

# How Memristors Operate

*In the race to build a computer that mimics the massive computational power of the human brain, researchers are increasingly turning to memristors, which can vary their electrical resistance based on the memory of past activity. [31]*

*Engineers worldwide have been developing alternative ways to provide greater memory storage capacity on even smaller computer chips. Previous research into two-dimensional atomic sheets for memory storage has failed to uncover their potential—until now. [30]*

*Scientists used spiraling X-rays at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) to observe, for the first time, a property that gives handedness to swirling electric patterns – dubbed polar vortices – in a synthetically layered material. [28]*

*To build tomorrow's quantum computers, some researchers are turning to dark excitons, which are bound pairs of an electron and the absence of an electron called a hole. [27]*

*Concerning the development of quantum memories for the realization of global quantum networks, scientists of the Quantum Dynamics Division led by Professor Gerhard Rempe at the Max Planck Institute of Quantum Optics (MPQ) have now achieved a major breakthrough: they demonstrated the long-lived storage of a photonic qubit on a single atom trapped in an optical resonator. [26]*

*Achieving strong light-matter interaction at the quantum level has always been a central task in quantum physics since the emergence of quantum information and quantum control. [25]*

*Operation at the single-photon level raises the possibility of developing entirely new communication and computing devices, ranging from hardware random number generators to quantum computers. [24]*

*Considerable interest in new single-photon detector technologies has been scaling in this past decade. [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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## 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 magnetic induction also. The changing acceleration of the electrons will create a  $-\mathbf{E}$  electric field by changing the charge distribution, increasing acceleration lowering the charge density and decreasing acceleration causing an increasing charge density.

Since 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 gravitation is also an electromagnetic effect. The same charges would attract each other if they are moving parallel by the magnetic effect.

## Team takes a deep look at memristors

In the race to build a computer that mimics the massive computational power of the human brain, researchers are increasingly turning to memristors, which can vary their electrical resistance based on the memory of past activity. Scientists at the National Institute of Standards and Technology (NIST) have now unveiled the long-mysterious inner workings of these semiconductor elements, which can act like the short-term memory of nerve cells.

Just as the ability of one nerve cell to signal another depends on how often the cells have communicated in the recent past, the resistance of a memristor depends on the amount of current that recently flowed through it. Moreover, a memristor retains that memory even when electrical power is switched off.

But despite the keen interest in memristors, scientists have lacked a detailed understanding of how these devices work and have yet to develop a standard toolset to study them.

Now, NIST scientists have identified such a toolset and used it to more deeply probe how memristors operate. Their findings could lead to more efficient operation of the devices and suggest ways to minimize the leakage of current.

Brian Hoskins of NIST and the University of California, Santa Barbara, along with NIST scientists Nikolai Zhitenev, Andrei Kolmakov, Jabez McClelland and their colleagues from the University of Maryland's NanoCenter in College Park and the Institute for Research and Development in Microtechnologies in Bucharest, reported the findings in a recent *Nature Communications*.

To explore the electrical function of memristors, the team aimed a tightly focused beam of electrons at different locations on a titanium dioxide memristor. The beam knocked free some of the [device's](#) electrons, which formed ultrasharp images of those locations. The beam also induced four distinct currents to flow within the device. The team determined that the currents are

associated with the multiple interfaces between materials in the memristor, which consists of two metal (conducting) layers separated by an insulator.

"We know exactly where each of the currents are coming from because we are controlling the location of the beam that is inducing those currents," said Hoskins.

In imaging the device, the team found several dark spots—regions of enhanced conductivity—which indicated places where current might leak out of the memristor during its normal operation. These leakage pathways resided outside the memristor's core—where it switches between the low and high resistance levels that are useful in an electronic device. The finding suggests that reducing the size of a memristor could minimize or even eliminate some of the unwanted current pathways. Although researchers had suspected that might be the case, they had lacked experimental guidance about just how much to reduce the size of the device.

Because the leakage pathways are tiny, involving distances of only 100 to 300 nanometers, "you're probably not going to start seeing some really big improvements until you reduce dimensions of the memristor on that scale," Hoskins said.

To their surprise, the team also found that the current that correlated with the memristor's switch in resistance didn't come from the active switching material at all, but the metal layer above it. The most important lesson of the [memristor](#) study, Hoskins noted, "is that you can't just worry about the resistive switch, the switching spot itself, you have to worry about everything around it." The team's study, he added, "is a way of generating much stronger intuition about what might be a good way to engineer memristors." [31]

## Ultra-thin memory storage device paves way for more powerful computing

Engineers worldwide have been developing alternative ways to provide greater memory storage capacity on even smaller computer chips. Previous research into two-dimensional atomic sheets for memory storage has failed to uncover their potential—until now.

A team of electrical engineers at The University of Texas at Austin, in collaboration with Peking University scientists, has developed the thinnest [memory storage](#) device with dense [memory](#) capacity, paving the way for faster, smaller and smarter computer chips for everything from consumer electronics to big data to brain-inspired computing.

"For a long time, the consensus was that it wasn't possible to make memory devices from materials that were only one atomic layer thick," said Deji Akinwande, associate professor in the Cockrell School of Engineering's Department of Electrical and Computer Engineering. "With our new 'atomristors,' we have shown it is indeed possible."

Made from 2-D nanomaterials, the "atomristors"—a term Akinwande coined—improve upon memristors, an emerging memory storage technology with lower memory scalability. He and his team published their findings in the January issue of *Nano Letters*.

"Atomristors will allow for the advancement of Moore's Law at the system level by enabling the 3-D integration of nanoscale memory with nanoscale transistors on the same chip for advanced computing systems," Akinwande said.

Memory storage and transistors have, to date, always been separate components on a microchip, but atomristors combine both functions on a single, more efficient computer system. By using metallic atomic sheets (graphene) as electrodes and semiconducting atomic sheets (molybdenum sulfide) as the active layer, the entire memory cell is a sandwich about 1.5 nanometers thick, which makes it possible to densely pack atomristors layer by layer in a plane. This is a substantial advantage over conventional flash memory, which occupies far larger space. In addition, the thinness allows for faster and more efficient electric current flow.

Given their size, capacity and integration flexibility, atomristors can be packed together to make advanced 3-D chips that are crucial to the successful development of brain-inspired computing. One of the greatest challenges in this burgeoning field of engineering is how to make a memory architecture with 3-D connections akin to those found in the human brain.

"The sheer density of memory storage that can be made possible by layering these synthetic atomic sheets onto each other, coupled with integrated transistor design, means we can potentially make computers that learn and remember the same way our brains do," Akinwande said.

The research team also discovered another unique application for the technology. In existing ubiquitous devices such as smartphones and tablets, radio frequency switches are used to connect incoming signals from the antenna to one of the many wireless communication bands in order for different parts of a device to communicate and cooperate with one another. This activity can significantly affect a smartphone's battery life.

The atomristors are the smallest radio frequency memory switches to be demonstrated with no DC battery consumption, which can ultimately lead to longer battery life.

"Overall, we feel that this discovery has real commercialization value as it won't disrupt existing technologies," Akinwande said. "Rather, it has been designed to complement and integrate with the silicon chips already in use in modern tech devices." [30]



## X-rays reveal chirality in swirling electric vortices

Scientists used spiraling X-rays at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) to observe, for the first time, a property that gives handedness to swirling electric patterns – dubbed polar vortices – in a synthetically layered material.

This property, also known as chirality, potentially opens up a new way to store data by controlling the left- or right-handedness in the material's array in much the same way magnetic materials are manipulated to store data as ones or zeros in a computer's memory.

Researchers said the behavior also could be explored for coupling to magnetic or optical (light-based) devices, which could allow better control via electrical switching.

Chirality is present in many forms and at many scales, from the spiral-staircase design of our own DNA to the spin and drift of spiral galaxies; it can even determine whether a molecule acts as a medicine or a poison in our bodies.

A molecular compound known as d-glucose, for example, which is an essential ingredient for human life as a form of sugar, exhibits right-handedness. Its left-handed counterpart, l-glucose, though, is not useful in human biology.

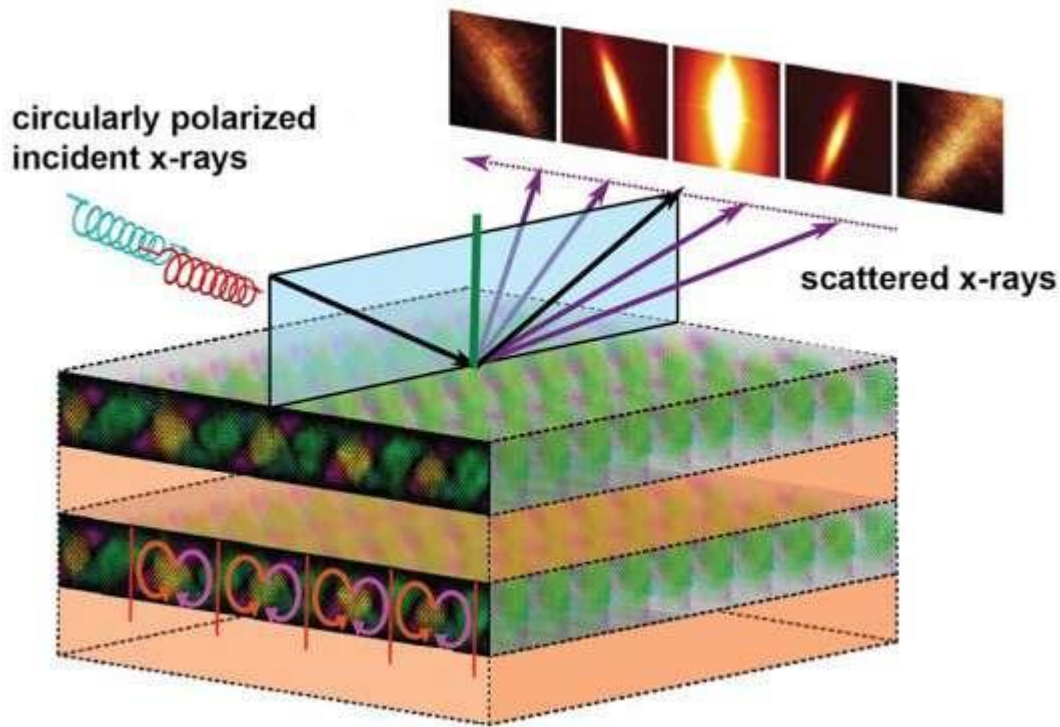
"Chirality hadn't been seen before in this electric structure," said Elke Arenholz, a senior staff scientist at Berkeley Lab's Advanced Light Source (ALS), which is home to the X-rays that were key to the study, published Jan. 15 in the journal *Proceedings of the National Academy of Sciences*.

The experiments can distinguish between left-handed chirality and right-handed chirality in the samples' vortices. "This offers new opportunities for fundamentally new science, with the potential to open up applications," she said.

"Imagine that one could convert a right-handed form of a molecule to its left-handed form by applying an electric field, or artificially engineer a material with a particular chirality," said Ramamoorthy Ramesh, a faculty senior scientist in Berkeley Lab's Materials Sciences Division and associate laboratory director of the Lab's Energy Technologies Area, who co-led the latest study.

Ramesh, who is also a professor of materials science and physics at UC Berkeley, custom-made the novel materials at UC Berkeley.

Padraic Shafer, a research scientist at the ALS and the lead author of the study, worked with Arenholz to carry out the X-ray experiments that revealed the chirality of the material.



This diagram shows the setup for the X-ray experiment that explored chirality, or handedness, in a layered material. The blue and red spirals at upper left show the X-ray light that was used to probe the material. The X-rays scattered off [...more](#)

The samples included a layer of lead titanate ( $\text{PbTiO}_3$ ) and a layer of strontium titanate ( $\text{SrTiO}_3$ ) sandwiched together in an alternating pattern to form a material known as a superlattice. The materials have also been studied for their tunable electrical properties that make them candidates for components in precise sensors and for other uses.

Neither of the two compounds show any handedness by themselves, but when they were combined into the precisely layered superlattice, they developed the swirling vortex structures that exhibited chirality.

"Chirality may have additional functionality," Shafer said, when compared to devices that use magnetic fields to rearrange the magnetic structure of the material.

The electronic patterns in the material that were studied at the ALS were first revealed using a powerful electron microscope at Berkeley Lab's National Center for Electron Microscopy, a part of the Lab's Molecular Foundry, though it took a specialized X-ray technique to identify their chirality.

"The X-ray measurements had to be performed in extreme geometries that can't be done by most experimental equipment," Shafer said, using a technique known as resonant soft X-ray diffraction that probes periodic nanometer-scale details in their electronic structure and properties.

Spiraling forms of X-rays, known as circularly polarized X-rays, allowed researchers to measure both left-handed and right-handed chirality in the samples.

Arenholz, who is also a faculty member of the UC Berkeley Department of Materials Science & Engineering, added, "It took a lot of time to understand the results, and a lot of modeling and discussions." Theorists at the University of Cantabria in Spain and their network of computational experts performed calculations of the vortex structures that aided in the interpretation of the X-ray data.

The same science team is pursuing studies of other types and combinations of materials to test the effects on chirality and other properties.

"There is a wide class of materials that could be substituted," Shafer said, "and there is the hope that the layers could be replaced with even higher functionality materials."

Researchers also plan to test whether there are new ways to control the [chirality](#) in these layered materials, such as by combining [materials](#) that have electrically switchable properties with those that exhibit magnetically switchable properties.

"Since we know so much about magnetic structures," Arenholz said, "we could think of using this well-known connection with magnetism to implement this newly discovered property into devices." [28]

## Using the dark side of excitons for quantum computing

To build tomorrow's quantum computers, some researchers are turning to dark excitons, which are bound pairs of an electron and the absence of an electron called a hole. As a promising quantum bit, or qubit, it can store information in its spin state, analogous to how a regular, classical bit stores information in its off or on state. But one problem is that dark excitons do not emit light, making it hard to determine their spins and use them for quantum information processing.

In new experiments, however, not only can researchers read the spin states of dark excitons, but they can also do it more efficiently than before. Their demonstration, described this week in *APL Photonics*, can help researchers scale up dark [exciton](#) systems to build larger devices for [quantum](#) computing.

"Large photon extraction and collection efficiency is required to push experiments beyond the proof-of-principle stage," said Tobias Heindel of the Technical University of Berlin.

When an electron in a semiconductor is excited to a higher energy level, it leaves behind a hole. But the electron can still be bound to the positively charged hole, together forming an exciton. Researchers can trap these excitons in quantum dots, nanoscale semiconductor particles whose quantum properties are like those of individual atoms.

If the electron and hole have opposite spins, the two particles can easily recombine and emit a photon. These electron-hole pairs are called bright excitons. But if they have the same spins, the electron and hole cannot easily recombine. The exciton can't emit light and is thus called a dark exciton.

This darkness is part of why dark excitons are promising qubits. Because dark excitons cannot emit light, they can't relax to a lower energy level. Therefore, dark excitons persist with a relatively long life, lasting for over a microsecond—a thousand times longer than a bright exciton and long enough to function as a qubit.

Still, the darkness poses a challenge. Because the dark exciton is closed off to light, you can't use photons to read the spin states—or any [information](#) a dark exciton qubit may contain.

But in 2010, a team of physicists at the Technion-Israel Institute of Technology figured out how to penetrate the darkness. It turns out that two excitons together can form a metastable state. When this so-called spin-blockaded biexciton state relaxes to a lower energy level, it leaves behind a dark exciton while emitting a photon. By detecting this photon, the researchers would know a dark exciton was created.

To then read the spin of the dark exciton, the researchers introduce an additional electron or hole. If the new charge carrier is a spin-up electron, for example, it combines with the spin-down hole of the dark exciton, forming a bright exciton that quickly decays and produces a photon. The dark exciton is destroyed. But by measuring the polarization of the emitted [photon](#), the researchers can determine what the dark exciton's spin was.

Like in the 2010 experiments, the new ones measure dark excitons inside quantum dots. But unlike the earlier study, the new experiments use a microlens that fits over an individual quantum dot that was selected in advance. The lens allows researchers to capture and measure more photons, crucial for larger-scale [quantum information](#) devices. Their approach also lets them choose the brightest [quantum dots](#) to measure.

"This means we can detect more photons of the related exciton states per time, which allows us to access the dark exciton spins more often," Heindel said.

Measuring the dark exciton spins also reveals the frequency of its precession, an oscillation between a state in which the spins are either up or down. Knowing this number, Heindel explained, is needed when using dark excitons to generate quantum states of light that are promising for quantum information applications. For these states, called cluster states of entangled photons, the quantum mechanical properties are preserved even if parts of the state are destroyed—needed for error-resistant quantum information systems.

## **Quantum memory with record-breaking capacity based on laser-cooled atoms**

The emerging domain of parallelized quantum information processing opens up new possibilities for precise measurements, communication and imaging. Precise control of multiple stored photons allows efficient handling of this subtle information in large amounts. In the Quantum Memories Laboratory at Faculty of Physics, University of Warsaw, a group of laser-cooled atoms

has been used as a memory that can store up to 665 quantum states of light simultaneously. The experimental results have been published in *Nature Communications*.

Every [information processing](#) task requires memory. Quantum memory is capable of storage and on-demand retrieval of [quantum](#) states. The key parameter of such memory is its capacity, the number of qubits (quantum bits) that the memory can effectively process. Simultaneous operation on many qubits is a key to efficient quantum parallel computation, providing new possibilities in the fields on imaging or communication.

The on demand generation of many photons remains a key challenge for experimental groups dealing with quantum information. For a widely-used method of multiplexing single-photon emitters into one network, the complexity of the system grows along with its advantages. Using [quantum memory](#), researchers can generate a group of a dozen photons within seconds rather than years. Spatial multiplexing aided by a single-photon sensitive camera stands out as an effective way to obtain high capacity at low cost.

In the Quantum Memories Laboratory (Faculty of Physics, University of Warsaw), researchers have built such high-capacity memory. The system holds a world record for the largest capacity, as other experiments have only harnessed tens of independent states of light. The heart of the setup comprises a so-called magneto-optical trap (MOT). A group of rubidium atoms inside a glass vacuum chamber is trapped and cooled by lasers in the presence of a magnetic field to about 20 micro-Kelvins. The memory light-atoms interface is based on off-resonant light scattering. In the write-in process, the cloud of atoms is illuminated by a laser beam, resulting in photon scattering.

Each scattered [photon](#) is emitted in a random direction and registered on a [sensitive camera](#). The information about scattered photons is stored inside the atomic ensemble in the form of collective excitations—spin-waves that can be retrieved on demand as another group of photons. By measuring correlations between emission angles of photons created during the write-in and read-out process, the researchers determined that the memory is, indeed, quantum, and that the properties of the generated state of light cannot be described by classical optics. The prototype quantum [memory](#) from Faculty of Physics at University of Warsaw now takes two optical tables and functions with the help of nine lasers and three control computers. [27]

## **Long-lived storage of a photonic qubit for worldwide teleportation**

Concerning the development of quantum memories for the realization of global quantum networks, scientists of the Quantum Dynamics Division led by Professor Gerhard Rempe at the Max Planck Institute of Quantum Optics (MPQ) have now achieved a major breakthrough: they demonstrated the long-lived storage of a photonic qubit on a single atom trapped in an optical resonator. The coherence time of the stored quantum bit outlasts 100 milliseconds and therefore matches the requirement for the creation of a global quantum network in which qubits are directly teleported between end nodes. "The coherence times that we achieve represent an improvement by two orders of magnitude compared to the current state-of-the-art," says Professor Rempe. The study is published in *Nature Photonics* today.

Light is an ideal carrier for quantum information encoded on single photons, but transfer over long distances is inefficient and unreliable due to losses. Direct teleportation between the end nodes of a network can be utilized to prevent the loss of precious quantum bits. First, remote entanglement has to be created between the nodes; then, a suitable measurement on the sender side triggers the "spooky action at a distance," i.e. the instantaneous transport of the qubit to the receiver's node. However, the quantum bit may be rotated when it reaches the receiver and hence has to be reverted. To this end, the necessary information has to be classically communicated from sender to receiver. This takes a certain amount of time, during which the qubit has to be preserved at the receiver. Considering two network nodes at the most distant places on earth, this corresponds to a time span of 66 milliseconds.

In 2011, Professor Rempe's group has demonstrated a successful technique for storing a photonic quantum bit on a single atom. The atom is placed in the centre of an optical cavity which is formed by two high-finesse mirrors and held in place by standing light waves. A single photon which carries the quantum bit in a coherent superposition of two polarization states starts to strongly interact with the single atom once it is sent into the resonator. Ultimately, the photon is absorbed by the atom and the quantum bit is transferred into a coherent superposition of two atomic states. The challenge is to maintain the atomic superposition as long as possible. In former experiments, the storage time was limited to a few hundreds of microseconds.

"The major problem for storing quantum bits is the phenomenon of dephasing," explains Stefan Langenfeld, a doctoral candidate at the experiment. "Characteristic of a quantum bit is the relative phase of the wave functions of the atomic states that are coherently superimposed. Unfortunately, in real-world experiments, this phase relation is lost over time mostly due to interaction with fluctuating ambient magnetic fields."

In their current experiment, the scientists take new measures to counteract the impact of those fluctuations. Once the information is transferred from the photon to the atom, the population of one atomic state is coherently transferred to another state. This is done by using a pair of laser beams to induce a Raman transition. In this new configuration, the stored qubit is 500 times less sensitive to magnetic field fluctuations.

Before the retrieval of the stored photonic quantum bit, the Raman transition is reversed. For a storage time of 10 milliseconds, the overlap of the stored photon with the retrieved photon is about 90%. This means, that the mere transfer of the atomic qubit to a less sensitive state configuration extends the coherence time by a factor of 10. Another factor of 10 was gained by adding a so-called "spin echo" to the experimental sequence. Here, the population of the two atomic states used for storage is swapped in the middle of the storage time. "The new technique allows us to preserve the quantum nature of the stored bit for more than 100 milliseconds," says Matthias Körber, a doctoral candidate at the experiment. "Although an envisioned global quantum network which allows for secure and reliable transport of quantum information still demands a lot of research, the long-lived storage of quantum bits is one of the key technologies and we believe that the current improvements will bring us a significant step closer to its realization." [26]

## Microcavity-engineered plasmonic resonances for strong light-matter interaction

Achieving strong light-matter interaction at the quantum level has always been a central task in quantum physics since the emergence of quantum information and quantum control. However, the scale mismatch between the quantum emitters (nanometers) and photons (micrometers) makes the task challenging. Metallic nanostructures resolve the mismatch by squeezing the light into nanoscale volume, but their severe dissipations make quantum controls unlikely. Now, a group led by Xiao Yun-Feng at Peking University (China) has theoretically demonstrated that the strong light-matter interaction at quantum level can be achieved using microcavity-engineered metallic nanostructures. This result has been published in a recent issue of *Physical Review Letters*.

Strong coupling is fundamental to implementing quantum gates in quantum computers and also crucial to increasing the signal-to-noise ratio in sensing applications. To realize strong coupling, the coherent interaction strength should exceed the system dissipation rates. Although the metallic nanostructures provide high interaction rate, the dissipations intrinsic to metals are usually even stronger. As a result, [strong coupling](#) in metallic nanostructures has only been realized in extreme experimental conditions.

In this work, the researchers report that the dissipation can be suppressed by engineering the electromagnetic environment of metallic nanostructures. An optical microcavity provides a nontrivial electromagnetic environment which substantially broadens the radiative output channel of the metallic nanostructures, guiding the energy out from the dissipative region and thus suppressing the dissipations. With such an interface, energy and information can be guided out from the single quantum emitter at both high speed and high efficiency.

"Theoretical model shows that microcavities-engineered metallic structures can boost the radiation efficiency of a quantum emitter by 40 times and the radiation output rate by 50 times, compared to metallic nanostructures in the vacuum", said Peng Pai, who was an undergraduate at Peking University and now is a Ph.D. student at Massachusetts Institute of Technology. Importantly, reversible energy exchange between the photon and the quantum emitter at THz rate can be achieved, manifesting the strong light-matter interaction at the [quantum level](#).

"Our approach to reducing the dissipations is not restricted by the scale, shape, and material of the metallic nanostructures," said Professor Xiao. "In combination with previous approaches, it is promising to build the state-of-the-art light-matter interface at nanoscale using microcavity-engineered [metallic nanostructures](#), providing a new platform for the study of quantum plasmonics, [quantum information](#) processing, precise sensing and advanced spectroscopy."

## Physicists develop new design for fast, single-photon guns

Researchers from the Moscow Institute of Physics and Technology and the University of Siegen have explained the mechanism of single-photon generation in diamond diodes. Their findings, published in *Physical Review Applied*, offer new avenues for the development of high-speed single-photon sources for quantum communication networks and quantum computers of the future.

Operation at the single-photon level raises the possibility of developing entirely new communication and computing devices, ranging from hardware random number generators to quantum computers. Perhaps the most highly anticipated quantum technology is quantum communication. Quantum cryptography, which is based on the laws of quantum physics, guarantees unconditional communication security. In other words, it is fundamentally impossible to intercept the transmitted message, no matter the equipment or amount of computing power available to the hacker. Even a powerful quantum computer cannot help in this case. However, the implementation of quantum communication lines and other quantum devices inevitably relies on efficient single-photon sources.

It is a practical necessity that single-photon sources operate under standard conditions and be electrically pumped, that is, they should work at room temperature and be powered by a battery. These crucial requirements are not that easy to meet. First, quantum systems are not really compatible with high temperatures, which means they must operate in a refrigerator or cryostat in order to cool them to the temperature of liquid helium or even colder, to below 1 kelvin, which is equal to -272 degrees Celsius. Although the use of such devices has become standard practice in physical research, a cooling system of this kind is wildly impractical, inhibiting mass production of quantum devices. Also, the notion of a quantum system implies the absence of uncontrolled interactions with the surrounding environment. A classic example of such a system is a single atom in a vacuum chamber. Though its interaction with the environment is negligible, physicists can nevertheless control its electron states with a laser. By illuminating the chamber with a laser beam, an electron is promoted from an occupied lower-energy orbital to an empty higher-energy orbital. After that, the atom relaxes to the initial state via photon emission. The problem is that such a system cannot be electrically pumped.

Over the past two decades, ongoing research in the field of quantum optics and electronics has shown that even semiconductor quantum systems do not produce satisfactory results under electrical pumping at room temperature, whereas many of the other materials do not conduct electricity at all.

The surprising solution to this problem was previously found in diamond, a material that exhibits properties at the interface between semiconductors and dielectrics. Researchers found that certain points in the crystal lattice of diamond can function as quantum systems with outstanding photon emission characteristics. Moreover, they found that these quantum systems are capable of emitting single photons when an electric current is passed through diamond. Nevertheless, the physics behind this phenomenon remained unknown and it was unclear how to design fast and efficient single-photon sources based on color centers.



In the new paper, the researchers from MIPT and the University of Siegen established a mechanism of single-photon emission from electrically pumped nitrogen-vacancy centers in diamond and determined the factors affecting photon emission dynamics. According to their research, the single-photon emission process can be divided into three stages: (1) the electron capture by a color center, (2) the hole capture, meaning the loss of an electron, and (3) the electron or hole transitions between energy levels of the color center. Together, these three stages are analogous to a firing revolver.

Shooting a bullet in this analogy means emitting a single photon. An electron is captured by the defect—think of this as pulling back the hammer of a gun. Then the trigger is pulled, which sets the triggering mechanism in motion, throwing the hammer against the primer of the cartridge. This reversed motion of the hammer corresponds to the capture of a hole by the color center. Then the primer explodes, igniting the propellant, and the combustion gases drive the bullet along and out of the barrel. Similarly, the captured hole in the color center undergoes transitions between ground and excited states, which results in the emission of a photon.

Subsequent cycles repeat the first cycle, with the exception that there is no need for a new cartridge, because the color center is capable of emitting any number of photons one at a time.

An important requirement for a practical single-photon source is that it has to emit photons at predetermined times, since the moment the photon is emitted, it flies away at the speed of light. "In a way, it's like a fast-draw duel in the Wild West," says Dmitry Fedyanin. "Two cowboys draw their guns the moment the clock strikes. Whoever shoots first is usually the winner. Any delay might cost each one of them his life. With quantum devices, the story is pretty much the same: It is crucial to generate a photon at precisely the time we need it." In their paper, the researchers show what determines the response time of a single-photon source, that is, the delay before the source emits a photon. They also evaluated the probability of emitting a new photon at time  $t$  after the emission of the first photon. As it turns out, the response time can be adjusted and improved several orders of magnitude by changing the characteristics of diamond via doping or controlling the densities of electrons and holes injected into diamond. Apart from this, Fedyanin says, the initial state of the color center can be controlled by varying its position in the diamond diode. This is similar to how a gunslinger might cock the revolver for a faster shot or put the gun on half cock.

The physical model advanced by the researchers sheds light on the behavior of color centers in diamond. In addition to providing a qualitative interpretation, the proposed theoretical approach reproduces recent experimental results. This opens up a new possibility for the design and development of practical single-photon sources with desired characteristics, which are vital for the realization of quantum information devices, such as unconditionally secure communication lines based on quantum cryptography. [24]

## Graphene single photon detectors

Considerable interest in new single-photon detector technologies has been scaling in this past decade. Nowadays, quantum optics and quantum information applications are, among others, one of the main precursors for the accelerated development of single-photon detectors. Capable of sensing an increase in temperature of an individual absorbed photon, they can be used to help us study and understand, for example, galaxy formation through the cosmic infrared background, observe entanglement of superconducting qubits or improve quantum key distribution methods for ultra-secure communications.

Current detectors are efficient at detecting incoming photons that have relatively high energies, but their sensitivity drastically decreases for low frequency, low energy photons. In recent years, graphene has shown to be an exceptionally efficient photo-detector for a wide range of the electromagnetic spectrum, enabling new types of applications for this field.

Thus, in a recent paper published in the journal *Physical Review Applied*, and highlighted in *APS Physics*, ICFO researcher and group leader Prof. Dmitri Efetov, in collaboration with researchers from Harvard University, MIT, Raytheon BBN Technologies and Pohang University of Science and Technology, have proposed the use of graphene-based Josephson junctions (GJJs) to detect single photons in a wide electromagnetic spectrum, ranging from the visible down to the low end of radio frequencies, in the gigahertz range.

In their study, the scientists envisioned a sheet of graphene that is placed in between two superconducting layers. The so created Josephson junction allows a supercurrent to flow across the graphene when it is cooled down to 25 mK. Under these conditions, the heat capacity of the graphene is so low, that when a single photon hits the graphene layer, it is capable of heating up the electron bath so significantly, that the supercurrent becomes resistive – overall giving rise to an easily detectable voltage spike across the device. In addition, they also found that this effect would occur almost instantaneously, thus enabling the ultrafast conversion of absorbed light into electrical signals, allowing for a rapid reset and readout.

The results of the study confirm that we can expect a rapid progress in integrating graphene and other 2-D materials with conventional electronics platforms, such as in CMOS-chips, and shows a promising path towards single-photon-resolving imaging arrays, quantum information processing applications of optical and microwave photons, and other applications that would benefit from the quantum-limited detection of low-energy photons. [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  $-269^{\circ}\text{C}$ ), 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  $-196^{\circ}\text{C}$ , 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  $10^{\circ}\text{C}$  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  $-213\text{ }^{\circ}\text{C}$  using a new molecule based on the rare earth element dysprosocenium, as reported in a letter to the journal Nature. With a leap of  $56\text{ }^{\circ}\text{C}$ , this is only  $17\text{ }^{\circ}\text{C}$  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-writable 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-writable 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 MAPbBr<sub>3</sub> 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. Vally 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.

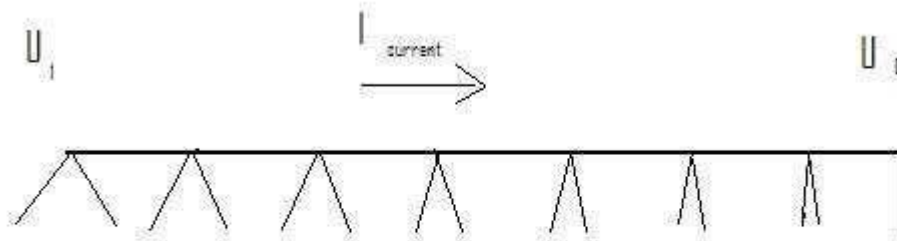


Figure 1.) Aluminium foils shows the charge distribution on the electric wire

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  $x = \frac{1}{2} at^2$  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:  $-dU/dx = E = \text{const}$ .

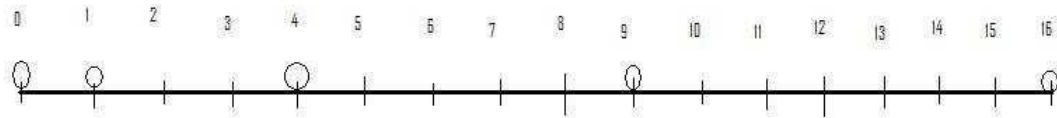


Figure 2.) The accelerating electrons created charge distribution on the electric wire

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  $\mathbf{U}$  potential, and with this accelerated motion they are maintaining the linear potential decreasing of the  $\mathbf{U}$  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  $\mathbf{U}$  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 $\mathbf{U}$ electric potential**

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

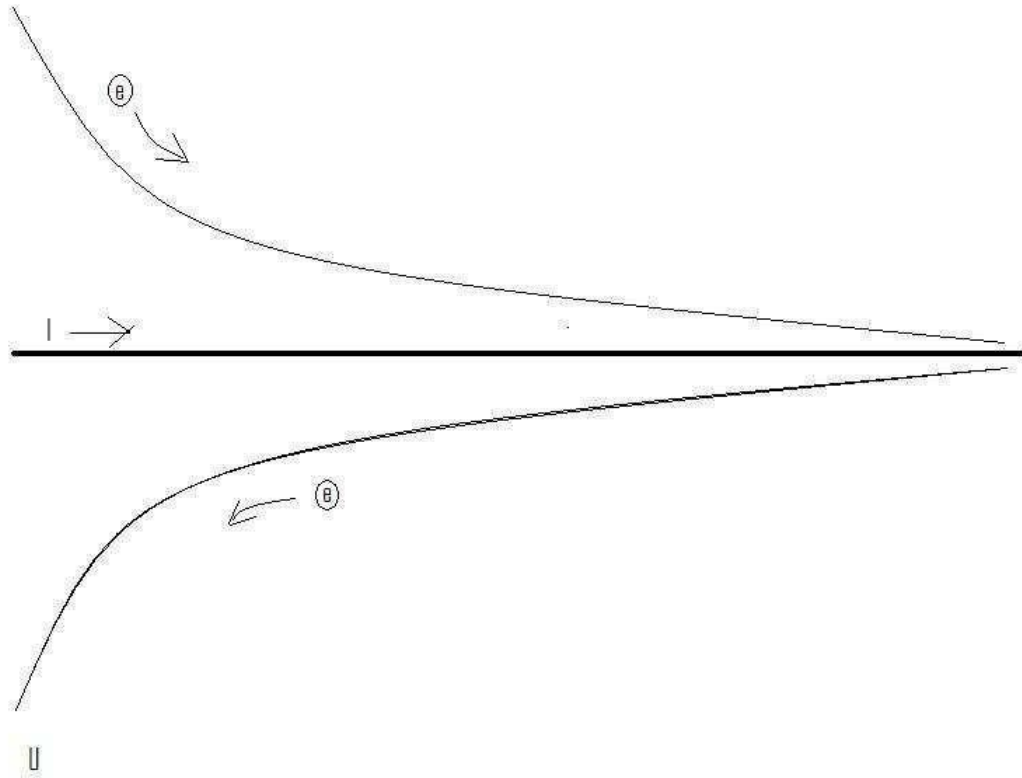


Figure 3.) Concentric parabolic equipotential surfaces around the electric wire causes the magnetic effect on the external moving charges

Considering that the magnetic effect is  $\underline{F} = q \underline{v} \times \underline{B}$ , where the  $\underline{B}$  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  $\underline{v} \times \underline{B} = \underline{0}$ . 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  $\underline{v} \times \underline{B}$  magnetic force.

Getting the magnetic force from the  $\underline{F} = d\underline{p}/dt$  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

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

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  $\phi$  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 linear 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  $\underline{a}$  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  $\Delta x$  position difference and with a  $\Delta p$  momentum difference such a way that they product is about the half Planck reduced constant. For the proton this  $\Delta x$  much less in the nucleon, than in the orbit of the electron in the atom, the  $\Delta p$  is much higher because of the greater proton mass.

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

## Wave – Particle Duality

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

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

## Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and it's kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only 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:  $\frac{1}{2} \hbar = \Delta x \Delta p$  or  $\frac{1}{2} \hbar = \Delta t \Delta E$ , 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  $\nu$  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  $\nu$ , wavelength  $\lambda$ , 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  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  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 lambda 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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