Information from Quantum Materials

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Rice University physicist Qimiao Si began mapping quantum criticality more than a decade ago, and he's finally found a traveler that can traverse the final frontier. [32]

Physicists studying the strange behavior of metal alloys called heavy fermions have made a surprising discovery that could be useful in safeguarding the information stored in quantum bits, or qubits, the basic units of encoded information in quantum computers. [31]

Properties of complex materials are often determined by the interplay of several electron properties. TU Wien (Vienna) has now succeeded in disentangling this mess. [30]

Physicists have found "electron pairing," a hallmark feature of superconductivity, at temperatures and energies well above the critical threshold where superconductivity happens. [29]

It was a three-hour nighttime road trip that capped off a journey begun seven years ago. [28]

Discovered more than 100 years ago, superconductivity continues to captivate scientists who seek to develop components for highly efficient energy transmission, ultrafast electronics or quantum bits for next-generation computation. [27]

One of the greatest mysteries in condensed matter physics is the exact relationship between charge order and superconductivity in cuprate superconductors. [26]

Cuprates hold the record high superconducting temperature at ambient pressure so far, but understanding their superconducting mechanism remains one of the great challenges of physical sciences listed as one of 125 quests announced by Science. [25]

Now, scientists at Tokyo Institute of Technology (Tokyo Tech), the University of Tokyo and Tohoku University report curious multi-state transitions of these superconductors in which they change from superconductor to special metal and then to insulator. [24]

Researchers at the Zavoisky Physical-Technical Institute and the Southern Scientific Center of RAS, in Russia, have recently fabricated quasi-2-D superconductors at the *interface between a ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ film and an insulating parent compound of La_2CuO_4. [23]*

Scientists seeking to understand the mechanism underlying superconductivity in "stripe-ordered" cuprates—copper-oxide materials with alternating areas of electric charge and magnetism—discovered an unusual metallic state when attempting to turn superconductivity off. [22]

This discovery makes it clear that in order to understand the mechanism behind the enigmatic high temperature superconductivity of the cuprates, this exotic PDW state needs to be taken into account, and therefore opens a new frontier in cuprate research. [21]

High-temperature (Tc) superconductivity typically develops from antiferromagnetic insulators, and superconductivity and ferromagnetism are always mutually exclusive. [20]

Scientists at the U.S. Department of Energy's Ames Laboratory have developed a method to accurately measure the "exact edge" or onset at which a magnetic field enters a superconducting material. [19]

TU Wien has now made a major advance towards achieving this goal and, at the same time, has furthered an understanding of why conventional materials only become superconducting at around -200°C [18]

The emerging field of spintronics leverages electron spin and magnetization. [17]

The first known superconductor in which spin-3/2 quasiparticles form Cooper pairs has been created by physicists in the US and New Zealand. [16]

Now a team of researchers from the University of Maryland (UMD) Department of Physics together with collaborators has seen exotic superconductivity that relies on highly unusual electron interactions. [15]

A group of researchers from institutions in Korea and the United States has determined how to employ a type of electron microscopy to cause regions within an iron-based superconductor to flip between superconducting and non-superconducting states. [14]

In new research, scientists at the University of Minnesota used a first-of-its-kind device to demonstrate a way to control the direction of the photocurrent without deploying an electric voltage. [13]

Brown University researchers have demonstrated for the first time a method of substantially changing the spatial coherence of light. [12]

Researchers at the University of Central Florida have generated what is being deemed the fastest light pulse ever developed. [11]

Physicists at Chalmers University of Technology and Free University of Brussels have now found a method to significantly enhance optical force. [10]

Nature Communications today published research by a team comprising Scottish and South African researchers, demonstrating entanglement swapping and teleportation of orbital angular momentum 'patterns' of light. [9]

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer using Quantum Information.

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods.

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 Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass rate and the Weak and Strong Interactions by the diffraction patterns. The Weak Interaction changes the diffraction patterns by moving the electric charge from one side to the other side of the diffraction pattern, which violates the CP and Time reversal symmetry.

The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the Relativistic Quantum Theory and making possible to build the Quantum Computer with the help of Quantum Information.

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Author: George Rajna

Preface

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer.

Australian engineers detect in real-time the quantum spin properties of a pair of atoms inside a silicon chip, and disclose new method to perform quantum logic operations between two atoms. [5]

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

I think that we have a simple bridge between the classical and quantum mechanics by understanding the Heisenberg Uncertainty Relations. It makes clear that the particles are not point like but have a dx and dp uncertainty.

An ultra-fast optical way to extract critical information from quantum materials

Topological insulators are quantum materials, which, due to their exotic electronic structure, on surfaces and edges conduct electric current like metal, while acting as an insulator in bulk. Scientists from the Max-Born Institute for Nonlinear Optics and Short Pulse Spectroscopy (MBI) have demonstrated for the first time how to tell apart topological materials from their regular—trivial—counterparts within a millionth of a billionth of a second by probing it with ultra-fast laser light. Their method could open the way for such materials to be used as logic elements in light-controlled electronics able to process information tens of thousands times faster as currently possible. Their study appeared in *Nature Photonics*.

The most common illustration of the topology concept involves an elastic pretzel, which can be stretched, bent, or twisted in any way; no matter the deformation, it is impossible to make a bagel out of a pretzel or add holes to it, without tearing it apart. The number of holes in a pretzel is thus invariant and provides topological information about the pretzel shape.

In a solid material, quantum-mechanical laws restrict which energies electrons can have, leading to the formation of bands with either allowed or forbidden energies. Using the concept of topology, physicists can describe complex shapes of allowed energy bands and assign them a specific topological number. A special topology of the band structure in a material system manifests itself in exotic properties that can be observed—such as the surface conductivity in topological insulators.

"The most remarkable aspect of topology is its robustness: properties induced by topology are protected by it," explains one of the two main authors of the article Dr. Álvaro Jiménez-Galán from MBI. In the same way that we cannot change the number of holes in a pretzel without breaking it, impurities and other perturbations that usually disrupt the ability of the material to conduct electricity do not affect high electron mobility on the surface of topological insulators. The immunity to impurities is the reason why topological materials strongly appeal to electronic industries.

Making electrons "speak" about topology

Although the topology of the system is deeply linked to the behavior of electrons in it, the imprint of topological properties on electron dynamics at the time scale of a millionth of a billionth of a second has not been discovered up to now. By using numerical simulations and theoretical analysis, the group from MBI has proved that information about system topology is indeed encoded in this extremely fast electron dynamics and can be retrieved by looking at light emitted by electrons as they are excited with laser light. "If we imagine the electrons in a solid moving within energy bands as runners on the racing track, then our method allows to learn about the topology of this racing track, by simply measuring the acceleration of the runners," clarifies Prof. Dr. Olga Smirnova, head of an MBI Theory group. The ultra-short laser pulses excite electrons of the system, making them hop from one energy band to a higher one, accelerating them on the new track. The accelerated electrons then emit light and quickly fall back to the lower position. This process lasts merely an infinitesimal part of a second but is enough for an electron to "feel" the fine difference between the energy structures of trivial and topological insulators and "encode" this information into the emitted light.

On the way toward ultrafast lightwave electronics

The current work demonstrates how to distinguish between trivial and topological insulators at an ultra-fast rate, in other words, to "read out" the topological information of the system using laser spectroscopy. For the next step, the MBI researchers plan to use this knowledge to convert a trivial insulator into a topological and vice versa with laser light—that is to "write" the topological information into a material at a similar rate. The theoretical proof of this effect could bring forward the implementation of topological materials in optically-controlled electronics, where only the speed of electronic response to light defines the limit for the speed of information processing. [33]

Quantum material goes where none have gone before

Rice University physicist Qimiao Si began mapping quantum criticality more than a decade ago, and he's finally found a traveler that can traverse the final frontier.

The traveler is an alloy of cerium palladium and aluminum, and its journey is described in a study published online this week in *Nature Physics* by Si, a theoretical physicist and director of the Rice Center for Quantum Materials (RCQM), and colleagues in China, Germany and Japan.

Si's map is a graph called a phase diagram, a tool that condensed-matter physicists often use to interpret what happens when a material changes phase, as when a solid block of ice melts into liquid water.

The regions on Si's map are areas where electrons follow different sets of rules, and the paper describes how the researchers used the geometric arrangement of atoms in the alloy in combination with various pressures and magnetic fields to alter the alloy's path and bring it into a region where physicists have only been able to speculate about the rules that govern electron behavior.

"That's the corner, or portion, of this road map that everybody really wants to access," Si said, pointing to the upper left side of the phase diagram, high up the vertical axis marked G. "It has taken the community a huge amount of effort to look through candidate materials that have the feature of geometrical frustration, which is one way to realize this large G."

The frustration stems from the arrangement of cerium atoms in the alloy in a series of equilateral triangles. The kagome lattice arrangement is so named because of its similarity to patterns in traditional Japanese kagome baskets, and the triangular arrangement ensures that spins, the magnetic states of electrons, cannot arrange themselves as they normally would under certain conditions. This frustration provided an experimental lever that Si and his collaborators could use to explore a new region of the phase diagram where the boundary between two well-studied and well-understood states—one marked by an orderly arrangement of electron spins and the other by disorder—diverged.

Qimiao Si is the Harry C. and Olga K. Wiess Professor in Rice University's Department of Physics and Astronomy and director of RCQM, the Rice Center for Quantum Materials. Credit: Jeff Fitlow/Rice University

"If you start with an ordered, antiferromagnetic pattern of spins in an up-down, up-down arrangement, there are several ways of softening this hard pattern of the spins," said Si, the Harry C. and Olga K. Wiess Professor in Rice's Department of Physics and Astronomy. "One way is through coupling to a background of conduction electrons, and as you change conditions to enhance this coupling, the spins get more and more scrambled. When the scrambling is strong enough, the ordered pattern is destroyed, and you end up with a non-ordered phase, a paramagnetic phase."

Physicists can plot this journey from order to disorder as a line on a phase diagram. In the example above, the line would begin in a region marked "AF" for antiferromagnetic phase, and continue across one border into a neighboring region marked "P" for paramagnetic. The border crossing is the "quantum critical point" where billions upon trillions of electrons act in unison, adjusting their stances to conform to the rules of the regime they have just entered.

Si is a leading proponent of quantum criticality, a theoretical framework that seeks to describe and predict the behavior of quantum materials in relation to these critical points and phase changes.

"What the geometrical frustration does is to extend the process where the spin order becomes more and more fragile so that it's no longer just a point that the system passes through on the way to being disordered," he said. "In fact, that point sort of splits out into a separate region, with distinct borders on either side."

Si said the team, which included co-corresponding authors and RCQM partners Frank Steglich of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany and Peijie Sun of the Chinese Academy of Sciences in Beijing, performed experiments that provided evidence that the cerium palladium aluminum alloy undergoes two border crossings.

Physicists have conducted numerous experiments to see how various materials behave in the ordered phase where the alloy began its journey and in the disordered phase where it ended, but Si said these are the first experiments to trace a path through the intervening phase that is enabled by a high degree of geometrical frustration.

He said measurements of the alloy's electronic properties as it passed through the region couldn't be explained by traditional theories that describe the behavior of metals, which means the alloy behaved as a "strange" metal in the mystery territory.

"The system acted as a kind of spin liquid, albeit a metallic one," he said.

Si said the results demonstrate that geometrical frustration can be used as a design principle to create strange metals.

"That is significant because the unusual electronic excitations in strange metals are also the underlying exotic properties of other strongly correlated quantum materials, including most high-temperature superconductors," he said. [32]

Quantum criticality could be a boon for qubit designers

Physicists studying the strange behavior of metal alloys called heavy fermions have made a surprising discovery that could be useful in safeguarding the information stored in quantum bits, or qubits, the basic units of encoded information in quantum computers.

In a study in the *Proceedings of the National Academy of Sciences*, researchers from Rice University and the Vienna University of Technology (TU Wien) in Austria examined the behavior of an intermetallic crystal of cerium, palladium and silicon as it was subjected to extreme cold and a strong magnetic field. To their surprise, they found they could transform the quantum behavior of the material in two unique ways, one in which electrons compete to occupy orbitals and another where they compete to occupy spin states.

"The effect is so pronounced with one degree of freedom that it ends up liberating the other one," said Rice's Qimiao Si, co-corresponding author of the study and the director of the Rice Center for Quantum Materials (RCQM). "You can essentially tune the system to maximize damage to one of these, leaving the other well-defined."

Si said the result could be important for companies like Google, IBM, Intel and others who are competing to develop quantum computers. Unlike today's digital computers, which use electricity or light to encode bits of information, quantum computers use the quantum states of subatomic particles like electrons to store information in qubits. A practical quantum computer could outperform its digital counterpart in many ways, but the technology is still in its infancy, and one of the chief obstacles is the fragility of the quantum states inside the qubits.

"You need a well-defined quantum state if you wish to be assured that the information that is stored in a qubit will not change due to background interference," Si said.

Every electron acts like a spinning magnet, and its spin is described in one of two values, up or down. In many qubit designs, information is encoded in these spins, but these states can be so fragile that even tiny amounts of light, heat, vibration or sound can cause them to flip from one state to another. Minimizing the information that's lost to such "decoherence" is a major concern in qubit design, Si said.

In the new study, Si worked with longtime collaborator Silke Paschen of TU Wien to study a material where the quantum states of electrons were scrambled not just in terms of their spins but also in terms of their orbitals.

"We designed a system, realized in some theoretical models and concurrently realized in a material, where spins and orbitals are almost on an equal footing and are strongly coupled together," he said.

From previous research in 2012, Si, Paschen and colleagues knew that electrons in the compound could be made to interact so strongly that the material would undergo a dramatic change at a critically cold temperature. On either side of this "quantum critical point," electrons in key orbitals would arrange themselves in a completely different way, with the shift occurring solely due to the quantum interactions between them.

The earlier study invoked a well-known theory Si and collaborators developed in 2001 that prescribes how the spins of these localized electrons, which are part of atoms inside the alloy, strongly couple with free-flowing conduction electrons at the quantum critical point. According to this "local quantum critical" theory, as the material is cooled and approaches the critical point, the spins of localized electrons and conduction electrons begin to compete to occupy particular spin states. The quantum critical point is the tipping point where this competition destroys the ordered arrangement of the localized electrons and they instead become completely entangled with the conduction electrons.

Even though Si has studied quantum criticality for almost 20 years, he was surprised by the results of Paschen's latest experiments.

"The new data was completely baffling to all of us," he said. "That is, until we realized that the system contained not only spins but also orbitals as active degrees of freedom."

With that realization, Si's team, including Rice graduate student Ang Cai, built a theoretical model that contains both the spins and orbitals. Their detailed analysis of the model revealed a surprising form of quantum criticality that provided a clear understanding of the experiments.

"It was a shock to me, both from the theoretical model perspective and the experiments," he said. "Even though this is a soup of things—spins, orbitals that are all strongly coupled to each other and to background conduction electrons—we could resolve two quantum critical points in this one system under the tuning of one parameter, which is the magnetic field. And at each one of the quantum critical points, only the spin or the orbital is driving the quantum criticality. The other one is more or less a bystander." [31]

Switching electron properties on and off individually

Properties of complex materials are often determined by the interplay of several electron properties. TU Wien (Vienna) has now succeeded in disentangling this mess.

Only at extremely low temperatures does order prevail. At the Vienna University of Technology, materials are cooled to almost absolute zero, so that electrons, which otherwise occupy different states quite randomly, show certain regularities. But even the behavior of such extremely cold electrons is difficult to understand, on the one hand because the electrons strongly influence each other and cannot be described separately, and on the other hand because different electron characteristics play a role at the same time. However, the understanding is now made easier by experiments at the TU Vienna: It was possible to influence different characteristics of the electrons separately from each other. Closely interwoven quantum phenomena can thus be understood individually. The results have now been published in the journal *PNAS*.

Chess pieces and electrons

Imagine we have a big bag of chess pieces that you place on a chess board one after the other until it is full. There are different ways to create ordered patterns: For example, you can always place a white and a black piece alternately. You can also ignore the colors and alternately place a knight and a rook, or think up more complicated order patterns that combine color and figure type.

It is similar with electrons in a solid: As in a chessboard, there are regularly arranged places where electrons can sit. And like chess pieces, electrons have different properties that can be used to create order.

"The simplest property of the electrons is their charge—it is responsible for the flow of electric current. However, the charge is the same for all electrons," says Prof. Silke Bühler-Paschen from the Institute of Solid State Physics at the TU Vienna. "Things become more interesting if we also consider the electron spin. For the spin, there are always two different possibilities. Its magnetic properties are determined by the regular arrangement of electron spins in a solid body."

Where is the electron located? The orbital degree of freedom

However, for localized electrons there is another property, another degree of freedom, which plays an important role: The orbital degree of freedom. If an electron is bound to a certain atom, different spatial arrangements are possible. Quantum physics allows for different geometric relationships between electron and atom—and this also allows for ordered structures in the solid, for example when many identical atoms are arranged in a crystal, and each has an electron that is in the same orbital state.

"We investigated a material made of palladium, silicon and cerium," says Silke Bühler-Paschen. "We focus on the electrons located at the cerium atom and on the conduction electrons, which can move freely through the crystal." With the help of conduction electrons, it is possible to influence the order of the electrons at the cerium atom—both their spin degree of freedom and their orbital degree of freedom. "This is done by shielding," explains Bühler-Paschen. "The conduction electrons can virtually hide both the spin and the orbital state of the fixed electrons, which is called the Kondo effect. This means that order is no longer possible." As has now been shown, the order of these two degrees of freedom can be switched on and off separately at very low temperatures—with the help of tiny magnetic field changes.

"The fact that order in quantum systems collapses or reappears in certain situations is not new," says Silke Bühler-Paschen. "But here we have a system in which the order can be switched on and off individually in relation to two different degrees of freedom that are closely interwoven at high temperatures—and that is quite remarkable."

This possibility could now help to uncover particularly interesting properties of complex materials. "There are reasons to assume that the orbital degree of freedom also plays an important role in the phenomenon of unconventional superconductivity," says Silke Bühler-Paschen. "We now have a new instrument at our disposal to better understand such technologically important effects." [30]

'Electron pairing' found well above superconductor's critical temperature

Physicists have found "electron pairing," a hallmark feature of superconductivity, at temperatures and energies well above the critical threshold where superconductivity happens.

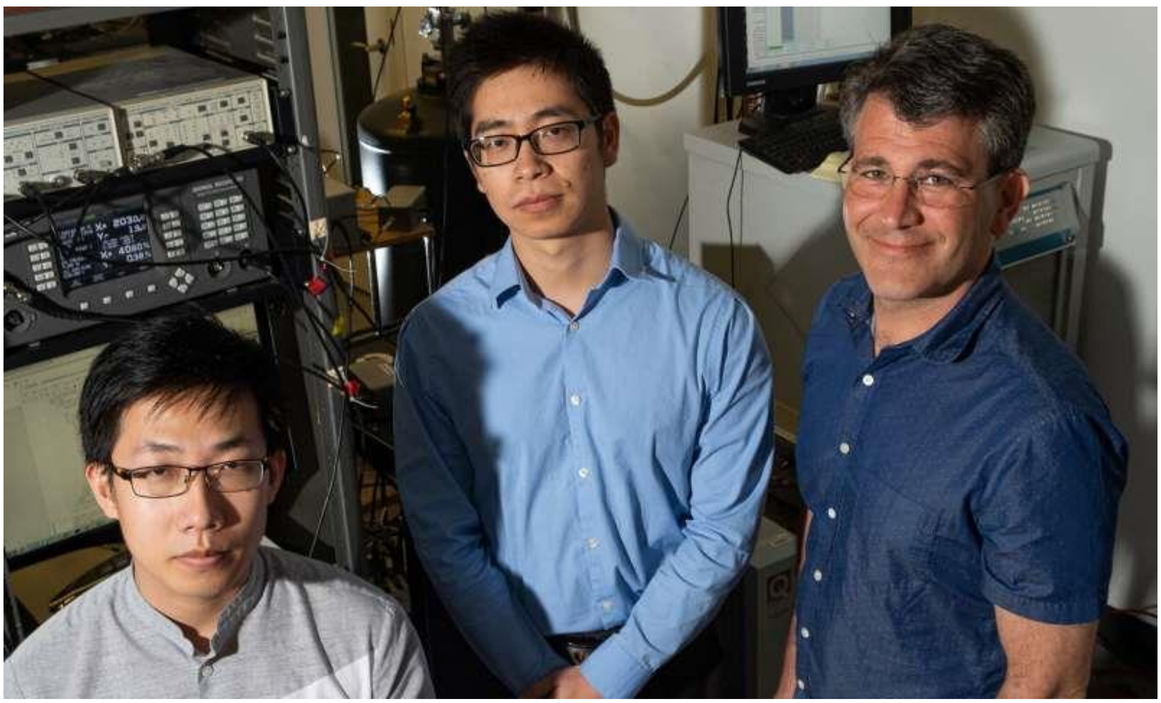
Rice University's Doug Natelson, co-corresponding author of a paper about the work in this week's *Nature*, said the discovery of Cooper pairs of electrons "a bit above the critical temperature won't be 'crazy surprising' to some people. The thing that's more weird is that it looks like there are two different energy scales. There's a higher energy scale where the pairs form, and there's a lower energy scale where they all decide to join hands and act collectively and coherently, the behavior that actually brings about superconductivity."

Electrical resistance is so common in the modern world that most of us take it for granted that computers, smartphones and electrical appliances warm up during use. That heating happens because electricity doesn't flow freely through the metal wires and silicon chips inside the devices. Instead, flowing electrons occasionally bump into atoms or one another, and each collision produces a tiny bit of heat.

Physicists have known since 1911 that electricity can flow without resistance in materials called superconductors. And in 1957, they figured out why: Under specific conditions, including typically very cold temperatures, electrons join together in pairs—something that's normally forbidden due to their mutual repulsion—and as pairs, they can flow freely.

"To get superconductivity, the general feeling is that you need pairs, and you need to achieve some sort of coherence among them," said Natelson, who partnered on the research with experts at Rice, Brookhaven National Laboratory and the University of Connecticut. "The question, for a long time, was, 'When do you get pairs?' Because in conventional superconductors as soon as you formed pairs, coherence and superconductivity would follow."

Electron pairs are named for Leon Cooper, the physicist who first described them. In addition to explaining classical superconductivity, physicists believe Cooper pairs bring about high-temperature superconductivity, an unconventional variant discovered in the 1980s. It was dubbed "high-temperature" because it occurs at temperatures that, although still very cold, are considerably higher those of classical superconductors. Physicists have long dreamed of making high-temperature superconductors that work at room temperature, a development that would radically change the way energy is made, moved and used worldwide.



Rice University physicists (from left) Liyang Chen, Panpan Zhou and Doug Natelson and colleagues at Brookhaven National Laboratory and the University of Connecticut found evidence of electron pairing -- a hallmark feature of superconductivity -- at temperatures and energies well above the critical threshold where superconductivity occurs. The research appears this week in *Nature*. Credit: Jeff Fitlow/Rice University

But while physicists have a clear understanding of how and why electron pairinghappens in classical superconductors, the same cannot be said of high-temperature superconductors like the lanthanum strontium copper oxide (LSCO) featured in the new study.

Every superconductor has a critical temperature at which electrical resistance disappears. Natelson said theories and studies of copper-oxide superconductors over that past 20 years have suggested that Cooper pairs form above this critical temperature and only become coherently mobile when the material is cooled to the critical temperature.

"If that's true, and you've already got pairs at higher temperatures, the question is, 'Can you also get coherence at those temperatures?'" Natelson said. "Can you somehow convince them to start their dance in the region known as the pseudogap, a phase space at higher temperatures and energy scales than the superconducting phase."

In the *Nature* study, Natelson and colleagues found evidence of this higher energy pairing in the conduction noise in ultrapure LCSO samples grown in the lab of Brookhaven's Ivan Božović, co-corresponding author of the study.

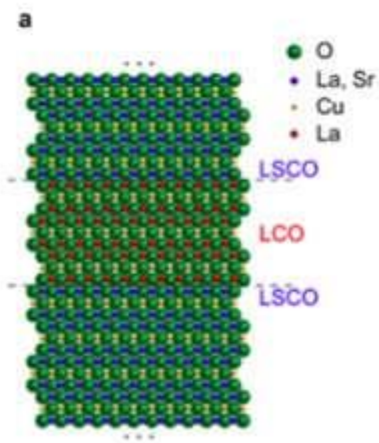
"He grows the best material in the world, and our measurements and conclusions were only possible because of the purity of those samples," Natelson said. "He and his team made devices called tunnel junctions, and instead of just looking at the electrical current, we looked at fluctuations in the current called shot noise.

"In most cases, if you measure current, you're measuring an average and ignoring the fact that current comes in chunks of charge," Natelson said. "It's something like the difference between measuring the average daily rainfall at your home as opposed to measuring the number of raindrops that are falling at any given time."

By measuring the variation in the discrete amount of electrical charge flowing through LCSO junctions, Natelson and colleagues found that the passage of single electrons could not account for the amount of charge flowing through the junctions at temperatures and voltages well above the critical temperature where superconductivity occurred.

"Some of the charge must be coming in larger chunks, which are the pairs," he said. "That's unusual, because in a conventional superconductor, once you go above the characteristic energy scale associated with superconductivity, the pairs get ripped apart, and you only see single charges.

"It looks like LCSO contains another energy scale where the pairs form but aren't yet acting collectively," Natelson said. "People have previously offered theories about this sort of thing, but this is the first direct evidence for it."



A schematic showing the three-layered structure: superconducting lanthanum strontium copper oxide (LSCO) on the top and bottom, and insulating lanthanum copper oxide (LCO) in between. Credit: Brookhaven National laboratory

Natelson said it's too early to say whether physicists can make use of the new knowledge to coax pairs to flow freely at higher temperatures in unconventional superconductors. But Božović said the discovery has "profound implications" for theoretical physicists who study high-temperature superconductors and other types of condensed matter.

"In some sense, the textbook chapters have to be rewritten," Božović said. "From this study, it appears that we have a new type of metal, in which a significant fraction of the electrical current is carried by electron pairs. On the experimental side, I expect that this finding will trigger much follow-up work—for example, using the same technique to test other cuprates or superconductors, insulators and layer thicknesses." [29]

First major superconducting component for new high-power particle accelerator arrives at Fermilab

It was a three-hour nighttime road trip that capped off a journey begun seven years ago.

From about 12:30-3 a.m. on Friday, Aug. 16, the first major superconducting section of a particle accelerator that will power the biggest neutrino experiment in the world made its way along a series of Chicagoland roadways at a deliberate 10 miles per hour.

Hauled on a special carrier created just for its 25-mile journey, at 3:07 a.m. the nine-ton structure pulled into its permanent home at the Department of Energy's Fermilab. It arrived from nearby Argonne National Laboratory, also a DOE national laboratory.

The high-tech component is the first completed cryomodule for the PIP-II particle accelerator, a powerful machine that will become the heart of Fermilab's accelerator complex. The accelerator will generate high-power beams of protons, which will in turn produce the world's most powerful neutrino beam, for the international Deep Underground Neutrino Experiment, hosted by Fermilab and provides for the long-term future of the Fermilab research program.

PIP-II is the first particle accelerator project in the United States with significant international contribution, with cavities and cryomodules built in France, India, Italy, the United Kingdom and the United States.

The cryomodule effort at Argonne began in 2012. Scientists and engineers at Argonne led its design, working with a Fermilab team. The Argonne group also built the cryomodule, tested its subcomponents and assembled it, evolving a design used in one of Argonne's particle accelerators.

And now it's arrived.

"There is a profound significance in the arrival of the first PIP-II cryomodule: it ushers in a new era for the Fermilab accelerator complex, the era of superconducting radio-frequency acceleration," said Fermilab PIP-II Project Director Lia Merminga.

The PIP-II accelerator blueprint

A cryomodule is the major unit of a particle accelerator. Like the cars of a train, cryomodules are hitched together end-to-end. The PIP-II linear accelerator will comprise 23 of them, adding up to a roughly 200-meter, near-light-speed runway for powerful protons.

This architectural rendering shows the buildings that will house the new PIP-II accelerators. Credit: Fermilab

Very powerful protons. The new accelerator will enable a 1.2-megawatt proton beam for the lab's experiments. That's 60% more power than the lab's current accelerator chain can provide.

And it's put together one cryomodule at a time. Each houses a string of superconducting acceleration cavities. These shiny metal tubes impart energy to the beam, and they too are placed end-to-end. As the proton beam shoots through one cavity after the next, it picks up energy, thanks to the electromagnetic fields inside the cavities, propelling the beam forward.

By the time the beam exits the final cavity of the last PIP-II cryomodule, it will have gained 800 million electronvolts of energy and travel at 84% of the speed of light.

Then it's really off to the races: After the beam leaves the PIP-II linac, it will continue down any of a number of paths, charging through Fermilab's accelerators and eventually smashing into a block of material. The resulting shower of particles will be sorted and routed to various experiments, where scientists study these morsels of matter to better understand how our universe operates at its most fundamental level.

The 60% boost in PIP-II power —with the potential to increase power into the multimegawatt range at a later time—will provide more particles for scientists to study, accelerating the path to discovery.

The PIP-II accelerator is expected to be integrated into the Fermilab accelerator complex in 2026.

Riding the half-wave

The Argonne-designed PIP-II cryomodule contains eight accelerating cavities that look like big balloon bow ties. They're a special type, called half-wave resonators. ("Half-wave," because the profile of the electromagnetic field inside it resembles half of a standing wave.)

The half-wave resonator cryomodule will be first in the line of 23 and the only one of its kind at PIP-II.

The job of the half-wave resonator cryomodule is to get the beam going almost as soon as it comes out of the gate, taking it from 2 to 10 million electronvolts. Each cryomodule after that takes its turn ramping up the beam to its final energy of 800 million electronvolts.

Scientists and engineers at Argonne led the design of these eight accelerator cavities, of a type called half-wave resonators, for the PIP-II accelerator. The Argonne team worked with Fermilab in the design. Credit: Argonne National Laboratory. Fermi National Accelerator Laboratory

Its design is based on those used in Argonne's ATLAS particle accelerator, which accelerates heavy ions for nuclear physics research.

The PIP-II version features a few improvements. For one, the cavity performance is top-notch, thanks to advances in acceleration technology. The cavities are made of superconducting niobium. Refinements over the past decade in both niobium treatment and cavity manufacture have made it possible for PIP-II cavities to kick the beam to higher energies over shorter distances compared to ATLAS and other comparable cavities. They're also more energy-efficient.

"We're proud of the cavities we've built and their performance," said Argonne physicist Zack Conway, who led the effort to build the cavities. "They're truly world-leading."

The cryomodule keeps the cavities at a cool 2 kelvins, or minus 270 degrees Celsius. Niobium superconducts at 9.2 K, but its performance soars at 2 K. Advanced cryogenics (the "cryo" in cryomodule) ensure that the PIP-II cavities maintain their chill temperature.

The result is a high-performance vehicle for beam.

"It's been good to collaborate with one of our sister labs," said Fermilab scientist Joe Ozelis, who oversees the cryomodule project. "This model of collaborative effort with our partners is key to the continued future success of PIP-II. It's gratifying to now know that it can indeed work."

Time to test

The recently arrived cryomodule has a way to go before it will be permanently installed as part of the PIP-II linear accelerator. For the next several months, Fermilab's PIP-II group will perform a series of tests to make sure it meets specifications. Then, next year, a Fermilab group will test it with beam, putting the cryomodule through its paces.

"The first of anything in a project like this is always exciting, but there's more to this for me personally," said Genfa Wu, Fermilab physicist and a PIP-II SRF and cryogenics system manager. "This is the first low-beta superconducting cryomodule I'll get to test in my professional experience."

It's also an initial run-through for the PIP-II cryomodule collaboration more generally. Twenty-two cryomodules are yet to be built and tested at Fermilab, of which 15 will arrive from outside the United States, including one prototype.

"PIP-II is an international collaboration," Wu said. "We're actively working with our international partners to make sure all the cryomodules work together."

Partners in global science

PIP-II's internationality reflects the biggest experiment it will power, the Deep Underground Neutrino Experiment, supported by the Long-Baseline Neutrino Facility at Fermilab. The flagship science project aims to unlock the mysteries of neutrinos, subtle particles that may carry the imprint of the universe's beginnings.

Protons from the PIP-II beam will produce a beam of neutrinos, which will be sent 800 miles straight through Earth's crust from Fermilab to particle detectors located a mile underground at the Sanford Underground Research Facility in South Dakota. DUNE scientists will study how the neutrinos change over that long distance. Their findings aim to tell us why we live in a universe dominated by matter.

More than 1,000 scientists from dozens of countries participate in LBNF/DUNE, which will start in the mid-2020s. It's a global project with the ambitious research goals to match. And four of the LBNF/DUNE international partners also contribute to PIP-II. For the United States, the international nature of the PIP-II project is a new way of building large accelerator projects.

"The half-wave resonator cryomodule is a stellar example of how DOE labs work together to execute major projects that involve technological aptitude that no single lab has by itself," Merminga said. "By leveraging Argonne's experience in half-wave resonator technology, Fermilab is taking a major step in realizing its future while paving the road for even more collaboration. Exactly the same principle applies to our international partnerships, making PIP-II a very powerful new paradigm for future accelerator projects."

And in some ways, it is all starting to come together when a truck with a huge, high-tech metal container rolls down a street in the middle of the night.

"The collaboration between has been very smooth, from design through fabrication," Conway said. "That's been wonderful."

It pays dividends in other dimensions, too.

"We've learned so much from this for future collaborations, and those lessons are going to be vital for the linac project as a whole," Ozelis said. "This is more than institutional. It's a human endeavor as well." [28]

For superconductors, discovery comes from disorder

Discovered more than 100 years ago, superconductivity continues to captivate scientists who seek to develop components for highly efficient energy transmission, ultrafast electronics or quantum bits for next-generation computation. However, determining what causes substances to become—or stop being—superconductors remains a central question in finding new candidates for this special class of materials.

In potential superconductors, there may be several ways electrons can arrange themselves. Some of these reinforce the superconducting effect, while others inhibit it. In a new study, scientists at the U.S. Department of Energy's (DOE) Argonne National Laboratory have explained the ways in which two such arrangements compete with each other and ultimately affect the temperature at which a material becomes superconducting.

In the superconducting state, electrons join together into so-called Cooper pairs, in which the motion of electrons is correlated; at each moment, the velocities of the electrons participating in a given pair are opposite. Ultimately, the motion of all electrons is coupled—no single electron can do its own thing—which leads to the lossless flow of electricity: superconductivity.

Generally, the more strongly the pairs couple and the larger the number of electrons that participate, the higher will be the superconducting transition temperature.

The materials that are potential high-temperature superconductors are not simple elements, but are complex compounds containing many elements. It turns out that, besides superconductivity, electrons may exhibit different properties at low temperatures, including magnetism or charge density wave order. In a charge density wave, electrons form a periodic pattern of high and low concentration inside the material. Electrons that are bound in the charge density wave do not participate in superconductivity, and the two phenomena compete.

"If you remove some electrons to put into a charge density wave, the strength of your superconducting effect will diminish," said Argonne materials scientist Ulrich Welp, a corresponding author of the study.

The work of the Argonne team is based on the realization that charge density wave order and superconductivity are affected differently by imperfections in the material. By introducing disorder, the researchers suppressed a charge density wave, disrupting the periodic charge density wave pattern while having only a small effect on superconductivity. This opens a way to tune the balance between the competing charge density wave order and superconductivity.

To introduce disorder in such a way that impaired the charge density wave state, but left the superconducting state largely intact, the researchers used particle irradiation. By hitting the material with a proton beam, the researchers knocked out a few atoms, changing the overall electronic structure while keeping the chemical composition of the material intact.

To get a picture of the fate of the charge density waves, researchers utilized state-of-the-art X-ray scattering at Argonne's Advanced Photon Source (APS), a DOE Office of Science User Facility, and the Cornell High Energy Synchrotron Source. "X-ray scattering was essential to observe the subtleties of this electronic order in the material," said Argonne physicist and study author Zahir Islam. "We discovered that a dilute concentration of disordered atoms really diminished the charge density wave to enhance superconductivity."

According to Islam, while the current brilliance of the APS allowed for systematic studies of charge density waves from tiny single-crystal samples despite its relatively weak scattering strength, the upcoming planned upgrade to the facility will afford researchers utmost sensitivity to observe these phenomena. Furthermore, he said, scientists will benefit from studying these materials in extreme environments, in particular, under high magnetic fields to tip the balance in favor of charge density waves to gain necessary insights into high-temperature superconductivity.

In the research, the scientists investigated a material called lanthanum barium copper oxide (LBCO). In this material, the superconducting temperature plummeted almost to absolute zero (-273 degrees Celsius) when the material achieved a certain chemical makeup. However, for closely related compositions, the transition temperature remained relatively high. The scientists believe this effect of chilling superconductivity is due to the presence of charge density waves and that suppressing the charge density wave could induce even higher transition temperatures.

With charge density waves impaired by disorder, superconductivity reaps the benefit, Wai-Kwong Kwok, Argonne Distinguished Fellow and study author, explained. "From the perspective of the superconductor, the enemy of my enemy truly is my friend," he said.

A paper based on the study, "Disorder raises the critical temperature of a cuprate superconductor," appeared in the May 13 online issue of the *Proceedings of the National Academy of Sciences*. [27]

Unraveling the stripe order mystery

One of the greatest mysteries in condensed matter physics is the exact relationship between charge order and superconductivity in cuprate superconductors. In superconductors, electrons move freely through the material—there is zero resistance when it's cooled below its critical temperature. However, the cuprates simultaneously exhibit superconductivity and charge order in patterns of alternating stripes. This is paradoxical in that charge order describes areas of confined electrons. How can superconductivity and charge order coexist?

Now researchers at the University of Illinois at Urbana-Champaign, collaborating with scientists at the SLAC National Accelerator Laboratory, have shed new light on how these disparate states can exist adjacent to one another. Illinois Physics post-doctoral researcher Matteo Mitrano, Professor Peter Abbamonte, and their team applied a new X-ray scattering technique, time-resolved resonant soft X-ray scattering, taking advantage of the state-of-the-art equipment at SLAC. This method enabled the scientists to probe the striped charge order phase with an unprecedented energy resolution. This is the first time this has been done at an energy scale relevant to superconductivity.

The scientists measured the fluctuations of charge order in a prototypical copper-oxide superconductor, $La_{2-x}Ba_xCuO_4$ (LBCO) and found the fluctuations had an energy that matched the material's superconducting critical temperature, implying that superconductivity in this material—and by extrapolation, in the cuprates—may be mediated by charge-order fluctuations.

The researchers further demonstrated that, if the charge order melts, the electrons in the system will reform the striped areas of charge order within tens of picoseconds. As it turns out, this process obeys a universal scaling law. To understand what they were seeing in their experiment, Mitrano and Abbamonte turned to Illinois Physics Professor Nigel Goldenfeld and his graduate student Minhui Zhu, who were able to apply theoretical methods borrowed from soft condensed matter physics to describe the formation of the striped patterns.

These findings were published on August 16, 2019, in the online journal *Science Advances*.

Cuprates have stripes

The significance of this mystery can be understood within the context of research in high-temperature superconductors (HTS), specifically the cuprates—layered materials that contain copper complexes. The cuprates, some of the first discovered HTS, have significantly higher critical temperatures than "ordinary" superconductors (e.g., aluminum and lead superconductors have a critical temperature below 10 K). In the 1980s, LBCO, a cuprate, was found to have a superconducting critical temperature of 35 K (-396°F), a discovery for which Bednorz and Müller won the Nobel Prize.

That discovery precipitated a flood of research into the cuprates. In time, scientists found experimental evidence of inhomogeneities in LBCO and similar materials: insulating and metallic phases that were coexisting. In 1998, Illinois Physics Professor Eduardo Fradkin, Stanford Professor Steven Kivelson, and others proposed that Mott insulators—materials that ought to conduct under conventional band theory but insulate due to repulsion between electrons—are able to host stripes of charge order and superconductivity. La_2CuO_4, the parent compound of LBCO, is an example of a Mott insulator. As Ba is added to that compound, replacing some La atoms, stripes form due to the spontaneous organization of holes—vacancies of electrons that act like positive charges.

Still, other questions regarding the behavior of the stripes remained. Are the areas of charge order immobile? Do they fluctuate?

"The conventional belief is that if you add these doped holes, they add a static phase which is bad for superconductivity—you freeze the holes, and the material cannot carry electricity," Mitrano comments. "If they are dynamic—if they fluctuate—then there are ways in which the holes could aid high-temperature superconductivity."

Probing the fluctuations in LBCO

To understand what exactly the stripes are doing, Mitrano and Abbamonte conceived of an experiment to melt the charge order and observe the process of its reformation in LBCO. Mitrano and Abbamonte reimagined a measurement technique called resonant inelastic X-ray scattering, adding a time-dependent protocol to observe how the charge order recovers over a duration of 40 picoseconds. The team shot a laser at the LBCO sample, imparting extra energy into the electrons to melt the charge order and introduce electronic homogeneity.

"We used a novel type of spectrometer developed for ultra-fast sources, because we are doing experiments in which our laser pulses are extremely short," Mitrano explains. "We performed our measurements at the Linac Coherent Light Source at SLAC, a flagship in this field of investigation. Our measurements are two orders of magnitude more sensitive in energy than what can be done at any other conventional scattering facility."

Professor Peter Abbamonte (middle, in navy sweater) and postdoctoral researcher Matteo Mitrano (right, in white dress shirt) pose with their team at the SLAC National Accelerator Laboratory in Menlo Park, California. The experimental team used a new investigative technique called time-resolved resonant soft x-ray scattering, to probe the striped charge order phase in a well-studied cuprate superconductor, with an unprecedented energy resolution, finding that superconductivity in cuprates may be mediated by charge-order fluctuations. This is the first time such an experiment has been done at an energy scale relevant to superconductivity. Credit: SLAC

Abbamonte adds, "What is innovative here is using time-domain scattering to study collective excitations at the sub-meV energy scale. This technique was demonstrated previously for phonons. Here, we have shown the same approach can be applied to excitations in the valence band."

Hints of a mechanism for superconductivity

The first significant result of this experiment is that the charge order does in fact fluctuate, moving with an energy that almost matches the energy established by the critical temperatureof LBCO. This suggests that Josephson coupling may be crucial for superconductivity.

The idea behind the Josephson effect, discovered by Brian Josephson in 1962, is that two superconductors can be connected via a weak link, typically an insulator or a normal metal. In this type of system, superconducting electrons can leak from the two superconductors into the weak link, generating within it a current of superconducting electrons.

Josephson coupling provides a possible explanation for the coupling between superconductivity and striped regions of charge order, wherein the stripes fluctuate such that superconductivity leaks into the areas of charge order, the weak links.

Obeying universal scaling laws of pattern formation

After melting the charge order, Mitrano and Abbamonte measured the recovery of the stripes as they evolved in time. As the charge order approached its full recovery, it followed an unexpected time dependence. This result was nothing like what the researchers had encountered in the past. What could possibly explain this?

The answer is borrowed from the field of soft condensed matter physics, and more specifically from a scaling law theory Goldenfeld had developed two decades prior to describe pattern formation in liquids and polymers. Goldenfeld and Zhu demonstrated the stripes in LBCO recover according to a universal, dynamic, self-similar scaling law.

Goldenfeld explains, "By the mid-1990s, scientists had an understanding of how uniform systems approach equilibrium, but how about stripe systems? I worked on this question about 20 years ago, looking at the patterns that emerge when a fluid is heated from below, such as the hexagonal spots of circulating, upwelling white flecks in hot miso soup. Under some circumstances these systems form stripes of circulating fluid, not spots, analogous to the stripe patterns of electrons in the cuprate superconductors. And when the pattern is forming, it follows a universal scaling law. This is exactly what we see in LBCO as it reforms its stripes of charge order."

Through their calculations, Goldenfeld and Zhu were able to elucidate the process of time-dependent pattern reformation in Mitrano and Abbamonte's experiment. The stripes reform with a logarithmic time dependence—a very slow process. Adherence to the scaling law in LBCO further implies that it contains topological defects, or irregularities in its lattice structure. This is the second significant result from this experiment.

Zhu comments, "It was exciting to be a part of this collaborative research, working with solid-state physicists, but applying techniques from soft condensed matter to analyze a problem in a strongly correlated system, like high-temperature superconductivity. I not only contributed my calculations, but also picked up new knowledge from my colleagues with different backgrounds, and in this way gained new perspectives on physical problems, as well as new ways of scientific thinking."

In future research, Mitrano, Abbamonte, and Goldenfeld plan to further probe the physics of charge order fluctuations with the goal of completely melting the charge order in LBCO to observe the physics of stripe formation. They also plan similar experiments with other cuprates, including yttrium barium copper oxide compounds, better known as YBCO.

Goldenfeld sees this and future experiments as ones that could catalyze new research in HTS: "What we learned in the 20 years since Eduardo Fradkin and Steven Kivelson's work on the periodic modulation of charge is that we should think about the HTS as electronic liquid crystals," he states. "We're now starting to apply the soft condensed matter physics of liquid crystals to HTS to understand why the superconducting phase exists in these materials." [26]

New cuprate superconductor may challenge classical wisdom

Superconductivity is one of the most mysterious phenomena in nature in that materials can conduct electrical current without any resistance. Cuprates hold the record high superconducting temperature at ambient pressure so far, but understanding their superconducting mechanism remains one of the great challenges of physical sciences listed as one of 125 quests announced by *Science*.

The recent discovery by Prof. Jin Changqing's team at Institute of Physics of the Chinese Academy of Sciences (IOPCAS) on a new high Tc superconductor $Ba_2CuO_{4-\delta}$ shows two unique features: an exceptionally compressed local octahedron and heavily over-doped hole carriers.

These two features are in sharp contrast to the favorable criteria for all previously known cuprate superconductors.

The compressed local octahedron results into a reversed orbital order with $3z^2$ lifted above $3dx^2-y^2$ leading to a strong multiband scenario, while the overdoped state violates the previous holding for a superconducting phase.

Impressively, the new material demonstrates superconducting transition temperature with Tc above 73 K, 30 K higher than that of the isostructural classical "conventional" superconductor based on La_2CuO_4.

Thus, the discovery of high Tc superconductivity in $Ba_2CuO_{4-\delta}$ calls into question the widely accepted scenario of superconductivity in the cuprates.

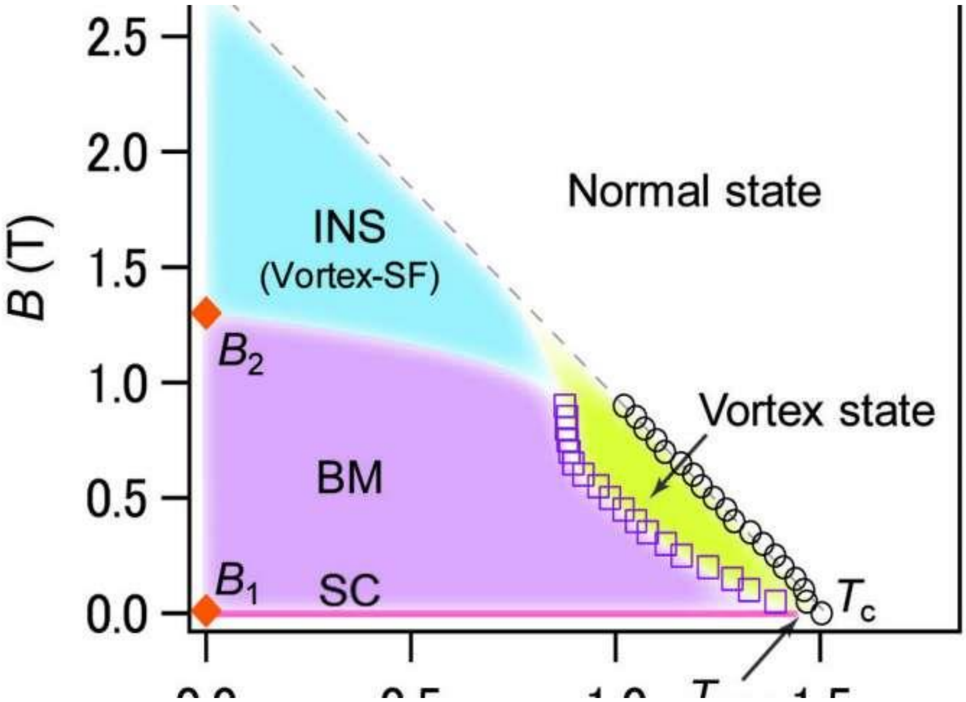
This discovery provides a totally new direction to search for further high Tc superconductors. [25]

A peculiar ground-state phase for 2-D superconductors

The application of large enough magnetic fields results in the disruption of superconducting states in materials, even at drastically low temperature, thereby changing them directly into insulators—or so was traditionally thought. Now, scientists at Tokyo Institute of Technology (Tokyo Tech), the University of Tokyo and Tohoku University report curious multi-state transitions of these superconductors in which they change from superconductor to special metal and then to insulator.

Characterized by their zero electrical resistance, or alternatively, their ability to completely expel external magnetic fields, superconductors have fascinating prospects for both fundamental physics and applications for e.g., superconducting coils for magnets. This phenomenon is understood by considering a highly ordered relationship between the electrons of the system .Due to a coherence over the entire system, electrons form bounded pairs and flow without collisions as a collective, resulting in a perfect conducting state without energy dissipation. However, upon introducing a magnetic field, the electrons are no longer able to maintain their coherent relationship, and the superconductivity is lost. For a given temperature, the highest magnetic field under which a material remains superconducting is known as the critical field.

Often these critical points are marked by phase transitions. If the change is abrupt like in the case of melting of ice, it is a first-order transition. If the transition takes place in a gradual and continuous manner by the growth of change-driving fluctuations extending on the entire system, it is called a second-order transition. Studying the transition path of superconductors when subjected to the critical field can yield insights into the quantum processes involved and allows us to design smarter superconductors (SCs) for application to advanced technologies.



Schematically drawn phase diagram of superconductivity-related states in ultrathin NbSe2. SC; superconductor, BM; Bose metal, INS; insulator, B1, B2, Bc2; magnetic fields at boundaries between the phases. Credit: *Physical Review B*

Interestingly, two-dimensional superconductors (2-D SCs) are the perfect candidates to study this type of phase transitions and one such novel candidate is a mono-unit layer of $NbSe_2$. Because smaller dimension (thickness) of superconductor implies a smaller number of possible partners for electrons to form superconducting pairs, the smallest perturbation can set a phase transition. Furthermore, 2-D SC is relevant from the perspective of applications in small-scale electronics.

In such materials, raising the applied magnetic field past a critical value leads to a fuzzy state in which the magnetic field penetrates the material, but the resistance is still minimal. It is only upon increasing the magnetic field further that the superconductivity is destroyed and the material is rendered an ordinary insulator. This is called the superconductor-to-insulator phase transition. Because this phenomenon is observed at very low temperatures, the quantum fluctuations in the system become comparable to, or even larger than, the classical thermal fluctuations. Therefore, this is called a quantum phase transition.

To understand the path of phase transition as well as the fuzzy or mixed state that exists between the critical field strengths in the $NbSe_2$ ultrathin superconductor, a group of researchers measured the magnetoresistance of the material (see Fig. 1), or the response of a SC's resistivity when subjected to external magnetic field. Professor Ichinokura lead says, "Using a four-point probe, we estimated the critical magnetic field at the respective quantum phase boundaries in the mono-layered $NbSe_2$." (see Fig. 2)

They found that as a small magnetic field is applied to the SC, the coherent flow of electrons is broken, but the electron pairs still remain. This is due to motion of vortices; the moving vortices create a finite resistance. The origin of this minimal resistance was interpreted as the material entering a special Bose metal (BM) state, which changed into an insulating state upon further increasing the magnetic field. The team also found that the transition between normal and SC states around the critical temperature was driven by quantum fluctuations, also reflecting a similar multi-transition pathway. Professor Ichinokura says, "The scaling analysis based on the model of the Bose metal explained the two-step transition, suggesting the existence of a bosonic ground state."

This study bolsters the theoretical claims of multi-phase transitions in superconductors thanks to the thinnest sample of atomic-scale thickness, and pushes the boundary of research further. [24]

A new quasi-2D superconductor that bridges a ferroelectric and an insulator

Researchers at the Zavoisky Physical-Technical Institute and the Southern Scientific Center of RAS, in Russia, have recently fabricated quasi-2-D superconductors at the interface between a ferroelectric $Ba_{0.8}Sr_{0.2}TiO_3$ film and an insulating parent compound of La_2CuO_4. Their study, presented in a paper published in *Physical Review Letters*, is the first to achieve superconductivity in a heterostructure consisting of a ferroelectric and an insulator.

The idea of forming a quasi-2-D superconducting layer at the interface between two different compounds has been around for several years. One past study, for instance, tried to achieve this by creating a thin superconducting layer between two insulating oxides ($LaAlO_3$ and $SrTiO_3$) with a critical temperature of 300mK. Other researchers observed the thin superconducting layer in bilayers of an insulator (La_2CuO_4) and a metal ($La_{1.55}Sr_{0.45}CuO_4$), neither of which is superconducting in isolation.

"Here we put forward the idea that thin charged layer on the interface between ferroelectric and insulator is formed in order to screen the electric field," Viktor Kabanov and Rinat Mamin, two researchers who carried out the study, told Phys.org via email. "This thin layer may be conducting or superconducting depending on the properties of the insulator. In order to get a superconducting layer, we chose La_2CuO_4 – an insulator that becomes a high $T_c$superconductor when it is doped by carriers."

The heterostructure fabricated by Kabanov, Mamin and their colleagues consists of a ferroelectric magnetron sputtered on the surface of the parent compound of high $T_c$superconductor La_2CuO_4. At the interface between these two components, the researchers observed the appearance of a thin superconducting layer, which attains its superconductivity at temperatures below 30K.

The researchers detected the layer's superconducting properties by measuring its resistivity and via the Meissner effect. They found that a finite resistance is created when applying a weak magnetic field perpendicular to the interface, which confirms the quasi-2-D quality of the layer's superconductive state.

"The key advantage of our technique is the relative simplicity of the creation of the heterostructure, because the requirements for the roughness of the surface are not so stringent," Kabanov and Mamin said. "On the other hand, the changing the polarization in the ferroelectric allows to control the properties of the conducting layer."

Kabanov, Mamin and their colleagues are the first ever to observe superconductivity on the interface between a ferroelectric and an insulator. In the future, their approach and the superconductors they fabricated could inform the design of new electronic devices with a ferroelectrically controlled superconductivity.

"As far as plans for the future are concerned, we would like to learn how we can control the superconducting properties of the interface by rotating the polarization of the ferroelectric," Kabanov and Mamin said. "Another idea is to try to control the properties of the interface by laser illumination. This is basically the direction we are working on now." [23]

Electron (or 'hole') pairs may survive effort to kill superconductivity

Scientists seeking to understand the mechanism underlying superconductivity in "stripe-ordered" cuprates—copper-oxide materials with alternating areas of electric charge and magnetism—discovered an unusual metallic state when attempting to turn superconductivity off. They found that under the conditions of their experiment, even after the material loses its ability to carry electrical current with no energy loss, it retains some conductivity—and possibly the electron (or hole) pairs required for its superconducting superpower.

"This work provides circumstantial evidence that the stripe-ordered arrangement of charges and magnetism is good for forming the charge-carrier pairs required for superconductivity to emerge," said John Tranquada, a physicist at the U.S. Department of Energy's Brookhaven National Laboratory.

Tranquada and his co-authors from Brookhaven Lab and the National High Magnetic Field Laboratory at Florida State University, where some of the work was done, describe their findings in a paper just published in *Science Advances*. A related paper in the *Proceedings of the National*

Academy of Sciences by co-author Alexei Tsvelik, a theorist at Brookhaven Lab, provides insight into the theoretical underpinnings for the observations.

The scientists were studying a particular formulation of lanthanum barium copper oxide (LBCO) that exhibits an unusual form of superconductivity at a temperature of 40 Kelvin (-233 degrees Celsius). That's relatively warm in the realm of superconductors. Conventional superconductors must be cooled with liquid helium to temperatures near -273°C (0 Kelvin or absolute zero) to carry current without energy loss. Understanding the mechanism behind such "high-temperature" superconductivity might guide the discovery or strategic design of superconductors that operate at higher temperatures.

"In principle, such superconductors could improve the electrical power infrastructure with zero-energy-loss power transmission lines," Tranquada said, "or be used in powerful electromagnets for applications like magnetic resonance imaging (MRI) without the need for costly cooling."

The mystery of high-Tc

LBCO was the first high-temperature (high-Tc) superconductor discovered, some 33 years ago. It consists of layers of copper-oxide separated by layers composed of lanthanum and barium. Barium contributes fewer electrons than lanthanum to the copper-oxide layers, so at a particular ratio, the imbalance leaves vacancies of electrons, known as holes, in the cuprate planes. Those holes can act as charge carriers and pair up, just like electrons, and at temperatures below 30K, current can move through the material with no resistance in three dimensions—both within and between the layers.

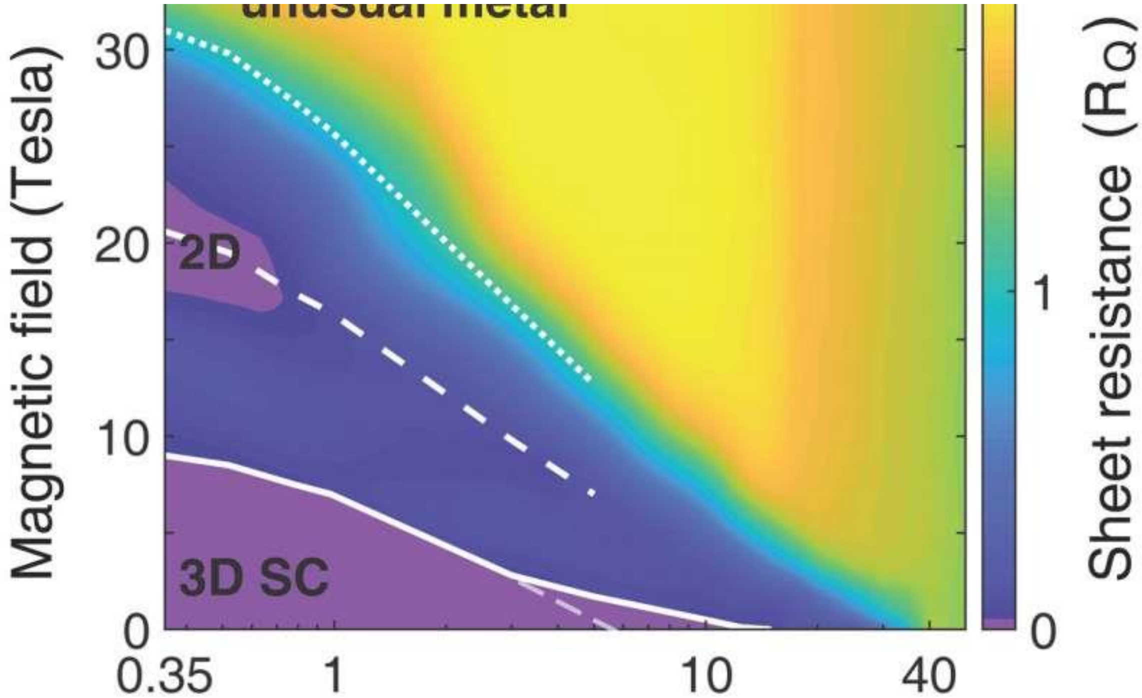
An odd characteristic of this material is that, in the copper-oxide layers, at the particular barium concentration, the holes segregate into "stripes" that alternate with areas of magnetic alignment. Since this discovery, in 1995, there has been much debate about the role these stripes play in inducing or inhibiting superconductivity.

In 2007, Tranquada and his team discovered the most unusual form of superconductivity in this material at the higher temperature of 40K. If they altered the amount of barium to be just under the amount that allowed 3-D superconductivity, they observed 2-D superconductivity—meaning just within the copper-oxide layers but not between them.

"The superconducting layers seem to decouple from one another," Tsvelik, the theorist, said. The current can still flow without loss in any direction within the layers, but there is resistivity in the direction perpendicular to the layers. This observation was interpreted as a sign that charge-carrier pairs were forming "pair density waves" with orientations perpendicular to one another in neighboring layers. "That's why the pairs can't jump from layer to another. It would be like trying to merge into traffic moving in a perpendicular direction. They can't merge," Tsvelik said.

Superconducting stripes are hard to kill

In the new experiment, the scientists dove deeper into exploring the origins of the unusual superconductivity in the special formulation of LBCO by trying to destroy it. "Often times we test things by pushing them to failure," Tranquada said. Their method of destruction was exposing the material to powerful magnetic fields generated at Florida State.



A phase diagram of LBCO at different temperatures and magnetic field strengths. Colors represent how resistant the material is to the flow of electrical current, with purple being a superconductor with no resistance. When cooled to near absolute zero with no magnetic field, the material acts as a 3-D superconductor. As the magnetic field strength goes up, 3-D superconductivity disappears, but 2-D superconductivity reappears at higher field strength, then disappears again. At the highest fields, resistance grew, but the material retained some unusual metallic conductivity, which the scientists interpreted as an indication that charge-carrier pairs might persist even after superconductivity is destroyed. Credit: Brookhaven National Laboratory

"As the external field gets bigger, the current in the superconductor grows larger and larger to try to cancel out the magnetic field," Tranquada explained. "But there's a limit to the current that can flow without resistance. Finding that limit should tell us something about how strong the superconductor is."

For example, if the stripes of charge order and magnetism in LBCO are bad for superconductivity, a modest magnetic field should destroy it. "We thought maybe the charge would get frozen in the stripes so that the material would become an insulator," Tranquada said.

But the superconductivity turned out to be a lot more robust.

Using perfect crystals of LBCO grown by Brookhaven physicist Genda Gu, Yangmu Li, a postdoctoral fellow who works in Tranquada's lab, took measurements of the material's resistance and conductivity under various conditions at the National High Magnetic Field Laboratory. At a temperature just above absolute zero with no magnetic field present, the material exhibited full, 3-D superconductivity. Keeping the temperature constant, the scientists had to ramp up the external magnetic field significantly to make the 3-D superconductivity disappear. Even more surprising, when they increased the field strength further, the resistance within the copper-oxide planes went down to zero again!

"We saw the same 2-D superconductivity we'd discovered at 40K," Tranquada said.

Ramping up the field further destroyed the 2-D superconductivity, but it never completely destroyed the material's ability to carry ordinary current.

"The resistance grew but then leveled off," Tranquada noted.

Signs of persistent pairs?

Additional measurements made under the highest-magnetic-field indicated that the charge-carriers in the material, though no longer superconducting, may still exist as pairs, Tranquada said.

"The material becomes a metal that no longer deflects the flow of current," Tsvelik said. "Whenever you have a current in a magnetic field, you would expect some deflection of the charges—electrons or holes—in the direction perpendicular to the current [what scientists call the Hall effect]. But that's not what happens. There is no deflection."

In other words, even after the superconductivity is destroyed, the material keeps one of the key signatures of the "pair density wave" that is characteristic of the superconducting state.

"My theory relates the presence of the charge-rich stripes with the existence of magnetic moments between them to the formation of the pair density wave state," Tsvelik said. "The observation of no charge deflection at high field shows that the magnetic field can destroy the coherence needed for superconductivity without necessarily destroying the pair density wave."

"Together these observations provide additional evidence that the stripes are good for pairing," Tranquada said. "We see the 2-D superconductivity reappear at high field and then, at an even higher field, when we lose the 2-D superconductivity, the material doesn't just become an insulator. There's still some current flowing. We may have lost coherent motion of pairs between the stripes, but we may still have pairs within the stripes that can move incoherently and give us an unusual metallic behavior." [22]

Discovery of field-induced pair density wave state in high temperature superconductors

Superconductors are quantum materials that are perfect transmitters of electricity and electronic information. Although they form the technological basis of solid-state quantum computing, they are also its key limiting factor because conventional superconductors only work at temperatures near -270 °C. This has motivated a worldwide race to try to discover higher temperature superconductors. Materials containing CuO_2 crystal layers (cuprates) are, at present, the best candidate for highest temperature superconductivity, operating at approximately -120 °C. But room temperature superconductivity in these compounds appears to be frustrated by the existence of a competing electronic phase, and focus has recently been on identifying and controlling that mysterious second phase.

Superconductivity occurs when electrons form pairs of opposite spin and opposite momentum, and these "Cooper pairs" condense into a homogeneous electronic fluid. However, theory also allows the possibility that these electron pairs crystallize into a "pair density wave" (PDW) state where the density of pairs modulates periodically in space. Intense theoretical interest has emerged in whether such a PDW is the competing phase in cuprates.

To search for evidence of such a PDW state, a team led by Prof. JC Seamus Davis (University of Oxford) and Prof. Andrew P. Mackenzie (Max Planck Institute CPfS, Dresden) with key collaborators Dr. Stephen D. Edkins and Dr. Mohammad Hamidian (Cornell University) and Dr. Kazuhiro Fujita (Brookhaven National Lab.), used high magnetic fields to suppress the homogeneous superconductivity in the cupratesuperconductor $Bi_2Sr_2Ca_2CuO_2$. They then carried out atomic-scale visualization of the electronic structure of the new field-induced phase. Under these circumstances, modulations in the density of electronic states containing multiple signatures of a PDW state were discovered. The phenomena are in detailed agreement with theoretical predictions for a field-induced PDW state, implying that it is a pair density wave which competes with superconductivity in cuprates.

This discovery makes it clear that in order to understand the mechanism behind the enigmatic high temperature superconductivity of the cuprates, this exotic PDW state needs to be taken into account, and therefore opens a new frontier in cuprate research. [21]

Electric-field-controlled superconductor-ferromagnetic insulator transition

High-temperature (Tc) superconductivity typically develops from antiferromagnetic insulators, and superconductivity and ferromagnetism are always mutually exclusive. Recently, Xianhui Chen's group at the University of Science and Technology of China observed an electric-field controlled reversible transition from superconductor to ferromagnetic insulator in (Li,Fe)OHFeSe thin flake. This work offers a unique platform to study the relationship between superconductivity and ferromagnetism in Fe-based superconductors and may provide some clue about understanding the electron pairing mechanism beyond conventional electron-phonon superconductivity.

The relationship between superconductivity and magnetism is key to understanding the electron pairing mechanism beyond conventional electron-phonon superconductivity. Controlling the magnetism near the superconducting region could explain the competing or intertwined electronic states in superconducting and magnetic phases. Modulating carrier density via field electric transistors (FET) is one of the most effective ways to manipulating the collectively ordered electronic states in condensed matter physics. However, only the carrier concentration on the surface of materials can be tuned with conventional gating technique and controlling the charge density in the bulk is plagued due to the Thomas-Fermi screening. Recently, a new type of FET has been developed using solid ion conductor (SIC) as the gate dielectric. In such a SIC-FET, the electric field can not only tune the carrier density to induce electronic phase transitions, but also drive ions into a crystal to transform it from one crystalline phase to another.

By this new developed gating technique, Xianhui Chen's group at University of Science and Technology of China observed an electric-field controlled reversible transition from superconductor to ferromagnetic insulator in (Li,Fe)OHFeSe thin flake. Using SIC-FET, Li ions can be driven into or extracted out from the (Li,Fe)OHFeSe thin flake by electric field. When the Li ions are initially driven into the thin flake, Li ions replace the Fe in the hydroxide layers and the Fe ions expelled by Li can migrate away from the hydroxide layers to fill the vacancies in the selenide layers. Once the vacancies are filled, the thin flake achieves the optimal Tc ~ 43 K. With further Li injection, the Fe ions extruded from the hydroxide layers migrate to the interstitial sites, and then the interstitial Fe ions become ordered and eventually lead to a long-range ferromagnetic order. So, a dome-shaped superconducting phase with optimal Tc (= 43 K) is continuously tuned into a ferromagnetic insulating phase, which exhibits an electric-field-controlled quantum critical behavior. The device is fabricated on a solid ion conductor, which can reversibly manipulate collectively ordered electronic states of the materials and stabilize new metastable structures by electric field. This work paves a way to access metastable phases and to control structural phase transformation as well as physical properties by the electric field.

These surprising findings offer a unique platform to study the relationship between superconductivity and ferromagnetism in Fe-based superconductors. This work also demonstrates the superior performance of SIC-FET in regulating the physical properties of layered crystals and its potential applications for multifunctional devices. [20]

Scientists measure exact edge between superconducting and magnetic states

Scientists at the U.S. Department of Energy's Ames Laboratory have developed a method to accurately measure the "exact edge" or onset at which a magnetic field enters a superconducting material. The knowledge of this threshold— called the lower critical field— plays a crucial role in untangling the difficulties that have prevented the broader use of superconductivity in new technologies.

In condensed matter physics, scientists distinguish between various superconducting states. When placed in a magnetic field, the upper critical field is the strength at which it completely destroys superconducting behavior in a material. The Meissner effect can be thought of as its opposite, which happens when a material transitions into a superconducting state, completely expelling a magnetic field from its interior, so that it is reduced to zero at a small (typically less than a micrometer) characteristic length called the London penetration depth.

But what happens in the gray area between the two? Practically all superconductors are classified as type II, meaning that at larger magnetic fields, they do not show a complete Meissner effect. Instead, they develop a mixed state, with quantized magnetic vortices—called Abrikosov vortices— threading the material, forming a two-dimensional vortex lattice, and significantly affecting the behavior of superconductors. Most importantly, these vortices can be pushed around by flowing electrical current, causing superconductivity to dissipate.

The point when these vortices first begin to penetrate a superconductor is called the lower critical field, one that's been notoriously difficult to measure due to a distortion of the magnetic field near sample edges. However, knowledge of this field is needed for better understanding and controlling superconductors for use in applications.

"The boundary line, the temperature-dependent value of the magnetic field at which this happens, is very important; the presence of Abrikosov vortices changes the behavior of the superconductor a great deal," said Ruslan Prozorov, an Ames Laboratory physicist who is an expert in superconductivity and magnetism. "Many of the applications for which we'd like to use superconductivity, like the transmission of electricity, are hindered by the existence of this vortex phase."

To validate the novel technique developed to measure this boundary line, Prozorov and his team probed three already well-studied superconducting materials. They used a recently developed optical magnetometer that takes advantage of the quantum state of a particular kind of an atomic defect, called nitrogen-vacancy (NV) centers, in diamond. The highly sensitive instrument allowed the scientists to measure very small deviations in the magnetic signal very close to the sample edge detecting the onset of vortices penetration.

"Our method is non-invasive, very precise and has better spatial resolution than previously used methods," said Prozorov.

In addition, theoretical calculations conducted together with another Ames Laboratory scientist, Vladimir Kogan, allowed extraction of the lower critical field values from the measured onset of vortex penetration. [19]

Superconduction—why does it have to be so cold?

Currently, there is no precise computation method to describe superconducting materials. TU Wien has now made a major advance towards achieving this goal and, at the same time, has furthered an understanding of why conventional materials only become superconducting at around -200°C

Why does it always have to be so cold? We now know of a whole range of materials that – under certain conditions – conduct electrical current entirely without resistance. We call this phenomenon superconduction. All these materials do nonetheless experience a common problem: they only become superconducting at extremely low temperatures. The search to find theoretical computational methods to represent and understand this fact has been going on for many years. As yet, no one has fully succeeded in finding the solution. However, TU Wien has now developed a new method that enables a significantly better understanding of superconduction.

Many particles, complex computation

"Actually, it's surprising that superconduction only occurs at extremely low temperatures," says Professor Karsten Held of the Institute of Solid State Physics at TU Wien. "When you consider the energy released by the electrons involved in superconduction, you would actually expect superconduction to be possible at much higher temperatures as well."

In response to this conundrum, he and his team set about looking for a better method of representing superconduction theoretically. Dr. Motoharu Kitatani is the lead author of a new publication that brings forward significant improvements and enables a more in-depth understanding of high-temperature superconductivity.

It is not possible to understand superconduction by imagining the electrons in the material like tiny spheres following a distinct trajectory like balls on a snooker table. The only way you can explain superconduction is by applying the laws of quantum physics. "The problem is that many particles are involved in the phenomenon of superconduction, all at the same time," explains Held. "This makes the computations extremely complex."

The individual electrons in the material cannot be considered as objects that are independent of one another; they need to be treated together. Yet this task is so complex that it would not be possible to solve it accurately, even using the biggest computers in the world. "However, there are various approximation methods that can help us to represent the complex quantum correlations between the electrons," according to Held. One of these is the "dynamical mean-field theory" that is ideal for situations where computing the quantum correlations between the electrons is particularly difficult.

Improved representation of interactions

The research group at TU Wien is now presenting an addition to the existing theory that relies on a new 'Feynman diagram' calculation. Feynman diagrams – devised by Nobel prize winner Richard Feynman – are a way of representing the interactions between particles. All possible interactions – such as when particles collide, but also the emission or absorption of particles – are represented in diagrams and can be used to make very precise calculations.

Feynman developed this method for use in studying individual particles in a vacuum, however it can also be used to depict complex interactions between particles in solid objects. The problem in solid state physics is that you need to allow for a huge number of Feynman diagrams, because the interaction between the electrons is so intense. "In a method developed by Professor Toschi and myself, we no longer use the Feynman diagrams solely to depict interactions, but also use a complex, time-dependent vertex as a component," explains Held. "This vertex itself consists of an infinite number of Feynman diagrams, but using a clever trick, it can still be used for calculations on a supercomputer."

Painstaking detective work

This has created an extended form of the dynamical mean-field-theory that enables a good approximation of the complex quantum interaction of the particles to be calculated. "The exciting thing in terms of physics is that we can show it is actually the time dependence of the vertex that means superconduction is only possible at low temperatures." Following a great deal of painstaking detective work, Motoharu Kitatani and Professor Held were even able to identify the orthodox Feynman diagram that shows why conventional materials only become superconducting at -200°C and not at room temperature.

In conjunction with experiments currently being carried out at the Institute of Solid State Physics in a working group headed up by Professor Barisic, the new method should make a significant contribution to the better understanding of superconduction and so enable the development of even better superconducting materials. Identifying a material that is also superconducting at room temperature would be a huge breakthrough, and would enable a whole series of revolutionary technological innovations. [18]

Underlying mechanism discovered for magnetic effect in superconducting spintronics

The emerging field of spintronics leverages electron spin and magnetization. This could enhance the storage capacity of computer hard drives and potentially play an important role in quantum computing's future. Superconductor-ferromagnet (SF) structures are widely regarded as the building blocks of this superconducting spintronic technology. More conventional spintronic devices typically require large currents, so researchers are investigating the viability of low-resistance superconductors. Their new results could answer longstanding questions about how SF structures interact.

An international team of researchers recently revealed a general mechanism of the long-range electromagnetic proximity effect in SF structures in *Applied Physics Letters*. They explain that SF interactions led to a strong spread of stray magnetic field to the superconductor from the ferromagnet. The group's findings could help determine why ferromagnetic films transferred magnetic fields to their corresponding superconductors at distances longer than theoretically predicted.

"We expect our work will not only explain the existing puzzling experimental data on electrodynamics of superconductor-ferromagnet structures but also will provide the basis for the analysis of electrodynamics of any device of superconducting spintronics," Alexander Buzdin and Alexander Mel'nikov, co-authors of the paper, said in a joint statement.

Magnetic layers are used in spintronic devices to change and read the spin signals of an electron in an adjacent conducting material. In extremely low-temperature superconducting spintronics, bound electrons, called Cooper pairs, penetrate the ferromagnet layer. This in turn accelerates superconducting carriers to induce a current in the superconductor.

Scientists previously thought that the interplay between the system's superconducting and ferromagnetic components occurred solely from superconducting Cooper pairs penetrating into the adjacent ferromagnet. Buzdin explained how in the case of normal, nonsuperconducting metal, for example, the spread of the magnetic field in the opposite direction from the ferromagnet into the metal layers is possible only at the atomic length scale. "For a superconducting material, it was believed that the scale of this spread [small] is of the order of the size of the Cooper pair, about 10 nanometers," said Buzdin.

Recent experimental results by other groups, however, showed a magnetic field could be present in the superconductor at distances one order of magnitude greater than expected. To start solving this puzzle, the group modeled a SF bilayer system before and after its superconductor and ferromagnet components came into contact. They found that screening currents accompanied the penetrating magnetic field, whereas these stray fields are absent in the superconductor's normal state.

Themagnetic vector potential, which is commonly used to describe the local magnetic field, was the only non-zero electromagnetic characteristic in the region of the stray fields in the superconductor. The vector potential is generally not observable in a normal metal in these conditions. This led Buzdin and his colleagues to conclude that the penetration of Cooper pairs into the ferromagnet through the direct proximity effect is responsible for supercurrent flow inside the ferromagnet and the resulting appearance of the compensating supercurrents that generate magnetic fields inside the superconducting component.

The team plans to further study the electrodynamics of SF structures and use their findings to one day create new types of spin valves, which can be used in magnetic sensors and computer memory devices. [17]

Spin-3/2 superconductor is a first, say physicists

The first known superconductor in which spin-3/2 quasiparticles form Cooper pairs has been created by physicists in the US and New Zealand. The unconventional superconductor is an alloy of yttrium, platinum and bismuth, which is normally a topological semimetal.

The research was done by Johnpierre Paglione and colleagues at the University of Maryland, Iowa State's Ames Laboratory, the Lawrence Berkeley National Laboratory and the Universities of Otago and Wisconsin.

Conventional superconductivity arises in a material when spin-1/2 electrons form "Cooper pairs" because of interactions between the electrons and vibrations of the material's crystalline lattice. These pairs are bosons with integer (usually zero) spin, which means that at very low temperatures they can condense to form a state that conducts electrical current with no resistance.

Spin-orbit interaction

In the alloy studied by Paglione and colleagues, charge is carried by particle-like quasiparticles with spin-3/2. These quasiparticles arise from interactions between the spins of electrons and the positive charges of the atoms that make up the alloy. This effect is called spin-orbit coupling and is particularly strong in this material. The result is that the spin-3/2 state – which combines spin and orbital angular momentum – is the lowest energy state.

When the team cooled the material, they found that it is a superconductor at temperatures below about 800 mK. This came as a surprise because this temperature is nearly 1000 times higher than expected if the superconductivity involved conventional Cooper pairs.

Paglione and colleagues also studied how magnetic fields penetrate the material. Superconductors can expel magnetic fields but the process is not perfect, with some magnetic field lines penetrating the surface of the material and persisting to small depths. Measuring this penetration effect gives important details about the nature of the pairing responsible for superconductivity.

Mind the gap

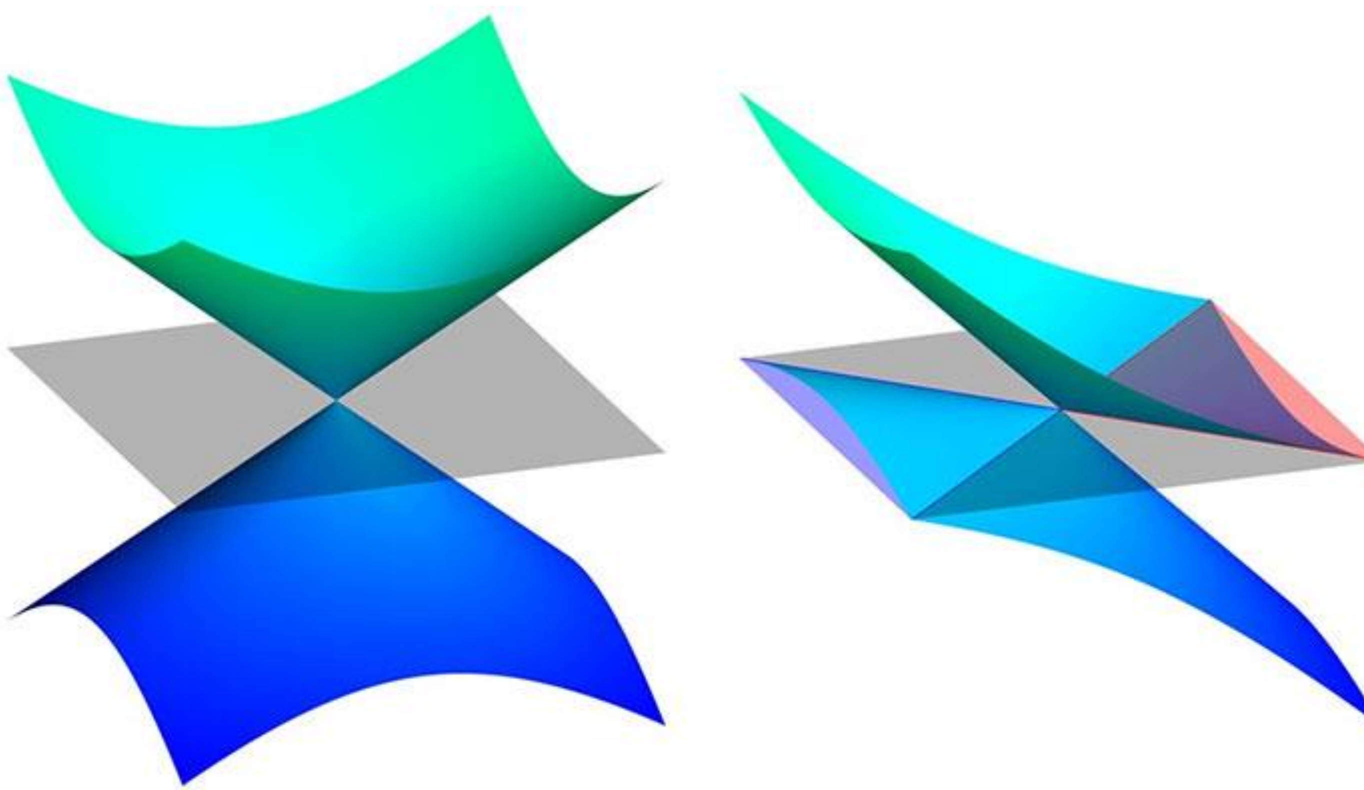
When the team measured the penetration depth as a function of temperature, they found that it increased linearly rather than exponentially – the latter being a characteristic of a conventional superconductor. This suggests that the energy gap between the superconducting and normal states of the material is not isotropic in space, as is the case in conventional superconductors.

This rule out spin-1/2 Cooper pairs so the team investigated other possibilities. They found that all possible pairings of spin-1/2 and spin-3/2 s in the alloy resulted in isotropic gaps except the case where two spin-3/2 quasiparticles join to make a pair with a combined spin of 3.

“No one had really thought that this was possible in solid materials,” says Paglione, adding it “was quite a surprise given the simplicity of the electronic structure in this system”.

Non-trivial topology

What is particularly exciting about the material, say the researchers, is the topological nature of how the superconductivity arises. The spin-3/2 quasiparticles are a result of topology related to the strong spin-orbit coupling. Paglione also says, “the superconductivity that forms may itself have a non-trivial topology”. “This is a more subtle thing and harder to prove,” he adds, “but essentially the phase of the superconducting wave function may have a ‘twist’ in it that gives a non-trivial (chiral) topology. This has profound implications, such as possibility of Majorana fermion excitations from the superconducting condensate.”



Type-II Dirac fermions spotted in two different materials

Paglione says that spin-3/2 superconductivity could exist in other materials and the phenomenon could have technological and fundamental applications. If such superconductors are indeed topological, he believes that they could form the basis for fault-tolerant quantum computers. On a fundamental level, he says that spin-3/2 fermions provide a very rich spectrum of possible pairing configurations for physicists to study – adding that their work has already garnered significant interest from other physicists.

Indeed, an important fundamental question, says Paglione, is how the spin-3/2 fermions pair up in the first place. "What's the glue that holds these pairs together?" he asks. "There are some ideas of what might be happening, but fundamental questions remain – which makes it even more fascinating."

The research is described in Science Advances. [16]

A different spin on superconductivity—Unusual particle interactions open up new possibilities in exotic materials

Now a team of researchers from the University of Maryland (UMD) Department of Physics together with collaborators has seen exotic superconductivity that relies on highly unusual electron interactions. While predicted to occur in other non-material systems, this type of behavior has remained elusive. The team's research, published in the April 6 issue of *Science Advances*, reveals effects that are profoundly different from anything that has been seen before with superconductivity.

Electron interactions in superconductors are dictated by a quantum property called spin. In an ordinary superconductor, electrons, which carry a spin of ½, pair up and flow uninhibited with the help of vibrations in the atomic structure. This theory is well-tested and can describe the behavior of most superconductors. In this new research, the team uncovers evidence for a new type of superconductivity in the material YPtBi, one that seems to arise from spin-3/2 particles.

"No one had really thought that this was possible in solid materials," explains Johnpierre Paglione, a UMD physics professor and senior author on the study. "High-spin states in individual atoms are possible but once you put the atoms together in a solid, these states usually break apart and you end up with spin one-half. "

Finding that YPtBi was a superconductor surprised the researchers in the first place. Most superconductors start out as reasonably good conductors, with a lot of mobile electrons—an ingredient that YPtBi is lacking. According to the conventional theory, YPtBi would need about a thousand times more mobile electrons in order to become superconducting at temperatures below 0.8 Kelvin. And yet, upon cooling the material to this temperature, the team saw superconductivity happen anyway. This was a first sign that something exotic was going on inside this material.

After discovering the anomalous superconducting transition, researchers made measurements that gave them insight into the underlying electron pairing. They studied a telling feature of superconductors—their interaction with magnetic fields. As the material undergoes the transition to a superconductor, it will try to expel any added magnetic field from its interior. But the expulsion is not completely perfect. Near the surface, the magnetic field can still enter the material but then quickly decays away. How far it goes in depends on the nature of the electron pairing, and changes as the material is cooled down further and further.

To probe this effect, the researchers varied the temperature in a small sample of the material while exposing it to a magnetic field more than ten times weaker than the Earth's. A copper coil surrounding the sample detected changes to the superconductor's magnetic properties and allowed the team to sensitively measure tiny variations in how deep the magnetic field reached inside the superconductor.

The measurement revealed an unusual magnetic intrusion. As the material warmed from absolute zero, the field penetration depth for YPtBi increased linearly instead of exponentially as it would for a conventional superconductor. This effect, combined with other measurements and theory calculations, constrained the possible ways that electrons could pair up. The researchers concluded that the best explanation for the superconductivity was electrons disguised as particles with a higher spin—a possibility that hadn't even been considered before in the framework of conventional superconductivity.

The discovery of this high-spin superconductor has given a new direction for this research field. "We used to be confined to pairing with spin one-half particles," says Hyunsoo Kim, lead author and a UMD assistant research scientist. "But if we start considering higher spin, then the landscape of this superconducting research expands and just gets more interesting."

For now, many open questions remain, including how such pairing could occur in the first place. "When you have this high-spin pairing, what's the glue that holds these pairs together?" says Paglione. "There are some ideas of what might be happening, but fundamental questions remain-which makes it even more fascinating." [15]

Scientists control superconductivity using spin currents

A group of researchers from institutions in Korea and the United States has determined how to employ a type of electron microscopy to cause regions within an iron-based superconductor to flip between superconducting and non-superconducting states. This study, published in the December 1 edition of *Physical Review Letters*, is the first of its kind, and it opens a door to a new way of manipulating and learning about superconductors.

The iron-based superconductors, one of which was studied in this work, are one of several classes of these fascinating materials, which have the ability to conduct electricity with virtually zero resistance below a certain temperature. Scientists are still working out the complex atomic-level details that underlie these materials' electronic and magnetic behaviors. The iron-based materials, in particular, are known to display intriguing phenomena related to co-existing superconducting and magnetic states.

Here, researchers studied a compound composed of strontium (Sr), vanadium (V), oxygen (O), iron (Fe), and arsenic (As), with a structure consisting of alternating FeAs and Sr_2VO_3 layers. They probed its magnetic and electronic properties with a spin-polarized scanning tunneling microscope (SPSTM), a device that passes an atomically sharp metal tip – just a few atoms wide – over the surface of a sample. The tip and the sample do not touch but are brought in quantum-scale proximity to each other so that a bias voltage applied between them causes a current to flow between the tip and the sample. In this case, the current is spin-polarized, meaning its electrons tend to have the same spin – the tiny magnetic field carried by an electron that points either "up" or "down," like a bar magnet.

Typically, this material's FeAs layer is strongly superconducting and prefers a certain magnetic order, dubbed C_2 order, that refers to how the magnetic fields of its atoms (which are due, in turn, to electron spins) are arranged. Results of the SPSTM scan show that the injected spin-polarized current, when sufficiently high, induces a different magnetic order, C_4 order, in the FeAs layer. In that same local area, superconductivity somehow magically disappears.

"To our knowledge, our study is the first report of a direct real-space observation of this type of control by a local probe, as well as the first atomic-scale demonstration of the correlation between magnetism and superconductivity," said the paper's corresponding author, Jhinhwan Lee, a physicist at the Korea Advanced Institute of Science and Technology, to *Phys.org*.

Lee and his group introduced new ways to perform SPSTM using an antiferromagnetic chromium (Cr) tip. An antiferromagnet is a material in which the magnetic fields of its atoms are ordered in an alternating up-down pattern such that it has a minimal stray magnetic field that can inadvertently kill local superconductivity (which can happen with ferromagnetic tips, such as Fe tips, that other SPSTM researchers use). They compared these Cr tip scans with those taken with an unpolarized tungsten (W) tip. At low bias voltages, the surface scans were qualitatively identical. But as the voltage was increased using the Cr tip, the surface started to change, revealing the C_4 magnetic symmetry. The C_4 order held even when the voltage was lowered again, although was erased when thermally annealed (heat-treated) beyond a specific temperature above which any magnetic order in the FeAs layer disappears.

To study the connection between the C_4 magnetic order and the suppression of superconductivity, Lee and his group performed high-resolution SPSTM scans of the C_4 state with Cr tips and compared them with simulations. The results led them to suggest one possible explanation: that the low-energy spin fluctuations in the C_4 state cannot mediate pairing between electrons. This is critical because this pairing of electrons, defying their natural urge to repel each other, leads to superconductivity.

Spin-fluctuation-based pairing is one theory of electron pairing in iron-based superconductors; another set of theories assume that fluctuations in the electron orbitals are the key. Lee and his group believe that their results seem to support the former, at least in this superconductor.

"Our findings may be extended to future studies where magnetism and superconductivity are manipulated using spin-polarized and unpolarized currents, leading to novel antiferromagnetic memory devices and transistors controlling superconductivity," said Lee. [14]

Researchers steer the flow of electrical current with spinning light

Light can generate an electrical current in semiconductor materials. This is how solar cells generate electricity from sunlight and how smart phone cameras can take photographs. To collect the generated electrical current, called photocurrent, an electric voltage is needed to force the current to flow in only one direction.

In new research, scientists at the University of Minnesota used a first-of-its-kind device to demonstrate a way to control the direction of the photocurrent without deploying an electric voltage. The new study was recently published in the scientific journal *Nature Communications*.

The study reveals that control is effected by the direction in which the particles of light, called photons, are spinning—clockwise or counterclockwise. The photocurrent generated by the spinning light is also spin-polarized, which means there are more electrons with spin in one direction than in the other. This new device holds significant potential for use in the next generation of microelectronics using electron spin as the fundamental unit of information. It could also be used for energy efficient optical communication in data centers.

"The observed effect is very strong and robust in our devices, even at room temperature and in open air," said Mo Li, a University of Minnesota electrical and computer engineering associate professor and a lead author of the study. "Therefore, the device we demonstrate has great potential for being implemented in next-generation computation and communication systems."

Optical spin and topological insulators

Light is a form of electromagnetic wave. The way the electric field oscillates, either in a straight line or rotating, is called polarization. (Your polarized sunglasses block part of the unpleasant reflected light that is polarized along a straight line.) In circularly polarized light, the electric field can spin in the clockwise or counterclockwise direction. In such a state, the particle of light (photon) is said to have positive or negative optical spin angular momentum. This optical spin is analogous to the spin of electrons, and endows magnetic properties to materials.

Recently, a new category of materials, called topological insulators (TI), was discovered to have an intriguing property not found in common semiconductor materials. Imagine a road on which red cars only drive on the left lane, and blue cars only in the right lane. Similarly, on the surface of a TI, the electrons with their spins pointing one way always flow in one direction. This effect is called spin-momentum locking—the spin of the electrons is locked in the direction they travel.

Interestingly, shining a circularly polarized light on a TI can free electrons from its inside to flow on its surface in a selective way, for example, clockwise light for spin-up electrons and counterclockwise for spin-down electrons. Because of this effect, the generated photocurrent on the surface of the TI material spontaneously flows in one direction, requiring no electric voltage. This particular feature is significant for controlling the direction of a photocurrent. Because most of the electrons in this current have their spins pointing in a single direction, this current is spin-polarized.

Controlling direction and polarization

To fabricate their unique device that can change the direction of a photocurrent without the use of an electric voltage, the University's research team integrated a thin film of a TI material, bismuth selenide, on an optical waveguide made of silicon. Light flows through the waveguide (a tiny wire measuring 1.5 microns wide and 0.22 micron high) just like electrical current flows through a copper wire. Because light is tightly squeezed in the waveguide, it tends to be circularly polarized along a direction normal to the direction in which it flows. This is akin to the spin-momentum locking effect of the electrons in a TI material.

The scientists supposed that integrating a TI material with the optical waveguide will induce strong coupling between the light in the waveguide and the electrons in the TI material, both having the same, intriguing spin-momentum locking effect. The coupling will result in a unique optoelectronic effect—light flowing along one direction in the waveguide generates an electrical current flowing in the same direction with electron spin polarized.

Reversing the light direction reverses both the direction of the current and its spin polarization. And this is exactly what the team observed in their devices. Other possible causes of the observed effect, such as heat generated by the light, have been ruled out through careful experiments.

Future prospects

The outcome of the research is exciting for the researchers. It bears enormous potential for possible applications.

"Our devices generate a spin-polarized current flowing on the surface of a topological insulator. They can be used as a current source for spintronic devices, which use electron spin to transmit and process information with very low energy cost," said Li He, a University of Minnesota physics graduate student and an author of the paper.

"Our research bridges two important fields of nanotechnology: spintronics and nanophotonics. It is fully integrated with a silicon photonic circuit that can be manufactured on a large scale and has already been widely used in optical communication in data centers," He added. [13]

Research demonstrates method to alter coherence of light

Brown University researchers have demonstrated for the first time a method of substantially changing the spatial coherence of light.

In a paper published in the journal Science Advances, the researchers show that they can use surface plasmon polaritons—propagating electromagnetic waves confined at a metal-dielectric interface—to transform light from completely incoherent to almost fully coherent and vice versa. The ability to modulate coherence could be useful in a wide variety of applications from structural coloration and optical communication to beam shaping and microscopic imaging.

"There had been some theoretical work suggesting that coherence modulation was possible, and some experimental results showing small amounts of modulation," said Dongfang Li, a postdoctoral researcher in Brown's School of Engineering and the study's lead author. "But this is the first time very strong modulation of coherence has been realized experimentally."

Coherence deals with the extent to which propagating electromagnetic waves are correlated with each other. Lasers, for example, emit light that's highly coherent, meaning the waves are strongly correlated. The sun and incandescent light bulbs emit weakly correlated waves, which are generally said to be "incoherent", although, more precisely, they are characterized by low yet measurable degrees of coherence.

"Coherence, like color and polarization, is a fundamental property of light," said Domenico Pacifici, an associate professor of engineering and physics at Brown and coauthor of the research. "We have filters that can manipulate the color of light and we have things like polarizing sunglasses that can manipulate polarization. The goal with this work was to find a way to manipulate coherence like we can these other properties."

To do that, Li and Pacifici took a classic experiment used to measure coherence, Young's double slit, and turned it into a device that can modulate coherence of light by controlling and finely tuning the interactions between light and electrons in metal films.

In the classic double-slit experiment, an opaque barrier is placed between a light source and a detector. The light passes through two parallel slits in the barrier to reach the detector on the other side. If the light shown on the barrier is coherent, the rays emanating from the slits will interfere with each other, creating an interference pattern on the detector—a series of bright and dark bands called interference fringes. The extent to which the light is coherent can be measured by the intensity of bands. If the light is incoherent, no bands will be visible.

"As this is normally done, the double-slit experiment simply measures the coherence of light rather than changing it," Pacifici said. "But by introducing surface plasmon polaritons, Young's double slits become a tool not just for measurement but also modulation."

To do that, the researchers used a thin metal film as the barrier in the double slit experiment. When the light strikes the film, surface plasmon polaritons—ripples of electron density created when the electrons are excited by light—are generated at each slit and propagate toward the opposite slit.

"The surface plasmon polaritons open up a channel for the light at each slit to talk to each other," Li said. "By connecting the two, we're able to change the mutual correlations between them and therefore change the coherence of light."

In essence, surface plasmon polaritons are able to create correlation where there was none, or to cancel any existing correlation that was there, depending on the nature of the light coming in and the distance between the slits.

One of the study's key results is the strength of the modulation they achieved. The technique is able to modulate coherence across a range from 0 percent (totally incoherent) to 80 percent (nearly full coherent). Modulation of such strength has never been achieved before, the researchers say, and it was made possible by using nanofabrication methods that allowed to maximize the generation efficiencies of surface plasmon polaritons existing on both surfaces of the slitted screen.

This initial proof-of-concept work was done at the micrometer scale, but Pacifici and Li say there's no reason why this couldn't be scaled up for use in a variety of settings.

"We've broken a barrier in showing that it's possible to do this," Pacifici said. "This clears the way for new two-dimensional beam shapers, filters and lenses that can manipulate entire optical beams by using the coherence of light as a powerful tuning knob." [12]

53 attoseconds: Research produces shortest light pulse ever developed

Researchers at the University of Central Florida have generated what is being deemed the fastest light pulse ever developed.

The 53-attosecond pulse, obtained by Professor Zenhgu Chang, UCF trustee chair and professor in the Center for Research and Education in Optics and Lasers, College of Optics and Photonics, and Department of Physics, and his group at the university, was funded by the U.S. Army Research Laboratory's Army Research Office.

Specifically, it was funded by ARO's Multidisciplinary University Research Initiative titled "Post-BornOppenheimer Dynamics Using Isolated Attosecond Pulses," headed by ARO's Jim Parker and Rich Hammond.

This beats the team's record of a 67-attosecond extreme ultraviolet light pulse set in 2012.

Attosecond light pulses allow scientists to capture images of fast-moving electrons in atoms and molecules with unprecedented sharpness, enabling advancements in solar panel technology, logic and memory chips for mobile phones and computers, and in the military in terms of increasing the speed of electronics and sensors, as well as threat identification.

"This is the shortest laser pulse ever produced," Hammond said. "It opens new doors in spectroscopy, allowing the identification of pernicious substances and explosive residue."

Hammond noted that this achievement is also a new and very effective tool to understand the dynamics of atoms and molecules, allowing observations of how molecules form and how electrons in atoms and molecules behave.

"This can also be extended to condensed matter systems, allowing unprecedented accuracy and detail of atomic, molecular, and even phase, changes," Hammond said. "This sets the stage for many new kinds of experiments, and pushes physics forward with the ability to understand matter better than ever before."

Chang echoed Hammond's sentiments about this achievement being a game-changer for continued research in this field.

"The photon energy of the attosecond X-ray pulses is two times higher than previous attosecond light sources and reached the carbon K-edge (284 eV), which makes it possible to probe and control core electron dynamics such as Auger processes," Chang said. "In condensed matter physics, the ultrafast electronic process in carbon containing materials, such as graphene and diamond, can be studied via core to valence transitions. In chemistry, electron dynamics in carbon containing molecules, such as carbon dioxide, Acetylene, Methane, etc., may now be studied by attosecond transient absorption, taking advantage of the element specificity."

This development is the culmination of years of ARO funding of attosecond science.

It all started with an ARO MURI about eight years ago titled "Attosecond Optical Technology Based on Recollision and Gating" from the Physics Division. This was followed by single investigator awards, Defense University Research Instrumentation Programs and finally an ARO MURI titled "Attosecond Electron Dynamics" from the Chemistry Division.

From the ARL/ARO perspective, Hammond said that this achievement, which included researchers from around the globe, shows how continued funding into fundamental research using several instruments, such as MURIs, DURIPS, and single investigator awards, can be used in a coherent and meaningful way to push the forward the frontiers of science.

Chang's team includes Jie Li, Xiaoming Ren, Yanchun Yin, Andrew Chew, Yan Cheng, Eric Cunningham, Yang Wang, Shuyuan Hu, and Yi Wu, who are all affiliated with the Institute for the Frontier of Attosecond Science and Technology, or iFAST; Kun Zhao, who is also affiliated with the Chinese Academy of Sciences, and Michael Chini with the UCF Department of Physics. [11]

Method to significantly enhance optical force

Light consists of a flow of photons. If two waveguides – cables for light – are side by side, they attract or repel each other. The interaction is due to the optical force, but the effect is usually extremely small. Physicists at Chalmers University of Technology and Free University of Brussels have now found a method to significantly enhance optical force. The method opens new possibilities within sensor technology and nanoscience. The results were recently published in Physical Review Letters.

To make light behave in a completely new way, the scientists have studied waveguides made of an artificial material to trick the photons. The specially designed material makes all the photons move to one side of the waveguide. When the photons in a nearby waveguide do the same, a collection of photons suddenly gather very closely. This enhances the force between the waveguides up to 10 times.

"We have found a way to trick the photons so that they cluster together at the inner sides of the waveguides. Photons normally don't prefer left or right, but our metamaterial creates exactly that effect," says Philippe Tassin, Associate Professor at the Department of Physics at Chalmers University of Technology.

Philippe Tassin and Sophie Viaene at Chalmers and Lana Descheemaeker and Vincent Ginis at Free University of Brussels have developed a method to use the optical force in a completely new way. It can, for example, be used in sensors or to drive nanomotors. In the future, such motors might be used to sort cells or separate particles in medical technology.

"Our method opens up new opportunities for the use of waveguides in a range of technical applications. It is really exciting that man-made materials can change the basic characteristics of light propagation so dramatically," says Vincent Ginis, assistant professor at the Department of Physics at Free University of Brussels. [10]

Researchers demonstrate quantum teleportation of patterns of light

Nature Communications today published research by a team comprising Scottish and South African researchers, demonstrating entanglement swapping and teleportation of orbital angular momentum 'patterns' of light. This is a crucial step towards realizing a quantum repeater for high-dimensional entangled states.

Quantum communication over long distances is integral to information security and has been demonstrated in free space and fibre with two-dimensional states, recently over distances exceeding 1200 km between satellites. But using only two states reduces the information capacity of the photons, so the link is secure but slow. To make it secure and fast requires a higher-dimensional alphabet, for example, using patterns of light, of which there are an infinite number. One such pattern set is the orbital angular momentum (OAM) of light. Increased bit rates can be achieved by using OAM as the carrier of information. However, such photon states decay when transmitted over long distances, for example, due to mode coupling in fibre or turbulence in free space, thus requiring a way to amplify the signal. Unfortunately such "amplification" is not allowed in the quantum world, but it is possible to create an analogy, called a quantum repeater, akin to optical fibre repeaters in classical optical networks.

An integral part of a quantum repeater is the ability to entangle two photons that have never interacted - a process referred to as "entanglement swapping". This is accomplished by interfering two photons from independent entangled pairs, resulting in the remaining two photons becoming entangled. This allows the establishment of entanglement between two distant points without requiring one photon to travel the entire distance, thus reducing the effects of decay and loss. It also means that you don't have to have a line of sight between the two places.

An outcome of this is that the information of one photon can be transferred to the other, a process called teleportation. Like in the science fiction series, Star Trek, where people are "beamed" from one place to another, information is "teleported" from one place to another. If two photons are entangled and you change a value on one of them, then other one automatically changes too. This happens even though the two photons are never connected and, in fact, are in two completely different places.

In this latest work, the team performed the first experimental demonstration of entanglement swapping and teleportation for orbital angular momentum (OAM) states of light. They showed that quantum correlations could be established between previously independent photons, and that this could be used to send information across a virtual link. Importantly, the scheme is scalable to higher dimensions, paving the way for long-distance quantum communication with high information capacity.

Background

Present communication systems are very fast, but not fundamentally secure. To make them secure researchers use the laws of Nature for the encoding by exploiting the quirky properties of the quantum world. One such property is entanglement. When two particles are entangled they are connected in a spooky sense: a measurement on one immediately changes the state of the other no matter how far apart they are. Entanglement is one of the core resources needed to realise a quantum network.

Yet a secure quantum communication link over long distance is very challenging: Quantum links using patterns of light languish at short distances precisely because there is no way to protect the link against noise without detecting the photons, yet once they are detected their usefulness is destroyed. To overcome this one can have a repeating station at intermediate distances - this allows one to share information across a much longer distance without the need for the information to physically flow over that link. The core ingredient is to get independent photons to become entangled. While this has been demonstrated previously with two-dimensional states, in this work the team showed the first demonstration with OAM and in high-dimensional spaces. [9]

How to Win at Bridge Using Quantum Physics

Contract bridge is the chess of card games. You might know it as some stuffy old game your grandparents play, but it requires major brainpower, and preferably an obsession with rules and strategy. So how to make it even geekier? Throw in some quantum mechanics to try to gain a competitive advantage. The idea here is to use the quantum magic of entangled photons–which are essentially twins, sharing every property–to transmit two bits of information to your bridge partner for the price of one. Understanding how to do this is not an easy task, but it will help elucidate some basic building blocks of quantum information theory. It’s also kind of fun to consider whether or not such tactics could ever be allowed in professional sports. [6]

Quantum Information

In quantum mechanics, quantum information is physical information that is held in the "state" of a quantum system. The most popular unit of quantum information is the qubit, a two-level quantum system. However, unlike classical digital states (which are discrete), a two-state quantum system can actually be in a superposition of the two states at any given time.

Quantum information differs from classical information in several respects, among which we note the following:

However, despite this, the amount of information that can be retrieved in a single qubit is equal to one bit. It is in the processing of information (quantum computation) that a difference occurs.

The ability to manipulate quantum information enables us to perform tasks that would be unachievable in a classical context, such as unconditionally secure transmission of information. Quantum information processing is the most general field that is concerned with quantum information. There are certain tasks which classical computers cannot perform "efficiently" (that is, in polynomial time) according to any known algorithm. However, a quantum computer can compute the answer to some of these problems in polynomial time; one well-known example of this is Shor's factoring algorithm. Other algorithms can speed up a task less dramatically - for example, Grover's search algorithm which gives a quadratic speed-up over the best possible classical algorithm.

Quantum information, and changes in quantum information, can be quantitatively measured by using an analogue of Shannon entropy. Given a statistical ensemble of quantum mechanical systems with the density matrix S, it is given by.

Many of the same entropy measures in classical information theory can also be generalized to the quantum case, such as the conditional quantum entropy. [7]

Quantum Teleportation

Quantum teleportation is a process by which quantum information (e.g. the exact state of an atom or photon) can be transmitted (exactly, in principle) from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location. Because it depends on classical communication, which can proceed no faster than the speed of light, it cannot be used for superluminal transport or communication of classical bits. It also cannot be used to make copies of a system, as this violates the no-cloning theorem. Although the name is inspired by the teleportation commonly used in fiction, current technology provides no possibility of anything resembling the fictional form of teleportation. While it is possible to teleport one or more qubits of information between two (entangled) atoms, this has not yet been achieved between molecules or anything larger. One may think of teleportation either as a kind of transportation, or as a kind of communication; it provides a way of transporting a qubit from one location to another, without having to move a physical particle along with it.

The seminal paper first expounding the idea was published by C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters in 1993. Since then, quantum teleportation has been realized in various physical systems. Presently, the record distance for quantum teleportation is 143 km (89 mi) with photons, and 21 m with material systems. In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

Quantum Computing

A team of electrical engineers at UNSW Australia has observed the unique quantum behavior of a pair of spins in silicon and designed a new method to use them for "2-bit" quantum logic operations.

These milestones bring researchers a step closer to building a quantum computer, which promises dramatic data processing improvements.

Quantum bits, or qubits, are the building blocks of quantum computers. While many ways to create a qubits exist, the Australian team has focused on the use of single atoms of phosphorus, embedded inside a silicon chip similar to those used in normal computers.

The first author on the experimental work, PhD student Juan Pablo Dehollain, recalls the first time he realized what he was looking at.

"We clearly saw these two distinct quantum states, but they behaved very differently from what we were used to with a single atom. We had a real 'Eureka!' moment when we realized what was happening – we were seeing in real time the `entangled' quantum states of a pair of atoms." [5]

Quantum Entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

The Bridge

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. [1]

Accelerating charges

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field. In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion. The same thing happens on the atomic scale giving a dp impulse difference and a dx way difference between the different part of the not point like particles.

Relativistic effect

Another bridge between the classical and quantum mechanics in the realm of relativity is that the charge distribution is lowering in the reference frame of the accelerating charges linearly: ds/dt = at (time coordinate), but in the reference frame of the current it is parabolic: $s = a/2\ t^2$ (geometric coordinate).

Heisenberg Uncertainty Relation

In the atomic scale the Heisenberg uncertainty relation gives the same result, since the moving electron in the atom accelerating in the electric field of the proton, causing a charge distribution on delta x position difference and with a delta p momentum difference such a way that they product is about the half Planck reduced constant. For the proton this delta x much less in the nucleon, than in the orbit of the electron in the atom, the delta p is much higher because of the greater proton mass.

This means that the electron and proton are not point like particles, but has a real charge distribution.

Wave – Particle Duality

The accelerating electrons explains the wave – particle duality of the electrons and photons, since the elementary charges are distributed on delta x position with delta p impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and it's kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only that changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

The Relativistic Bridge

Commonly accepted idea that the relativistic effect on the particle physics it is the fermions' spin - another unresolved problem in the classical concepts. If the electric charges can move only with accelerated motions in the self maintaining electromagnetic field, once upon a time they would reach the velocity of the electromagnetic field. The resolution of this problem is the spinning particle, constantly accelerating and not reaching the velocity of light because the acceleration is radial. One origin of the Quantum Physics is the Planck Distribution Law of the electromagnetic oscillators, giving equal intensity for 2 different wavelengths on any temperature. Any of these two wavelengths will give equal intensity diffraction patterns, building different asymmetric constructions, for example proton - electron structures (atoms), molecules, etc. Since the particles are centers of diffraction patterns they also have particle – wave duality as the electromagnetic waves have. [2]

The weak interaction

The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry. The Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

Another important issue of the quark model is when one quark changes its flavor such that a linear oscillation transforms into plane oscillation or vice versa, changing the charge value with 1 or -1. This kind of change in the oscillation mode requires not only parity change, but also charge and time changes (CPT symmetry) resulting a right handed anti-neutrino or a left handed neutrino.

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions, the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

The neutrino is a 1/2spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with ½ spin. The weak interaction changes the entropy since more or less particles will give more or less freedom of movement. The entropy change is a result of temperature change and breaks the equality of oscillator diffraction intensity of the Maxwell–Boltzmann statistics. This way it changes the time coordinate measure and
makes possible a different time dilation as of the special relativity.

The limit of the velocity of particles as the speed of light appropriate only for electrical charged particles, since the accelerated charges are self maintaining locally the accelerating electric force. The neutrinos are CP symmetry breaking particles compensated by time in the CPT symmetry, that is the time coordinate not works as in the electromagnetic interactions, consequently the speed of neutrinos is not limited by the speed of light.

The weak interaction 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 the
weak interaction, for example the Hydrogen fusion.

Probably because it is a spin creating movement changing linear oscillation to 2 dimensional oscillation by changing d to u quark and creating anti neutrino going back in time relative to the proton and electron created from the neutron, it seems that the anti neutrino fastest then the velocity of the photons created also in this weak interaction?

A quark flavor changing shows that it is a reflection changes movement and the CP- and T-symmetry breaking!!! This flavor changing oscillation could prove that it could be also on higher level such as atoms, molecules, probably big biological significant molecules and responsible on the aging of the life.

Important to mention that the weak interaction is always contains particles and antiparticles, where the neutrinos (antineutrinos) present the opposite side. It means by Feynman's interpretation that these particles present the backward time and probably because this they seem to move faster than the speed of light in the reference frame of the other side.

Finally since the weak interaction is an electric dipole change with ½ spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

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. A good example of this is the neutron decay, creating more particles with less known information about them.
The neutrino oscillation of the Weak Interaction shows that it is a general electric dipole change and it is possible to any other temperature dependent entropy and information changing diffraction pattern of atoms, molecules and even complicated biological living structures.

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater then subatomic matter structures as an electric dipole change.
There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.
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. So the Weak Interaction has two directions, samples for one direction is the Neutron decay, and Hydrogen fusion is the opposite direction.

Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing.

Van Der Waals force

Named after the Dutch scientist Johannes Diderik van der Waals – who first proposed it in 1873 to explain the behaviour of gases – it is a very weak force that only becomes relevant when atoms and molecules are very close together. Fluctuations in the electronic cloud of an atom mean that it will have an instantaneous dipole moment. This can induce a dipole moment in a nearby atom, the result being an attractive dipole–dipole interaction.

Electromagnetic inertia and mass

Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

Relativistic change of mass

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

The frequency dependence of mass

Since $E = hv$ and $E = mc^2$, $m = hv / c^2$ that is the m depends only on the v frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the m_o inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [2]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

Gravity from the point of view of quantum physics

The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass rate Mp=1840 Me. In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have + parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

Since the Higgs boson is necessary to the W and Z bosons, the dipole change of the Weak interaction and the change in the magnetic effect caused gravitation must be conducted. The Wien law is also important to explain the Weak interaction, since it describes the T_{max} change and the diffraction patterns change. [2]

Higgs mechanism and Quantum Gravity

The magnetic induction creates a negative electric field, causing an electromagnetic inertia. Probably it is the mysterious Higgs field giving mass to the charged particles? We can think about the photon as an electron-positron pair, they have mass. The neutral particles are built from negative and positive charges, for example the neutron, decaying to proton and electron. The wave – particle duality makes sure that the particles are oscillating and creating magnetic induction as an inertial mass, explaining also the relativistic mass change. Higher frequency creates stronger magnetic induction, smaller frequency results lesser magnetic induction. It seems to me that the magnetic induction is the secret of the Higgs field.

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The spontaneous symmetry breaking of the underlying local symmetry triggers conversion of components of this Higgs field to Goldstone bosons which interact with (at least some of) the other fields in the theory, so as to produce mass terms for (at least some of) the gauge bosons. This mechanism may also leave behind elementary scalar (spin-0) particles, known as Higgs bosons.

In the Standard Model, the phrase "Higgs mechanism" refers specifically to the generation of masses for the $W^{\pm}$, and Z weak gauge bosons through electroweak symmetry breaking. The Large Hadron Collider at CERN announced results consistent with the Higgs particle on July 4, 2012 but stressed that further testing is needed to confirm the Standard Model.

What is the Spin?

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particles like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [3]

Conclusions

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also. [1]

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves. [2]

The key breakthrough to arrive at this new idea to build qubits was to exploit the ability to control the nuclear spin of each atom. With that insight, the team has now conceived a unique way to use the nuclei as facilitators for the quantum logic operation between the electrons. [5]

Basing the gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions also.

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