Accelerated Computing for Accelerated Particles

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A potentially useful material for building quantum computers has been unearthed at the National Institute of Standards and Technology (NIST), whose scientists have found a superconductor that could sidestep one of the primary obstacles standing in the way of effective quantum logic circuits. [29]

Important challenges in creating practical quantum computers have been addressed by two independent teams of physicists in the US. [28]

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies. [27]

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

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

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

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Author: George Rajna

The Quest of Superconductivity

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

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

Experiences and Theories

A glimpse into the future: Accelerated computing for accelerated particles

Every proton collision at the Large Hadron Collider is different, but only a few are special. The special collisions generate particles in unusual patterns—possible manifestations of new, rule-breaking physics—or help fill in our incomplete picture of the universe.

Finding these collisions is harder than the proverbial search for the needle in the haystack. But game-changing help is on the way. Fermilab scientists and other collaborators successfully tested a prototype machine-learning technology that speeds up processing by 30 to 175 times compared to traditional methods.

Confronting 40 million collisions every second, scientists at the LHC use powerful, nimble computers to pluck the gems—whether it's a Higgs particle or hints of dark matter—from the vast static of ordinary collisions.

Rifling through simulated LHC collision data, the machine learning technology successfully learned to identify a particular postcollision pattern—a particular spray of particles flying through a detector—as it flipped through an astonishing 600 images per second. Traditional methods process less than one image per second.

The technology could even be offered as a service on external computers. Using this offloading model would allow researchers to analyze more data more quickly and leave more LHC computing space available to do other work.

It is a promising glimpse into how machine learning services are supporting a field in which already enormous amounts of data are only going to get bigger.

The challenge: more data, more computing power

Researchers are currently upgrading the LHC to smash protons at five times its current rate. By 2026, the 17-mile circular underground machine at the European laboratory CERN will produce 20 times more data than it does now.

CMS is one of the particle detectors at the Large Hadron Collider, and CMS collaborators are in the midst of some upgrades of their own, enabling the intricate, stories-high instrument to take more sophisticated pictures of the LHC's particle collisions. Fermilab is the lead U.S. laboratory for the CMS experiment.

If LHC scientists wanted to save all the raw collision data they'd collect in a year from the High-Luminosity LHC, they'd have to find a way to store about 1 exabyte (about 1 trillion personal external hard drives), of which only a sliver may unveil new phenomena. LHC computers are programmed to select this tiny fraction, making split-second decisions about which data is valuable enough to be sent downstream for further study.

Currently, the LHC's computing system keeps roughly one in every 100,000 particle events. But current storage protocols won't be able to keep up with the future data flood, which will accumulate over decades of data taking. And the higher-resolution pictures captured by the upgraded CMS detector won't make the job any easier. It all translates into a need for more than 10 times the computing resources than the LHC has now.

Particle physicists are exploring the use of computers with machine learning capabilities for processing images of particle collisions at CMS, teaching them to rapidly identify various collision patterns. Credit: Eamonn Maguire/Antarctic Design

The recent prototype test shows that, with advances in machine learning and computing hardware, researchers expect to be able to winnow the data emerging from the upcoming High-Luminosity LHC when it comes online.

"The hope here is that you can do very sophisticated things with machine learning and also do them faster," said Nhan Tran, a Fermilab scientist on the CMS experiment and one of the leads on the recent test. "This is important, since our data will get more and more complex with upgraded detectors and busier collision environments."

Machine learning to the rescue: the inference difference

Machine learning in particle physics isn't new. Physicists use machine learning for every stage of data processing in a collider experiment.

But with machine learning technology that can chew through LHC data up to 175 times faster than traditional methods, particle physicists are ascending a game-changing step on the collision-computation course.

The rapid rates are thanks to cleverly engineered hardware in the platform, Microsoft's Azure ML, which speeds up a process called inference.

To understand inference, consider an algorithm that's been trained to recognize the image of a motorcycle: The object has two wheels and two handles that are attached to a larger metal body. The algorithm is smart enough to know that a wheelbarrow, which has similar attributes, is not a motorcycle. As the system scans new images of other two-wheeled, two-handled objects, it predicts—or infers—which are motorcycles. And as the algorithm's prediction errors are corrected, it becomes pretty deft at identifying them. A billion scans later, it's on its inference game.

Most machine learning platforms are built to understand how to classify images, but not physics-specific images. Physicists have to teach them the physics part, such as recognizing tracks created by the Higgs boson or searching for hints of dark matter.

Researchers at Fermilab, CERN, MIT, the University of Washington and other collaborators trained Azure ML to identify pictures of top quarks—a short-lived elementary particle that is about 180 times heavier than a proton—from simulated CMS data. Specifically, Azure was to look for images of top quark jets, clouds of particles pulled out of the vacuum by a single top quark zinging away from the collision.

"We sent it the images, training it on physics data," said Fermilab scientist Burt Holzman, a lead on the project. "And it exhibited state-of-the-art performance. It was very fast. That means we can pipeline a large number of these things. In general, these techniques are pretty good."

One of the techniques behind inference acceleration is to combine traditional with specialized processors, a marriage known as heterogeneous computing architecture.

Data from particle physics experiments are stored on computing farms like this one, the Grid Computing Center at Fermilab. Outside organizations offer their computing farms as a service to particle physics experiments, making more space available on the experiments' servers. Credit: Reidar Hahn

Different platforms use different architectures. The traditional processors are CPUs (central processing units). The best known specialized processors are GPUs (graphics processing units) and FPGAs (field programmable gate arrays). Azure ML combines CPUs and FPGAs.

"The reason that these processes need to be accelerated is that these are big computations. You're talking about 25 billion operations," Tran said. "Fitting that onto an FPGA, mapping that on, and doing it in a reasonable amount of time is a real achievement."

And it's starting to be offered as a service, too. The test was the first time anyone has demonstrated how this kind of heterogeneous, as-a-service architecture can be used for fundamental physics.

In the computing world, using something "as a service" has a specific meaning. An outside organization provides resources—machine learning or hardware—as a service, and users—scientists—draw on those resources when needed. It's similar to how your video streaming company provides hours of binge-watching TV as a service. You don't need to own your own DVDs and DVD player. You use their library and interface instead.

Data from the Large Hadron Collider is typically stored and processed on computer servers at CERN and partner institutions such as Fermilab. With machine learning offered up as easily as any other web service might be, intensive computations can be carried out anywhere the service is offered—including off site. This bolsters the labs' capabilities with additional computing power and resources while sparing them from having to furnish their own servers.

"The idea of doing accelerated computing has been around decades, but the traditional model was to buy a computer cluster with GPUs and install it locally at the lab," Holzman said. "The idea of offloading the work to a farm off site with specialized hardware, providing machine learning as a service—that worked as advertised."

The Azure ML farm is in Virginia. It takes only 100 milliseconds for computers at Fermilab near Chicago, Illinois, to send an image of a particle event to the Azure cloud, process it, and return it. That's a 2,500-kilometer, data-dense trip in the blink of an eye.

"The plumbing that goes with all of that is another achievement," Tran said. "The concept of abstracting that data as a thing you just send somewhere else, and it just comes back, was the most pleasantly surprising thing about this project. We don't have to replace everything in our own computing center with a whole bunch of new stuff. We keep all of it, send the hard computations off and get it to come back later."

Scientists look forward to scaling the technology to tackle other big-data challenges at the LHC. They also plan to test other platforms, such as Amazon AWS, Google Cloud and IBM Cloud, as they explore what else can be accomplished through machine learning, which has seen rapid evolution over the past few years.

"The models that were state-of-the-art for 2015 are standard today," Tran said.

As a tool, machine learning continues to give particle physics new ways of glimpsing the universe. It's also impressive in its own right.

"That we can take something that's trained to discriminate between pictures of animals and people, do some modest amount computation, and have it tell me the difference between a top quark jet and background?" Holzman said. "That's something that blows my mind." [30]

Newfound superconductor material could be the 'silicon of quantum computers'

A potentially useful material for building quantum computers has been unearthed at the National Institute of Standards and Technology (NIST), whose scientists have found a superconductor that could sidestep one of the primary obstacles standing in the way of effective quantum logic circuits.

Newly discovered properties in the compound uranium ditelluride, or UTe_2, show that it could prove highly resistant to one of the nemeses of quantum computer development—the difficulty with making such a computer's memory storage switches, called qubits, function long enough to finish a computation before losing the delicate physical relationship that allows them to operate as a group. This relationship, called quantum coherence, is hard to maintain because of disturbances from the surrounding world.

The compound's unusual and strong resistance to magnetic fields makes it a rare bird among superconducting (SC) materials, which offer distinct advantages for qubit design, chiefly their resistance to the errors that can easily creep into quantum computation. UTe_2's exceptional behaviors could make it attractive to the nascent quantum computer industry, according to the research team's Nick Butch.

"This is potentially the silicon of the quantum information age," said Butch, a physicist at the NIST Center for Neutron Research (NCNR). "You could use uranium ditelluride to build the qubits of an efficient quantum computer."

Research results from the team, which also includes scientists from the University of Maryland and Ames Laboratory, appear today in the journal *Science*. Their paper details UTe_2's uncommon properties, which are interesting from the perspectives of both technological application and fundamental science.

One of these is the unusual way the electrons that conduct electricity through UTe_2 partner up. In copper wire or some other ordinary conductor, electrons travel as individual particles, but in all SCs they form what are called Cooper pairs. The electromagnetic interactions that cause these pairings are responsible for the material's superconductivity. The explanation for this kind of superconductivity is named BCS theory after the three scientists who uncovered the pairings (and shared the Nobel Prize for doing so).

What's specifically important to this Cooper pairing is a property that all electrons have. Known as quantum "spin," it makes electrons behave as if they each have a little bar magnet running through them. In most SCs, the paired electrons have their quantum spins oriented in a single way—one electron's points upward, while its partner points down. This opposed pairing is called a spin singlet.

A small number of known superconductors, though, are nonconformists, and UTe_2 looks to be among them. Their Cooper pairs can have their spins oriented in one of three combinations, making them spin triplets. These combinations allow for the Cooper-pair spins to be oriented in parallel rather than in opposition. Most spin-triplet SCs are predicted to be "topological" SCs as well, with a highly useful property in which the superconductivity would occur on the surface of the material and would remain superconducting even in the face of external disturbances.

"These parallel spin pairs could help the computer remain functional," Butch said. "It can't spontaneously crash because of quantum fluctuations."

All quantum computers up until this point have needed a way to correct the errors that creep in from their surroundings. SCs have long been understood to have general advantages as the basis for quantum computer components, and several recent commercial advances in quantum computer development have involved circuits made from superconductors. A topological SC's properties—which a quantum computer might employ—would have the added advantage of not needing quantum error correction.

"We want a topological SC because it would give you error-free qubits. They could have very long lifetimes," Butch said. "Topological SCs are an alternate route to quantum computing because they would protect the qubit from the environment."

The team stumbled upon UTe_2 while exploring uranium-based magnets, whose electronic properties can be tuned as desired by changing their chemistry, pressure or magnetic field—a useful feature to have when you want customizable materials. (None of these parameters are based on radioactivity. The material contains "depleted uranium," which is only slightly radioactive. Qubits made from UTe_2 would be tiny, and they could easily be shielded from their environment by the rest of the computer.)

The team did not expect the compound to possess the properties they discovered.

"UTe_2 had first been created back in the 1970s, and even fairly recent research articles described it as unremarkable," Butch said. "We happened to make some UTe_2 while we were synthesizing related materials, so we tested it at lower temperatures to see if perhaps some phenomenon might have been overlooked. We quickly realized that we had something very special on our hands."

The NIST team started exploring UTe_2 with specialized tools at both the NCNR and the University of Maryland. They saw that it became superconducting at low temperatures (below -271.5 degrees Celsius, or 1.6 kelvin). Its superconducting properties resembled those of rare superconductors that are also simultaneously ferromagnetic—acting like low-temperature permanent magnets. Yet, curiously, UTe_2 is itself not ferromagnetic.

"That makes UTe_2 fundamentally new for that reason alone," Butch said.

It is also highly resistant to magnetic fields. Typically a field will destroy superconductivity, but depending on the direction in which the field is applied, UTe_2 can withstand fields as high as 35 tesla. This is 3,500 times as strong as a typical refrigerator magnet, and many times more than most low-temperature topological SCs can endure.

While the team has not yet proved conclusively that UTe_2 is a topological SC, Butch says this unusual resistance to strong magnetic fields means that it must be a spin-triplet SC, and therefore it is likely a topological SC as well. This resistance also might help scientists understand the nature of UTe_2 and perhaps superconductivity itself.

"Exploring it further might give us insight into what stabilizes these parallel-spin SCs," he said. "A major goal of SC research is to be able to understand superconductivity well enough that we know where to look for undiscovered SC materials. Right now we can't do that. What about them is essential? We are hoping this material will tell us more."

The study is published in the journal *Science*. [29]

Superconducting and diamond qubits get a boost

Important challenges in creating practical quantum computers have been addressed by two independent teams of physicists in the US. One team has created a new way of reading-out superconducting quantum bits (qubits), while the other has come-up with a new way to get spin qubits in diamond to interact with each other.

Any viable quantum computer needs isolated quantum states that can store qubits of information for relatively long periods of time. It must also be possible for these qubits to interact with each other at appropriate times so that the information can be processed and the results read-out. It is these often-conflicting requirements that made it very difficult to create a practical quantum computer

In one of two papers published in *Science*, Robert McDermott of University of Wisconsin-Madison and colleagues in Wisconsin and New York describe a new detector for reading-out superconducting qubits. These qubits are superconducting circuits containing Josephson junctions that are cooled to millikelvin temperatures and function as quantized oscillators. The qubit can be switched between two quantum states by a photon at the oscillator's resonant frequency. The circuits also interact strongly to process information.

Complicated measurement

However, reading a qubit's state is difficult because it involves coupling the oscillator to a resonant cavity. "If the qubit is in the ground state, you've got a cavity resonance at one frequency; if it's in the excited state you've got a cavity resonance at a different frequency," explains McDermott. Reading the state can therefore be done by measuring the cavity resonance, which involves probing the cavity with microwaves and detecting the phase of the reflected or transmitted waves. This requires low noise amplifiers and separate circuitry at both cryogenic and room temperatures – making it impractical for scaling-up in a practical quantum computer.

Instead, the group coupled the qubit's resonant cavity to a second cavity connected to another Josephson junction with two easily-distinguishable states: a metastable state loaded with photons and an empty ground state. If the qubit is in one specific state, the photons remain trapped in the metastable state. However, if the qubit is in the other state, the photons will tunnel immediately to the ground state.

"It's a very simple circuit," says McDermott. The researchers detected the qubit states with a fidelity of 92%. They are confident that, with optimization, they can get to over 99%. While other qubit technologies can also reach this fidelity, McDermott's qubits could be easier to scale-up to create a practical quantum computer.

Diamond vacancies

In a second paper in *Science*, Mikhail Lukin and colleagues at Harvard University used two silicon-vacancy centres (SiVs) in diamond as two qubits. A SiV occurs when two neighbouring carbon atoms in the diamond lattice are replaced by one silicon atom. The spin of the SiV makes a good qubit because it is isolated from electrical noise yet interacts with light at certain frequencies.

The challenge is getting SiVs to interact with each other. The team placed two SiVs in an optical cavity, which dramatically increases the probability that they would interact: "The two SiVs are a bit like two people in a dark room trying to send Morse code signals to each other using dim flashlights," explains Harvard's Ruffin Evans, "If you form a cavity by placing mirrors back-to-back on each wall, the light bounces back and forth and gives the people many more chances to see the signal." When tuned into resonance at the same frequency, states from the two silicon vacancy centre states were mixed by the interaction to form a super-radiant "bright" state and a non-radiant "dark" state.

Creating two interacting qubits is not new and other researchers have gone further and created working quantum-logic gates using different qubit technologies. Evans explains, "The novelty of our work is that, even though the interaction between light and matter is normally very weak, we've still been able to create an interaction between these two silicon vacancy centres using light. The next step is to harness this interaction to create a real quantum gate." Such a device system should lend itself naturally to the creation of a "quantum internet" that uses photon-based qubits sent long distances through fibre optic cables.

"Beautiful scheme"

Barry Sanders of the University of Calgary in Canada told *Physics World* that both teams' research is significant – but for different reasons. He believes the McDermott group's work has clear potential for direct application to quantum computation if the measurement fidelity can be increased. "Superconducting circuits are generally regarded as the most promising direction towards making scaleable quantum computing, but a big drawback has always been the lack of single photon detection," he says. "This is a beautiful scheme and it looks scaleable to me."

The relevance of Lukin group's work to quantum computation is less clear but it may have unforeseen applications. Sanders says, "For a long time, we've got away with treating multi-atom systems as a single atom with an effective background. When we get to phenomena like super- and sub-radiance, we're talking about two-body effects with atoms sharing photons between them. These guys have done everything just right that they're able to tune into and out of this collective behaviour. It's a huge challenge in fabrication and control and their results are convincing and elegant." [28]

Superconducting qubits can function as quantum engines

Physicists have shown that superconducting circuits—circuits that have zero electrical resistance—can function as piston-like mechanical quantum engines. The new perspective may help researchers design quantum computers and other devices with improved efficiencies.

The physicists, Kewin Sachtleben, Kahio T. Mazon, and Luis G. C. Rego at the Federal University of Santa Catarina in Florianópolis, Brazil, have published a paper on their work on superconducting qubits in a recent issue of Physical Review Letters.

In their study, the physicists explain that superconducting circuits are functionally equivalent to quantum systems in which quantum particles tunnel in a double-quantum well. These wells have the ability to oscillate, meaning the width of the well changes repeatedly. When this happens, the system behaves somewhat like a piston that moves up and down in a cylinder, which changes the volume of the cylinder. This oscillatory behavior allows work to be performed on the system. The researchers show that, in the double-quantum well, part of this work comes from quantum coherent dynamics, which creates friction that decreases the work output. These results provide a better understanding of the connection between quantum and classical thermodynamic work.

"The distinction between 'classical' thermodynamic work, responsible for population transfer, and a quantum component, responsible for creating coherences, is an important result," Mazon told Phys.org. "The creation of coherences, in turn, generates a similar effect to friction, causing a notcompletely-reversible operation of the engine. In our work we have been able to calculate the reaction force caused on the quantum piston wall due to the creation of coherences. In principle this force can be measured, thus constituting the experimental possibility of observing the emergence of coherences during the operation of the quantum engine."

One of the potential benefits of viewing superconducting qubits as quantum engines is that it may allow researchers to incorporate quantum coherent dynamics into future technologies, in particular quantum computers. The physicists explain that a similar behavior can be seen in nature, where quantum coherences improve the efficiency of processes such as photosynthesis, light sensing, and other natural processes.

"Quantum machines may have applications in the field of quantum information, where the energy of quantum coherences is used to perform information manipulation in the quantum regime," Mazon said. "It is worth remembering that even photosynthesis can be described according to the working principles of a quantum machine, so unraveling the mysteries of quantum thermodynamics can help us to better understand and interpret various natural processes." [27]

Conventional superconductivity

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

High-temperature superconductivity

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

Superconductivity and magnetic fields

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

Room-temperature superconductivity

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

Exciton-mediated electron pairing

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

Resonating valence bond theory

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

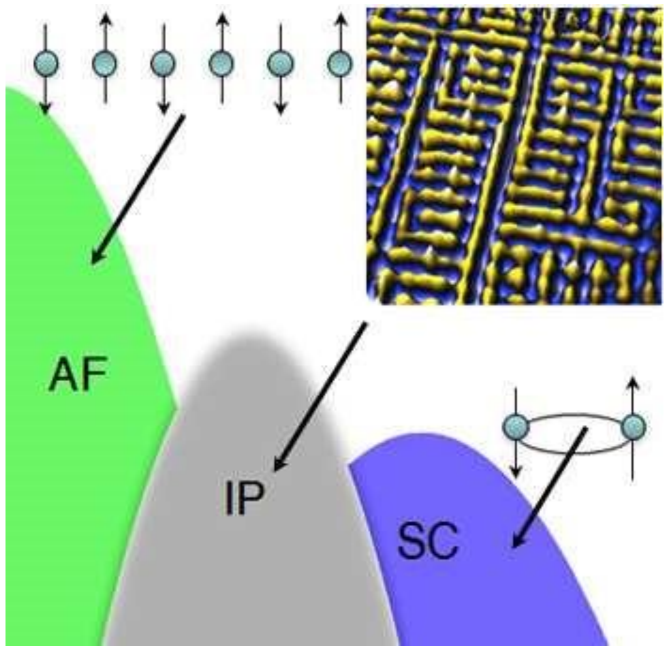
Strongly correlated materials

Strongly correlated materials are a wide class of electronic materials that show unusual (often technologically useful) electronic and magnetic properties, such as metal-insulator transitions or half-metallicity. The essential feature that defines these materials is that the behavior of their electrons cannot be described effectively in terms of non-interacting entities. Theoretical models of the electronic structure of strongly correlated materials must include electronic correlation to be accurate. Many transition metal oxides belong into this class which may be subdivided according to their behavior, *e.g.* high-T_c, spintronic materials, Mott insulators, spin Peierls materials, heavy fermion materials, quasi-low-dimensional materials, etc. The single most intensively studied effect is probably high-temperature superconductivity in doped cuprates, e.g. $La_{2-x}Sr_xCuO_4$. Other ordering or magnetic phenomena and temperature-induced phase transitions in many transition-metal oxides are also gathered under the term "strongly correlated materials." Typically, strongly correlated materials have incompletely filled *d*- or *f*-electron shells with narrow

energy bands. One can no longer consider any electron in the material as being in a "sea" of the averaged motion of the others (also known as mean field theory). Each single electron has a complex influence on its neighbors.
[11]

New superconductor theory may revolutionize electrical engineering

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



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

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

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

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

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

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

A grand unified theory of exotic superconductivity?

The role of magnetism

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

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

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

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

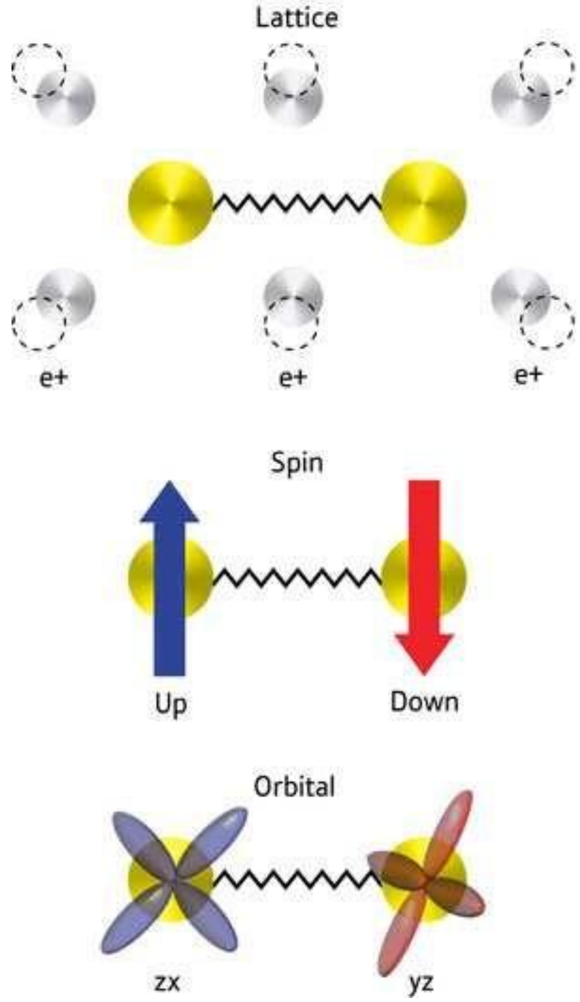
Unconventional superconductivity (SC) is said to occur when Cooper pair formation is dominated by repulsive electron–electron interactions, so that the symmetry of the pair wave function is other than an isotropic s-wave. The strong, on-site, repulsive electron–electron interactions that are the proximate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

Indeed, it is the suppression of commensurate antiferromagnetism (AF) that usually allows this type of unconventional superconductivity to emerge. Importantly, however, intervening between these AF and SC phases, intertwined electronic ordered phases (IP) of an unexpected nature are frequently discovered. For this reason, it has been extremely difficult to distinguish the microscopic essence of the correlated superconductivity from the often spectacular phenomenology of the IPs. Here we introduce a model conceptual framework within which to understand the relationship between AF electron–electron interactions, IPs, and correlated SC. We demonstrate its effectiveness in simultaneously explaining the consequences of AF interactions for the copper-based, iron-based, and heavy-fermion superconductors, as well as for their quite distinct IPs.

Significance

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

Superconductivity's third side unmasked



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

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

Strongly correlated materials

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

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

Fermions and Bosons

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

The General Weak Interaction

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

Higgs Field and Superconductivity

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

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

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

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

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

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

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

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

$$\psi \rightarrow e^{iq\phi(x)}\psi$$

$$A \rightarrow A + \nabla\phi.$$

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

The condensate wave function can be written as

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

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

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

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

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

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

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

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

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

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

This is a harmonic oscillator with frequency

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

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

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

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

Superconductivity and Quantum Entanglement

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

Conclusions

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

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

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

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

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

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