on the substrates. The team then used synchrotron X-ray radiation to probe the domain structure of individual rods.

The contact area of the rods with the substrate was greatly reduced and the domain properties were influenced more by the surrounding environment, which mixed up the domain structure. The team found that coating the rods with a metal could screen the effects of the air and they tended to recover the original domain structure, as determined by the substrate.

"There are few effective ways of manipulating the domain structure of ferroelectric materials, and this becomes more difficult when the material is nanostructured and the contact area with the substrate is small." says collaborator Nava Setter. "We have learned that it's possible to nanostructure these materials with control over their domains, which is an essential step towards the new functional nanoscale devices promised by these materials."

The article, "Charge screening strategy for domain pattern control in nanoscale ferroelectric systems," was published in Scientific Reports. [34]

Research team flips the switch on ferroelectrics

Many next-generation electronic and electro-mechanical device technologies hinge on the development of ferroelectric materials. The unusual crystal structures of these materials have regions in their lattices, called domains, that behave like molecular switches. The alignment of a domain can be toggled by an electric field, which changes the position of atoms in the crystal and switches the polarization direction. These crystals are typically grown on supporting substrates that help to define and organize the behavior of domains. Control over the switching of domains when making crystals of ferroelectric materials is essential for future applications.

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New X-ray laser technique reveals magnetic skyrmion fluctuations

A new way of operating the powerful X-ray laser at the Department of Energy's SLAC National Accelerator Laboratory has enabled researchers to detect and measure fluctuations in magnetic structures being considered for new data storage and computing technologies.

In a paper published earlier this month in Physical Review Letters, a team led by Joshua Turner, SLAC staff scientist, and Sujoy Roy, staff scientist at Lawrence Berkeley National Laboratory (Berkeley Lab), reported measuring the fluctuations in these structures, called magnetic skyrmions, with billionth-of-a-second resolution, 1,000 times better than had been possible before.

Catching Fluctuating Spin Textures

Skyrmions are multi-atom vortex spin textures in which the atoms' spin orientations change from one direction in the middle to the opposite direction at the circumference. They move easily in response to electric fields, which makes them attractive for use in data storage technologies, shift-register memories as well as advanced computing technologies.

The charge and spin aspects of atoms are not rigid. They respond to a host of forces with vibrations and other movements – collectively called fluctuations – some of which even affect the motion of the atoms themselves. Theorists have proposed recently that fluctuations may have key roles in determining how complex materials behave, such as in the phenomenon of high-temperature superconductivity.

Until now, however, there was no way to analyze skyrmion fluctuations in the thin-film structures needed for technological applications. This new result was made possible by a recently developed "two-bucket" mode for creating pairs of X-ray pulses at SLAC's Linac Coherent Light Source (LCLS) free-electron laser that allows researchers to study equilibrium phenomena that takes place in time periods less than a billionth of a second long for the first time.

While individual LCLS pulses are usually separated by about 8 thousandths of a second, the two-bucket technique creates pulse pairs that can be as close as a third of a billionth of a second apart. When he learned of the two-bucket mode two years ago, Turner knew immediately that it should be useful for measuring fluctuations in magnetic systems, such as skyrmions.

"Before this study, scientists have used LCLS to study non-equilibrium physics at even faster timescales," Turner explained. "The new technique opens the door to a whole category of experiments that can be now be done in equilibrium at a X-ray free electron lasers."

By coincidence, Roy, a longtime friend of Turner's, had been using soft X-rays at Berkeley Lab's Advanced Light Source (ALS) to examine skyrmions and their fluctuations, most recently in an iron-gadolinium layered material grown by UC-San Diego professor Eric Fullerton. The two quickly agreed to use LCLS to see if they, in collaboration with Fullerton, could see rapid skyrmion fluctuations using the same sample.

Using X-rays to Tease Out Magnetic Changes

The detection process used to view the fluctuations is called X-ray Photon Correlation Spectroscopy. Shining an ultrashort pulse of coherent X-rays on the sample produces a speckle interference pattern that represents the sample's magnetic features. Following up quickly with a second pulse adds a second speckle pattern on top of the first on the same detector. Any fluctuations will cause the second pattern to be different, so the level of fuzziness in the combined image indicates the magnitude of the fluctuations in the sample.

"This technique is similar to measuring the twinkling of stars to elucidate details of turbulence in the earth's atmosphere," Turner said. "In this case, the goal of measuring the 'twinkling' of the detected X-rays is understanding how the material's magnetic structure is fluctuating and how it impacts the material's properties."

One of several challenges to making these measurements was reducing the intensity of LCLS's X-ray pulses so they would not create their own fluctuations in the sample. Various techniques ultimately reduced the flux of X-rays hitting the sample to a millionth of the original pulse energy.

"We want to just tickle the sample," Turner said. "It's a far cry from the typical LCLS 'pump-probe' experiment, where the intense X-ray pulses can, by design, modify, or even blast the samples away."

Developing ways to measure the X-ray intensities of each pair's pulses and their time intervals and to detect so few photons in the speckle patterns were also very difficult, added Matt Seaberg, SLAC associate staff scientist and first author of the paper. The researchers adjusted the time between each pair's pulses from a fraction of a nanosecond to 25 nanoseconds (a nanosecond is a billionth of a second) and also tuned an external magnetic field to span a range of magnetic conditions in the sample.

"This is a completely new way of doing this kind of measurement," Roy said. "The time resolution is limited by the time separating the two pulses that the accelerator produces."

When they tuned the external magnetic field to be most ideal for skyrmions in the sample, they saw that fluctuations occurred with a period of about 4 nanoseconds. But when the magnetic field was reduced slightly to where the circular skyrmion structures begin to give way to another phase with striped magnetic domain structures, the fluctuation period plummeted to only a fraction of a nanosecond.

"This result indicates that the fluctuations are larger and more rapid near the boundary of the skyrmion and stripe phases," Joshua Turner said. "This information is important in deciphering the role that magnetic fluctuations play as the material transforms from one phase to the other. It also will allow us to connect to theoretical models used to understand how fluctuations promote phase transitions in a multitude of magnetic and magnetic-type solids."

The collegial culture at SLAC played a big role in the success of this research, Turner added. The scientists worked closely with accelerator physicists Jim Turner and Franz-Josef Decker, who devised the two-bucket technique.

"This all came about because of the close working relationship between the LCLS physicists on the X-ray side together with those on the accelerator physics side," he said. "Sometimes it's not clear how we can use their amazing developments. But working together made this a very fruitful endeavor."

The same team is continuing to use the same techniques to examine Fullerton's material in more detail, and future work planned for this winter will explore other magnetically complex materials, such as spin ices and high-temperature superconductors. [32]

Neutron scattering clarifies the arrangement of skyrmions in material

Measurements at the Australian Centre for Neutron Scattering have helped clarify the arrangement of magnetic vortices, known as skyrmions, in manganese silicide (MnSi).

A skyrmion is the smallest possible change in a uniform magnet: a point-like region of reversed magnetisation, surrounded by a whirling twist of spins.

The magnetic configuration is attracting attention as a potential data carrier in next-generation memory devices.

A group of researchers at the RIKEN Center for Emergent Matter Science in Japan have discovered that a magnetic field can be used to switch a group of skyrmions back and forth between two different lattice arrangements, demonstrating the kind of control needed for advanced memory devices.

The study has been published in Science Advances.

The atoms in certain materials carry their own intrinsic magnetism, with each atom acting like a bar magnet. When these miniature magnets are swept into tiny swirling patterns, they collectively form skyrmions which behave as discrete particles.

It only forms in magnets in which the interaction of spins prefer a magnetic structure with chiral symmetry, such as twist that is either left or right-handed.

Being circular, skyrmions typically pack together in a triangular lattice.

Taro Nakajima and Hiroshi Oike of RIKEN and colleagues studied how this skyrmion lattice can be manipulated in manganese silicide.

Generally, skyrmion lattices appear in this material only within a narrow range of temperatures and magnetic fields. "That makes the lattices too fragile to rearrange," said Nakajima.

The team investigated a more robust skyrmion lattice by applying electrical pulses to the material at 12.5 kelvin (K) and a magnetic field of 0.2 tesla (T).

The pulses rapidly heated the material, causing skyrmions to form in a window of stability between 27 and 29 K.

The sample quickly cooled, locking the skyrmions into a triangular lattice that were stable over a much wider range of temperatures and magnetic fields.

The researchers then cooled the sample to 1.5 K and used small angle neutron scattering (SANS) on the QUOKKA instrument to understand how the skyrmion lattice changed under different magnetic fields.

At magnetic fields below 0.1 T, the lattice re-arranged into a square pattern which was stable only within a relatively confined range of very low temperatures and magnetic fields. Raising the field to 0.2 T resurrected the triangular lattice.

"On QUOKKA it was possible to measure changes to the skyrmion lattice in situ when an electric current was applied under different magnetic fields," said instrument scientist Dr Elliot Gilbert, and co-author on the publication.

Although SANS does not see the particle-like properties of skyrmions directly, the patterns can be interpreted to provide information on the packing of the particles.

The researchers suggest that these lattice transitions are influenced by unevenness, or anisotropy, in the underlying magnetism of the manganese atoms in the material.

At low magnetic fields and temperatures, this anisotropy allows the skyrmions to partially overlap, moving closer together to adopt a square lattice arrangement.

This effect could well occur in other materials, according to the research team.

"Our experiments revealed that the skyrmions do indeed have a particle nature in bulk crystals," says Nakajima.

"These are expected to be applicable for future magnetic memory devices in which each skyrmion particle behaves as an information carrier." [31]

Observation of skyrmion breathing motion with X-ray technique

Skyrmions are swirling spin structures with spiral shapes described in 2009. They have attracted attention in academia as representing a possible basic unit of ultra-high-density next-generation memory devices due to their unique topological stability, small size, and efficient movement. Recently, Korean researchers have developed a technology that can be applied to communication devices using skyrmions.

Researchers have predicted that it is possible to implement a unique kinetic dynamic of skyrmions called "skyrmion breathing" in next-generation high-frequency oscillator devices and memory devices. However, due to the ultra-small size and ultra-fast motion of skyrmions, direct observations of skyrmion breathing have been considered difficult to achieve.

The results of this research are the first to describe skyrmion breathing based on experimental observations. The DGIST-KIST collaborative research team successfully observed and measured the controlled motion and breathing of a skyrmion in response to external signals that occur within a few nanoseconds using a synchrotron X-ray technique with excellent time and space resolving powers.

In addition, this research has also developed an efficient skyrmion generation method using external current pulses. The results of this study are important, because they suggest that skyrmions can play a significant role in many other future electronic devices, beyond memory devices, which had been of primary focus till now.

Director Jung-Il Hong from the DGIST-LBNL Research Center for Emerging Materials said, "The new approach utilizing skyrmions presented in the results of this study suggest a new method of operation for an entire device, so its implications are great in light of the existing research trends."

Senior researcher Seong-hoon Woo from the KIST Center for Spintronics said, "The research results show that high-efficiency, next-generation communication devices based on skyrmions are actually feasible. This research will contribute to accelerating the development of next-generation communication devices for efficient communication among future high-performance electronic devices." [30]

Researchers image quasiparticles that could lead to faster circuits, higher bandwidths

Zhe Fei pointed to the bright and dark vertical lines running across his computer screen. This nano-image, he explained, shows the waves associated with a half-light, half-matter quasiparticle moving inside a semiconductor.

"These are waves just like water waves," said Fei, an Iowa State University assistant professor of physics and astronomy and an associate of the U.S. Department of Energy's Ames Laboratory. "It's like dropping a rock on the surface of water and seeing waves. But these waves are exciton-polaritons."

Exciton-polaritons are a combination of light and matter. Like all quasiparticles, they're created within a solid and have physical properties such as energy and momentum. In this study, they were launched by shining a laser on the sharp tip of a nano-imaging system aimed at a thin flake of molybdenum diselenide ($MoSe_2$), a layered semiconductor that supports excitons.

Excitons can form when light is absorbed by a semiconductor. When excitons couple strongly with photons, they create exciton-polaritons.

It's the first time researchers have made real-space images of exciton-polaritons. Fei said past research projects have used spectroscopic studies to record exciton-polaritons as resonance peaks or dips in optical spectra. Until recent years, most studies have only observed the quasiparticles at extremely cold temperatures - down to about -450 degrees Fahrenheit.

But Fei and his research group worked at room temperature with the scanning near-field optical microscope in his campus lab to take nano-optical images of the quasiparticles.

"We are the first to show a picture of these quasiparticles and how they propagate, interfere and emit," Fei said.

The researchers, for example, measured a propagation length of more than 12 microns - 12 millionths of a meter - for the exciton-polaritons at room temperature.

Fei said the creation of exciton-polaritons at room temperature and their propagation characteristics are significant for developing future applications for the quasiparticles. One day they could even be used to build nanophotonic circuits to replace electronic circuits for nanoscale energy or information transfer.

Fei said nanophotonic circuits with their large bandwidth could be up to 1 million times faster than current electrical circuits.

A research team led by Fei recently reported its findings in the scientific journal Nature Photonics. The paper's first author is Fengrui Hu, an Iowa State postdoctoral research associate in physics and astronomy. Additional co-authors are Yilong Luan, an Iowa State doctoral student in physics and astronomy; Marie Scott, a recently graduated undergraduate at the University of Washington; Jiaqiang Yan and David Mandrus of Oak Ridge National Laboratory and the University of Tennessee; and Xiaodong Xu of the University of Washington.

The researchers' work was supported by funds from Iowa State and the Ames Laboratory to launch Fei's research program. The W.M. Keck Foundation of Los Angeles also partially supported the nano-optical imaging for the project.

The researchers also learned that by changing the thickness of the MoSe2 semiconductor, they could manipulate the properties of the exciton-polaritons.

Fei, who has been studying quasiparticles in graphene and other 2-D materials since his graduate school days at University of California San Diego, said his earlier work opened the doors for studies of exciton-polaritons.

"We need to explore further the physics of exciton-polaritons and how these quasiparticles can be manipulated," he said.

That could lead to new devices such as polariton transistors, Fei said. And that could one day lead to breakthroughs in photonic and quantum technologies. [29]

Researchers shape the future of nano-electronics

The future of nano-electronics is here. A team of researchers from the Air Force Research Laboratory, Colorado School of Mines, and the Argonne National Laboratory in Illinois have developed a novel method for the synthesis of a composite material that has the potential of vastly improving the electronics used by the Air Force.

The material, hexagonal boron nitride (hBN), is similar to graphene and can be formed and stabilized to a layered thickness of one atom. This synthesis of hBN in a controlled layer-by-layer fashion is critical to a number of applications, including tunneling barriers, used in transistors for low power devices, atomically thin capacitors, and two-dimensional (2D) transistors, which are smaller and use much less power than traditional silicon transistors.

"Fabricating devices from atomically thin 2D layers represents the future of nano-electronics," states Dr. Michael Snure, AFRL senior research physicist. "This development significantly increases device density, improving flexibility and significantly reducing power requirements."

As a 2D material, hBN has been of international interest for close to a decade. Researchers with AFRL's Sensors Directorate have been working on experimental methods for developing this technology since 2013, with Dr. Snure leading the effort. Dr. Stefan Badescu, AFRL research physicist, joined the team in 2015 to lead the computational modeling research that has assisted the team with understanding the system's properties and the mechanism for growth.

So how is a composite material intended for use in electronics scaled down to the thickness of a mere atom? Through a novel and complex method of synthesis, of course. Using a process that involves metal-organic chemical vapor disposition, the team discovered how to control the growth of hBN layers on a nanoscale.

The hBN from AFRL's work is currently being used in the development of prototype 2D electronics devices including transistors and photodetectors. However, the impact of this development reaches further.

"By developing a model of growth, our work more broadly benefits the field of materials science in the areas of thin film growth and chemical vapor disposition," reflects Badescu. "This modeling will help drive new discoveries in the synthesis of 2D materials."

Badescu adds that future applications of hBN include transistors for switching and logic devices that are flexible, transparent, low power, and high frequency. The next steps are to demonstrate the feasibility of integrating hBN with other 2D semiconductors, including graphene and phosphorene.

The team's work was published in a paper by Nano Letters, a scientific journal of the American Chemical Society, and the team is considering filing a patent for the technology and synthesis method pending successful future experiments with hBN and metal combinations. [28]

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

Physicists predict supercurrent driven by potential information transfer

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

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

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

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

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

The physicists hope that this intriguing relation between superconductivity and potential information transfer can lead to some novel capabilities. For example, as they write in their paper, supercurrent might be used to "probe the potential for information transfer without actually transferring the information." The physicists expect that it should be possible to experimentally observe the effect in graphene-based chiral channels, and they hope to further investigate this possibility in the future. [27]

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

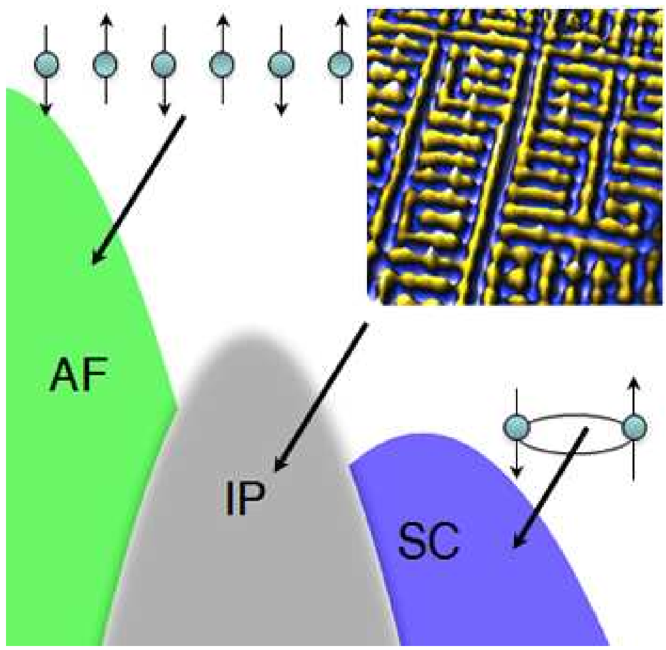
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

Strongly correlated materials

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

New superconductor theory may revolutionize electrical engineering

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



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

Unconventional superconductivity in $Ba^{0.6}K^{0.4}Fe^{2}As^{2}$ from inelastic neutron scattering

In BCS superconductors, the energy gap between the superconducting and normal electronic states is constant, but in unconventional superconductors the gap varies with the direction the electrons are moving. In some directions, the gap may be zero. The puzzle is that the gap does not seem to vary with direction in the iron arsenides. Theorists have argued that, while the size of the gap shows no directional dependence in these new compounds, the sign of the gap is opposite for different electronic states. The standard techniques to measure the gap, such as photoemission, are not sensitive to this change in sign.

But inelastic neutron scattering is sensitive. Osborn, along with Argonne physicist Stephan Rosenkranz, led an international collaboration to perform neutron experiments using samples of the new compounds made in Argonne's Materials Science Division, and discovered a magnetic excitation in the superconducting state that can only exist if the energy gap changes sign from one electron orbital to another.

"Our results suggest that the mechanism that makes electrons pair together could be provided by antiferromagnetic fluctuations rather than lattice vibrations," Rosenkranz said. "It certainly gives direct evidence that the superconductivity is unconventional."

Inelastic neutron scattering continues to be an important tool in identifying unconventional superconductivity, not only in the iron arsenides, but also in new families of superconductors that may be discovered in the future. [23]

A grand unified theory of exotic superconductivity?

The role of magnetism

In all known types of high-Tc superconductors—copper-based (cuprate), iron-based, and so-called heavy fermion compounds—superconductivity emerges from the "extinction" of antiferromagnetism, the ordered arrangement of electrons on adjacent atoms having anti-aligned spin directions. Electrons arrayed like tiny magnets in this alternating spin pattern are at their lowest energy state, but this antiferromagnetic order is not beneficial to superconductivity.

However if the interactions between electrons that cause antiferromagnetic order can be maintained while the actual order itself is prevented, then superconductivity can appear. "In this situation, whenever one electron approaches another electron, it tries to anti-align its magnetic state," Davis said. Even if the electrons never achieve antiferromagnetic order, these antiferromagnetic interactions exert the dominant influence on the behavior of the material. "This antiferromagnetic influence is universal across all these types of materials," Davis said.

Many scientists have proposed that these antiferromagnetic interactions play a role in the ability of electrons to eventually pair up with anti-aligned spins—a condition necessary for them to carry current with no resistance. The complicating factor has been the existence of many different types of "intertwined" electronic phases that also emerge in the different types of high-Tc superconductors—sometimes appearing to compete with superconductivity and sometimes coexisting with it. [24]

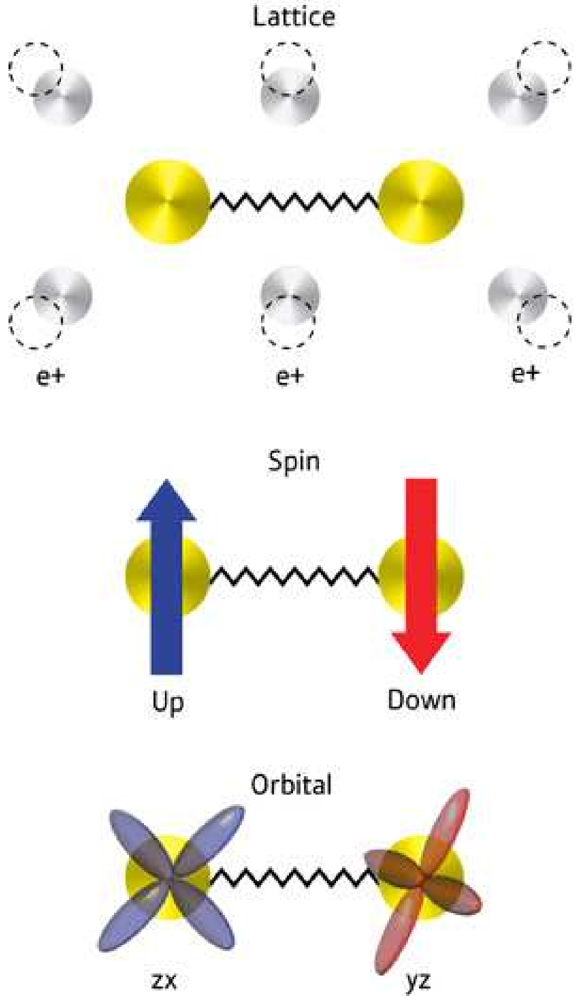
Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

Unconventional superconductivity (SC) is said to occur when Cooper pair formation is dominated by repulsive electron–electron interactions, so that the symmetry of the pair wave function is other than an isotropic s-wave. The strong, on-site, repulsive electron–electron interactions that are the proximate cause of such SC are more typically drivers of commensurate magnetism. Indeed, it is the suppression of commensurate antiferromagnetism (AF) that usually allows this type of unconventional superconductivity to emerge. Importantly, however, intervening between these AF and SC phases, intertwined electronic ordered phases (IP) of an unexpected nature are frequently discovered. For this reason, it has been extremely difficult to distinguish the microscopic essence of the correlated superconductivity from the often spectacular phenomenology of the IPs. Here we introduce a model conceptual framework within which to understand the relationship between AF electron–electron interactions, IPs, and correlated SC. We demonstrate its effectiveness in simultaneously explaining the consequences of AF interactions for the copper-based, iron-based, and heavy-fermion superconductors, as well as for their quite distinct IPs.

Significance

This study describes a unified theory explaining the rich ordering phenomena, each associated with a different symmetry breaking, that often accompany high-temperature superconductivity. The essence of this theory is an ”antiferromagnetic interaction,” the interaction that favors the development of magnetic order where the magnetic moments reverse direction from one crystal unit cell to the next. We apply this theory to explain the superconductivity, as well as all observed accompanying ordering phenomena in the copper-oxide superconductors, the iron-based superconductors, and the heavy fermion superconductors. [25]

Superconductivity's third side unmasked



Shimojima and colleagues were surprised to discover that interactions between electron spins do not cause the electrons to form Cooper pairs in the pnictides. Instead, the coupling is mediated by the electron clouds surrounding the atomic cores. Some of these so-called orbitals have the same energy, which causes interactions and electron fluctuations that are sufficiently strong to mediate superconductivity.

This could spur the discovery of new superconductors based on this mechanism. “Our work establishes the electron orbitals as a third kind of pairing glue for electron pairs in superconductors, next to lattice vibrations and electron spins,” explains Shimojima. “We believe that this finding is a step towards the dream of achieving room-temperature superconductivity,” he concludes. [17]

Strongly correlated materials

Strongly correlated materials give us the idea of diffraction patterns explaining the electron-proton mass rate. [13]

This explains the theories relating the superconductivity with the strong interaction. [14]

Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing. We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too.

The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. [18] One of these new matter formulas is the superconducting matter.

Higgs Field and Superconductivity

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The specific spontaneous symmetry breaking of the underlying local symmetry, which is similar to that one appearing in the theory of superconductivity, triggers conversion of the longitudinal field component to the Higgs boson, which interacts with itself and (at least of part of) the other fields in the theory, so as to produce mass terms for the above-mentioned three gauge bosons, and also to the above-mentioned fermions (see below). [16]

The Higgs mechanism occurs whenever a charged field has a vacuum expectation value. In the nonrelativistic context, this is the Landau model of a charged Bose–Einstein condensate, also known as a superconductor. In the relativistic condensate, the condensate is a scalar field, and is relativistically invariant.

The Higgs mechanism is a type of superconductivity which occurs in the vacuum. It occurs when all of space is filled with a sea of particles which are charged, or, in field language, when a charged field has a nonzero vacuum expectation value. Interaction with the quantum fluid filling the space prevents certain forces from propagating over long distances (as it does in a superconducting medium; e.g., in the Ginzburg–Landau theory).

A superconductor expels all magnetic fields from its interior, a phenomenon known as the Meissner effect. This was mysterious for a long time, because it implies that electromagnetic forces somehow become short-range inside the superconductor. Contrast this with the behavior of an ordinary metal. In a metal, the conductivity shields electric fields by rearranging charges on the surface until the total field cancels in the interior. But magnetic fields can penetrate to any distance, and if a magnetic monopole (an isolated magnetic pole) is surrounded by a metal the field can escape without collimating into a string. In a superconductor, however, electric charges move with no dissipation, and this allows for permanent surface currents, not just surface charges. When magnetic fields are introduced at the boundary of a superconductor, they produce surface currents which exactly neutralize them. The Meissner effect is due to currents in a thin surface layer, whose thickness, the London penetration depth, can be calculated from a simple model (the Ginzburg–Landau theory).

This simple model treats superconductivity as a charged Bose–Einstein condensate. Suppose that a superconductor contains bosons with charge *q*. The wavefunction of the bosons can be described by introducing a quantum field, ψ, which obeys the Schrödinger equation as a field equation (in units where the reduced Planck constant, ℏ, is set to 1):

$$i\frac{\partial}{\partial t}\psi = \frac{(\nabla - iqA)^2}{2m}\psi.$$

The operator ψ(*x*) annihilates a boson at the point *x*, while its adjoint $\psi^\dagger$ creates a new boson at the same point. The wavefunction of the Bose–Einstein condensate is then the expectation value ψ of ψ(*x*), which is a classical function that obeys the same equation. The interpretation of the expectation value is that it is the phase that one should give to a newly created boson so that it will coherently superpose with all the other bosons already in the condensate.

When there is a charged condensate, the electromagnetic interactions are screened. To see this, consider the effect of a gauge transformation on the field. A gauge transformation rotates the phase of the condensate by an amount which changes from point to point, and shifts the vector potential by a gradient:

$$\psi \rightarrow e^{iq\phi(x)}\psi$$
$$A \rightarrow A + \nabla\phi.$$

When there is no condensate, this transformation only changes the definition of the phase of ψ at every point. But when there is a condensate, the phase of the condensate defines a preferred choice of phase.

The condensate wave function can be written as

$$\psi(x) = \rho(x)\, e^{i\theta(x)},$$

where ρ is real amplitude, which determines the local density of the condensate. If the condensate were neutral, the flow would be along the gradients of θ, the direction in which the phase of the Schrödinger field changes. If the phase θ changes slowly, the flow is slow and has very little energy. But now θ can be made equal to zero just by making a gauge transformation to rotate the phase of the field.

The energy of slow changes of phase can be calculated from the Schrödinger kinetic energy,

$$H = \frac{1}{2m}|(qA + \nabla)\psi|^2,$$

and taking the density of the condensate ρ to be constant,

$$H \approx \frac{\rho^2}{2m}(qA + \nabla\theta)^2.$$

Fixing the choice of gauge so that the condensate has the same phase everywhere, the electromagnetic field energy has an extra term,

$$\frac{q^2\rho^2}{2m}A^2.$$

When this term is present, electromagnetic interactions become short-ranged. Every field mode, no matter how long the wavelength, oscillates with a nonzero frequency. The lowest frequency can be read off from the energy of a long wavelength A mode,

$$E \approx \frac{\dot{A}^2}{2} + \frac{q^2\rho^2}{2m}A^2.$$

This is a harmonic oscillator with frequency

$$\sqrt{\frac{1}{m}q^2\rho^2}.$$

The quantity $|\psi|^2$ ($=\rho^2$) is the density of the condensate of superconducting particles.

In an actual superconductor, the charged particles are electrons, which are fermions not bosons. So in order to have superconductivity, the electrons need to somehow bind into Cooper pairs. [12]

The charge of the condensate *q* is therefore twice the electron charge *e*. The pairing in a normal superconductor is due to lattice vibrations, and is in fact very weak; this means that the pairs are very loosely bound. The description of a Bose–Einstein condensate of loosely bound pairs is actually more difficult than the description of a condensate of elementary particles, and was only worked out in 1957 by Bardeen, Cooper and Schrieffer in the famous BCS theory. [3]

Superconductivity and Quantum Entanglement

We have seen that the superconductivity is basically a quantum mechanical phenomenon and some entangled particles give this opportunity to specific matters, like Cooper Pairs or other entanglements, as strongly correlated materials and Exciton-mediated electron pairing. [26]

Conclusions

Probably in the superconductivity there is no electric current at all, but a permanent magnetic field as the result of the electron's spin in the same direction in the case of the circular wire on a low temperature. [6]

We think that there is an electric current since we measure a magnetic field. Because of this saying that the superconductivity is a quantum mechanical phenomenon.

Since the acceleration of the electrons is centripetal in a circular wire, in the atom or in the spin, there is a steady current and no electromagnetic induction. This way there is no changing in the Higgs field, since it needs a changing acceleration. [18]

The superconductivity is temperature dependent; it means that the General Weak Interaction is very relevant to create this quantum state of the matter. [19]

We have seen that the superconductivity is basically a quantum mechanical phenomenon and some entangled particles give this opportunity to specific matters, like Cooper Pairs or other entanglements. [26]

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