

# Magnetic Quantum Superconductors

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*Researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and Argonne National Laboratory have collaborated to design, build and test two devices that utilize different superconducting materials and could make X-ray lasers more powerful, versatile, compact and durable. [34]*

*A team of researchers at the U.S. Department of Energy's (DOE) Argonne National Laboratory has identified a nickel oxide compound as an unconventional but promising candidate material for high-temperature superconductivity. [33]*

*An international team led by scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University has detected new features in the electronic behavior of a copper oxide material that may help explain why it becomes a perfect electrical conductor – a superconductor – at relatively high temperatures. [32]*

*An artistic representation of the data showing the breaking of spatial inversion and rotational symmetries in the pseudogap region of superconducting materials -- evidence that the pseudogap is a distinct phase of matter. [31]*

*Superconductivity is a state in a material in which there is no resistance to electric current and all magnetic fields are expelled. This behavior arises from a so-called "macroscopic quantum state" where all the electrons in a material act in concert to move cooperatively through the material without energy loss. [30]*

*Harvard researchers found a way to transmit spin information through superconducting materials. [29]*

*Researchers at the National Institute of Information and Communications Technology, in collaboration with researchers at the Nippon Telegraph and Telephone Corporation and the Qatar Environment and Energy Research Institute have discovered qualitatively new states of a superconducting artificial atom dressed with virtual photons. [28]*

*A group of scientists from Moscow Institute of Physics and Technology and from the Moscow State University has developed a fundamentally new type of memory cell based on superconductors – this type of memory works hundreds of times faster than the memory devices commonly used today, according to an article published in the journal Applied Physics Letters. [27]*

*Superconductivity is a rare physical state in which matter is able to conduct electricity—maintain a flow of electrons—without any resistance. It can only be found in certain materials, and even then it can only be achieved under controlled conditions of low temperatures and high pressures. New research from a team including Carnegie's Elissaios Stavrou, Xiao-Jia Chen, and Alexander Goncharov hones in on the structural changes underlying superconductivity in iron arsenide compounds—those containing iron and arsenic. [26]*

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

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

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## The Quest of Superconductivity

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

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

## Experiences and Theories

### Magnetic quantum objects in a 'nano egg carton'

Magnetic quantum objects in superconductors, so-called "fluxons," are particularly suitable for the storage and processing of data bits. Computer circuits based on fluxons could be operated with significantly higher speed while dissipating much less heat. Physicists working with Wolfgang Lang at the University of Vienna and their colleagues at the Johannes-Kepler-University Linz have developed a "quantum egg carton" with a novel and simple method. They realized a stable and regular arrangement of hundreds of thousands of fluxons—a groundbreaking development for circuits based on fluxons. The results appear in the journal Physical Review Applied of the American Physical Society.

Speeding up data processing in computers goes hand in hand with higher heat generation, which limits the performance of fast computers. Researchers therefore pursue digital circuits based on superconductors, materials that can transport electricity without loss when cooled below a certain critical temperature.

### Magnetic quantum objects in superconductors

Inside a superconductor, a magnetic field can exist only in small quantized pieces called fluxons. These are particularly suitable for the storage and processing of data bits. In a homogeneous superconductor, the fluxons are arranged in a hexagonal lattice. Using modern nanotechnology,

researchers at the University of Vienna and the Johannes-Kepler-University Linz have built artificial traps for fluxons. By means of these traps, the fluxons are forced into a predefined formation.

### **The importance of the non-equilibrium**

Until now, the fluxons could only be observed in a thermodynamic equilibrium, i.e., in a uniform arrangement. "If we try to stack two eggs on top of each other in an egg carton and leave the adjacent pit empty, the egg would quickly roll down to an equilibrium state with exactly one egg in each pit," explains Wolfgang Lang from the University of Vienna. From the viewpoint of data processing, however, the fully filled egg carton contains little information and is therefore useless. It would be much more useful to place the eggs in a predefined pattern. In such a way, for example, QR codes recognized by smartphones could be realized in an egg carton—obviously, a large amount of information.

At the nanoscale, the researchers have now made a major step by demonstrating for the first time a stable non-equilibrium state of fluxons in an array of more than 180,000 artificial traps. Depending on the external magnetic field, the fluxons arrange themselves in terraced zones in which each trap either captures no fluxon, exactly one, or several fluxons. "Even after a period of days, we have observed precisely the same arrangement of fluxons—a long-term stability that is rather surprising for a quantum system," says Georg Zechner of the University of Vienna, the lead author of the study.

### **Nanopatterning of superconductors by ion beams**

"Masked ion-beam irradiation allows for the fabrication of nanostructures in superconductors in a single step. It can be applied time efficiently to large areas, can be ramped up to an industrial scale and does not require any chemical processes," says Johannes D. Pedarnig of the Institute of Applied Physics at the Johannes-Kepler-University Linz. Depending on the mask used, virtually any desired structure can be patterned into the superconductor. The scientists are now planning further experiments on more sophisticated nanostructures, which should demonstrate the systematic transfer of fluxons from one trap to the next. This could be another pioneering step towards the development of fast computer circuits based on fluxons. [38]

### **First direct observation and measurement of ultra-fast moving vortices in superconductors**

Researchers have made the first direct visual observation and measurement of ultra-fast vortex dynamics in superconductors. Their technique, detailed in the journal *Nature Communications*, could contribute to the development of novel practical applications by optimizing superconductor properties for use in electronics.

Superconductivity is a state of matter in which an electric current can flow with absolutely no resistance. This occurs when certain materials are cooled below a critical temperature. The effect is useful for various applications, from magnetically levitating trains to MRI machines and particle accelerators. It also sparks the imagination with thoughts of lossless power transfer and much faster computation.

However, superconductivity is, generally speaking, suppressed in the presence of magnetic fields, limiting the ability to use these materials in real life applications. A certain family of superconductors, called type 2, can withstand much higher values of magnetic fields. This is thanks to their ability to allow the magnetic field to thread through the material in a quantized manner, in a

local tubular-shaped form called a vortex. Unfortunately, in the presence of electric currents these vortices experience a force and may begin to move. Motion of vortices allows for electrical resistance, which, again, poses an obstacle for applications.

Understanding when and how vortices will move or remain localized is the focus of much scientific research. Until now, addressing the physics of fast moving vortices experimentally has proven extremely challenging, mainly because of the lack of adequate tools.

Now an international team of researchers, led by Prof. Eli Zeldov from the Weizmann Institute of Science and Dr. Yonathan Anahory, senior lecturer at the Hebrew University of Jerusalem's Racah Institute of Physics, has shown for the first time how these vortices move in superconducting materials and how fast they may travel.

They used a novel microscopy technique called scanning SQUID-on-tip, which allows magnetic imaging at unprecedented high resolution (about 50 nm) and magnetic sensitivity. The technique was developed over the last decade at the Weizmann Institute by a large team including Ph.D. student Lior Embon and Ella Lachman and is currently being implemented at the Hebrew University in Dr. Anahory's lab as well.

Using this microscope, they observed vortices flowing through a thin superconducting film at rates of tens of GHz, and traveling at velocities much faster than previously thought possible—up to about 72 000 km/hr (45 000 mph). This is not only much faster than the speed of sound, but also exceeds the pair-breaking speed limit of superconducting condensate—meaning that a vortex can travel 50 times faster than the speed limit of the supercurrent that drives it. This would be like driving an object to travel around the earth in just over 30 minutes.

In photos and videos shown for the first time, the vortex trajectories appear as smeared lines crossing from one side of the film to another. This is similar to the blurring of images in photographs of fast-moving objects. They show a tree-like structure with a single stem that undergoes a series of bifurcations into branches. This channel flow is quite surprising since vortices normally repel each other and try to spread out as much as possible. Here vortices tend to follow each other, which generates the tree-like structure.

A team of theoretical physicists from the USA and Belgium, led by Professors Alexander Gurevich and Milorad Milošević, partially explained this finding by the fact that when a vortex moves, the appearance of resistance locally heats the material, which makes it easier for following vortices to travel the same route.

"This work offers an insight into the fundamental physics of vortex dynamics in superconductors, crucial for many applications," said Dr. Lior Embon, who was, at the time, the student in charge of this study. "These findings can be essential for further development of superconducting electronics, opening new challenges for theories and experiments in the yet unexplored range of very high electromagnetic fields and currents."

"The research shows that the SQUID-on-tip technique can address some outstanding problems of non-equilibrium superconductivity, ultrafast vortices and many other magnetic phenomena at the nanometer scale," said Dr. Yonathan Anahory, senior lecturer at the Hebrew University's Racah Institute of Physics.

Furthermore, simulation results obtained by Ph.D. student ?eljko Jeli? from Belgium suggest that by proper sample design and improved heat removal it should be possible to reach even higher velocities. In that regime, the calculated frequencies of penetration of vortices may be pushed to the much technologically desired THz frequency gap.

The research uncovers the rich physics of ultrafast vortices in superconducting films, and offers a broad outlook for further experimental and theoretical investigations. In the future, this technology could allow researchers to test designs that aim to reduce vortex motion and improve the properties of superconductors. [37]

## **Supercool breakthrough brings new quantum benchmark**

By gently prodding a swirling cloud of supercooled lithium atoms with a pair of lasers, and observing the atoms' response, researchers at Swinburne have developed a new way to probe the properties of quantum materials.

Quantum materials—a family that includes superfluids, superconductors, exotic magnets, ultracold atoms and recently-discovered 'topological insulators'—display on a large scale some of the remarkable quantum effects usually associated with microscopic and subatomic particles.

But, while quantum mechanics explains the behaviour of microscopic particles, applying quantum theory to larger systems is far more challenging.

"While the potential of quantum materials, such as superconductors, is undeniable, we need to fully grasp the underlying quantum physics at play in these systems to establish their true capabilities," says Chris Vale, an Associate Professor at the Centre for Quantum and Optical Science, who led the research. "That's a big part of the motivation for what we do."

Associate Professor Vale and his colleagues, including Sascha Hoinka and Paul Dyke, also at Swinburne, developed a new way to explore the behaviour of this family of materials. They detected when a 'Fermi gas' of lithium atoms, a simple quantum material, entered a quantum 'superfluid' state.

### **New system checks theories against experiment**

Their system allows theories of superconductivity and related quantum effects to be precisely checked against experiment, to see whether the theories are accurate and how they could be refined.

The researchers' advance was based on the fact that quantum materials' special properties emerge when their constituent particles enter a synchronised state. The zero-resistance flow of electrons through superconductors, for example, emerges when electrons can team up to form 'Cooper pairs'.

The team's sophisticated experimental set-up allowed this co-ordinated quantum behaviour to be detected. By fine-tuning the interaction of their lasers with the Fermi gas, Associate Professor Vale and his colleagues were for the first time able to detect the elusive, low energy Goldstone mode, an excitation that only appears in systems that have entered a synchronised quantum state.

"Because our experiment provides a well-controlled environment and the appearance of the Goldstone mode is very clear, our measurements provide a benchmark that quantum theories can

be tested against before they're applied to more complex systems like superconductors," Associate Professor Vale says.

"By developing methods to understand large systems that behave quantum mechanically, we're building the knowledge base that will underpin future quantum-enabled technologies." [36]

### **Tiny magnetic tremors unlock exotic superconductivity**

Deep within solids, individual electrons zip around on a nanoscale highway paved with atoms. For the most part, these electrons avoid one another, kept in separate lanes by their mutual repulsion. But vibrations in the atomic road can blur their lanes and sometimes allow the tiny particles to pair up. The result is smooth and lossless travel, and it's one way to create superconductivity.

But there are other, less common ways to achieve this effect. Scientists from the University of Maryland (UMD), the University of California, Irvine (UCI) and Fudan University have now shown that tiny magnetic tremors lead to superconductivity in a material made from metallic nano-layers. And, beyond that, the resulting electron pairs shatter a fundamental symmetry between past and future. Although the material is a known superconductor, these researchers provide a theoretical model and measurement, which, for the first time, unambiguously reveals the material's exotic nature.

In quantum materials, breaking the symmetry between the past and the future often signifies unconventional phases of matter. The nickel-bismuth (Ni-Bi) sample studied here is the first example of a 2-D material where this type of superconductivity is intrinsic, meaning that it happens without the help of external agents, such as a nearby superconductor. These findings, recently published in *Science Advances*, make Ni-Bi an appealing choice for use in future quantum computers. This research may also assist scientists in their search for other similarly strange superconductors.

Mehdi Kargarian, a postdoctoral researcher at UMD and a co-author of the paper, explains that even after a century of study, superconductivity remains a vibrant area of research. "It is a rather old problem, so it is surprising that people are still discovering types of superconductivity in the lab that are unprecedented," Kargarian says, adding that there are typically two questions scientists ask of a new superconductor. "First, we want to understand the underlying electron pairing—what is causing the superconductivity," he says. "The second thing, related to applications, is to see if superconductivity is possible at higher temperatures."

Superconductors, particularly the exotic types, largely remain shackled to unwieldy cryogenic equipment. Scientists are searching for ways to push superconducting temperatures higher, thus making these materials easier to use for things like improved electricity distribution and building quantum devices. In this new research, the team tackles Kargarian's first question and the material hints at a positive outlook for the second question. Its exotic superconductivity, although still cryogenic, occurs at a higher temperature compared to other similar systems.

Ni-Bi superconductivity was first observed in the early 1990s. But later, when Fudan University scientists published studies of an ultrapure, ultra-thin sample, they noticed something unusual happening.

The strangeness starts with the superconductivity itself. Bismuth alone is not a superconductor, except under extraordinarily low temperatures and high pressure—conditions that are not easy to achieve. Nickel is magnetic and not a superconductor. In fact, strong magnets are known to suppress



the effect. This means that too much nickel destroys the superconductivity, but a small amount induces it.

UMD theorists proposed that fluctuations in nickel's magnetism are at the heart of this peculiar effect. These tiny magnetic tremors help electrons to form pairs, thus doing the work performed by vibrations in conventional superconductors. If there is too much nickel, magnetism dominates and the effect of the fluctuations diminishes. If there is too much bismuth, then the top surface, where superconductivity takes place, is too far away from the source of magnetic fluctuations.

The goldilocks zone occurs when a twenty-nanometer-thick bismuth layer is grown on top of two nanometers of nickel. For this layer combination, superconductivity happens at around 4 degrees above absolute zero. While this is about as cold as deep space, it is actually quite lab-friendly and reachable using standard cryogenic equipment.

The idea that magnetic fluctuations can promote superconductivity is not new and dates back to the end of the 20th century. However, most earlier examples of such behavior require strict operating conditions, such as high pressure. The researchers explain that Ni-Bi is different because straightforward cooling is enough to achieve this type of exotic superconductivity, which breaks time symmetry.

The researchers employed a highly customized apparatus to search for signs of the broken symmetry. Light should rotate when reflected from samples that have this property. For Ni-Bi, the expected amount of light rotation is tens of nanoradians, which is about 100 billionths of a tick on a watch face. Jing Xia, a co-author of the paper and a professor at UCI, has one of the only devices in the world capable of measuring such an imperceptible light rotation.

In order to measure this rotation for Ni-Bi, light waves are first injected into one end of a single special-purpose optical fiber. The two waves travel through the fiber, as if on independent paths. They hit the sample and then retrace their paths. Upon return, the waves are combined and form a pattern. Rotations of the light waves—from, say, symmetry breaking—will show up in the analyzed pattern as small translations. Xia and his colleagues at UCI measured around 100 nanoradians of rotation, confirming the broken symmetry. Importantly, the effect appeared just as the Ni-Bi sample became a superconductor, suggesting that the broken time symmetry and the appearance of superconductivity are strongly linked.

This form of superconductivity is rare and researchers say that there is still no recipe for making it happen. But, as Xia points out, there is guidance in the math behind the electron behavior. "We know mathematically how to make electron pairs break time-reversal symmetry," Xia says. Practically, how do you achieve this formulaically? That is the million-dollar question. But my instinct is that when you do get magnetic fluctuation-mediated superconductivity, like in this material, then it is highly likely you get break that symmetry." [35]

## **New prototypes for superconducting undulators show promise for more powerful, versatile X-ray beams**

Researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and Argonne National Laboratory have collaborated to design, build and test two devices that

utilize different superconducting materials and could make X-ray lasers more powerful, versatile, compact and durable.

These prototype devices, called superconducting undulators (SCUs), successfully produced stronger magnetic fields than conventional permanent magnetic undulators of the same size. These fields, in turn, can produce higher-energy laser light to open up a broader range of experiments.

Several large-scale X-ray lasers are in the works around the globe to allow scientists to probe the properties of matter at ever smaller and faster scales, and superconducting undulators are considered among the most enabling technologies for the next generation of these and other types of light sources.

Such light sources are powerful tools for studying the microscopic structure and other properties of samples, such as proteins that are key to drug design, exotic materials relevant to electronics and energy applications, and chemistry that is central to industrial processes like fuel production.

The recent development effort was motivated by SLAC National Accelerator Laboratory's upgrade of its Linac Coherent Light Source (LCLS), which is the nation's only X-ray free-electron laser (FEL). The new project, now underway, is known as LCLS-II.

X-ray FELs now use permanent magnetic undulators to produce X-ray light by wiggling high-energy bunches of electrons in alternating magnetic fields produced by a sequence of permanent magnets.

But for the first time, Argonne scientists have demonstrated that a superconducting undulator could be used as a free-electron laser amplifier for the contemporary X-ray FELs.

The team at the Department of Energy's Advanced Photon Source (APS) at Argonne successfully built and tested a 1.5-meter-long prototype SCU magnet designed to meet FEL undulator requirements. This SCU utilizes niobium-titanium superconducting wire for winding its magnetic coils.

This significant achievement could pave the way to expanding the X-ray energy range at existing light sources without increasing the electron beam energy. This is an important point because the construction cost of light facilities is mainly defined by the energy of the electron beam, said Efim Gluskin, an Argonne Distinguished Fellow and a physicist and interim group leader of the Magnetic Devices Group in the APS's Accelerator Systems Division.

Gluskin said the niobium-titanium-based SCU has been designed to meet all challenging technical requirements applied to the X-ray FEL undulator, including high-precision field quality and consistency all along the magnet. In fact, it has been experimentally proven that this device has met all of these requirements. The APS SCU team has used in-house-developed cryogenic systems and magnetic measurement techniques to validate the SCU performance.

"The main challenge is to maintain the consistent wiggle motion of electrons inside of an SCU," said Gluskin, adding that the range of accepted deviation from the straight line of the beam motion across the distance of several meters is just a few microns. For comparison, an average human hair is 100 microns wide.

"That leads to very stringent requirements on the quality of the magnetic field generated by SCU magnets," Gluskin said.

SLAC's Paul Emma, the accelerator physics lead for the LCLS-II upgrade project coordinated the superconducting undulator development effort.

"With superconducting undulators," Emma said, "you don't necessarily lower the cost but you get better performance for the same stretch of undulator."

A superconducting undulator equivalent in length to a permanent magnetic undulator could produce light that is at least two to three times and perhaps up to 10 times more powerful, and could also access a wider range in X-ray wavelengths, Emma said. This produces a more efficient FEL.

Superconducting undulators have no macroscopic moving parts, so they could conceivably be tuned more quickly with high precision. Superconductors also are far less prone to damage by high-intensity radiation than permanent-magnet materials, a significant issue in high-power accelerators such as those that will be installed for LCLS-II.

There appears to be a clear path forward to developing superconducting undulators for upgrades of existing and new X-ray free-electron lasers, Emma said, and for other types of light sources.

"Superconducting undulators will be the technology we go to eventually, whether it's in the next 10 or 20 years," he said. "They are powerful enough to produce the light we are going to need – I think it's going to happen. People know it's a big enough step, and we've got to get there."

In this case, the APS team developed the technology of SCU construction to deliver a ready-to-go device right off the assembly bench.

"The SCU team found unique solutions for making this undulator performance within strict specifications of the LCLS undulator system," said Yury Ivanyushenkov, a physicist with the Argonne Accelerator Systems Division. "Over the years, the SCU team has put together a robust set of technological steps and processes to design and build state-of-the-art superconducting undulators that successfully operate at the APS. The success of this project is the direct result of the systems and facilities in place at the APS."

Geoffrey Pile, Associate Division Director of the APS Engineering Support Division at Argonne and former director of the APS LCLS-I undulator project, said the APS has a long history and expertise with designing and constructing undulators for the APS and other national labs.

One of the Argonne projects was the design and construction of the LCLS-I undulator system – 440 feet of sophisticated technical components that incorporated 33 cutting-edge undulators. The LCLS-I facility at the SLAC National Accelerator Laboratory has now been operating successfully for more than seven years.

In addition, APS scientists and engineers recently designed and built a revolutionary new Horizontal-Gap Vertically Polarizing Undulator prototype for the LCLS-II project. It was adopted and incorporated into the LCLS-II final design, and 32 production units will be constructed for SLAC by Lawrence Berkeley National Laboratory and industrial partners.

"For the past couple of decades, the APS engineering team has been constructing undulators for use at Argonne and across the country, and the SCU may be the most challenging project so far," Pile said. "It has moved the technology forward in leaps and bounds and highlights the expertise

throughout the APS. Importantly, many industrial partners, people at Argonne, and our collaborators at SLAC and Berkeley contributed to the success of this project and deserve credit."

Gluskin agreed: "The development of this prototype is a culmination of more than a decade of Argonne commitments to new and innovative SCU technology that will benefit all DOE light sources." [34]

## **Nickel for thought: Compound shows potential for high-temperature superconductivity**

A team of researchers at the U.S. Department of Energy's (DOE) Argonne National Laboratory has identified a nickel oxide compound as an unconventional but promising candidate material for high-temperature superconductivity.

The team successfully synthesized single crystals of a metallic trilayer nickelate compound, a feat the researchers believe to be a first.

"It's poised for superconductivity in a way not found in other nickel oxides. We're very hopeful that all we have to do now is find the right electron concentration."

This nickel oxide compound does not superconduct, said John Mitchell, an Argonne Distinguished Fellow and associate director of the laboratory's Materials Science Division, who led the project, which combined crystal growth, X-ray spectroscopy, and computational theory. But, he added, "It's poised for superconductivity in a way not found in other nickel oxides. We're very hopeful that all we have to do now is find the right electron concentration."

Mitchell and seven co-authors announced their results in this week's issue of Nature Physics.

Superconducting materials are technologically important because electricity flows through them without resistance. High-temperature superconductors could lead to faster, more efficient electronic devices, grids that can transmit power without energy loss and ultra-fast levitating trains that ride frictionless magnets instead of rails.

Only low-temperature superconductivity seemed possible before 1986, but materials that superconduct at low temperatures are impractical because they must first be cooled to hundreds of degrees below zero. In 1986, however, discovery of high-temperature superconductivity in copper oxide compounds called cuprates engendered new technological potential for the phenomenon.

But after three decades of ensuing research, exactly how cuprate superconductivity works remains a defining problem in the field. One approach to solving this problem has been to study compounds that have similar crystal, magnetic and electronic structures to the cuprates.

Nickel-based oxides - nickelates - have long been considered as potential cuprate analogs because the element sits immediately adjacent to copper in the periodic table. Thus far, Mitchell noted, "That's been an unsuccessful quest." As he and his co-authors noted in their Nature Physics paper, "None of these analogs have been superconducting, and few are even metallic."

The nickelate that the Argonne team has created is a quasi-two-dimensional trilayer compound, meaning that it consists of three layers of nickel oxide that are separated by spacer layers of praseodymium oxide.

"Thus it looks more two-dimensional than three-dimensional, structurally and electronically," Mitchell said.

This nickelate and a compound containing lanthanum rather than praseodymium both share the quasi-two-dimensional trilayer structure. But the lanthanum analog is non-metallic and adopts a so-called "charge-stripe" phase, an electronic property that makes the material an insulator, the opposite of a superconductor.

"For some yet-unknown reason, the praseodymium system does not form these stripes," Mitchell said. "It remains metallic and so is certainly the more likely candidate for superconductivity."

Argonne is one of a few laboratories in the world where the compound could be created. The Materials Science Division's high-pressure optical-image floating zone furnace has special capabilities. It can attain pressures of 150 atmospheres (equivalent to the crushing pressures found at oceanic depths of nearly 5,000 feet) and temperatures of approximately 2,000 degrees Celsius (more than 3,600 degrees Fahrenheit), conditions needed to grow the crystals.

"We didn't know for sure we could make these materials," said Argonne postdoctoral researcher Junjie Zhang, the first author on the study. But indeed, they managed to grow the crystals measuring a few millimeters in diameter (a small fraction of an inch).

The research team verified that the electronic structure of the nickelate resembles that of cupratematerials by taking X-ray absorption spectroscopy measurements at the Advanced Photon Source, a DOE Office of Science User Facility, and by performing density functional theory calculations. Materials scientists use density functional theory to investigate the electronic properties of condensed matter systems.

"I've spent my entire career not making high-temperature superconductors," Mitchell joked. But that could change in the next phase of his team's research: attempting to induce superconductivity in their nickelate material using a chemical process called electron doping, in which impurities are deliberately added to a material to influence its properties. [33]

### **Propagating "charge density wave" fluctuations are seen in superconducting copper oxides for the first time**

An international team led by scientists from the Department of Energy's SLAC National Accelerator Laboratory and Stanford University has detected new features in the electronic behavior of a copper oxide material that may help explain why it becomes a perfect electrical conductor – a superconductor – at relatively high temperatures.

Using an ultrahigh-resolution X-ray instrument in France, the researchers for the first time saw dynamic behaviors in the material's charge density wave (CDW) – a pattern of electrons that resembles a standing wave – that lend support to the idea that these waves may play a role in high-temperature superconductivity.

Data taken at low (20 kelvins) and high (240 kelvins) temperatures showed that as the temperature increased, the CDW became more aligned with the material's atomic structure. Remarkably, at the lower temperature, the CDW also induced an unusual increase in the intensity of the oxide's atomic lattice vibrations, indicating that the dynamic CDW behaviors can propagate through the lattice.

"Previous research has shown that when the CDW is static, it competes with and diminishes superconductivity," said co-author Wei-Sheng Lee, a SLAC staff scientist and investigator with the Stanford Institute for Materials and Energy Sciences (SIMES), which led the study published June 12 in *Nature Physics*. "If, on the other hand, the CDW is not static but fluctuating, theory tells us they may actually help form superconductivity."

#### A Decades-long Search for an Explanation

The new result is the latest in a decades-long search by researchers worldwide for the factors that enable certain materials to become superconducting at relatively high temperatures.

Since the 1950s, scientists have known how certain metals and simple alloys become superconducting when chilled to within a few degrees of absolute zero: Their electrons pair up and ride waves of atomic vibrations that act like a virtual glue to hold the pairs together. Above a certain temperature, however, the glue fails as thermal vibrations increase, the electron pairs split up and superconductivity disappears.

In 1986, complex copper oxide materials were found to become superconducting at much higher – although still quite cold – temperatures. This discovery was so unexpected it caused a worldwide scientific sensation. By understanding and optimizing how these materials work, researchers hope to develop superconductors that work at room temperature and above.

At first, the most likely glue holding superconducting electron pairs together at higher temperatures seemed to be strong magnetic excitations created by interactions between electron spins. But in 2014, a theoretical simulation and experiments led by SIMES researchers concluded that these high-energy magnetic interactions are not the sole factor in copper oxide's high-temperature superconductivity. An unanticipated CDW also appeared to be important.

The latest results continue the SIMES collaboration between experiment and theory. Building upon previous theories of how electron interactions with lattice vibrations can be probed with resonant inelastic X-ray scattering, or RIXS, the signature of CDW dynamics was finally identified, providing additional support for the CDW's role in determining the electronic structure in superconducting copper oxides.

#### **The Essential New Tool: RIXS**

The new results are enabled by the development of more capable instruments employing RIXS. Now available at ultrahigh resolution at the European Synchrotron Radiation Facility (ESRF) in France, where the team performed this experiment, RIXS will also be an important feature of SLAC's upgraded Linac Coherent Light Source X-ray free-electron laser, LCLS-II. The combination of ultrahigh energy resolution and a high pulse repetition rate at LCLS-II will enable researchers to see more detailed CDW fluctuations and perform experiments aimed at revealing additional details of its behavior and links to high-temperature superconductivity. Most importantly, researchers at LCLS-II

will be able to use ultrafast light-matter interactions to control CDW fluctuations and then take femtosecond-timescale snapshots of them.

RIXS involves illuminating a sample with X-rays that have just enough energy to excite some electrons deep inside the target atoms to jump up into a specific higher orbit. When the electrons relax back down into their previous positions, a tiny fraction of them emit X-rays that carry valuable atomic-scale information about the material's electronic and magnetic configuration that is thought to be important in high-temperature superconductivity.

"To date, no other technique has seen evidence of propagating CDW dynamics," Lee said.

RIXS was first demonstrated in the mid-1970s, but it could not obtain useful information to address key problems until 2007, when Giacomo Ghiringhelli, Lucio Braicovich at Milan Polytechnic in Italy and colleagues at Swiss Light Source made a fundamental change that improved its energy resolution to a level where significant details became visible – technically speaking to about 120 milli-electronvolts (meV) at the relevant X-ray wavelength, which is called a copper L edge. The new RIXS instrument at ESRF is three times better, routinely attaining an energy resolution down to 40 meV. Since 2014, the Milan group has collaborated with SLAC and Stanford scientists in their RIXS research.

"The new ultrahigh resolution RIXS makes a huge difference," Lee said. "It can show us previously invisible details." [32]

### **New clues emerge in 30-year-old superconductor mystery**

One of the greatest mysteries of experimental physics is how so-called high-temperature superconducting materials work. Despite their name, high-temperature superconductors—materials that carry electrical current with no resistance—operate at chilly temperatures less than minus 135 degrees Celsius. They can be used to make superefficient power cables, medical MRIs, particle accelerators, and other devices. Cracking the mystery of how these materials actually work could lead to superconducting devices that operate at room temperatures—and could revolutionize electrical devices, including laptops and phones.

In a new paper in the journal *Nature Physics*, researchers at Caltech have at last solved one piece of this enduring puzzle. They have confirmed that a transitional phase of matter called the pseudogap—one that occurs before these materials are cooled down to become superconducting—represents a distinct state of matter, with properties very different from those of the superconducting state itself.

When matter transitions from one state, or phase, to another—say, water freezing into ice—there is a change in the ordering pattern of the materials' particles. Physicists previously had detected hints of some type of ordering of electrons inside the pseudogap state. But exactly how they were ordering—and whether that ordering constituted a new state of matter—was unclear until now.

"A peculiar property of all these high-temperature superconductors is that just before they enter the superconducting state, they invariably first enter the pseudogap state, whose origins are equally if not more mysterious than the superconducting state itself," says David Hsieh, professor of physics at Caltech and principal investigator of the new research. "We have discovered that in the pseudogap state, electrons form a highly unusual pattern that breaks nearly all of the symmetries of space. This

provides a very compelling clue to the actual origin of the pseudogap state and could lead to a new understanding of how high-temperature superconductors work."

The phenomenon of superconductivity was first discovered in 1911. When certain materials are chilled to super-cold temperatures, as low as a few degrees above absolute zero (a few degrees Kelvin), they carry electrical current with no resistance, so that no heat or energy is lost. In contrast, our laptops are not made of superconducting materials and therefore experience electrical resistance and heat up.

Chilling materials to such extremely low temperatures requires liquid helium. However, because liquid helium is rare and expensive, physicists have been searching for materials that can function as superconductors at ever-higher temperatures. The so-called high-temperature superconductors, discovered in 1986, are now known to operate at temperatures up to 138 Kelvin (minus 135 degrees Celsius) and thus can be cooled with liquid nitrogen, which is more affordable than liquid helium. The question that has eluded physicists, however—despite three Nobel Prizes to date awarded in the field of superconductivity—is exactly how high-temperature superconductors work.

### **The dance of superconducting electrons**

Materials become superconducting when electrons overcome their natural repulsion and form pairs. This pairing can occur under extremely cold temperatures, allowing the electrons, and the electrical currents they carry, to move unencumbered. In conventional superconductors, electron pairing is caused by natural vibrations in the crystal lattice of the superconducting material, which act like glue to hold the pairs together.

But in high-temperature superconductors, this form of "glue" is not strong enough to bind the electron pairs. Researchers think that the pseudogap, and how electrons order themselves in this phase, holds clues about what this glue may constitute for high-temperature superconductors. To study electron ordering in the pseudogap, Hsieh and his team have invented a new laser-based method called nonlinear optical rotational anisotropy. In the method, a laser is pointed at the superconducting material; in this case, crystals of yttrium barium copper oxide (YBa<sub>2</sub>Cu<sub>3</sub>O<sub>y</sub>). An analysis of the light reflected back at half the wavelength compared to that going in reveals any symmetry in the arrangement of the electrons in the crystals.

### **Broken symmetries point to new phase**

Different phases of matter have distinct symmetries. For example, when water turns into ice, physicists say the symmetry has been "broken."

"In water," Hsieh explains, "the H<sub>2</sub>O molecules are pretty randomly oriented. If you were swimming in an infinite pool of water, your surroundings look the same no matter where you are. In ice, on the other hand, the H<sub>2</sub>O molecules form a regular periodic network, so if you imagine yourself submerged in an infinite block of ice, your surroundings appear different depending on whether you are sitting on an H or O atom. Therefore, we say that the translational symmetry of space is broken in going from water to ice."

With the new tool, Hsieh's team was able to show that the electrons cooled to the pseudogap phase broke a specific set of spatial symmetries called inversion and rotational symmetry. "As soon as the system entered the pseudogap region, either as a function of temperature or the amount of oxygen



in the compound, there was a loss of inversion and rotational symmetries, clearly indicating a transition into a new phase of matter," says Liuyan Zhao, a postdoctoral scholar in the Hsieh lab and lead author of the new study. "It is exciting that we are using a new technology to solve an old problem."

"The discovery of broken inversion and rotational symmetries in the pseudogap drastically narrows down the set of possibilities for how the electrons are self-organizing in this phase," says Hsieh. "In some ways, this unusual phase may turn out to be the most interesting aspect of these superconducting materials."

With one piece of the puzzle solved, the researchers are on to the next. They want to know what role this ordering of electrons in the pseudogap plays in inducing high-temperature superconductivity—and how to make it happen at even higher temperatures. [31]

### Manipulating quantum order

Cool a material to sufficiently low temperatures and it will seek some form of collective order. Add quantum mechanics or confine the geometry and the states of matter that emerge can be exotic, including electrons whose spins arrange themselves in spirals, pinwheels, or crystals.

In a recent pair of publications in *Nature Communications*, teams led by Caltech's Thomas F. Rosenbaum, professor of physics and holder of the Sonja and William Davidow Presidential Chair, report how they have combined magnetic fields and large pressures to not only induce these states at ultra-low temperatures, but also to nudge them between competing types of quantum order.

Rosenbaum is an expert on the quantum mechanical nature of materials—the physics of electronic, magnetic, and optical materials at the atomic level—that are best observed at temperatures near absolute zero. In the first of the two papers, published in June and led by Sara Haravifard, now on the faculty at Duke University, the team squeezed a collection of magnetic quantum particles in a pressure cell at temperatures near absolute zero and at magnetic fields more than 50,000 times stronger than the earth's field, and discovered the formation of new types of crystal patterns. The geometry of these crystal patterns not only reveals the underlying quantum mechanics of the interactions between the magnetic particles, but also bears on the kinds of collective states allowed for atomic systems, such as those that flow without friction.

In the work in the second paper, published in October and led by Caltech graduate student Yishu Wang and Argonne scientist Yejun Feng, Rosenbaum and colleagues also investigate how materials balance on the knife edge between different types of quantum order. In this case, however, the researchers focus on the relationship between magnetism and superconductivity—the complete disappearance of electrical resistance—and how those properties relate to one another when the material changes state under the pressures achievable in a diamond anvil cell.

The researchers used the Advanced Photon Source at Argonne National Laboratory to study the magnetic properties of the transition metal manganese phosphide (MnP) to see how it might be possible to manipulate the ordering of the spins—the intrinsic magnetic moments of the electrons—to either enhance or suppress the onset of superconductivity.

Superconductivity is a state in a material in which there is no resistance to electric current and all magnetic fields are expelled. This behavior arises from a so-called "macroscopic quantum state"

where all the electrons in a material act in concert to move cooperatively through the material without energy loss.

Rosenbaum and his colleagues delineated a spiral pattern of the magnetic moments of the electrons in MnP that could be tuned by increasing pressure to induce superconductivity. Here again the particular geometry of the magnetic pattern held the key to the ultimate state that the material reached. "The experiments reveal manifest opportunities to find new low-energy states via substitutions for manganese and phosphorus with neighboring elements from the periodic table such as chromium and arsenic. The taxonomy of allowable quantum states and the ability to manipulate them unites approaches across quantum physics and technology," Rosenbaum says.

The first paper, "Crystallization of spin superlattices with pressure and field in the layered magnet  $\text{SrCu}_2(\text{BO}_3)_2$ ," was published on June 20, 2016. Coauthors include Daniel M. Silevitch, research professor of physics at Caltech. Work at Caltech was supported by the National Science Foundation. The research in the second paper, entitled "Spiral magnetic order and pressure-induced superconductivity in transition metal compounds" and published on October 6, was funded at Caltech by a U.S. Department of Energy Basic Energy Sciences award. [30]

### **Physicists pass spin information through a superconductor**

Researchers from the Harvard John A. Paulson School of Engineering and Applied Sciences (SEAS) have made a discovery that could lay the foundation for quantum superconducting devices. Their breakthrough solves one of the main challenges to quantum computing: how to transmit spin information through superconducting materials.

Every electronic device—from a supercomputer to a dishwasher—works by controlling the flow of charged electrons. But electrons can carry so much more information than just charge; electrons also spin, like a gyroscope on axis.

Harnessing electron spin is really exciting for quantum information processing because not only can an electron spin up or down—one or zero—but it can also spin any direction between the two poles. Because it follows the rules of quantum mechanics, an electron can occupy all of those positions at once. Imagine the power of a computer that could calculate all of those positions simultaneously.

A whole field of applied physics, called spintronics, focuses on how to harness and measure electron spin and build spin equivalents of electronic gates and circuits.

By using superconducting materials through which electrons can move without any loss of energy, physicists hope to build quantum devices that would require significantly less power.

### **But there's a problem.**

According to a fundamental property of superconductivity, superconductors can't transmit spin. Any electron pairs that pass through a superconductor will have the combined spin of zero.

In work published recently in *Nature Physics*, the Harvard researchers found a way to transmit spin information through superconducting materials.

"We now have a way to control the spin of the transmitted electrons in simple superconducting devices," said Amir Yacoby, Professor of Physics and of Applied Physics at SEAS and senior author of the paper.

### **A new spin on superconductivity**

It's easy to think of superconductors as particle super highways but a better analogy would be a super carpool lane as only paired electrons can move through a superconductor without resistance.

These pairs are called Cooper Pairs and they interact in a very particular way. If the way they move in relation to each other (physicists call this momentum) is symmetric, then the pair's spin has to be asymmetric—for example, one negative and one positive for a combined spin of zero. When they travel through a conventional superconductor, Cooper Pairs' momentum has to be zero and their orbit perfectly symmetrical.

But if you can change the momentum to asymmetric—leaning toward one direction—then the spin can be symmetric. To do that, you need the help of some exotic (aka weird) physics.

Superconducting materials can imbue non-superconducting materials with their conductive powers simply by being in close proximity. Using this principle, the researchers built a superconducting sandwich, with superconductors on the outside and mercury telluride in the middle. The atoms in mercury telluride are so heavy and the electrons move so quickly, that the rules of relativity start to apply.

"Because the atoms are so heavy, you have electrons that occupy high-speed orbits," said Hechen Ren, coauthor of the study and graduate student at SEAS.

"When an electron is moving this fast, its electric field turns into a magnetic field which then couples with the spin of the electron. This magnetic field acts on the spin and gives one spin a higher energy than another."

So, when the Cooper Pairs hit this material, their spin begins to rotate.

"The Cooper Pairs jump into the mercury telluride and they see this strong spin orbit effect and start to couple differently," said Ren. "The homogenous breed of zero momentum and zero combined spin is still there but now there is also a breed of pairs that gains momentum, breaking the symmetry of the orbit. The most important part of that is that the spin is now free to be something other than zero."

The team could measure the spin at various points as the electron waves moved through the material. By using an external magnet, the researchers could tune the total spin of the pairs.

"This discovery opens up new possibilities for storing quantum information. Using the underlying physics behind this discovery provides also new possibilities for exploring the underlying nature of superconductivity in novel quantum materials," said Yacoby. [29]

### **Stable molecular state of photons and artificial atom discovered**

Researchers at the National Institute of Information and Communications Technology, in collaboration with researchers at the Nippon Telegraph and Telephone Corporation and the Qatar Environment and Energy Research Institute have discovered qualitatively new states of a

superconducting artificial atom dressed with virtual photons. The discovery was made using spectroscopic measurements on an artificial atom that is very strongly coupled to the light field inside a superconducting cavity. This result provides a new platform to investigate the interaction between light and matter at a fundamental level, helps understand quantum phase transitions and provides a route to applications of non-classical light such as Schrödinger cat states. It may contribute to the development of quantum technologies in areas such as quantum communication, quantum simulation and computation, or quantum metrology.

This result will be published online in the October 10 issue of the journal Nature Physics.

The indispensable technologies in modern life such as a time system measured by an atomic clock and a secure and energy-efficient communications system are based on the fundamental science of the interaction between light and matter at the single-photon level. The absorption and emission of light from any device is explained based on the interaction of light and atoms. A fundamental question in atomic physics, "How strong can the coupling of light and an atom be?" has not been answered in spite of years of research, because it is not easy to find appropriate methods to realize very strong coupling.

It was predicted over forty years ago that if the coupling is extremely strong a qualitatively new lowest energy state (the ground state) of light and an atom should be realized. A debate soon started as to whether this prediction would still apply when realistic conditions are considered. A few years ago, our collaborator at QEERI, Dr. Sahel Ashhab, performed theoretical investigations and identified desirable conditions for achieving this new state using superconducting circuits.

In the experiment, we used a microfabricated superconducting harmonic oscillator and a superconducting artificial atom (quantum bit or qubit) whose electronic states behave quantum mechanically, just like a natural atom. By carefully designing a superconducting persistent-current qubit interacting with an LC harmonic oscillator that has a large zero-point fluctuation current via a large shared Josephson inductance, we found the new ground state as predicted theoretically.

The total energy of the qubit and the oscillator is the sum of the photon energy in the oscillator, the qubit energy, and the coupling energy binding the photons to the qubit. Taking advantage of the macroscopic quantum system, we could realize circuits with coupling energy larger than both the photon energy and the qubit energy.

This situation is sometimes called 'deep strong coupling'.

In addition, we have observed that the transitions between energy levels are governed by selection rules stemming from the symmetry of the entangled energy eigenstates, including the ground state.

We plan to test whether deep strong coupling is possible or not using more than one superconducting artificial atom (qubit), which remains a question of debate.

We will also try to actively manipulate this new molecular state of photons and artificial atoms, for example, to observe and control the dynamics of photon absorption and emission, and to demonstrate new methods of entanglement generation. [28]

## Scientists develop a control system for rapid superconducting memory cells

A group of scientists from Moscow Institute of Physics and Technology and from the Moscow State University has developed a fundamentally new type of memory cell based on superconductors – this type of memory works hundreds of times faster than the memory devices commonly used today, according to an article published in the journal *Applied Physics Letters*.

"With the operational function that we have proposed in these memory cells, there will be no need for time-consuming magnetization and demagnetization processes. This means that read and write operations will take only a few hundred picoseconds, depending on the materials and the geometry of the particular system, while conventional methods take hundreds or thousands of times longer than this," said the study author Alexander Golubov, the head of MIPT's Laboratory of Quantum Topological Phenomena in Superconducting Systems.

Golubov and his colleagues have proposed creating basic memory cells based on quantum effects in superconductor "sandwiches." Superconductors were predicted in the 1960s by the British physicist Brian Josephson. The electrons in these "sandwiches," called "Josephson junctions," are able to tunnel from one layer of a superconductor to another, passing through the dielectric like balls passing through a perforated wall.

Today, Josephson junctions are used both in quantum devices and conventional devices. For example, superconducting qubits are used to build the D-wave quantum system, which is capable of finding the minima of complex functions using the quantum annealing algorithm. There are also ultra-fast analogue-to-digital converters, devices to detect consecutive events, and other systems that do not require fast access to large amounts of memory. There have also been attempts to use the Josephson Effect to create ordinary processors. An experimental processor of this type was created in Japan in the late 1980s. In 2014, the research agency IAPRA resumed its attempts to create a prototype of a superconducting computer.

Josephson junctions with ferromagnets used as the middle of the "sandwich" are currently of greatest practical interest. In memory elements that are based on ferromagnets, information is encoded in the direction of the magnetic field vector in the ferromagnet. However, there are two fundamental flaws with this process: first, the "packaging" of the memory elements has a very low density—additional chains need to be added to provide extra charge for the cells when reading or writing data. And second, the magnetization vector cannot be changed quickly, which limits the writing speed.

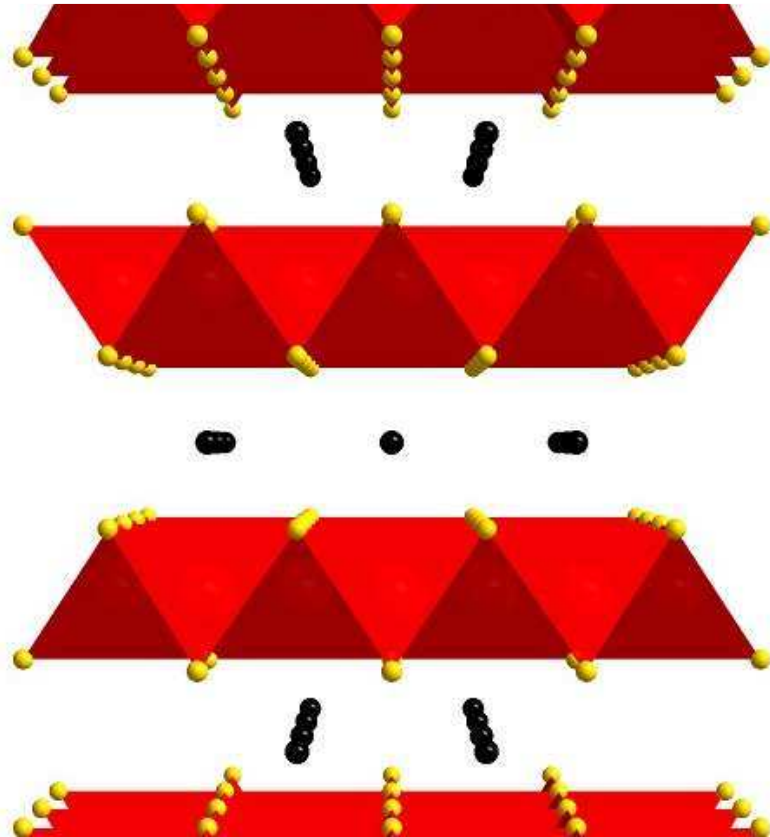
The researchers proposed encoding the data in Josephson cells in the value of the superconducting current. By studying the superconductor-normal metal/ferromagnet-superconductor-insulator-superconductor junctions, the scientists discovered that in certain longitudinal and transverse dimensions, the layers of the system may have two energy minima, meaning they are in one of two different states. These two minima can be used to record data—zeros and ones.

In order to switch the system from "zero" to "one" and back again, the scientists have suggested using injection currents flowing through one of the layers of the superconductor. They propose to read the status using the current that flows through the whole structure. These operations can be

performed hundreds of times faster than measuring the magnetization or magnetization reversal of a ferromagnet.

"In addition, our method requires only one ferromagnetic layer, which means that it can be adapted to so-called single flux quantum logic circuits, and this means that there will be no need to create an entirely new architecture for a processor. A computer based on single flux quantum logic can have a clock speed of hundreds of gigahertz, and its power consumption will be dozens of times lower," said Golubov. [27]

### Linking superconductivity and structure



Although superconductivity has many practical applications for electronics (including scientific research instruments), medical engineering (MRI and NMR machines), and potential future applications including high-performance power transmission and storage, and very fast train travel, the difficulty of creating superconducting materials prevents it from being used to its full potential. As such, any newly discovered superconducting ability is of great interest to scientists and engineers.

Iron arsenides are relatively recently discovered superconductors. The nature of superconductivity in these particular materials remains a challenge for modern solid state physics. If the complex links between superconductivity, structure, and magnetism in these materials are unlocked, then iron arsenides could potentially be used to reveal superconductivity at much higher temperatures than previously seen, which would vastly increase the ease of practical applications for superconductivity.

When iron arsenide is combined with a metal—such as in the sodium-containing  $\text{NaFe}_2\text{As}_2$  compound studied here—it was known that the ensuing compound is crystallized in a tetrahedral

structure. But until now, a detailed structure of the atomic positions involved and how they change under pressure had not been determined.

The layering of arsenic and iron (As-Fe-As) in this structure is believed to be key to the compound's superconductivity. However, under pressure, this structure is thought to be partially misshapen into a so-called collapsed tetragonal lattice, which is no longer capable of superconducting, or has diminished superconducting ability.

The team used experimental evidence and modeling under pressure to actually demonstrate these previously theorized structural changes—tetragonal to collapsed tetragonal—on the atomic level. This is just the first step toward definitively determining the link between structure and superconductivity, which could potentially make higher-temperature superconductivity a real possibility.

They showed that at about 40,000 times normal atmospheric pressure (4 gigapascals), NaFe<sub>2</sub>As<sub>2</sub> takes on the collapsed tetragonal structure. This changes the angles in the arsenic-iron-arsenic layers and is coincident with the loss in superconductivity. Moreover, they found that this transition is accompanied by a major change in bonding coordination in the formation of the interlayer arsenic-arsenic bonds. A direct consequence of this new coordination is that the system loses its two-dimensionality, and with it, superconductivity.

"Our findings are an important step in identifying the hypothesized connection between structure and superconductivity in iron-containing compounds," Goncharov said. "Understanding the loss of superconductivity on an atomic level could enhance our ease of manufacturing such compounds for practical applications, as well as improving our understanding of condensed matter physics." [26]

### Conventional superconductivity

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

### High-temperature superconductivity

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

### Superconductivity and magnetic fields

Superconductivity and magnetic fields are normally seen as rivals – very strong magnetic fields normally destroy the superconducting state. Physicists at the Paul Scherer Institute have now demonstrated that a novel superconducting state is only created in the material CeCoIn<sub>5</sub> when there are strong external magnetic fields. This state can then be manipulated by modifying the field

direction. The material is already superconducting in weaker fields, too. In strong fields, however, an additional second superconducting state is created which means that there are two different superconducting states at the same time in the same material. The new state is coupled with an anti-ferromagnetic order that appears simultaneously with the field. The anti-ferromagnetic order from whose properties the researchers have deduced the existence of the superconducting state was detected with neutrons at PSI and at the Institute Laue-Langevin in Grenoble. [6]

### Room-temperature superconductivity

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

### Exciton-mediated electron pairing

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

### Resonating valence bond theory

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

### Strongly correlated materials

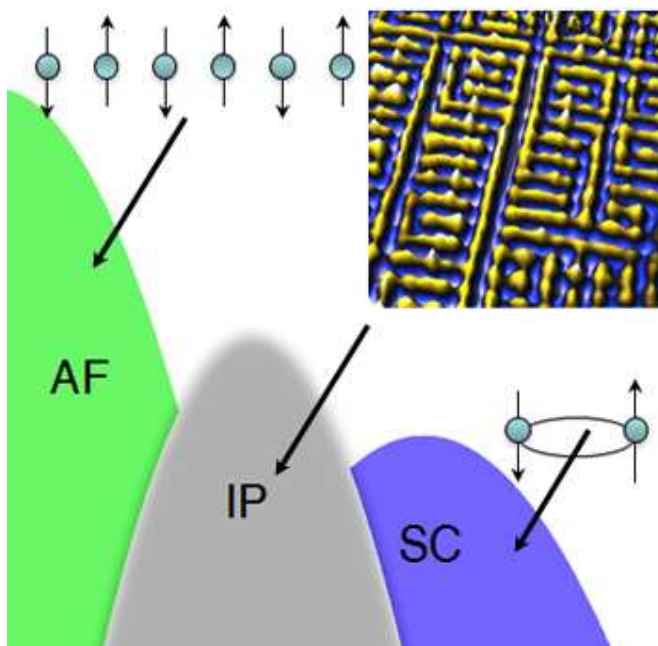
Strongly correlated materials are a wide class of electronic materials that show unusual (often technologically useful) electronic and magnetic properties, such as metal-insulator transitions or half-metallicity. The essential feature that defines these materials is that the behavior of their electrons cannot be described effectively in terms of non-interacting entities. Theoretical models of the electronic structure of strongly correlated materials must include electronic correlation to be accurate. Many transition metal oxides belong into this class which may be subdivided according to their behavior, e.g. high- $T_c$ , spintronic materials, Mott insulators, spin Peierls materials, heavy fermion materials, quasi-low-dimensional materials, etc. The single most intensively studied effect is probably high-temperature superconductivity in doped cuprates, e.g.  $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ . Other ordering or



magnetic phenomena and temperature-induced phase transitions in many transition-metal oxides are also gathered under the term "strongly correlated materials." Typically, strongly correlated materials have incompletely filled *d*- or *f*-electron shells with narrow energy bands. One can no longer consider any electron in the material as being in a "sea" of the averaged motion of the others (also known as mean field theory). Each single electron has a complex influence on its neighbors. [11]

### **New superconductor theory may revolutionize electrical engineering**

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



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

### **Unconventional superconductivity in $\text{Ba}^{0.6}\text{K}^{0.4}\text{Fe}_2\text{As}_2$ from inelastic neutron scattering**

In BCS superconductors, the energy gap between the superconducting and normal electronic states is constant, but in unconventional superconductors the gap varies with the direction the electrons are moving. In some directions, the gap may be zero. The puzzle is that the gap does not seem to vary with direction in the iron arsenides. Theorists have argued that, while the size of the gap shows

no directional dependence in these new compounds, the sign of the gap is opposite for different electronic states. The standard techniques to measure the gap, such as photoemission, are not sensitive to this change in sign.

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

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

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

## **A grand unified theory of exotic superconductivity?**

### **The role of magnetism**

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

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

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

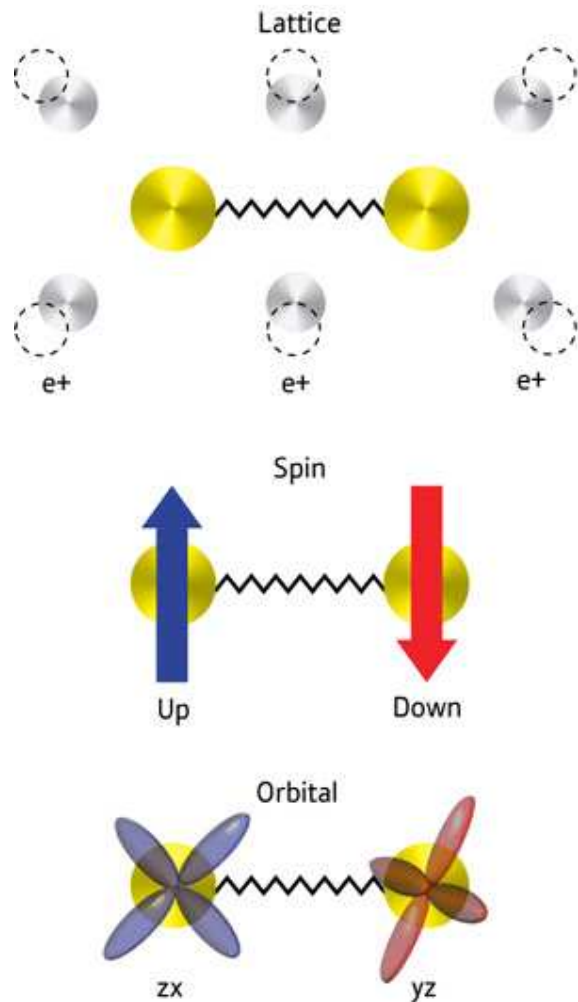
## Concepts relating magnetic interactions, intertwined electronic orders, and strongly correlated superconductivity

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

### Significance

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

## Superconductivity's third side unmasked



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

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

## Strongly correlated materials

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

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

## Fermions and Bosons

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

## The General Weak Interaction

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

## Higgs Field and Superconductivity

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

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

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

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

neutralize them. The Meissner effect is due to currents in a thin surface layer, whose thickness, the London penetration depth, can be calculated from a simple model (the Ginzburg–Landau theory).

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

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

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

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

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

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

The condensate wave function can be written as

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

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

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

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

and taking the density of the condensate  $\rho$  to be constant,

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

## Conclusions

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

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

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

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

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