

Hexagonal Graphene Quantum Dots

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Now, a Rutgers-led team has paved the way to solving one of the most enduring mysteries in materials physics by discovering that in the presence of a moiré pattern in graphene, electrons organize themselves into stripes, like soldiers in formation. [30]

Researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) have developed a graphene device that's thinner than a human hair but has a depth of special traits. [29]

Scientists at HZB have found evidence that double layers of graphene have a property that may let them conduct current completely without resistance. [28]

US researchers studying high-temperature cuprate superconductors outside the superconducting regime have used cutting-edge X-ray scattering to detect long-predicted – but never previously observed – excitations called plasmons perpendicular to the material's atomic planes. [27]

Using solid state nuclear magnetic resonance (ssNMR) techniques, scientists at the U.S. Department of Energy's Ames Laboratory discovered a new quantum criticality in a superconducting material, leading to a greater understanding of the link between magnetism and unconventional superconductivity. [26]

Improving these devices could mean more powerful computers, better detectors of disease and technological advances scientists can't even predict yet. [25]

Researchers at the Schliesser Lab at the Niels Bohr Institute, University of Copenhagen, have demonstrated a new way to address a central problem in quantum physics: at the quantum scale, any measurement disturbs the measured object. [24]

An answer to a quantum-physical question provided by the algorithm Melvin has uncovered a hidden link between quantum experiments and the mathematical field of Graph Theory. [23]

Engineers develop key mathematical formula for driving quantum experiments. [22]

Physicists are developing quantum simulators, to help solve problems that are beyond the reach of conventional computers. [21]

Engineers at Australia's University of New South Wales have invented a radical new architecture for quantum computing, based on novel 'flip-flop qubits', that promises to make the large-scale manufacture of quantum chips dramatically cheaper - and easier - than thought possible. [20]

A team of researchers from the U.S. and Italy has built a quantum memory device that is approximately 1000 times smaller than similar devices— small enough to install on a chip. [19]

The cutting edge of data storage research is working at the level of individual atoms and molecules, representing the ultimate limit of technological miniaturisation. [18]

This is an important clue for our theoretical understanding of optically controlled magnetic data storage media. [17]

A crystalline material that changes shape in response to light could form the heart of novel light-activated devices. [16]

Now a team of Penn State electrical engineers have a way to simultaneously control diverse optical properties of dielectric waveguides by using a two-layer coating, each layer with a near zero thickness and weight. [15]

Just like in normal road traffic, crossings are indispensable in optical signal processing. In order to avoid collisions, a clear traffic rule is required. A new method has now been developed at TU Wien to provide such a rule for light signals. [14]

Researchers have developed a way to use commercial inkjet printers and readily available ink to print hidden images that are only visible when illuminated with appropriately polarized waves in the terahertz region of the electromagnetic spectrum. [13]

That is, until now, thanks to the new solution devised at TU Wien: for the first time ever, permanent magnets can be produced using a 3D printer. This allows magnets to be produced in complex forms and precisely customised magnetic fields, required, for example, in magnetic sensors. [12]

For physicists, loss of magnetisation in permanent magnets can be a real concern. In response, the Japanese company Sumitomo created the strongest available magnet—one offering ten times more magnetic energy than previous versions—in 1983. [11]

New method of superstrong magnetic fields' generation proposed by Russian scientists in collaboration with foreign colleagues. [10]

By showing that a phenomenon dubbed the "inverse spin Hall effect" works in several organic semiconductors - including carbon-60 buckyballs - University of Utah physicists changed magnetic "spin current" into electric current. The efficiency of this new power conversion method isn't yet known, but it might find use in future electronic devices including batteries, solar cells and computers. [9]

Researchers from the Norwegian University of Science and Technology (NTNU) and the University of Cambridge in the UK have demonstrated that it is possible to directly generate an electric current in a magnetic material by rotating its magnetization. [8]

This paper explains the magnetic effect of the electric 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 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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Author: George Rajna

Preface

Surprisingly nobody found strange that by theory the electrons are moving with a constant velocity in the stationary electric current, although there is an accelerating force $\underline{F} = q \underline{E}$, imposed by the \underline{E} electric field along the wire as a result of the \underline{U} potential difference. The accelerated electrons are creating a charge density distribution and maintaining the potential change along the wire. This charge distribution also creates a radial electrostatic field around the wire decreasing along the wire. The moving external electrons in this electrostatic field are experiencing a changing electrostatic field causing exactly the magnetic effect, repelling when moving against the direction of the current and attracting when moving in the direction of the current. This way the \underline{A} magnetic potential is based on the real charge distribution of the electrons caused by their acceleration, maintaining the \underline{E} electric field and the \underline{A} magnetic potential at the same time.

The mysterious property of the matter that the electric potential difference is self maintained by the accelerating electrons in the electric current gives a clear explanation to the basic sentence of the relativity that is the velocity of the light is the maximum velocity of the electromagnetic matter. If the charge could move faster than the electromagnetic field, this self maintaining electromagnetic property of the electric current would be failed.

More importantly the accelerating electrons can explain the magnetic induction also. The changing acceleration of the electrons will create a $-\underline{E}$ electric field by changing the charge distribution, increasing acceleration lowering the charge density and decreasing acceleration causing an increasing charge density.

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as a relativistic changing electromagnetic mass. If the mass is electromagnetic, then the gravitation is also electromagnetic effect. The same charges would attract each other if they are moving parallel by the magnetic effect.

Synthesizing single-crystalline hexagonal graphene quantum dots

A KAIST team has designed a novel strategy for synthesizing single-crystalline graphene quantum dots, which emit stable blue light. The research team confirmed that a display made of their synthesized graphene quantum dots successfully emitted blue light with stable electric pressure, reportedly resolving the long-standing challenges of blue light emission in manufactured

displays. The study, led by Professor O Ok Park in the Department of Chemical and Biological Engineering, was featured online in *Nano Letters* on July 5.

Graphene has gained increased attention as a next-generation material for its heat and electrical conductivity as well as its transparency. However, single and multi-layered graphene have characteristics of a conductor so that it is difficult to apply into semiconductor. Only when downsized to the nanoscale, semiconductor's distinct feature of bandgap will be exhibited to emit the light in the graphene. This illuminating featuring of dot is referred to as a graphene quantum dot.

Conventionally, single-crystalline graphene has been fabricated by chemical vapor deposition (CVD) on copper or nickel thin films, or by peeling graphite physically and chemically. However, graphene made via chemical vapor deposition is mainly used for large-surface transparent electrodes. Meanwhile, graphene made by chemical and physical peeling carries uneven size defects.

The research team explained that their graphene quantum dots exhibited a very stable single-phase reaction when they mixed amine and acetic acid with an aqueous solution of glucose. Then, they synthesized single-crystalline graphene quantum dots from the self-assembly of the reaction intermediate. In the course of fabrication, the team developed a new separation method at a low-temperature precipitation, which led to successfully creating a homogeneous nucleation of graphene quantum dots via a single-phase reaction.

Professor Park and his colleagues have developed solution phase synthesis technology that allows for the creation of the desired crystal size for single nanocrystals down to 100 nano meters. It is reportedly the first synthesis of the homogeneous nucleation of graphene through a single-phase reaction.

Professor Park said, "This solution method will significantly contribute to the grafting of graphene in various fields. The application of this new graphene will expand the scope of its applications such as for flexible displays and varistors." [31]

Physicists make graphene discovery that could help develop superconductors

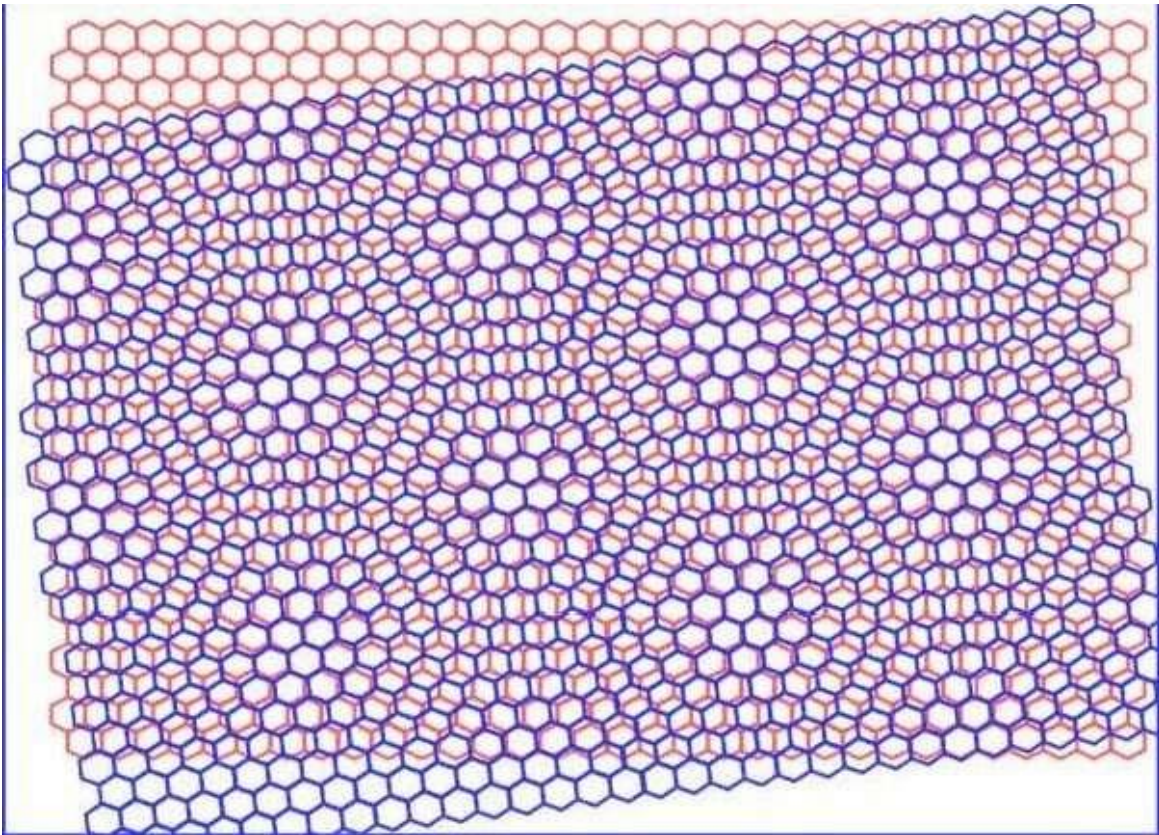
When two mesh screens are overlaid, beautiful patterns appear when one screen is offset. These "moiré patterns" have long intrigued artists, scientists and mathematicians and have found applications in printing, fashion and banknotes.

Now, a Rutgers-led team has paved the way to solving one of the most enduring mysteries in materials physics by discovering that in the presence of a moiré pattern in graphene, electrons organize themselves into stripes, like soldiers in formation.

Their findings, published in the journal *Nature*, could help in the search for quantum materials, such as superconductors, that would work at room temperature. Such materials would dramatically reduce energy consumption by making power transmission and electronic devices more efficient.

"Our findings provide an essential clue to the mystery connecting a form of graphene, called twisted bilayer graphene, to superconductors that could work at room temperature," said senior author Eva Y. Andrei, Board of Governors professor in the Department of Physics and Astronomy in the School of Arts and Sciences at Rutgers University–New Brunswick.

Graphene—an atomically thin layer of the graphite used in pencils—is a mesh made of carbon atoms that looks like a honeycomb. It's a great conductor of electricity and much stronger than steel.



Schematics of a moiré pattern in twisted bilayer graphene. Credit: Eva Andrei/Rutgers University-New Brunswick

The Rutgers-led team studied twisted bilayer graphene, created by superimposing two layers of graphene and slightly misaligning them. This creates a "twist angle" that results in a moiré pattern which changes rapidly when the twist angle changes.

In 2010, Andrei's team discovered that in addition to being pretty, moiré patterns formed with twisted bilayer graphene have a dramatic effect on the electronic properties of the material. This

is because the moiré pattern slows down the electrons that conduct electricity in graphene and zip past each other at great speeds.

At a twist angle of about 1.1 degrees—the so-called magic angle—these electrons come to an almost dead stop. The sluggish electrons start seeing each other and interact with their neighbors to move in lock-step. As a result, the material acquires amazing properties such as superconductivity or magnetism.

Using a technique invented by Andrei's group to study twisted bilayer graphene, the team discovered a state where the electrons organize themselves into stripes that are robust and difficult to break.

"Our team found a close resemblance between this feature and similar observations in high-temperature superconductors, providing new evidence of the deep link underlying these systems and opening the way to unraveling their enduring mystery," Andrei said. [30]

A graphene superconductor that plays more than one tune

Researchers at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) have developed a graphene device that's thinner than a human hair but has a depth of special traits. It easily switches from a superconducting material that conducts electricity without losing any energy, to an insulator that resists the flow of electric current, and back again to a superconductor—all with a simple flip of a switch. Their findings were reported today in the journal *Nature*.

"Usually, when someone wants to study how electrons interact with each other in a superconducting quantum phase versus an insulating phase, they would need to look at different materials. With our system, you can study both the superconductivity phase and the insulating phase in one place," said Guorui Chen, the study's lead author and a postdoctoral researcher in the lab of Feng Wang, who led the study. Wang, a faculty scientist in Berkeley Lab's Materials Sciences Division, is also a UC Berkeley physics professor.

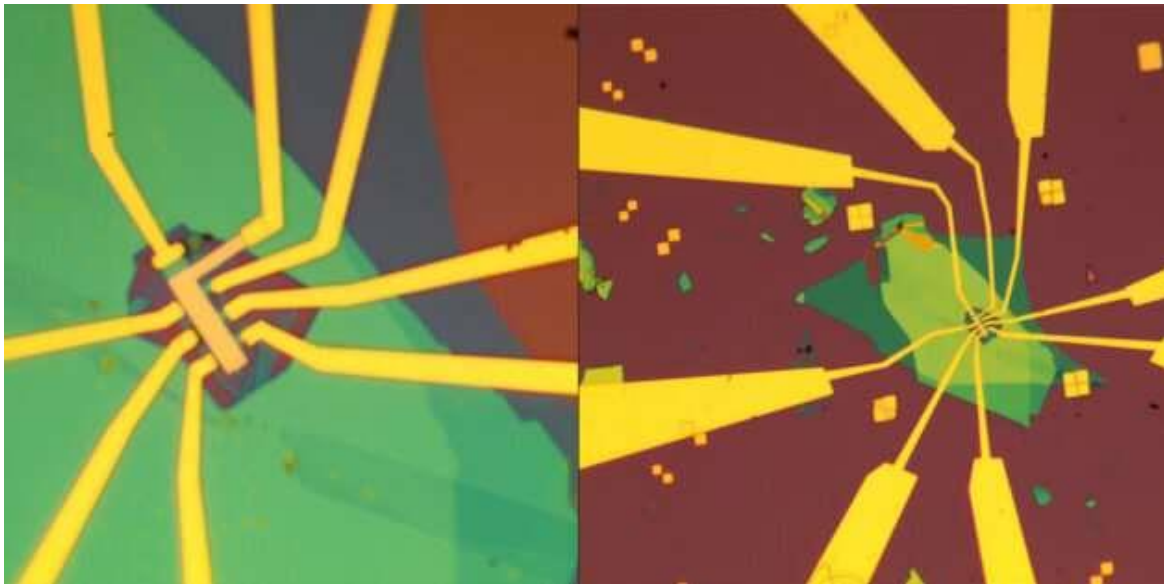
The graphene device is composed of three atomically thin (2-D) layers of graphene. When sandwiched between 2-D layers of boron nitride, it forms a repeating pattern called a moiré superlattice. The material could help other scientists understand the complicated mechanics behind a phenomenon known as high-temperature superconductivity, where a material can conduct electricity without resistance at temperatures higher than expected, though still hundreds of degrees below freezing.

In a previous study, the researchers reported observing the properties of a Mott insulator in a device made of trilayer graphene. A Mott insulator is a class of material that somehow stops conducting electricity at hundreds of degrees below freezing despite classical theory predicting electrical conductivity. But it has long been believed that a Mott insulator can become

superconductive by adding more electrons or positive charges to make it superconductive, Chen explained.

For the past 10 years, researchers have been studying ways to combine different 2-D materials, often starting with graphene—a material known for its ability to efficiently conduct heat and electricity. Out of this body of work, other researchers had discovered that moiré superlattices formed with graphene exhibit exotic physics such as superconductivity when the layers are aligned at just the right angle.

"So for this study we asked ourselves, 'If our trilayer graphene system is a Mott insulator, could it also be a superconductor?'" said Chen.



Two views of the trilayer graphene/boron nitride heterostructure device as seen through an optical microscope. The gold, nanofabricated electric contacts are shown in yellow; the silicon dioxide/silicon substrate is shown in brown; and the boron nitride flakes are shown in green. The trilayer graphene device is encapsulated between two boron nitride flakes. Credit: Guorui Chen/Berkeley Lab

Opening the gate to a new world of physics

Working with David Goldhaber-Gordon of Stanford University and the Stanford Institute for Materials and Energy Sciences at SLAC National Accelerator Laboratory, and Yuanbo Zhang of Fudan University, the researchers used a dilution refrigerator, which can reach intensely cold temperatures of 40 millikelvins—or nearly minus 460 degrees Fahrenheit—to cool the graphene/boron nitride device down to a temperature at which the researchers expected superconductivity to appear near the Mott insulator phase, said Chen.

Once the device reached a temperature of 4 kelvins (minus 452 degrees Fahrenheit), the researchers applied a range of electrical voltages to the tiny top and bottom gates of the device. As they expected, when they applied a high vertical electrical field to both the top and bottom gates, an electron filled each cell of the graphene/boron nitride device. This caused the electrons

to stabilize and stay in place, and this "localization" of electrons turned the device into a Mott insulator.

Then, they applied an even higher electrical voltage to the gates. To their delight, a second reading indicated that the electrons were no longer stable. Instead, they were shuttling about, moving from cell to cell, and conducting electricity without loss or resistance. In other words, the device had switched from the Mott insulator phase to the superconductor phase.

Chen explained that the boron nitride moiré superlattice somehow increases the electron-electron interactions that take place when an electrical voltage is applied to the device, an effect that switches on its superconducting phase. It's also reversible—when a lower electrical voltage is applied to the gates, the device switches back to an insulating state.

The multitasking device offers scientists a tiny, versatile playground for studying the exquisite interplay between atoms and electrons in exotic new superconducting materials with potential use in quantum computers—computers that store and manipulate information in qubits, which are typically subatomic particles such as electrons or photons—as well as new Mott insulator materials that could one day make tiny 2-D Mott transistors for microelectronics a reality.

"This result was very exciting for us. We never imagined that the graphene/boron nitride device would do so well," Chen said. "You can study almost everything with it, from single particles to superconductivity. It's the best system I know of for studying new kinds of physics," Chen said.

This study was supported by the Center for Novel Pathways to Quantum Coherence in Materials (NPQC), an Energy Frontier Research Center led by Berkeley Lab and funded by the DOE Office of Science. NPQC brings together researchers at Berkeley Lab, Argonne National Laboratory, Columbia University, and UC Santa Barbara to study how quantum coherence underlies unexpected phenomena in new materials such as trilayer graphene, with an eye toward future uses in quantum information science and technology. [29]

Graphene on the way to superconductivity

Scientists at HZB have found evidence that double layers of graphene have a property that may let them conduct current completely without resistance. They probed the band structure at BESSY II with extremely high resolution ARPES and could identify a flat area at a surprising location. Their research is published in *Science Advances*.

Carbon atoms can form bonds in multiple ways. Pure carbon can therefore occur in many forms, including diamond, graphite, nanotubes, football molecules or as a honeycomb net with hexagonal meshes, known as graphene. This exotic, strictly two-dimensional material conducts electricity well, but is not a superconductor. But perhaps this can be changed.

A complicated option for superconductivity

In April 2018, a group at MIT in the U.S. showed that it is possible to generate a form of superconductivity in a system of two layers of graphene under very specific conditions. To do this, the two hexagonal nets must be twisted against each other at a 1.1 degree angle. Under this condition, a flat band forms in the electronic structure. The preparation of samples from two layers of graphene with such an exactly adjusted twist is complex, and not suitable for mass production. Nevertheless, the study has attracted a lot of attention among experts.

The simple way to flat bands

But there is one more, much simpler way of flat band formation. This was shown by a group at the HZB around Prof. Oliver Rader and Dr. Andrei Varykhalov with investigations at BESSY II.

The samples were provided by Prof. Thomas Seyller, TU Chemnitz. There they are produced using a process that is also suitable for the production of larger areas and in large quantities: A silicon carbide crystal is heated until silicon atoms evaporate from the surface, leaving first a single-layer of graphene on the surface, and then a second layer of graphene. The two graphene layers are not twisted against each other, but lie exactly on top of each other.

Scanning the band structure with ARPES

At BESSY II, the physicists are able to scan the so-called band structure of the sample. This band structure provides information on how the charge carriers are distributed among the quantum-mechanically permitted states and which charge carriers are available for transport at all. The angle-resolved photoemission spectroscopy (ARPES) at BESSY II enables such measurements with extremely high resolution.

Via an exact analysis of the band structure, they identified an area that had previously been overlooked. "The double layer of graphene has been studied before because it is a semiconductor with a band gap," explains Varykhalov. "But on the ARPES instrument at BESSY II, the resolution is high enough to recognize the flat area next to this band gap."

"It is an overseen property of a well-studied system," says first author Dr. Dmitry Marchenko. "It was previously unknown that there is a flat area in the band structure in such a simple well-known system."

This flat area is a prerequisite for superconductivity, but only if it is situated exactly at the so-called Fermi energy. In the case of the two-layer graphene, its energy level is only 200 milli-electron volts below the Fermi energy, but it is possible to raise the energy level of the flat area to the Fermi energy either by doping with foreign atoms or by applying an external voltage, the so-called gate voltage.

The physicists have found that the interactions between the two graphene layers and between graphene and the silicon carbide lattice are jointly responsible for the formation of the flat band area. "We can predict this behavior with very few parameters and could use this mechanism to control the band structure," adds Oliver Rader. [28]

X-ray scattering reveals plasmons in high-temperature superconductors

US researchers studying high-temperature cuprate superconductors outside the superconducting regime have used cutting-edge X-ray scattering to detect long-predicted – but never previously observed – excitations called plasmons perpendicular to the material's atomic planes. Researchers hope the findings may help theorists to understand these highly unusual materials better, and perhaps even guide the quest for room-temperature superconductors.

The cuprate superconductors are archetypal “strongly correlated” materials, which are difficult to describe using current approximate models. “In most theories we have today you try to catch the main interaction and treat the others as a small perturbation,” explains condensed matter physicist [Wei-Sheng Lee](#) of Stanford University in California, “But for these strongly correlated materials, all the interactions are equally important.”

The materials therefore baffle theoreticians. For example, whereas the established BCS theory of superconductivity predicts that the property should disappear above about 30 K, some cuprates remain superconducting at temperatures up to 130 K. Something seems to preserve the superconducting state at relatively high temperatures, but what it is remains unclear.

I suspect acoustic plasmons may be a necessary, but not sufficient, condition for high-temperature superconductivity

Ivan Božović, Lawrence Berkeley National Laboratory

The crystal structure of cuprate superconductors comprises well-defined planes of copper and oxygen atoms, as well as various dopants. In the non-superconducting state, they show much higher electrical conductivity along the planes than perpendicular to them. Each plane effectively contains its own two-dimensional electron gas, which means that researchers studying a material's electrical properties often consider only a single plane. When the materials become superconductors, however, they show zero resistance in all directions. Some theorists have therefore suggested that the secret to high-temperature superconductivity may lie not within the planes but in the coupling between them.

Researchers such as Vladimir Kresin of Lawrence Berkeley National Laboratory and Ivan Božović of Brookhaven National Laboratory, both in the US, have suggested the inter-layer coupling could be mediated by quasi-particles called plasmons, which are formed from collective oscillations in the materials' electron density. These could mediate the Coulomb interaction between the conductive planes, without electrons moving from one plane to the next. Actually detecting such plasmons, however, has previously proved impossible. Some experiments have revealed plasmons within the copper-oxide planes, but not between them.



[The European Synchrotron in Grenoble](#)

In the new research, therefore, Wei-Sheng Lee and colleagues at Stanford University and elsewhere used a technique called RIXS (resonant inelastic X-ray scattering) to excite the plasmons. The technique advances the principles of traditional X-ray scattering, exploiting the ability of modern synchrotron radiation sources to produce a beam of X-ray photons with well-defined, tunable, energy and momentum.

The researchers bombarded samples of the electron-doped cuprate LCCO (lanthanum cerium copper oxide), held above its transition temperature, with X-ray photons from the [European Synchrotron Radiation Facility](#) in Grenoble, France. They varied the energies of incident photons and their momenta perpendicular to the copper-oxide planes, and then measured the effect on the proportion of photons absorbed by the sample, and the energies, momenta and polarizations of the scattered photons.

These experimental results were consistent with models that assume the planes interacted through acoustic plasmons. There was a clear absorption resonance, for example, at photon energies that would have excited a plasmon wavelength equal to the distance between the copper-oxide planes.

Raising the transition temperature

The researchers now plan to study hole-doped superconductors, some of which have been found to have higher transition temperatures than electron-doped ones like LCCO. “For electron-doped

materials, it's hard to investigate how the plasmons change as you go to the superconducting state because the transition temperature is much lower," explains Lee. "But for hole-doped cuprates, the transition temperature is generally higher. Therefore it should be easier for us to investigate first whether this phenomenon is universal in the cuprate family and secondly how it changes as you enter a superconducting state. Hopefully we might get a clue about how to make a superconductor with an even higher transition temperature."

Ivan Božović is intrigued: "I suspect acoustic plasmons may be a necessary, but not sufficient, condition for high-temperature superconductivity," he says. He notes that a number of other materials such as nickelates, cobaltates and iridates have very similar structures to the cuprates but have shown no superconductivity at any temperature. He suggests it would be interesting to repeat the experiments with these materials to look for evidence of plasmons "Let's see what's common and perhaps what's different," he says.

"This puts on the map the peculiar, layered two-dimensional nature of these materials," says Dirk van der Marel of the University of Geneva in Switzerland. "From that you get an entirely different interaction between the electrons. The ideas that this could be the source of the superconductivity have been worked out in some detail by the Nobel prize winner Tony Leggett, and I think this gives more fuel to those."

The research is published in [Nature](#). [27]

New quantum criticality discovered in superconductivity

Using solid state nuclear magnetic resonance (ssNMR) techniques, scientists at the U.S. Department of Energy's Ames Laboratory discovered a new quantum criticality in a superconducting material, leading to a greater understanding of the link between magnetism and unconventional superconductivity.

Most iron-arsenide superconductors display both magnetic and structural (or nematic) transitions, making it difficult to understand the role they play in superconducting states. But a compound of calcium, potassium, iron, and arsenic, and doped with small amounts of nickel, $\text{CaK}(\text{Fe}_{1-x}\text{Ni}_x)_4\text{As}_4$, first made at Ames Laboratory, has been discovered to exhibit a new magnetic state called a hedgehog spin-vortex crystal antiferromagnetic state without nematic transitions.

"Spin or nematic fluctuations can be considered to play an important role for [unconventional superconductivity](#)," said Yuji Furukawa, a senior scientist at Ames Laboratory and a professor of Physics and Astronomy at Iowa State University. "With this particular material, we were able to examine only the magnetic fluctuations, and NMR is one of the most sensitive techniques for examining them." He continued, "using 75As NMR, we discovered that $\text{CaK}(\text{Fe}_{1-x}\text{Ni}_x)_4\text{As}_4$ is located at a hedgehog spin-vortex crystal antiferromagnetic [quantum](#) critical point which is avoided due to [superconductivity](#). The discovery of the magnetic [quantum criticality](#) without

nematicity in $\text{CaK}(\text{Fe}_{1-x}\text{Ni}_x)_4\text{As}_4$ suggests that the spin fluctuations are the primary driver of superconductivity."

Furukawa's discovery was a collaboration between Ames Laboratory's world-leading SSNMR team and the lab's condensed matter physicists, including Paul Canfield, a senior scientist at Ames Laboratory and a Distinguished Professor and the Robert Allen Wright Professor of Physics and Astronomy at Iowa State University.

"This is a new type of magnetic order," said Canfield. "You have this interesting interaction between superconductivity and magnetism from high temperatures in the normal state. This gives us some sense that this [high temperature superconductivity](#) may be coming from this near quantum critical antiferromagnetic transition."

The research is further discussed in the paper, "Hedgehog Spin-vortex Crystal Antiferromagnetic Quantum Criticality in $\text{CaK}(\text{Fe}_{1-x}\text{Ni}_x)_4\text{As}_4$ revealed by NMR," published in *Physical Review Letters*. [26]

New method could lead to more powerful quantum sensors

As quantum technology continues to come into its own, investment is happening on a global scale. Soon, we could see improvements in machine learning models, financial risk assessment, efficiency of chemical catalysts and the discovery of new medications.

As numerous scientists, companies and governments rush to invest in the new era of quantum technology, a crucial piece of this wave of innovation is the quantum sensor. Improving these devices could mean more powerful computers, better detectors of disease and technological advances scientists can't even predict yet.

A scientific study from the University of Chicago's Institute for Molecular Engineering published Oct. 17 in *Nature Communications* could have exciting implications for the developing world of quantum sensing—and [quantum technology](#) as a whole.

"We took a recently proposed idea to make better optical classical sensors and asked whether the same idea would work in a quantum setting," said Aashish Clerk, one of the study's authors and a professor at the Institute for Molecular Engineering. "We found that this idea doesn't really work in quantum settings, but that another somewhat related approach could give you a huge advantage."

In a quantum setting, [optical sensors](#) are typically limited because light is made up of particles, and this discreteness leads to unavoidable noise. But this study revealed an unexpected method to combat that limitation.

"We think we've uncovered a new strategy for building extremely powerful [quantum sensors](#)," Clerk continued.

The path to the directional principle

Clerk and co-author Hoi-Kwan Lau, a postdoctoral scholar at UChicago, were inspired by recent high-profile studies that showed how to drastically enhance a common optical sensing technique. The "trick" involves tuning systems to an exceptional point, or a point at which two or more modes of light come together at one specific frequency.

Lau and Clerk wanted to see whether this method could succeed in settings where quantum effects were important. The goal was to account for unavoidable "quantum" noise—fluctuations associated with the fact that light has both a wave-like and a particle-like character, Clerk explained.

The study found the exceptional point technique to be unhelpful in a quantum setting, but the research still led to promising results.

"The good news is we found another way to build a powerful new type of sensor that has advantages even in quantum regimes," Clerk said. "The idea is to construct a system that is 'directional,' meaning photons can move in one direction only."

This directional principle—one based on photons being able to move in only one direction—is a brand-new development in quantum sensing.

New developments in quantum sensing

In terms of real-world applications, highly effective quantum sensors could be game-changing. Quantum systems are sensitive to the slightest environmental changes, so these detectors have the potential to be incredibly powerful.

In addition, some of the stranger aspects of quantum behavior, such as [quantum entanglement](#), could make them even stronger. Quantum entanglement, a puzzling phenomenon even for scientists, describes how two particles can be separated by a vast distance yet actions performed on one particle immediately affect the other. This entanglement can be harnessed to make quantum sensors surprisingly resilient against certain kinds of noise.

In the future, new developments in quantum sensing could translate to significant advances in a variety of areas. The class of optical sensors described in the study can be used to detect viruses in liquids, for example. They also can act as readout devices for quantum bits in a superconducting quantum computer.

"We think our idea has the potential to generate major improvements in many of these applications," Clerk explained.

The study's implications for quantum computing are especially exciting. Not only do quantum computers have the potential to dramatically increase computing speeds, but they could also tackle problems that are completely unfeasible with traditional computing.

Lau and Clerk plan to do further research on their enhanced sensing technique. Clerk still has a lot of questions: "What sets how fast our sensor is? Are there fundamental limits on its speed? Can it be used to detect signals that aren't necessarily small?"

Their biggest hope, Clerk explained, is to inspire other researchers to build improved [quantum sensors](#) that harness this newly uncovered principle. [25]

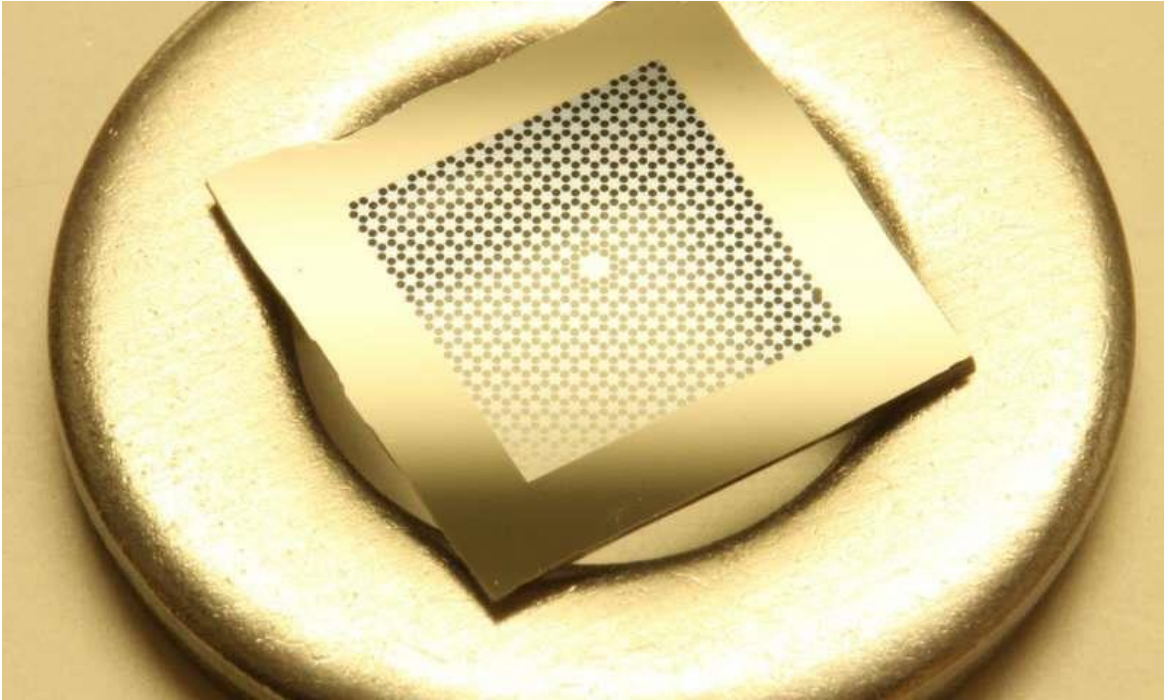
Active noise control for a quantum drum

Researchers at the Schliesser Lab at the Niels Bohr Institute, University of Copenhagen, have demonstrated a new way to address a central problem in quantum physics: at the quantum scale, any measurement disturbs the measured object. This disturbance limits, for example, the precision with which the motion of an object can be tracked. But in a millimeter-sized membrane that vibrates like a drumhead, the researchers have managed to precisely monitor the motion with a laser—and to undo the quantum disturbance by the measurement. This allows them to control the membrane's motion at the quantum level. The result has potential applications in ultraprecise sensors of position, velocity and force, and the architecture of a future quantum computer. It is now published in the prestigious scientific magazine, *Nature*.

At the quantum level, making measurements disturbs the object measured: using a laser beam to determine the position or velocity of an object requires bombarding it with many photons. The photons will kick it with every impact, and the object will start moving accordingly. As the photons arrive randomly, this results in additional random [motion](#) on top of the original movements, degrading the ability to measure and control the actual motional state. If the laser intensity is turned down, in order to reduce such measurement "backaction", the signal-to-noise ratio in the detector goes down and the measurement becomes imprecise – again. "A strong measurement is needed, even though it results in quantum backaction. All we have to do is to measure and undo the quantum backaction. And that is basically what we've succeeded in doing", Professor Albert Schliesser explains.

The experiment

"Our experiments offer us a really unique opportunity: our data very clearly show [quantum effects](#), such as quantum backaction, in the measurement of mechanical motion. So we can test in our labs if clever modifications of the measurement apparatus can improve precision—using tricks that in the last few decades could only be theorized," he continues.



A silicon nitride membrane resonator suspended from a mm-sized square silicon frame. The hole pattern in the membrane has a phononic bandgap that confines vibrations at certain frequencies to the island ('defect') in the center. Credit: Niels Bohr Institute

The experimental system is a ca. 3x3 mm-sized membrane made of the ceramic [silicon nitride](#) (Fig 1). It is under high tension and vibrates when struck—just like a drumhead. A special hole pattern invented in Schliesser's lab isolates these vibrations extremely well: once it vibrates, it undergoes a billion oscillation cycles before it loses a significant fraction of its energy to its surroundings. (For a normal drum, that number would be about one hundred.) An additional advantage of silicon nitride is that it does not absorb any of the laser light used to interrogate its motion—so the membrane does not heat up, which would again lead to some uncontrolled motion of the membrane.

Controlling the motional quantum state with active noise cancellation

Excluding external perturbations through such extreme isolation, the scientists can focus on quantum effects of the measurement. Using a very stable laser, they can indeed measure the motion, including measurement backaction, down to the [quantum level](#). "The remarkable thing is that we can then take this measurement record, run it through some electronics, and apply a counteracting force to the membrane, to undo the random effects of quantum backaction. It basically works like a set of noise-cancelling headphones, just in the quantum regime," explains Ph.D. student Massimiliano Rossi, one of the study's lead authors. In this manner, the scientists could deterministically prepare the motion of the [membrane](#) in a pure [quantum state](#)—an objective physicists from a range of communities have pursued for the last 20 years.

The reason lies in the versatility of such quantum control techniques when applied to motion. The LIGO interferometers are one example. They measure gravitational waves, emitted e.g. by merging black holes billions of light years away, by monitoring the motion of large mirrors on earth. To recover these extremely faint signals, they have to push the sensitivity to such an extreme that the quantum limits of motion measurements come into play. On the other hand, controlling the quantum state of mechanical systems could be of use for special components of a quantum computer. A memory element, for example, would benefit from the long lifetime of mechanical excitations. Ultimately, quantum-controlled vibrations are also interesting from a fundamental point of view: as vibration implies mass is moving, which role does gravity play? How does it influence the [quantum](#) state of motion? Today's accepted theories, let alone experiments, have yet to deliver clear answers to these question. [24]

Hidden bridge between quantum experiments and graph theory uncovered

An answer to a quantum-physical question provided by the algorithm Melvin has uncovered a hidden link between quantum experiments and the mathematical field of Graph Theory. Researchers from the Austrian Academy of Sciences and the University of Vienna found the deep connection between experimental quantum physics and this mathematical theory in the study of Melvin's unusual solutions, which lies beyond human intuition. They now report in the journal *Physical Review Letters*.

Phenomena of [quantum physics](#) are perfectly computable—but often elude human logic. In the future, it would be precisely computer algorithms that could make a decisive contribution to the solution of [quantum](#)-physical questions, where human logic does not get any further, as was demonstrated now by Melvin. The algorithm developed by researchers of the Austrian Academy of Sciences (ÖAW) and the University of Vienna is actually being created for the calculation of technical solutions for quantum physical experiments. For a general question asked last year, Melvin provided a solution that proved to be surprisingly practical—but initially completely out of touch with human intuition.

Remarkable number sequence

"The solution could practically be implemented in the form of an experiment in the laboratory," confirms quantum physicist Mario Krenn from the research group of Anton Zeilinger, professor at the University of Vienna and group leader at the Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences. "But at first we did not understand how it actually works," the researcher continues.

In the analysis of this [solution](#) calculated by Melvin, the researchers initially groped in the dark. Until they came up with a remarkable sequence of numbers known only in the so-called [graph theory](#)—a sophisticated area of mathematics that has been used to describe networks such as the Internet or neural networks.

New experimental methods

The unusual approach, which would have remained hidden to quantum physicists, prompted the scientists to further investigate this connection. As they now report in the journal *Physical Review Letters*, there are great similarities between experimental quantum physics and mathematical graph theory: If methods and knowledge from graph theory are used to calculate and plan a quantum experiment, it is possible to make very precise and novel statements about the results. "Properties of quantum experiments can be calculated using graph theory, and questions in [graph theory](#) can be answered in quantum experiments," explains Krenn. In this way, it is also possible to grasp quantum technology as a graph or a network in order to explore new experimental possibilities.

Also for quantum physicist Anton Zeilinger this bridge, discovered thanks to Melvin, is very promising: "It was very surprising to see that there is a new deep connection between quantum physics and mathematics." What concrete potential this finding holds, is currently not yet to estimate. "It is to be expected," says Zeilinger, "that this knowledge will be of importance for the development of both areas in the future." [23]

Engineers develop key mathematical formula for driving quantum experiments

Since he was a graduate student, Washington University in St. Louis systems engineer Jr-Shin Li has provided specific mathematical information to experimentalists and clinicians who need it to perform high-resolution magnetic resonance applications, such as body MRIs for medical diagnosis or spectroscopy for uncovering protein structures. Now, after more than a decade of work, he has developed a formula that researchers can use to generate that information themselves.

Li, the Das Family Career Development Distinguished Associate Professor in the School of Engineering & Applied Science, and his collaborators have derived a mathematical formula to design broadband pulse sequences to excite a population of nuclear spins over a wide band of frequencies. Such a broadband excitation leads to enhanced signal or sensitivity in diverse quantum experiments across fields from protein spectroscopy to quantum optics.

The research, the first to find that designing the pulse can be done analytically, was published in *Nature Communications* Sept. 5.

"This design problem is traditionally done by purely numerical optimization," Li said. "Because one has to design a common input—a magnetic field to excite many, many particles—the problem is challenging. In many cases in numerical optimization, the algorithms fail to converge or take enormous amounts of time to get a feasible solution."

For more than a decade, Li has sought a better way for pulse design using the similarity between spins and springs by applying numerical experiments. Spin is a form of angular momentum carried by elementary particles. Spin systems are nonlinear and difficult to work with, Li said,

while spring systems, or harmonic oscillators, are linear and easier to work with. While a doctoral student at Harvard University, Li found a solution by projecting the nonlinear spin system onto the linear spring system, but was unable to prove it mathematically until recently.

"We have very rigorous proof that such a projection from nonlinear to linear is valid, and we also have done a lot of numerical simulations to demonstrate the discovery," Li said. "My collaborator, Steffan Glaser (of the Technische Universität Munich), has been in this field of NMR spectroscopy for more than 20 years, and he is confident that if the quantum pulses perform well in computer simulations, they may perform the same in experimental systems."

The team plans to conduct various experiments in magnetic resonance to verify the analytical invention.

The theoretical work opens up new avenues for pulse sequence design in quantum control. Li plans to create a website where collaborators can enter their parameter values to generate the pulse formula they will need in their quantum experiments. [22]

New tool for characterizing quantum simulators

Physicists are developing quantum simulators, to help solve problems that are beyond the reach of conventional computers. However, they first need new tools to ensure that the simulators work properly. Innsbruck researchers around Rainer Blatt and Christian Roos, together with researchers from the Universities of Ulm and Strathclyde, have now implemented a new technique in the laboratory that can be used to efficiently characterize the complex states of quantum simulators. The technique, called matrix product state tomography, could become a new standard tool for characterizing quantum simulators.

Many phenomena in the quantum world cannot be investigated directly in the laboratory, and even supercomputers fail when trying to simulate them. However, scientists are now able to control various quantum systems in the laboratory very precisely and these systems can be used to simulate other quantum systems. Such Quantum Simulators are therefore considered to be one of the first concrete applications of the second quantum revolution.

However, the characterization of large quantum states, which is necessary to guide the development of large-scale quantum simulators, proves to be difficult. The current gold standard for quantum-state characterization in the laboratory - quantum-state tomography - is only suitable for small quantum systems composed of a handful of quantum particles. Researchers from the Institute of Experimental Physics at the University of Innsbruck and the Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences have now established a new method in the laboratory that can be used to efficiently characterize large quantum states.

A collaborative effort

In ion traps, charged atoms (ions) are cooled to temperatures close to absolute zero and manipulated with the aid of lasers. Such systems represent a promising approach to performing quantum simulations that can go beyond the capabilities of modern supercomputers. The Innsbruck quantum physicists are amongst the world leaders in this field and can currently entangle 20 or more ions in their traps. In order to fully characterize such large quantum systems, they need new methods. For this, theorists around Martin Plenio from the University of Ulm, Germany, came to their aid. In 2010, the Plenio team proposed a new method for the characterization of complex quantum states called matrix-product-state tomography. Using this method, the state of a group of entangled quantum particles can be estimated precisely without the effort increasing dramatically as the number of particles in the group is increased. In collaboration with the teams around Martin Plenio from Ulm and Andrew Daley from the University of Strathclyde in Scotland, the Innsbruck experimental physicists around Christian Roos, Ben Lanyon and Christine Maier have now implemented this procedure in the laboratory.

More efficient measurements

As a test case, the physicists built a quantum simulator with up to 14 quantum bits (atoms), that was first prepared in a simple initial state without quantum correlations. Next, the researchers entangled the atoms with laser light and observed the dynamical propagation of entanglement in the system. "With the new method, we can determine the quantum state of the whole system by measuring only a small fraction of the system properties," says START prize winner Ben Lanyon. The theorists around Martin Plenio took the characterization of the global quantum state from the measured data: "The method is based on the fact that we can theoretically describe locally-distributed entanglement well and can now also measure it in the laboratory."

When the work group of Rainer Blatt realized the first quantum byte in 2005, more than 6,000 measurements were required for the characterization of the quantum state, taken over a period of ten hours. The new method requires only 27 measurements to characterise the same size system, taken over around 10 minutes. "We were able to show that this method can be used to identify large and complex quantum states efficiently," says Christine Maier, a team member from Innsbruck. Now the scientists want to further develop the algorithms so that they can also be used flexibly by other research groups.

New gold standard

The new method allows the complete characterization of systems containing large numbers of correlated quantum particles and thus provides a comparison option for quantum simulations. "We can use the new technique to calibrate quantum simulators, by comparing the states that we find in the lab with the ones expected from analytical calculations," explains Christian Roos. "Then we know if the simulator does what we want." The new method offers physicians a tool for many applications and could become a new standard for quantum simulations. [21]

Flip-flop qubits: Radical new quantum computing design invented

Engineers at Australia's University of New South Wales have invented a radical new architecture for quantum computing, based on novel 'flip-flop qubits', that promises to make the large-scale manufacture of quantum chips dramatically cheaper - and easier - than thought possible.

The new chip design, detailed in the journal *Nature Communications*, allows for a silicon quantum processor that can be scaled up without the precise placement of atoms required in other approaches. Importantly, it allows quantum bits (or 'qubits') - the basic unit of information in a quantum computer - to be placed hundreds of nanometres apart and still remain coupled.

The design was conceived by a team led by Andrea Morello, Program Manager in UNSW-based ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) in Sydney, who said fabrication of the new design should be easily within reach of today's technology.

Lead author Guilherme Tosi, a Research Fellow at CQC2T, developed the pioneering concept along with Morello and co-authors Fahd Mohiyaddin, Vivien Schmitt and Stefanie Tenberg of CQC2T, with collaborators Rajib Rahman and Gerhard Klimeck of Purdue University in the USA.

"It's a brilliant design, and like many such conceptual leaps, it's amazing no-one had thought of it before," said Morello.

"What Guilherme and the team have invented is a new way to define a 'spin qubit' that uses both the electron and the nucleus of the atom. Crucially, this new qubit can be controlled using electric signals, instead of magnetic ones. Electric signals are significantly easier to distribute and localise within an electronic chip."

Tosi said the design sidesteps a challenge that all spin-based silicon qubits were expected to face as teams begin building larger and larger arrays of qubits: the need to space them at a distance of only 10-20 nanometres, or just 50 atoms apart.

"If they're too close, or too far apart, the 'entanglement' between quantum bits - which is what makes quantum computers so special - doesn't occur," Tosi said.

Researchers at UNSW already lead the world in making spin qubits at this scale, said Morello.

"But if we want to make an array of thousands or millions of qubits so close together, it means that all the control lines, the control electronics and the readout devices must also be fabricated at that nanometric scale, and with that pitch and that density of electrodes. This new concept suggests another pathway."

At the other end of the spectrum are superconducting circuits - pursued for instance by IBM and Google - and ion traps. These systems are large and easier to fabricate, and are currently leading the way in the number of qubits that can be operated. However, due to their larger dimensions, in the long run they may face challenges when trying to assemble and operate millions of qubits, as required by the most useful quantum algorithms.

"Our new silicon-based approach sits right at the sweet spot," said Morello, a professor of quantum engineering at UNSW. "It's easier to fabricate than atomic-scale devices, but still allows us to place a million qubits on a square millimetre."

In the single-atom qubit used by Morello's team, and which Tosi's new design applies, a silicon chip is covered with a layer of insulating silicon oxide, on top of which rests a pattern of metallic electrodes that operate at temperatures near absolute zero and in the presence of a very strong magnetic field.

At the core is a phosphorus atom, from which Morello's team has previously built two functional qubits using an electron and the nucleus of the atom. These qubits, taken individually, have demonstrated world-record coherence times.

Tosi's conceptual breakthrough is the creation of an entirely new type of qubit, using both the nucleus and the electron. In this approach, a qubit '0' state is defined when the spin of the electron is down and the nucleus spin is up, while the '1' state is when the electron spin is up, and the nuclear spin is down.

"We call it the 'flip-flop' qubit," said Tosi. "To operate this qubit, you need to pull the electron a little bit away from the nucleus, using the electrodes at the top. By doing so, you also create an electric dipole."

"This is the crucial point," adds Morello. "These electric dipoles interact with each other over fairly large distances, a good fraction of a micron, or 1,000 nanometres.

"This means we can now place the single-atom qubits much further apart than previously thought possible," he continued. "So there is plenty of space to intersperse the key classical components such as interconnects, control electrodes and readout devices, while retaining the precise atom-like nature of the quantum bit."

Morello called Tosi's concept as significant as Bruce Kane seminal 1998 paper in Nature. Kane, then a senior research associate at UNSW, hit upon a new architecture that could make a silicon-based quantum computer a reality - triggering Australia's race to build a quantum computer.

"Like Kane's paper, this is a theory, a proposal - the qubit has yet to be built," said Morello. "We have some preliminary experimental data that suggests it's entirely feasible, so we're working to fully demonstrate this. But I think this is as visionary as Kane's original paper."

Building a quantum computer has been called the 'space race of the 21st century' - a difficult and ambitious challenge with the potential to deliver revolutionary tools for tackling otherwise impossible calculations, with a plethora of useful applications in healthcare, defence, finance, chemistry and materials development, software debugging, aerospace and transport. Its speed and power lie in the fact that quantum systems can host multiple 'superpositions' of different

initial states, and in the spooky 'entanglement' that only occurs at the quantum level the fundamental particles.

"It will take great engineering to bring quantum computing to commercial reality, and the work we see from this extraordinary team puts Australia in the driver's seat," said Mark Hoffman, UNSW's Dean of Engineering. "It's a great example of how UNSW, like many of the world's leading research universities, is today at the heart of a sophisticated global knowledge system that is shaping our future."

The UNSW team has struck a A\$83 million deal between UNSW, telco giant Telstra, Australia's Commonwealth Bank and the Australian and New South Wales governments to develop, by 2022, a 10-qubit prototype silicon quantum integrated circuit - the first step in building the world's first quantum computer in silicon.

In August, the partners launched Silicon Quantum Computing Pty Ltd, Australia's first quantum computing company, to advance the development and commercialisation of the team's unique technologies. The NSW Government pledged A\$8.7 million, UNSW A\$25 million, the Commonwealth Bank A\$14 million, Telstra A\$10 million and the Federal Government A\$25 million. [20]

New quantum memory device small enough to fit on a chip

A team of researchers from the U.S. and Italy has built a quantum memory device that is approximately 1000 times smaller than similar devices—small enough to install on a chip. In their paper published in the journal *Science*, the team describes building the memory device and their plans for adding to its functionality.

Scientists have been working steadily toward building quantum computers and networks, and have made strides in both areas in recent years. But one inhibiting factor is the construction of quantum memory devices. Such devices have been built, but until now, they have been too large to put on a chip, a requirement for practical applications. In this new effort, the researchers report developing a quantum memory device that is not only small enough to fit on a chip, but is also able to retrieve data on demand.

The device is very small, approximately 10 by 0.7 micrometers and has an odd shape, like a Toblerone candy bar—long and thin with a notched triangular shape, with mirrors on either end. It is made of yttrium orthovanadate with small amounts of neodymium, which form a cavity. These cavities in turn hold a crystal cavity that traps single photons encoding data information (zero, one or both).

To operate the device, the researchers fired laser pulses at it, causing photons to assemble in the comb, which forced them to be absorbed—the configuration also caused the photons to emerge from the comb after 75 nanoseconds. During the time period when the photons were absorbed, the researchers fired dual laser pulses at the comb to delay the reemergence of the

photons for 10 nanoseconds, which allowed for on-demand retrieval of data. During the time period when the photons were held, they existed as dual pulses—early and late.

To show that the device was actually storing data information, the team compared the wavefunction of the photons both before and after storage and found them to be virtually unchanged, meaning they still held their zero, one or both state—it had not been destroyed, which meant the device was truly a quantum memory device. [19]

How to store data on magnets the size of a single atom

The cutting edge of data storage research is working at the level of individual atoms and molecules, representing the ultimate limit of technological miniaturisation.

Magnetism is useful in many ways, and the magnetic memory effect appears even at the atomic level.

There is an adage that says that data will expand to fill all available capacity. Perhaps ten or 20 years ago, it was common to stockpile software programs, MP3 music, films and other files, which may have taken years to collect. In the days when hard disk drives offered a few tens of gigabytes of storage, running out of space was almost inevitable.

Now that we have fast broadband internet and think nothing of downloading a 4.7 gigabyte DVD, we can amass data even more quickly. Estimates of the total amount of data held worldwide are to rise from 4.4 trillion gigabytes in 2013 to 44 trillion gigabytes by 2020. This means that we are generating an average of 15m gigabytes per day. Even though hard disk drives are now measured in thousands of gigabytes rather than tens, we still have a storage problem.

Research and development is focused on developing new means of data storage that are more dense and so can store greater amounts of data, and do so in a more energy efficient way. Sometimes this involves updating established techniques: recently IBM announced a new magnetic tape technology that can store 25 gigabytes per square inch, a new world record for the 60-year-old technology. While current magnetic or solid-state consumer hard drives are more dense at around 200 gigabytes per square inch, magnetic tapes are still frequently used for data back-up.

However, the cutting edge of data storage research is working at the level of individual atoms and molecules, representing the ultimate limit of technological miniaturisation.

The quest for atomic magnets

Current magnetic data storage technologies – those used in traditional hard disks with spinning platters, the standard until a few years ago and still common today – are built using “top-down” methods. This involves making thin layers from a large piece of ferromagnetic material, each containing the many magnetic domains that are used to hold data. Each of these magnetic

domains is made of a large collection of magnetised atoms, whose magnetic polarity is set by the hard disk's read/write head to represent data as either a binary one or zero.

An alternative “bottom-up” method would involve constructing storage devices by placing individual atoms or molecules one by one, each capable of storing a single bit of information. Magnetic domains retain their magnetic memory due to communication between groups of neighbouring magnetised atoms.

Single-atom or single-molecule magnets on the other hand do not require this communication with their neighbours to retain their magnetic memory. Instead, the memory effect arises from quantum mechanics. So because atoms or molecules are much, much smaller than the magnetic domains currently used, and can be used individually rather than in groups, they can be packed more closely together which could result in an enormous increase in data density.

Working with atoms and molecules like this is not science fiction. Magnetic memory effects in single-molecule magnets (SMMs) were first demonstrated in 1993, and similar effects for singleatom magnets were shown in 2016.

Raising the temperature

The main problem standing in the way of moving these technologies out of the lab and into the mainstream is that they do not yet work at ambient temperatures. Both single atoms and SMMs require cooling with liquid helium (at a temperature of -269°C), an expensive and limited resource. So research effort over the last 25 years has concentrated on raising the temperature at which magnetic hysteresis – a demonstration of the magnetic memory effect – can be observed. An important target is -196°C , because this is the temperature that can be achieved with liquid nitrogen, which is abundant and cheap.

It took 18 years for the first substantive step towards raising the temperature in which magnetic memory is possible in SMMs – an increase of 10°C achieved by researchers in California. But now our research team at the University of Manchester's School of Chemistry have achieved magnetic hysteresis in a SMM at -213°C using a new molecule based on the rare earth element dysprosocenium, as reported in a letter to the journal Nature. With a leap of 56°C , this is only 17°C away from the temperature of liquid nitrogen.

Future uses

There are other challenges, however. In order to practically store individual bits of data, molecules must be fixed to surfaces. This has been demonstrated with SMMs in the past, but not for this latest generation of high-temperature SMMs. On the other hand, magnetic memory in single atoms has already been demonstrated on a surface.

Optical control of magnetic memory—New insights into fundamental mechanisms

This is an important clue for our theoretical understanding of optically controlled magnetic data storage media. The findings are published at August 25th in the journal Scientific Reports.

The demands placed on digital storage media are continuously increasing. Rapidly increasing quantities of data and new technological applications demand memory that can store large amounts of information in very little space and permit this information to be utilised dependably with high access speeds.

Re-writeable magnetic data storage devices using laser light appear to have especially good prospects. Researchers have been working on this new technology for several years. "However, there are still unresolved questions about the fundamental mechanisms and the exact manner in which optically controlled magnetic storage devices operate", says Dr. Florian Kronast, assistant head of the Materials for Green Spintronics department at the Helmholtz-Zentrum Berlin (HZB).

A research team led by him has now succeeded in making an important step toward better understanding of this very promising storage technology. The scientists were able to empirically establish for the first time that the warming of the storage material by the energy of the laser light plays an instrumental role when toggling the magnetisation alignments and that the change in the material only takes place under certain conditions.

Making precise measurements in tiny laser spots

The HZB scientists together with those of Freie Universität Berlin and Universität Regensburg studied the microscopic processes at extremely high resolution while irradiating a thin layer of magnetic material using circularly polarised laser light. To do this, they directed the light of an infrared laser onto a nanometre-thick layer of alloy made from the metals terbium and iron (TbFe). What was special about the experimental set-up was that the narrowly focussed spot of laser light had a diameter of only three microns. "That is far less than was usual in prior experiments", says HZB scientist Ashima Arora, first author of the study. And it provided the researchers with unsurpassed detail resolution for studying the phenomena. The images of the magnetic domains in the alloy that the team created with the help of X-rays from the BESSY II synchrotron radiation source revealed fine features that themselves were only 30 nanometres in size.

The crucial thing occurs in the boundary ring

The results of the measurements prove that a ring-shaped region forms around the tiny laser spot and separates the two magnetically contrasting domains from one another. The extant magnetisation pattern inside the ring is completely erased by the thermal energy of the laser light. Outside the ring, however, it remains in its original state. Within the boundary zone itself, a temperature distribution arises that facilitates a change in magnetisation by displacing the

domain boundaries. "It is only there that the toggling of magnetic properties can proceed, permitting a device to store re-writeable data", explains Arora.

Surprising influence of the layer thickness

"These new insights will assist in the development of optically controlled magnetic storage devices having the best possible properties," in the view of Kronast. An additional effect contributes to better understanding the physical processes that are important in this phenomenon, which researchers at HZB unexpectedly observed for the first time. The way the toggling of the magnetisations happens is highly dependent on the layer thickness of the material irradiated by the laser. It changes over an interval of 10 to 20 nanometres thickness.

"This is a clear indication that two contrasting mechanisms are involved and compete with one another", Kronast explains. He and his team suspect two complex physical effects for this. To confirm their suspicions, though, further empirical and theoretical studies are necessary. [17]

Photosensitive perovskites change shape when exposed to light

A crystalline material that changes shape in response to light could form the heart of novel lightactivated devices. Perovskite crystals have received a lot of attention for their efficiency at converting sunlight into electricity, but new work by scientists at KAUST shows their potential uses extend far beyond the light-harvesting layer of solar panels.

Photostriction is the property of certain materials to undergo a change in internal strain, and therefore shape, with exposure to light. Organic photostrictive materials offer the greatest shape change so far reported in response to light—a parameter known as their photostrictive coefficient—but their response is slow and unstable under ambient conditions.

KAUST electrical engineer Jr-Hau He and his colleagues have looked for photostriction in a new family of materials, the perovskites. "Perovskites are one of the hottest optical materials," says He. His work now shows there's more to their interesting optical properties than solar energy harvesting. The researchers tested a perovskite called MAPbBr₃ and revealed it had strong and robust photostriction behavior.

To extensively test the material's photostriction capabilities, the team developed a new method. They used Raman spectroscopy, which probes the molecular vibrations within the structure. When bathed in light, photostriction alters the internal strain in the material, which then shifts the internal pattern of vibrations. By measuring the shift in the Raman signal when the material was placed under mechanical pressure, the team could calibrate the technique and so use it to quantify the effect of photostriction.

"We demonstrated that in situ Raman spectroscopy with confocal microscopy is a powerful characterization tool for conveniently measuring intrinsic photoinduced lattice deformation," says Tzu-Chiao Wei, a member of the team. "The same approach could be applied to measure photostriction in other materials," he adds.

The perovskite material proved to have a significant photostriction coefficient of 1.25%. The researchers also showed that the perovskite's photostriction was partly due to the photovoltaic effect—the phenomenon at the heart of most solar cell operation. The spontaneous generation of positive and negative charges when the perovskite is bathed in light polarizes the material, which induces a movement in the ions the material is made from.

The robust and stable photostriction of perovskite makes it useful for a range of possible devices, says Wei. "We will use this material to fabricate next-generation optoelectronic devices, including wireless remote switchable devices and other light-controlled applications," he says. [16]

Conformal metasurface coating eliminates crosstalk and shrinks waveguides

The properties of materials can behave in funny ways. Tweak one aspect to make a device smaller or less leaky, for example, and something else might change in an undesirable way, so that engineers play a game of balancing one characteristic against another. Now a team of Penn State electrical engineers have a way to simultaneously control diverse optical properties of dielectric waveguides by using a two-layer coating, each layer with a near zero thickness and weight.

"Imagine the water faucet in your home, which is an essential every-day device," said Douglas H. Werner, John L. and Genevieve H. McCain Chair Professor of Electrical Engineering. "Without pipes to carry the water from its source to the faucet, the device is worthless. It is the same with 'waveguides.' They carry electromagnetic or optical signals from the source to the device—an antenna or other microwave, millimeter-wave or terahertz device. Waveguides are an essential component in any electromagnetic or optical system, but they are often overlooked because much of the focus has been on the devices themselves and not the waveguides."

According to Zhi Hao Jiang, former postdoctoral fellow at Penn State and now a professor at Southeast University, Nanjing, China, metasurface coatings allow researchers to shrink the diameter of waveguides and control the waveguiding characteristics with unprecedented flexibility.

The researchers developed a material that is so thin it is almost 2-dimensional, with characteristics that manipulate and enhance properties of the waveguide.

They developed and tested two conformal coatings, one for guiding the signal and one to cloak the waveguide. They created the coatings by judiciously engineering the patterning on the surfaces to enable new and transformative waveguide functionality. The coatings are applied to a rod-shaped, Teflon waveguide with the guiding layer touching the Teflon and the cloaking layer on the outside.

This quasi 2-dimensional conformal coating that is configured as a cloaking material can solve the crosstalk and blockage problem. Dielectric waveguides are not usually used singly, but in bundles. Unfortunately, conventional waveguides leak, allowing the signal from one waveguide to interfere with those located nearby.

The researchers also note in today's (Aug. 25) issue of Nature Communications that "the effectiveness of the artificial coating can be well maintained for waveguide bends by properly matching the dispersion properties of the metasurface unit cells." Although the coating can be applied to a bend in the waveguide, the waveguide cannot be bent after the coating is applied.

Improving the properties of the waveguide to carefully control polarization and other attributes allows the waveguides to be smaller, and alleviating crosstalk allows these smaller waveguides to be more closely bundled. Smaller waveguides more closely bundled could lead to increased miniaturization.

"In terms of applications these would include millimeter-wave/terahertz/infrared systems for sensing, communications, and imaging that need to manipulate polarization, squeeze signals through waveguides with a smaller cross-section, and/or require dense deployment of interconnected components," said Jiang.

Also working on this project was Lei Kang, research associate in electrical engineering, Penn State. [15]

A nano-roundabout for light

Just like in normal road traffic, crossings are indispensable in optical signal processing. In order to avoid collisions, a clear traffic rule is required. A new method has now been developed at TU Wien to provide such a rule for light signals. For this purpose, the two glass fibers were coupled at their intersection point to an optical resonator, in which the light circulates and behaves as in a roundabout. The direction of circulation is defined by a single atom coupled to the resonator. The atom also ensures that the light always leaves the roundabout at the next exit. This rule is still valid even if the light consists merely of individual photons. Such a roundabout will consequently be installed in integrated optical chips - an important step for optical signal processing.

Signal processing using light instead of electronics

The term "optical circulators" refers to elements at the intersection point of two mutually perpendicular optical fibers which direct light signals from one fiber to the other, so that the direction of the light always changes, for example, by 90° clockwise.

"These components have long been used for freely propagating light beams," says Arno Rauschenbeutel from the Vienna Center for Quantum Science and Technology at the Institute of Atomic and Subatomic Physics of TU Wien. "Such optical circulators are mostly based on the so-called Faraday effect: a strong magnetic field is applied to a transparent material, which is

located between two polarization beam splitters which are rotated with respect to each other. The direction of the magnetic field breaks the symmetry and determines in which direction the light is redirected."

However, for technical reasons, components that make use of the Faraday effect cannot be realized on the small scales of nanotechnology. This is unfortunate as such components are important for future technological applications. "Today, we are trying to build optical integrated circuits with similar functions as they are known from electronics," says Rauschenbeutel. Other methods to break the symmetry of the light function only at very high light intensities or suffer from high optical losses. However, in nanotechnology one would like to be able to process very small light signals, ideally light pulses that consist solely of individual photons.

Two glass fibers and a bottle for light

The team of Arno Rauschenbeutel chooses a completely different way: they couple a single rubidium atom to the light field of a so-called "bottle resonator" - a microscopic bulbous glass object on the surface of which the light circulates. If such a resonator is placed in the vicinity of two ultrathin glass fibers, the two systems couple to one another. Without an atom, the light changes from one glass fiber to the other via the bottle resonator. In this way, however, no sense of circulation is defined for the circulator: light, which is deflected by 90° in the clockwise direction, can also travel backwards via the same route, i.e. counter-clockwise.

In order to break this forward/backward symmetry, Arno Rauschenbeutel's team additionally couples an atom to the resonator, which prevents the coupling of the light into the resonator, and thus the overcoupling into the other glass fiber for one of the two directions of circulation. For this trick, a special property of the light is used at TU Wien: the direction of oscillation of the light wave, also known as its polarization.

The interaction between the light wave and the bottle resonator results in an unusual oscillation state. "The polarization rotates like the rotor of a helicopter," Arno Rauschenbeutel explains. The direction of rotation depends on whether the light in the resonator travels clockwise or counter-clockwise: in one case the polarization rotates counter-clockwise, while in the other case it rotates clockwise. The direction of circulation and the polarization of the light are therefore locked together.

If the rubidium atom is correctly prepared and coupled to the resonator, one can make its interaction with the light differ for the two directions of circulation. "The clockwise circulating light is not affected by the atom. The light in the opposite direction, on the other hand, strongly couples to the atom and therefore cannot enter the resonator," says Arno Rauschenbeutel. This asymmetry of the light-atom coupling with respect to the propagation direction of the light in the resonator allows control over the circulator operation: the desired sense of circulation can be adjusted via the internal state of the atom.

"Because we use only a single atom, we can subtly control the process," says Rauschenbeutel. "The atom can be prepared in a state in which both traffic rules apply at the same time: all light

particles then travel together through the circulator in both clockwise and counterclockwise direction." Luckily, this is impossible according to the rules of classical physics, as it would result in chaos in road traffic. In quantum physics however, such superpositions of different states are permitted which opens up entirely new and exciting possibilities for the optical processing of quantum information. [14]

Researchers create hidden images with commercial inkjet printers

Researchers have developed a way to use commercial inkjet printers and readily available ink to print hidden images that are only visible when illuminated with appropriately polarized waves in the terahertz region of the electromagnetic spectrum. The inexpensive method could be used as a type of invisible ink to hide information in otherwise normal-looking images, making it possible to distinguish between authentic and counterfeit items, for example.

"We used silver and carbon ink to print an image consisting of small rods that are about a millimeter long and a couple of hundred microns wide," said Ajay Nahata from the University of Utah, leader of the research team. "We found that changing the fraction of silver and carbon in each rod changes the conductivity in each rod just slightly, but visually, you can't see this modification. Passing terahertz radiation at the correct frequency and polarization through the array allows extraction of information encoded into the conductivity."

In The Optical Society's journal for high impact research, *Optica*, the researchers demonstrated their new method to hide image information in an array of printed rods that all look nearly identical. They used the technique to conceal both grayscale and 64-color QR codes, and even embedded two QR codes into a single image, with each code viewable using a different polarization. To the naked eye the images look like an array of identical looking lines, but when viewed with terahertz radiation, the embedded QR code image becomes apparent.

"Our very easy-to-use method can print complex patterns of rods with varying conductivity," said Nahata. "This cannot easily be done even using a multimillion dollar nanofabrication facility. An added benefit to our technique is that it can be performed very inexpensively."

Printing metamaterials

The new technique allows printing of different shapes that form a type of metamaterial - synthetic materials that exhibit properties that don't usually exist in nature. Although there is a great deal of interest in manipulating metamaterials to better control the propagation of light, most techniques require expensive lithography equipment found in nanofabrication facilities to pattern the material in a way that produces desired properties.

Nahata and his colleagues previously developed a simple method to use an off-the-shelf inkjet printer to apply inks made with silver and carbon, which can be purchased from specialty stores online. They wanted to see if their ink-jet printing technique could create various conductivities, a parameter that is typically difficult to modify because it requires changing the type of metal

applied at each spatial location. To do this using standard lithography would be time consuming and expensive because each metal would have to be applied in a separate process.

"As we were printing these rods we saw that, in many cases, we couldn't visually tell the difference between different conductivities," said Nahata. "That led to the idea of using this to encode an image without the need for standard encryption approaches."

Creating hidden images

To see if they could use the method to encode information, the researchers printed three types of QR codes, each 72 by 72 pixels. For one QR code they used arrays of rods to create nine different conductivities, each coding for one gray level. When they imaged this QR code with terahertz illumination, only 2.7 percent of the rods gave values that were different from what was designed. The researchers also used rods printed in a cross formation to create two separate QR codes that could each be read with a different polarization of terahertz radiation.

The team then created a color QR code by using non-overlapping rods of three different lengths to create each pixel. Each pixel in the image contained the same pattern of rods but varied in conductivity. By arranging the rods in a way that minimized errors, the researchers created three overlapping QR codes corresponding to RGB color channels. Because each pixel contained four different conductivities that could each correspond to a color, a total of 64 colors was observed in the final image. The researchers said they could likely achieve even more than 64 colors with improvements in the printing process.

"We have created the capability to fabricate structures that can have adjacent cells, or pixels, with very different conductivities and shown that the conductivity can be read with high fidelity," said Nahata. "That means that when we print a QR code, we see the QR code and not any blurring or bleeding of colors."

With the very inexpensive (under \$60) printers used in the paper, the technique can produce images with a resolution of about 100 microns. With somewhat more expensive but still commercially available printers, 20-micron resolution should be achievable. Although the researchers used QR codes that are relatively simple and small, the technique could be used to embed information into more complex and detailed images using a larger canvas.

Nahata's team used terahertz radiation to read the coded information because the wavelengths in this region are best suited for imaging the resolution available from commercial inkjet printers. The researchers are now working to expand their technique so the images can be interrogated with visible, rather than terahertz, wavelengths. This challenging endeavor will require the researchers to build new printers that can produce smaller rods to form images with higher resolutions.

The researchers are also exploring the possibility of developing additional capabilities that could make the embedded information even more secure. For example, they could make inks that

might have to be heated or exposed to light of a certain wavelength before the information would be visible using the appropriate terahertz radiation. [13]

For the first time, magnets are be made with a 3-D printer

Today, manufacturing strong magnets is no problem from a technical perspective. It is, however, difficult to produce a permanent magnet with a magnetic field of a specific pre-determined shape. That is, until now, thanks to the new solution devised at TU Wien: for the first time ever, permanent magnets can be produced using a 3D printer. This allows magnets to be produced in complex forms and precisely customised magnetic fields, required, for example, in magnetic sensors.

Designed on a computer

"The strength of a magnetic field is not the only factor," says Dieter Süss, Head of the Christian Doppler Advanced Magnetic Sensing and Materials laboratory at TU Wien. "We often require special magnetic fields, with field lines arranged in a very specific way - such as a magnetic field that is relatively constant in one direction, but which varies in strength in another direction."

In order to achieve such requirements, magnets must be produced with a sophisticated geometric form. "A magnet can be designed on a computer, adjusting its shape until all requirements for its magnetic field are met," explains Christian Huber, a doctoral student in Dieter Süss' team.

But once you have the desired geometric shape, how do you go about implementing the design? The injection moulding process is one solution, but this requires the creation of a mould, which is time-consuming and expensive, rendering this method barely worthwhile for producing small quantities.

Tiny magnetic particles in the polymer matrix

Now, there is a much simpler method: the first-ever 3D printer which can be used to produce magnetic materials, created at TU Wien. 3D printers which generate plastic structures have existed for some time, and the magnet printer functions in much the same way. The difference is that the magnet printer uses specially produced filaments of magnetic micro granulate, which is held together by a polymer binding material. The printer heats the material and applies it point by point in the desired locations using a nozzle. The result is a three-dimensional object composed of roughly 90% magnetic material and 10% plastic.

The end product is not yet magnetic, however, because the granulate is deployed in an unmagnetised state. At the very end of the process, the finished article is exposed to a strong external magnetic field, converting it into a permanent magnet.

"This method allows us to process various magnetic materials, such as the exceptionally strong neodymium iron boron magnets," explains Dieter Süss. "Magnet designs created using a computer can now be quickly and precisely implemented - at a size ranging from just a few centimetres through to decimetres, with an accuracy of well under a single millimetre."

A whole world of new possibilities

Not only is this new process fast and cost-effective, it also opens up new possibilities which would be inconceivable with other techniques: you can use different materials within a single magnet to create a smooth transition between strong and weak magnetism, for instance. "Now we will test the limits of how far we can go - but for now it is certain that 3D printing brings something to magnet design which we could previously only dream of," declares Dieter Süss. [12]

New method to make permanent magnets more stable over time

For physicists, loss of magnetisation in permanent magnets can be a real concern. In response, the Japanese company Sumitomo created the strongest available magnet—one offering ten times more magnetic energy than previous versions—in 1983. These magnets are a combination of materials including rare-earth metal and so-called transition metals, and are accordingly referred to as RE-TM-B magnets. A Russian team has now been pushing the boundaries of magnet design, as published in a recent study in EPJ Plus.

They have developed methods to counter the spontaneous loss of magnetisation, based on their understanding of the underlying physical phenomenon. Roman Morgunov from the Institute of Problems of Chemical Physics at the Russian Academy of Sciences and colleagues have now developed a simple additive-based method for ensuring the stability of permanent magnets over time, with no loss to their main magnetic characteristics.

To design magnets that retain their magnetic stability, the authors altered the chemical composition of a RE-TM-B magnet. Their method consists in inserting small amounts of Samarium atoms at random places within the crystalline sub-lattice of the magnet's rare-earth component. They observed a multi-fold increase in the magnet's stability over time with as little as 1% Samarium. The advantage of using such low quantity of additives to stabilise the magnet is that it does not alter the magnetic properties.

The authors believe this result is linked to Samarium's symmetry. It differs from the crystalline structure of Dysprosium atoms, which enter the composition of the magnet's rare-earth component. As a result, spontaneous magnetisation no longer takes place. This is because the potential barriers separating the magnetisation states of different energies are enhanced by the disrupted symmetry.

Further developments of this research will most likely focus on identifying the discrete magnetisation jumps—elementary events that initiate the reversible magnetisation, leading to a loss in stability. [11]

New method for generating superstrong magnetic fields

Researchers of MEPhI (Russia), the University of Rostock (Germany) and the University of Pisa (Italy) suggest a new method for generating extremely strong magnetic fields of several gigaGauss in the lab. Currently available techniques produce fields of one order of magnitude less than the new method. In nature, such superstrong fields exist only in the space. Therefore, generation of such fields in laboratory conditions provides new opportunities for the modeling of astrophysical processes. The results will contribute to the new research field of laboratory astrophysics.

The Faraday effect has been known for a long time. It refers to the polarization plane of an electromagnetic wave propagating through a non-magnetic medium, which is rotating in the presence of a constant magnetic field. There is also an inverse process of the generation of a magnetic field during the propagation of a circularly polarized wave through a crystal or plasma. It was considered theoretically in the 1960s by Soviet theorist Lev Pitaevsky, a famous representative of Landau's school. The stronger the wave, the higher the magnetic field it can generate when propagating through a medium. However, a peculiarity of the effect is that it requires absorption for its very existence—it does not occur in entirely transparent media. In highly intense electromagnetic fields, electrons become ultrarelativistic, which considerably reduces their collisions, suppressing conventional absorption. The researchers demonstrate that at very high laser wave intensities, the absorption can be effectively provided by radiation friction instead of binary collisions. This specific friction leads to the generation of a superstrong magnetic field.

According to physicist Sergey Popruzhenko, it will be possible to check the calculations in the near future. Several new laser facilities of record power will be completed in the next several years. Three such lasers are now under construction within the European project Extreme Light Infrastructure (ELI) in the Czech Republic, Romania and Hungary. The Exawatt Center for Extreme Light Studies – XCELS is under the development at the Applied Physics Institute RAS at Nizhny Novgorod. These laser facilities will be capable of the intensities required for the generation of superstrong magnetic fields due to radiation friction and also for the observation of many other fundamental strong-field effects. [10]

Inverse spin Hall effect: A new way to get electricity from magnetism

By showing that a phenomenon dubbed the "inverse spin Hall effect" works in several organic semiconductors - including carbon-60 buckyballs - University of Utah physicists changed magnetic "spin current" into electric current. The efficiency of this new power conversion method isn't yet known, but it might find use in future electronic devices including batteries, solar cells and computers.

"This paper is the first to demonstrate the inverse spin Hall effect in a range of organic semiconductors with unprecedented sensitivity," although a 2013 study by other researchers

demonstrated it with less sensitivity in one such material, says Christoph Boehme, a senior author of the study published April 18 in the journal Nature Materials.

"The inverse spin Hall effect is a remarkable phenomenon that turns so-called spin current into an electric current. The effect is so odd that nobody really knows what this will be used for eventually, but many technical applications are conceivable, including very odd new powerconversion schemes," says Boehme, a physics professor.

His fellow senior author, distinguished professor Z. Valy Vardeny, says that by using pulses of microwaves, the inverse spin Hall effect and organic semiconductors to convert spin current into electricity, this new electromotive force generates electrical current in a way different than existing sources.

Coal, gas, hydroelectric, wind and nuclear plants all use dynamos to convert mechanical force into magnetic-field changes and then electricity. Chemical reactions power modern batteries and solar cells convert light to electrical current. Converting spin current into electrical current is another method.

Scientists already are developing such devices, such as a thermoelectric generator, using traditional inorganic semiconductors. Vardeny says organic semiconductors are promising because they are cheap, easily processed and environmentally friendly. He notes that both organic solar cells and organic LED (light-emitting diode) TV displays were developed even though silicon solar cells and nonorganic LEDs were widely used.

A new way to get electricity from magnetism

Vardeny and Boehme stressed that the efficiency at which organic semiconductors convert spin current to electric current remains unknown, so it is too early to predict the extent to which it might one day be used for new power conversion techniques in batteries, solar cells, computers, phones and other consumer electronics.

"I want to invoke a degree of caution," Boehme says. "This is a power conversion effect that is new and mostly unstudied."

Boehme notes that the experiments in the new study converted more spin current to electrical current than in the 2013 study, but Vardeny cautioned the effect still "would have to be scaled up many times to produce voltages equivalent to household batteries."

The new study was funded by the National Science Foundation and the University of Utah-NSF Materials Research Science and Engineering Center. Study co-authors with Vardeny and Boehme were these University of Utah physicists: research assistant professors Dali Sun and Hans Malissa, postdoctoral researchers Kipp van Schooten and Chuang Zhang, and graduate students Marzieh Kavand and Matthew Groesbeck.

From spin current to electric current

Just as atomic nuclei and the electrons that orbit them carry electrical charges, they also have another inherent property: spin, which makes them behave like tiny bar magnets that can point north or south.

Electronic devices store and transmit information using the flow of electricity in the form of electrons, which are negatively charged subatomic particles. The zeroes and ones of computer binary code are represented by the absence or presence of electrons within silicon or other nonorganic semiconductors.

Spin electronics - spintronics - holds promise for faster, cheaper computers, better electronics and LEDs for displays, and smaller sensors to detect everything from radiation to magnetic fields.

The inverse spin Hall effect first was demonstrated in metals in 2008, and then in nonorganic semiconductors, Vardeny says. In 2013, researchers elsewhere showed it occurred in an organic semiconductor named PEDOT:PSS when it was exposed to continuous microwaves that were relatively weak to avoid frying the semiconductor. [9]

New electron spin secrets revealed: Discovery of a novel link between magnetism and electricity

The findings reveal a novel link between magnetism and electricity, and may have applications in electronics.

The electric current generation demonstrated by the researchers is called charge pumping. Charge pumping provides a source of very high frequency alternating electric currents, and its magnitude and external magnetic field dependency can be used to detect magnetic information.

The findings may, therefore, offer new and exciting ways of transferring and manipulating data in electronic devices based on spintronics, a technology that uses electron spin as the foundation for information storage and manipulation.

The research findings are published as an Advance Online Publication (AOP) on Nature Nanotechnology's website on 10 November 2014.

Spintronics has already been exploited in magnetic mass data storage since the discovery of the giant magnetoresistance (GMR) effect in 1988. For their contribution to physics, the discoverers of GMR were awarded the Nobel Prize in 2007.

The basis of spintronics is the storage of information in the magnetic configuration of ferromagnets and the read-out via spin-dependent transport mechanisms.

"Much of the progress in spintronics has resulted from exploiting the coupling between the electron spin and its orbital motion, but our understanding of these interactions is still

immature. We need to know more so that we can fully explore and exploit these forces," says Arne Brataas, professor at NTNU and the corresponding author for the paper.

An electron has a spin, a seemingly internal rotation, in addition to an electric charge. The spin can be up or down, representing clockwise and counterclockwise rotations.

Pure spin currents are charge currents in opposite directions for the two spin components in the material.

It has been known for some time that rotating the magnetization in a magnetic material can generate pure spin currents in adjacent conductors.

However, pure spin currents cannot be conventionally detected by a voltmeter because of the cancellation of the associated charge flow in the same direction.

A secondary spin-charge conversion element is then necessary, such as another ferromagnet or a strong spin-orbit interaction, which causes a spin Hall effect.

Brataas and his collaborators have demonstrated that in a small class of ferromagnetic materials, the spin-charge conversion occurs in the materials themselves.

The spin currents created in the materials are thus directly converted to charge currents via the spin-orbit interaction.

In other words, the ferromagnets function intrinsically as generators of alternating currents driven by the rotating magnetization.

"The phenomenon is a result of a direct link between electricity and magnetism. It allows for the possibility of new nano-scale detection techniques of magnetic information and for the generation of very high-frequency alternating currents," Brataas says. [8]

Simple Experiment

Everybody can repeat my physics teacher's - Nándor Toth - middle school experiment, placing aluminum folios in form V upside down on the electric wire with static electric current, and seeing them open up measuring the electric potential created by the charge distribution, caused by the acceleration of the electrons.

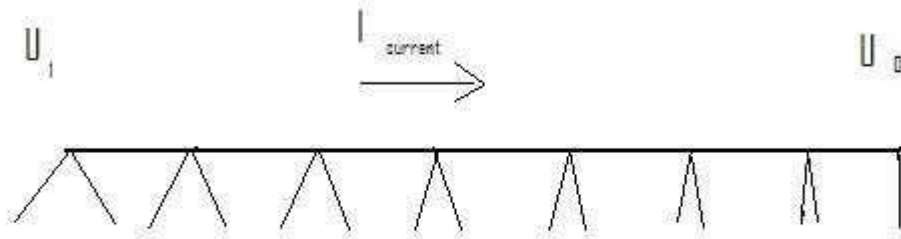


Figure 1.) Aluminium foils shows the charge distribution on the electric wire

He wanted to show us that the potential decreasing linearly along the wire and told us that in the beginning of the wire it is lowering harder, but after that the change is quite linear.

You will see that the foils will draw a parabolic curve showing the charge distribution along the wire, since the way of the accelerated electrons in the wire is proportional with the square of time. The free external charges are moving along the wire, will experience this charge distribution caused electrostatic force and repelled if moving against the direction of the electric current and attracted in the same direction – the magnetic effect of the electric current.

Uniformly accelerated electrons of the steady current

In the steady current $I = dq/dt$, the q electric charge crossing the electric wire at any place in the same time is constant. This does not require that the electrons should move with a constant v velocity and does not exclude the possibility that under the constant electric force created by the $E = -dU/dx$ potential changes the electrons could accelerating.

If the electrons accelerating under the influence of the electric force, then they would arrive to the $x = 1/2 at^2$ in the wire. The $dx/dt = at$, means that every second the accelerating q charge will take a linearly growing length of the wire. For simplicity if $a=2$ then the electrons would found in the wire at $x = 1, 4, 9, 16, 25 \dots$, which means that the dx between them should be $3, 5, 7, 9 \dots$, linearly increasing the volume containing the same q electric charge. It means that the density of the electric charge decreasing linearly and as the consequence of this the U field is decreasing linearly as expected: $-dU/dx = E = \text{const}$.

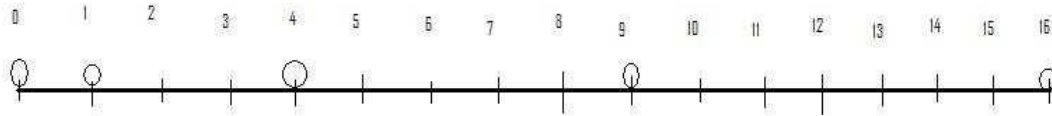


Figure 2.) The accelerating electrons created charge distribution on the electric wire

This picture remembers the Galileo's Slope of the accelerating ball, showed us by the same teacher in the middle school, some lectures before. I want to thank him for his enthusiastic and impressive lectures, giving me the associating idea between the Galileo's Slope and the accelerating charges of the electric current.

We can conclude that the electrons are accelerated by the electric U potential, and with this accelerated motion they are maintaining the linear potential decreasing of the U potential along they movement. Important to mention, that the linearly decreasing charge density measured in the referential frame of the moving electrons. Along the wire in its referential frame the charge density lowering parabolic, since the charges takes way proportional with the square of time.

The decreasing U potential is measurable, simply by measuring it at any place along the wire. One of the simple visualizations is the aluminum foils placed on the wire opening differently depending on the local charge density. The static electricity is changing by parabolic potential giving the equipotential lines for the external moving electrons in the surrounding of the wire.

Magnetic effect of the decreasing U electric potential

One q electric charge moving parallel along the wire outside of it with velocity v would experience a changing U electric potential along the wire. If it experiencing an emerging potential, it will repel the charge, in case of decreasing U potential it will move closer to the

wire. This radial electric field will move the external electric charge on the parabolic curve, on the equipotential line of the accelerated charges of the electric current. This is exactly the magnetic effect of the electric current. A constant force, perpendicular to the direction of the movement of the matter will change its direction to a parabolic curve.

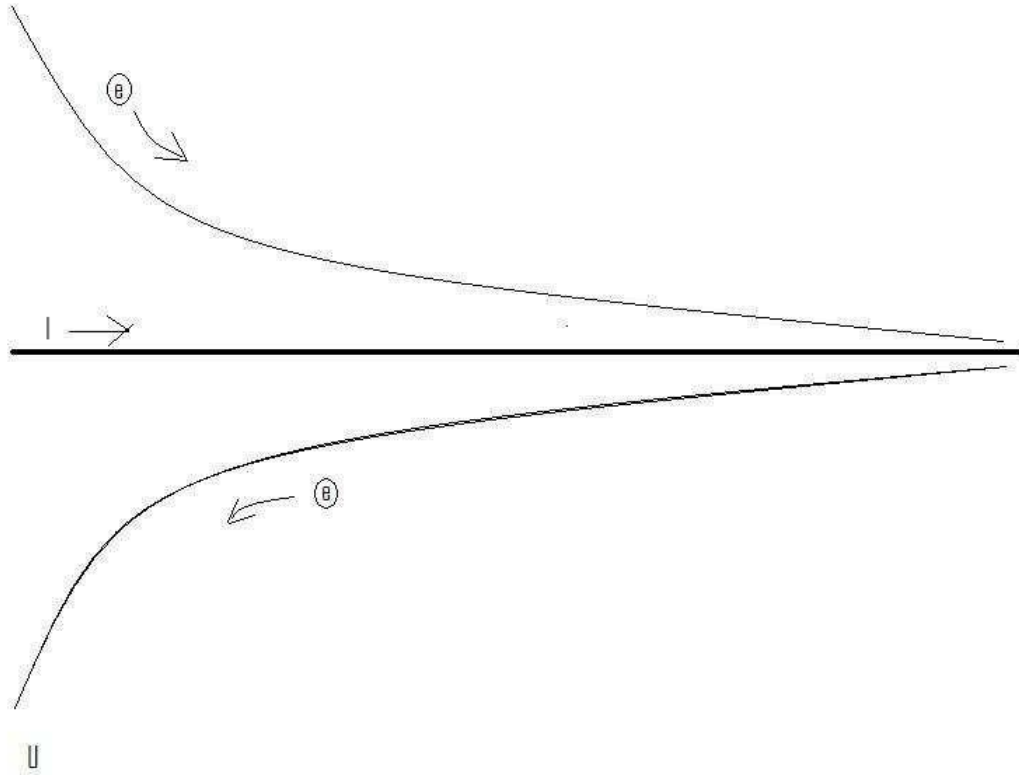


Figure 3.) Concentric parabolic equipotential surfaces around the electric wire causes the magnetic effect on the external moving charges

Considering that the magnetic effect is $\mathbf{F} = q \mathbf{v} \times \mathbf{B}$, where the \mathbf{B} is concentric circle around the electric wire, it is an equipotential circle of the accelerating electrons caused charge distribution. Moving on this circle there is no electric and magnetic effect for the external charges, since $\mathbf{v} \times \mathbf{B} = \mathbf{0}$. Moving in the direction of the current the electric charges crosses the biggest potential change, while in any other direction – depending on the angle between the current and velocity of the external charge there is a modest electric potential difference, giving exactly the same force as the $\mathbf{v} \times \mathbf{B}$ magnetic force.

Getting the magnetic force from the $\mathbf{F} = d\mathbf{p}/dt$ equation we will understand the magnetic field velocity dependency. Finding the appropriate trajectory of the moving charges we need simply get it from the equipotential lines on the equipotential surfaces, caused by the accelerating charges of the electric current. We can prove that the velocity dependent force causes to move the charges on the equipotential surfaces, since the force due to the potential difference according to the velocity angle – changing only the direction, but not the value of the charge's velocity.

The work done on the charge and the Hamilton Principle

One basic feature of magnetism is that, in the vicinity of a magnetic field, a moving charge will experience a force. Interestingly, the force on the charged particle is always perpendicular to the direction it is moving. Thus magnetic forces cause charged particles to change their direction of motion, but they do not change the speed of the particle. This property is used in high-energy particle accelerators to focus beams of particles which eventually collide with targets to produce new particles. Another way to understand this is to realize that if the force is perpendicular to the motion, then no work is done. Hence magnetic forces do no work on charged particles and cannot increase their kinetic energy. If a charged particle moves through a constant magnetic field, its speed stays the same, but its direction is constantly changing. [2]

In electrostatics, the work done to move a charge from any point on the equipotential surface to any other point on the equipotential surface is zero since they are at the same potential. Furthermore, equipotential surfaces are always perpendicular to the net electric field lines passing through it. [3]

Consequently the work done on the moving charges is zero in both cases, proving that they are equal forces, that is they are the same force.

The accelerating charges self-maintaining potential equivalent with the Hamilton Principle and the Euler-Lagrange equation. [4]

The Magnetic Vector Potential

Also the $\underline{\mathbf{A}}$ magnetic vector potential gives the radial parabolic electric potential change of the charge distribution due to the acceleration of electric charges in the electric current.

Necessary to mention that the $\underline{\mathbf{A}}$ magnetic vector potential is proportional with $\underline{\mathbf{a}}$, the acceleration of the charges in the electric current although this is not the only parameter.

The $\underline{\mathbf{A}}$ magnetic vector potential is proportional with $I=dQ/dt$ electric current, which is proportional with the strength of the charge distribution along the wire. Although it is proportional also with the U potential difference $I=U/R$, but the R resistivity depends also on the cross-sectional area, that is bigger area gives stronger I and $\underline{\mathbf{A}}$. [7] This means that the bigger potential differences with smaller cross-section can give the same I current and $\underline{\mathbf{A}}$ vector potential, explaining the gauge transformation.

Since the magnetic field B is defined as the curl of $\underline{\mathbf{A}}$, and the curl of a gradient is identically zero, then any arbitrary function which can be expressed as the gradient of a scalar function may be added to A without changing the value of B obtained from it. That is, A' can be freely substituted for A where

$$\vec{A}' = \vec{A} + \vec{\nabla}\phi$$

Such transformations are called gauge transformations, and there have been a number of "gauges" that have been used to advantage in specific types of calculations in electromagnetic theory. [5]

Since the potential difference and the vector potential both are in the direction of the electric current, this gauge transformation could explain the self-maintaining electric potential of the accelerating electrons in the electric current. Also this is the source of the special and general relativity.

The Constant Force of the Magnetic Vector Potential

Moving on the parabolic equipotential line gives the same result as the constant force of gravitation moves on a parabolic line with a constant velocity moving body.

Electromagnetic four-potential

The electromagnetic four-potential defined as:

$$A^\alpha = (\phi/c, \mathbf{A}) \quad \text{SI units} \quad A^\alpha = (\phi, \mathbf{A}) \quad \text{cgs units}$$

in which ϕ is the electric potential, and \mathbf{A} is the magnetic vector potential. [6] This is appropriate with the four-dimensional space-time vector (T, \mathbf{R}) and in stationary current gives that the potential difference is constant in the time dimension and vector potential (and its curl, the magnetic field) is constant in the space dimensions.

Magnetic induction

Increasing the electric current I causes increasing magnetic field \mathbf{B} by increasing the acceleration of the electrons in the wire. Since $I=at$, if the acceleration of electrons is growing, then the charge density dQ/dl will decrease in time, creating a $-\mathbf{E}$ electric field. Since the resistance of the wire is constant, only increasing U electric potential could cause an increasing electric current $I=U/R=dQ/dt$. The charge density in the static current changes linearly in the time coordinates. Changing its value in time will cause a static electric force, negative to the accelerating force change. This explains the relativistic changing mass of the charge in time also.

Necessary to mention that decreasing electric current will decrease the acceleration of the electrons, causing increased charge density and \mathbf{E} positive field.

The electric field is a result of the geometric change of the U potential and the timely change of the \mathbf{A} magnetic potential:

$$\mathbf{E} = -d\mathbf{A}/dt - dU/dr$$

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t},$$

The acceleration of the electric charges proportional with the A magnetic vector potential in the electric current and also their time dependence are proportional as well. Since the A vector potential is appears in the equation, the proportional \mathbf{a} acceleration will satisfy the same equation.

Since increasing acceleration of charges in the increasing electric current the result of increasing potential difference, creating a decreasing potential difference, the electric and magnetic vector potential are changes by the next wave - function equations:

$$\frac{1}{c^2} \frac{\partial^2 \varphi}{\partial t^2} - \nabla^2 \varphi = \frac{\rho}{\epsilon_0}$$

$$\nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{J}$$

The simple experiment with periodical changing \mathbf{U} potential and \mathbf{I} electric current will move the aluminium folios with a moving wave along the wire.

The Lorentz gauge says exactly that the accelerating charges are self maintain their accelerator fields and the divergence (source) of the A vector potential is the timely change of the electric potential.

$$\nabla \cdot \vec{A} + \frac{1}{c^2} \frac{\partial \varphi}{\partial t} = 0.$$

Or

$$\vec{E} = -\nabla \varphi - \frac{\partial \vec{A}}{\partial t}.$$

The timely change of the A vector potential, which is the proportionally changing acceleration of the charges will produce the negative electric field.

Lorentz transformation of the Special Relativity

In the referential frame of the accelerating electrons the charge density lowering linearly because of the linearly growing way they takes every next time period. From the referential frame of the wire there is a parabolic charge density lowering.

The difference between these two referential frames, namely the referential frame of the wire and the referential frame of the moving electrons gives the relativistic effect. Important to say that the moving electrons presenting the time coordinate, since the electrons are taking linearly increasing way every next time period, and the wire presenting the geometric coordinate.

The Lorentz transformations are based on moving light sources of the Michelson - Morley experiment giving a practical method to transform time and geometric coordinates without explaining the source of this mystery.

The real mystery is that the accelerating charges are maintaining the accelerating force with their charge distribution locally. The resolution of this mystery that the charges are simply the results of the diffraction patterns, that is the charges and the electric field are two sides of the same thing. Otherwise the charges could exceed the velocity of the electromagnetic field.

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

Heisenberg Uncertainty Relation

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

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

Wave – Particle Duality

The accelerating electrons explains the wave – particle duality of the electrons and photons, since the elementary charges are distributed on Δx position with Δp impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the

mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and it's kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is

right and only the changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

Fermions' spin

The moving charges are accelerating, since only this way can self maintain the electric field causing their acceleration. The electric charge is not point like! This constant acceleration possible if there is a rotating movement changing the direction of the velocity. This way it can accelerate forever without increasing the absolute value of the velocity in the dimension of the time and not reaching the velocity of the light.

The Heisenberg uncertainty relation says that the minimum uncertainty is the value of the spin: $\frac{1}{2} h = dx dp$ or $\frac{1}{2} h = dt dE$, that is the value of the basic energy status, consequently related to the m_0 inertial mass of the fermions.

The photon's 1 spin value and the electric charges 1/2 spin gives us the idea, that the electric charge and the electromagnetic wave two sides of the same thing, $1/2 - (-1/2) = 1$.

Fine structure constant

The Planck constant was first described as the proportionality constant between the energy E of a photon and the frequency ν of its associated electromagnetic wave. This relation between the energy and frequency is called the Planck relation or the Planck–Einstein equation:

$$E = h\nu .$$

Since the frequency ν , wavelength λ , and speed of light c are related by $\lambda\nu = c$, the Planck relation can also be expressed as

$$E = \frac{hc}{\lambda} .$$

Since this is the source of the Planck constant, the e electric charge countable from the Fine structure constant. This also related to the Heisenberg uncertainty relation, saying that the mass of the proton should be bigger than the electron mass because of the difference between their wavelengths, since $E = mc^2$.

The expression of the fine-structure constant becomes the abbreviated

$$\alpha = \frac{e^2}{\hbar c}$$

This is a dimensionless constant expression, 1/137 commonly appearing in physics literature.

This means that the electric charge is a result of the electromagnetic waves diffractions, consequently the proton – electron mass ratio is the result of the equal intensity of the corresponding electromagnetic frequencies in the Planck distribution law.

Planck Distribution Law

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry.

The Planck distribution law is temperature dependent and it should be true locally and globally. I think that Einstein's energy-matter equivalence means some kind of existence of electromagnetic oscillations enabled by the temperature, creating the different matter formulas, atoms, molecules, crystals, dark matter and energy.

One way dividing the proton to three parts is, dividing his oscillation by the three direction of the space. We can order 1/3 e charge to each coordinates and 2/3 e charge to one plane oscillation, because the charge is scalar. In this way the proton has two +2/3 e plane oscillation and one linear oscillation with -1/3 e charge. The colors of quarks are coming from the three directions of coordinates and the proton is colorless. [1]

Electromagnetic inertia and Gravitational attraction

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

It looks clear that the growing acceleration results the relativistic growing mass - limited also with the velocity of the electromagnetic wave.

The negatively changing acceleration causes a positive electric field, working as a decreasing mass.

Since $E = hv$ and $E = mc^2$, $m = hv/c^2$ that is the m depends only on the ν frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the m_0 inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

If the mass is electromagnetic, then the gravitation is also electromagnetic effect caused by the magnetic effect between the same charges, they would attract each other if they are moving parallel by the magnetic effect.

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different λ wavelengths. Also since the particles are diffraction patterns they have some closeness to each other – can be seen as the measured effect of the force of the gravitation, since the magnetic effect depends on this closeness. This way the mass and the magnetic attraction depend equally on the wavelength of the electromagnetic waves.

Conclusions

The generation and modulation of high-frequency currents are central wireless communication devices such as mobile phones, WLAN modules for personal computers, Bluetooth devices and future vehicle radars. [8]

Needless to say that the accelerating electrons of the steady stationary current are a simple demystification of the magnetic field, by creating a decreasing charge distribution along the wire, maintaining the decreasing U potential and creating the \underline{A} vector potential experienced by the electrons moving by \underline{v} velocity relative to the wire. This way it is easier to understand also the time dependent changes of the electric current and the electromagnetic waves as the resulting fields moving by c velocity.

There is a very important law of the nature behind the self maintaining \underline{E} accelerating force by the accelerated electrons. The accelerated electrons created electromagnetic fields are so natural that they occur as electromagnetic waves traveling with velocity c . It shows that the electric charges are the result of the electromagnetic waves diffraction.

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible their movement. The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. Basing the gravitational force on the magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions.

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