

# Researchers Create Time Crystals

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*Researchers from the Foundation for Fundamental Research on Matter and the University of Amsterdam (the Netherlands), together with researchers from the Institute for Materials Science in Tsukuba (Japan), have discovered an exceptional new quantum state within a superconducting material. This exceptional quantum state is characterised by a broken rotational symmetry – in other words, if you turn the material in a magnetic field, the superconductivity isn't the same everywhere in the material. [27]*

*Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, Cornell University, and collaborators have produced the first direct evidence of a state of electronic matter first predicted by theorists in 1964. The discovery, described in a paper published online April 13, 2016, in Nature, may provide key insights into the workings of high-temperature superconductors. [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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## Researchers create 'time crystals' envisioned by Princeton scientists

Time crystals may sound like something from science fiction, having more to do with time travel or Dr. Who. These strange materials—in which atoms and molecules are arranged across space and time—are in fact quite real, and are opening up entirely new ways to think about the nature of matter. They also eventually may help protect information in futuristic devices known as quantum computers.

Two groups of researchers based at Harvard University and the University of Maryland report March 9 in the journal *Nature* that they have successfully created time crystals using theories developed at Princeton University. The Harvard-based team included scientists from Princeton who played fundamental roles in working out the theoretical understanding that led to the creation of these exotic crystals.

"Our work discovered the essential physics of how time crystals function," said Shivaji Sondhi, a Princeton professor of physics. "What is more, this discovery builds on a set of developments at Princeton that gets at the issue of how we understand complex systems in and out of equilibrium, which is centrally important to how physicists explain the nature of the everyday world."

In 2015, Sondhi and colleagues including then-graduate student Vedika Khemani, who earned her Ph.D. at Princeton in 2016 and is now a junior fellow at Harvard, as well as collaborators Achilleas Lazarides and Roderich Moessner at the Max Planck Institute for the Physics of Complex Systems in Germany, published the theoretical basis for how time crystals—at first considered impossible—could actually exist. Published in the journal *Physics Review Letters* in June 2016, the paper spurred conversations about how to build such crystals.

Ordinary crystals such as diamonds, quartz or ice are made up of molecules that spontaneously arrange into orderly three-dimensional patterns. The sodium and chlorine atoms in a crystal of salt, for example, are spaced at regular intervals, forming a hexagonal lattice.

In time crystals, however, atoms are arranged in patterns not only in space, but also in time. In addition to containing a pattern that repeats in space, time crystals contain a pattern that repeats over time. One way this could happen is that the atoms in the crystal move at a certain rate. Were a time crystal of ice to exist, all of the water molecules would vibrate at an identical frequency. What is more, the molecules would do this without any input from the outside world.

The concept of time crystals originated with physicist Frank Wilczek at the Massachusetts Institute of Technology. In 2012, the Nobel laureate and former Princeton faculty member was thinking about the similarities between space and time. In physics parlance, crystals are said to "break translational symmetry in space" because the atoms assemble into rigid patterns rather than being evenly spread out, as they are in a liquid or gas. Shouldn't there also be crystals that break translational symmetry in time?

"The atoms move in time, but instead of moving in a fluid or continuous way, they move in a periodic way," Sondhi said. "It was an interesting idea." It also was an idea that led to hot debates in

the physics journals about whether such crystals could exist. The initial conclusion appeared to be that they could not, at least not in the settings Wilczek visualized.

Sondhi and Khemani were thinking about a completely different problem in 2015 when they worked out the theory of how time crystals could exist. They were exploring questions about how atoms and molecules settle down, or come to equilibrium, to form phases of matter such as solids, liquids and gases.

While it was common wisdom among physicists that all systems eventually settle down, work during the last decade or so had challenged that notion, specifically among atoms at very low temperatures where the rules of quantum physics apply. It was realized that there are systems that never go to equilibrium because of a phenomenon called "many-body localization," which occurs due to the behavior of many atoms in a disordered quantum system that are influencing each other.

Work in this area is a long Princeton tradition. The first and seminal concept of how quantum systems can be localized when they are disordered, called Anderson localization, stemmed from work by Philip Anderson, a Princeton professor and Nobel laureate, in 1958. This work was extended in 2006 to systems of many atoms by then Princeton professor Boris Altshuler, postdoctoral fellow Denis Basko, and Igor Aleiner of Columbia University.

While on sabbatical at the Max Planck Institute for the Physics of Complex Systems in Germany, Sondhi and Khemani realized that these ideas about how to prevent systems from reaching equilibrium would enable the creation of time crystals. A system in equilibrium cannot be a time crystal, but non-equilibrium systems can be created by periodically poking, or "driving," a crystal by shining a laser on its atoms. To the researchers' surprise, their calculations revealed that periodically prodding atoms that were in non-equilibrium many-body localized phases would cause the atoms to move at a rate that was twice as slow—or twice the period—as the initial rate at which they were prodded.

To explain, Sondhi compared the driving of the quantum system to squeezing periodically on a sponge. "When you release the sponge, you expect it to resume its shape. Imagine now that it only resumes its shape after every second squeeze even though you are applying the same force each time. That is what our system does," he said.

Princeton postdoctoral researcher Curt von Keyserlingk, who contributed additional theoretical work with Khemani and Sondhi, said, "We explained how the time crystal systems lock into the persistent oscillations that signify a spontaneous breaking of time translation symmetry." Additional work by researchers at Microsoft's Station Q and the University of California-Berkeley led to further understanding of time crystals.

As a result of these theoretical studies, two groups of experimenters began attempting to build time crystals in the laboratory. The Harvard-based team, which included Khemani at Harvard and von Keyserlingk at Princeton, used an experimental setup that involved creating an artificial lattice in a synthetic diamond. A different approach at the University of Maryland used a chain of charged particles called ytterbium ions. Both teams have now published the work this week in *Nature*.

Both systems show the emergence of time crystalline behavior, said Christopher Monroe, a physicist who led the effort at the University of Maryland. "Although any applications for this work are far in

the future, these experiments help us learn something about the inner workings of this very complex quantum state," he said.

The research may eventually lead to ideas about how to protect information in quantum computers, which can be disrupted by interference by the outside world. Many-body localization can protect quantum information, according to research published in 2013 by the Princeton team of David Huse, the Cyrus Fogg Brackett Professor of Physics, as well as Sondhi and colleagues Rahul Nandkishore, Vadim Oganesyan and Arijeet Pal. The research also sheds light on ways to protect topological phases of matter, research for which Princeton's F. Duncan Haldane, the Eugene Higgins Professor of Physics, shared the 2016 Nobel Prize in Physics.

Sondhi said that the work addresses some of the most fundamental questions about the nature of matter. "It was thought that if a system doesn't settle down and come to equilibrium, you couldn't really say that it is in a phase. It is a big deal when you can give a definition of a phase of matter when the matter is not in equilibrium," he said.

This out-of-equilibrium setting has enabled the realization of new and exciting phases of matter, according to Khemani. "The creation of time crystals has allowed us to add an entry into the catalog of possible orders in space-time, previously thought impossible," Khemani said.

The papers "Observation of discrete time-crystalline order in a disordered dipolar many-body system" and "Observation of a discrete time crystal" were published March 9 by Nature. [30]

## **Physicists unveil new form of matter—time crystals**

Normal crystals, like diamond, are an atomic lattice that repeats in space, but physicists recently suggested making materials that repeat in time. Last year, UC Berkeley's Norman Yao sketched out the phases surrounding a time crystal and what to measure in order to confirm that this new material is actually a stable phase of matter. This stimulated two teams to build a time crystal, the first examples of a non-equilibrium form of matter.

To most people, crystals mean diamond bling, semiprecious gems or perhaps the jagged amethyst or quartz crystals beloved by collectors.

To Norman Yao, these inert crystals are the tip of the iceberg.

If crystals have an atomic structure that repeats in space, like the carbon lattice of a diamond, why can't crystals also have a structure that repeats in time? That is, a time crystal?

In a paper published online last week in the journal *Physical Review Letters*, the University of California, Berkeley assistant professor of physics describes exactly how to make and measure the properties of such a crystal, and even predicts what the various phases surrounding the time crystal should be—akin to the liquid and gas phases of ice.

This is not mere speculation. Two groups followed Yao's blueprint and have already created the first-ever time crystals. The groups at the University of Maryland and Harvard University reported their successes, using two totally different setups, in papers posted online last year, and have submitted the results for publication. Yao is a co-author on both papers.

Time crystals repeat in time because they are kicked periodically, sort of like tapping Jell-O repeatedly to get it to jiggle, Yao said. The big breakthrough, he argues, is less that these particular crystals repeat in time than that they are the first of a large class of new materials that are intrinsically out of equilibrium, unable to settle down to the motionless equilibrium of, for example, a diamond or ruby.

"This is a new phase of matter, period, but it is also really cool because it is one of the first examples of non-equilibrium matter," Yao said. "For the last half-century, we have been exploring equilibrium matter, like metals and insulators. We are just now starting to explore a whole new landscape of non-equilibrium matter."

While Yao is hard put to imagine a use for a time crystal, other proposed phases of non-equilibrium matter theoretically hold promise as nearly perfect memories and may be useful in quantum computers.

### **An ytterbium chain**

The time crystal created by Chris Monroe and his colleagues at the University of Maryland employs a conga line of 10 ytterbium ions whose electron spins interact, similar to the qubit systems being tested as quantum computers. To keep the ions out of equilibrium, the researchers alternately hit them with one laser to create an effective magnetic field and a second laser to partially flip the spins of the atoms, repeating the sequence many times. Because the spins interacted, the atoms settled into a stable, repetitive pattern of spin flipping that defines a crystal.

Time crystals were first proposed in 2012 by Nobel laureate Frank Wilczek, and last year theoretical physicists at Princeton University and UC Santa Barbara's Station Q independently proved that such a crystal could be made. According to Yao, the UC Berkeley group was "the bridge between the theoretical idea and the experimental implementation."

From the perspective of quantum mechanics, electrons can form crystals that do not match the underlying spatial translation symmetry of the orderly, three-dimensional array of atoms, Yao said. This breaks the symmetry of the material and leads to unique and stable properties we define as a crystal.

A time crystal breaks time symmetry. In this particular case, the magnetic field and laser periodically driving the ytterbium atoms produce a repetition in the system at twice the period of the drivers, something that would not occur in a normal system.

"Wouldn't it be super weird if you jiggled the Jell-O and found that somehow it responded at a different period?" Yao said. "But that is the essence of the time crystal. You have some periodic driver that has a period 'T', but the system somehow synchronizes so that you observe the system oscillating with a period that is larger than 'T'."

Yao worked closely with Monroe as his Maryland team made the new material, helping them focus on the important properties to measure to confirm that the material was in fact a stable or rigid time crystal. Yao also described how the time crystal would change phase, like an ice cube melting, under different magnetic fields and laser pulsing.

The Harvard team, led by Mikhail Lukin, set up its time crystal using densely packed nitrogen vacancy centers in diamonds.

"Such similar results achieved in two wildly disparate systems underscore that time crystals are a broad new phase of matter, not simply a curiosity relegated to small or narrowly specific systems," wrote Phil Richerme, of Indiana University, in a perspective piece accompanying the paper published in *Physical Review Letters*. "Observation of the discrete time crystal... confirms that symmetry breaking can occur in essentially all natural realms, and clears the way to several new avenues of research."

Yao is continuing his own work on time crystals as he explores the theory behind other novel but not-yet-realized non-equilibrium materials. [28]

## **Time crystals might exist after all**

Are time crystals just a mathematical curiosity, or could they actually physically exist? Physicists have been debating this question since 2012, when Nobel laureate Frank Wilczek first proposed the idea of time crystals. He argued that these hypothetical objects can exhibit periodic motion, such as moving in a circular orbit, in their state of lowest energy, or their "ground state." Theoretically, objects in their ground states don't have enough energy to move at all.

In the years since, other physicists have proposed various arguments for why the physical existence of time crystals is impossible—and most physicists do seem to think that time crystals are physically impossible because of their odd properties. Even though time crystals couldn't be used to generate useful energy (since disturbing them makes them stop moving), and don't violate the second law of thermodynamics, they do violate a fundamental symmetry of the laws of physics.

However, now in a new paper published in *Physical Review Letters*, physicists from the University of California, Santa Barbara (UCSB) and Microsoft Station Q (a Microsoft research lab located on the UCSB campus) have demonstrated that it may be possible for time crystals to physically exist.

The physicists have focused on the implication of time crystals that seems most surprising, which is that time crystals are predicted to spontaneously break a fundamental symmetry called "time-translation symmetry." To understand what this means, the researchers explain what spontaneous symmetry breaking is.

"The crucial difference here is between explicit symmetry breaking and spontaneous symmetry breaking," coauthor Dominic Else, a physicist at UCSB, told *Phys.org*. "If a symmetry is broken explicitly, then the laws of nature do not have the symmetry anymore; spontaneous symmetry breaking means that the laws of nature have a symmetry, but nature chooses a state that doesn't."

If time crystals really do spontaneously break time-translation symmetry, then the laws of nature that govern time crystals wouldn't change with time, but the time crystals themselves would change over time due to their ground-state motion, spontaneously breaking the symmetry.

Although spontaneously broken time-translation symmetry has never been observed before, almost every other type of spontaneous symmetry breaking has been.

One very common example of a spontaneously broken symmetry occurs in magnets. The laws of nature do not impose which side of a magnet will be the north pole and which will be the south pole. The distinguishing feature of any magnetic material, however, is that it spontaneously breaks this symmetry and chooses one side to be the north pole. Another example is ordinary crystals. Although the laws of nature are invariant under rotating or shifting (translating) space, crystals spontaneously break these spatial symmetries because they look different when viewed from different angles and when shifted a little bit in space.

In their new study, the physicists specifically define what it would take to spontaneously break time-translation symmetry, and then use simulations to predict that this broken symmetry should occur in a large class of quantum systems called "Floquet-many-body-localized driven systems." The scientists explain that the key aspect of these systems is that they remain far from thermal equilibrium at all times, so the system never heats up.

The new definition of broken time-translation symmetry is similar to the definitions of other broken symmetries. Basically, when the size of a system (such as a crystal) grows, the time taken for a symmetry-breaking state to decay into a symmetry-respecting state increases, and in an infinite system the symmetry-respecting state can never be reached. As a result, symmetry for the entire system is broken.

"The significance of our work is two-fold: on one hand, it demonstrates that time-translation symmetry is not immune to being spontaneously broken," said coauthor Bela Bauer, a researcher at Microsoft Station Q. "On the other hand, it deepens our understanding that non-equilibrium systems can host many interesting states of matter that cannot exist in equilibrium systems."

According to the physicists, it should be possible to perform an experiment to observe time-translation symmetry breaking by using a large system of trapped atoms, trapped ions, or superconducting qubits to fabricate a time crystal, and then measure how these systems evolve over time. The scientists predict that the systems will exhibit the periodic, oscillating motion that is characteristic of time crystals and indicative of spontaneously broken time-translation symmetry.

"In collaboration with experimental research groups, we are exploring the possibility of realizing Floquet time crystals in systems of cold atomic gases," said coauthor Chetan Nayak at Microsoft Station Q and UCSB. [28]

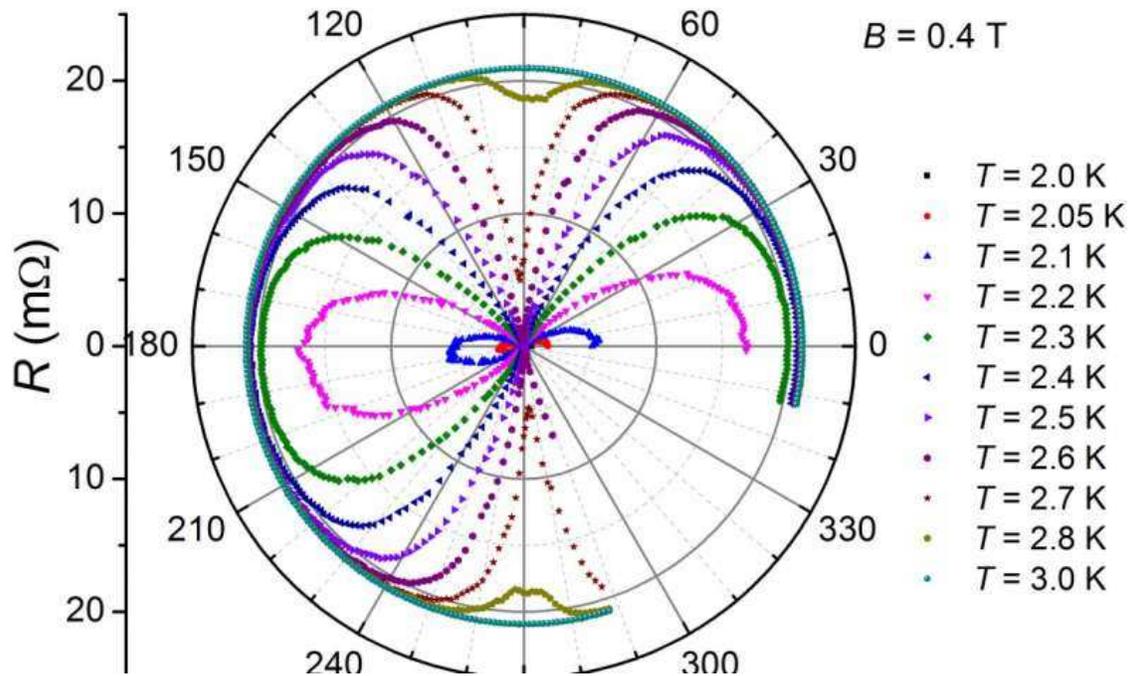
## **The Quest of Superconductivity**

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

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

## Experiences and Theories

### Superconductor's strange behaviour results in new laboratory tool



Researchers from the Foundation for Fundamental Research on Matter and the University of Amsterdam (the Netherlands), together with researchers from the Institute for Materials Science in Tsukuba (Japan), have discovered an exceptional new quantum state within a superconducting material. This exceptional quantum state is characterised by a broken rotational symmetry – in other words, if you turn the material in a magnetic field, the superconductivity isn't the same everywhere in the material.

The material in which the new quantum state was discovered is bismuth selenide, or  $\text{Bi}_2\text{Se}_3$ . This material is a topological insulator. This group of materials exhibits a strange quality: they don't conduct electricity on the inside, but only on their surface. What's more, the researchers are able to make the material even more exceptional – by adding a small amount of strontium to the bismuth-selenide, the material transforms into a superconductor. This means the material can conduct electricity extremely well at low temperatures, because the electrical resistance has completely disappeared.

#### Electron seeks mate

Superconductivity can be explained by the behaviour of electrons within the material. In a superconductor, certain electrons seek a mate and combine into pairs.

These pairs, so-called Cooper pairs, can move through the material without resistance or a loss of energy.

#### Broken symmetry

The research team placed the material in a magnetic field that suppresses the superconducting properties of the material. Bismuth selenide has a layered crystalline structure, and the magnetic field the researchers used was directed parallel to the plane of these layers. Usually, it makes no

difference in which direction the magnetic field points, because the suppression is the same in all directions. However, the researchers discovered that this isn't the case with their exceptional material. When they turned the magnetic field in the plane of the layers, they discovered that the superconductivity was suppressed to a greater and to a lesser extent, depending on the direction in which the field pointed. In other words, the material's rotational symmetry was broken.

### **Preferred direction**

The phenomenon of broken symmetry can only be explained if the electrons in this material form special Cooper pairs, namely spin-triplet pairs, instead of the usual spin-singlet pairs. Such Cooper pairs can adopt a preferred direction within the crystal.

### **New lab tool**

The team, including FOM PhD students Yu Pan and Artem Nikitin, points out that the discovery proves that this exceptional material forms a unique laboratory tool.

The superconductor will allow physicists to study the exceptional quantum effects of topological superconductivity. [27]

### **Elusive state of superconducting matter discovered after 50 years**

Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, Cornell University, and collaborators have produced the first direct evidence of a state of electronic matter first predicted by theorists in 1964. The discovery, described in a paper published online April 13, 2016, in *Nature*, may provide key insights into the workings of high-temperature superconductors.

The prediction was that "Cooper pairs" of electrons in a superconductor could exist in two possible states. They could form a "superfluid" where all the particles are in the same quantum state and all move as a single entity, carrying current with zero resistance—what we usually call a superconductor. Or the Cooper pairs could periodically vary in density across space, a so-called "Cooper pair density wave." For decades, this novel state has been elusive, possibly because no instrument capable of observing it existed.

Now a research team led by J.C. Séamus Davis, a physicist at Brookhaven Lab and the James Gilbert White Distinguished Professor in the Physical Sciences at Cornell, and Andrew P. Mackenzie, Director of the Max-Planck Institute CPMS in Dresden, Germany, has developed a new way to use a scanning tunneling microscope (STM) to image Cooper pairs directly.

The studies were carried out by research associate Mohammed Hamidian (now at Harvard) and graduate student Stephen Edkins (St. Andrews University in Scotland), working as members of Davis' research group at Cornell and with Kazuhiro Fujita, a physicist in Brookhaven Lab's Condensed Matter Physics and Materials Science Department.

Superconductivity was first discovered in metals cooled almost to absolute zero (-273.15 degrees Celsius or -459.67 Fahrenheit). Recently developed materials called cuprates - copper oxides laced with other atoms - superconduct at temperatures as "high" as 148 degrees above absolute zero (-125 Celsius). In superconductors, electrons join in pairs that are magnetically neutral so they do not interact with atoms and can move without resistance.

Hamidian and Edkins studied a cuprate incorporating bismuth, strontium, and calcium (Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8</sub>) using an incredibly sensitive STM that scans a surface with sub-nanometer

resolution, on a sample that is refrigerated to within a few thousandths of a degree above absolute zero.

At these temperatures, Cooper pairs can hop across short distances from one superconductor to another, a phenomenon known as Josephson tunneling. To observe Cooper pairs, the researchers briefly lowered the tip of the probe to touch the surface and pick up a flake of the cuprate material. Cooper pairs could then tunnel between the superconductor surface and the superconducting tip. The instrument became, Davis said, "the world's first scanning Josephson tunneling microscope." [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  $\text{CeCoIn}_5$  when there are strong external magnetic fields. This state can then be manipulated by modifying the field direction. The material is already superconducting in weaker fields, too. In strong fields, however, an additional second superconducting state is created which means that there are two different superconducting states at the same time in the same material. The new state is coupled with an anti-ferromagnetic order that appears simultaneously with the field. The anti-ferromagnetic order from whose properties the researchers have deduced the existence of the superconducting state was detected with neutrons at PSI and at the Institute Laue-Langevin in Grenoble. [6]

### Room-temperature superconductivity

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

## Exciton-mediated electron pairing

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

## Resonating valence bond theory

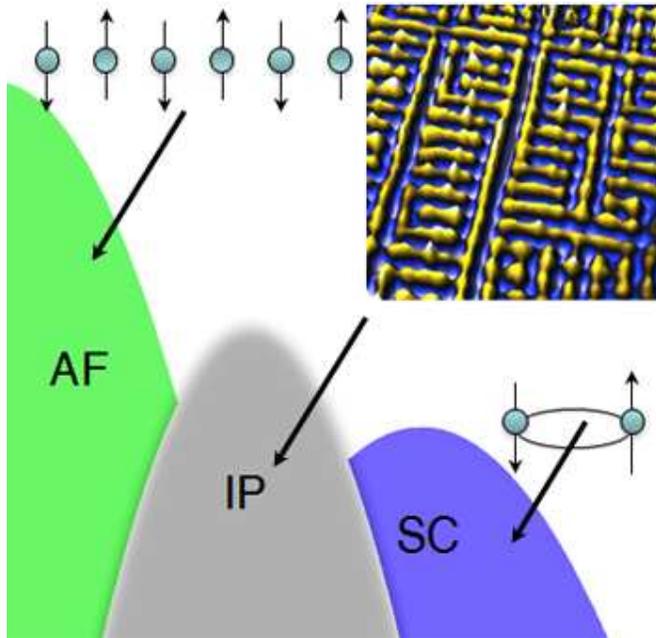
In condensed matter physics, the resonating valence bond theory (RVB) is a theoretical model that attempts to describe high temperature superconductivity, and in particular the superconductivity in cuprate compounds. It was first proposed by American physicist P. W. Anderson and the Indian theoretical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

## Strongly correlated materials

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

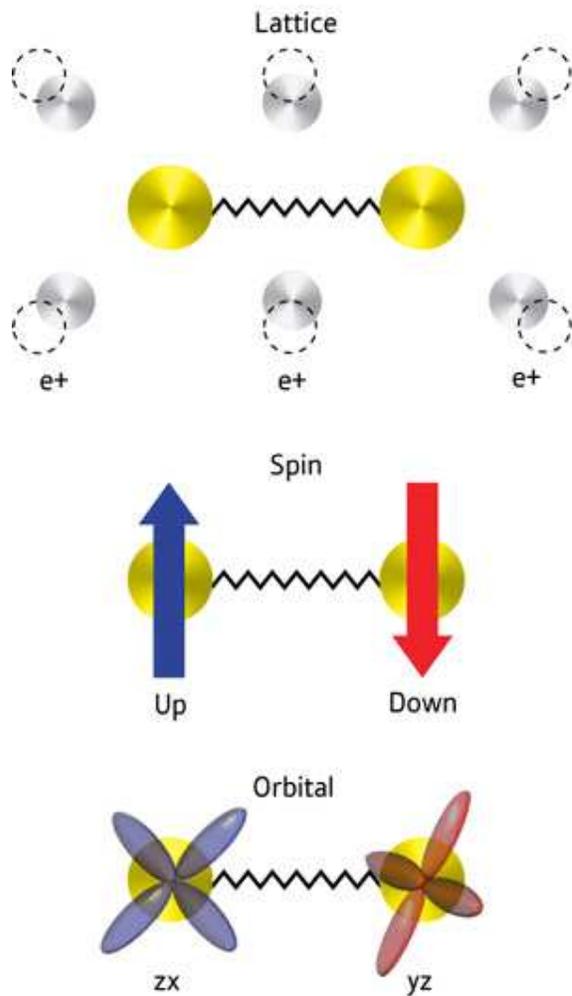
Unconventional superconductivity (SC) is said to occur when Cooper pair formation is dominated by repulsive electron–electron interactions, so that the symmetry of the pair wave function is other than an isotropic s-wave. The strong, on-site, repulsive electron–electron interactions that are the proximate 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



Shimajima 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 ratio. [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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