# Quantum Technologies Equation

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*Tobias Kippenberg, professor at EPFL, adds, "For the first time, we bring free electrons into the toolbox of quantum information science. More broadly, coupling free electrons and light using integrated photonics could open the way to a new class of hybrid quantum technologies." [41]*

*The time it takes for an atom to quantum-mechanically tunnel through an energy barrier has been measured by Aephraim Steinberg of the University of Toronto and colleagues. [40]*

*An international team led by researchers at Princeton University has uncovered a new class of magnet that exhibits novel quantum effects that extend to room temperature. [39]*

*Researchers from Brown and Columbia Universities have demonstrated previously unknown states of matter that arise in double-layer stacks of graphene, a two-dimensional nanomaterial. [38]*

*A quantum squeezing and amplification technique has been used to measure the position of a trapped ion to subatomic precision. [37]*

*A new theoretical model involves squeezing light to just the right amount to accurately transmit information using subatomic particles. [36]*

*The standard approach to building a quantum computer with majoranas as building blocks is to convert them into qubits. However, a promising application of quantum computing—quantum chemistry—would require these qubits to be converted again into so-called fermions. [35]*

*Scientists have shown how an optical chip can simulate the motion of atoms within molecules at the quantum level, which could lead to better ways of creating chemicals for use as pharmaceuticals. [34]*

*Chinese scientists Xianmin Jin and his colleagues from Shanghai Jiao Tong University have successfully fabricated the largest-scaled quantum chip and demonstrated the first two-dimensional quantum walks of single photons in real spatial space, which may* *provide a powerful platform to boost analog quantum computing for quantum supremacy. [33]*

*To address this technology gap, a team of engineers from the National University of Singapore (NUS) has developed an innovative microchip, named BATLESS, that can continue to operate even when the battery runs out of energy. [32]*

*Stanford researchers have developed a water-based battery that could provide a cheap way to store wind or solar energy generated when the sun is shining and wind is blowing so it can be fed back into the electric grid and be redistributed when demand is high. [31]*

*Researchers at AMOLF and the University of Texas have circumvented this problem with a vibrating glass ring that interacts with light. They thus created a microscale circulator that directionally routes light on an optical chip without using magnets. [30]*

*Researchers have discovered three distinct variants of magnetic domain walls in the helimagnet iron germanium (FeGe). [29]*

*Magnetic materials that form helical structures—coiled shapes comparable to a spiral staircase or the double helix strands of a DNA molecule—occasionally exhibit exotic behavior that could improve information processing in hard drives and other digital devices. [28]*

*In a new study, researchers have designed "invisible" magnetic sensors—sensors that are magnetically invisible so that they can still detect but do not distort the surrounding magnetic fields. [27]*

*At Carnegie Mellon University, Materials Science and Engineering Professor Mike McHenry and his research group are developing metal amorphous nanocomposite materials (MANC), or magnetic materials whose nanocrystals have been grown out of an amorphous matrix to create a two phase magnetic material that exploits both the attractive magnetic inductions of the nanocrystals and the large electrical resistance of a metallic glass. [26]*

*The search and manipulation of novel properties emerging from the quantum nature of matter could lead to next-generation electronics and quantum computers. [25]*

*A research team from the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) has found the first evidence that a shaking motion in the structure of an atomically thin (2-D) material possesses a naturally occurring circular rotation. [24]*

***Topological effects, such as those found in crystals whose surfaces conduct electricity while their bulk does not, have been an exciting topic of physics research in recent years and were the subject of the 2016 Nobel Prize in physics.*** *[23]*

*A new technique developed by MIT researchers reveals the inner details of photonic crystals, synthetic materials whose exotic optical properties are the subject of widespread research. [22]*

*In experiments at SLAC, intense laser light (red) shining through a magnesium oxide crystal excited the outermost "valence" electrons of oxygen atoms deep inside it. [21]*

*LCLS works like an extraordinary strobe light: Its ultrabright X-rays take snapshots of materials with atomic resolution and capture motions as fast as a few femtoseconds, or millionths of a billionth of a second. For comparison, one femtosecond is to a second what seven minutes is to the age of the universe. [20]*

*A 'nonlinear' effect that seemingly turns materials transparent is seen for the first time in X-rays at SLAC's LCLS. [19]*

*Leiden physicists have manipulated light with large artificial atoms, so-called quantum dots. Before, this has only been accomplished with actual atoms. It is an important step toward light-based quantum technology. [18]*

*In a tiny quantum prison, electrons behave quite differently as compared to their counterparts in free space. They can only occupy discrete energy levels, much like the electrons in an atom - for this reason, such electron prisons are often called "artificial atoms". [17]*

*When two atoms are placed in a small chamber enclosed by mirrors, they can simultaneously absorb a single photon. [16]*

*Optical quantum technologies are based on the interactions of atoms and photons at the single-particle level, and so require sources of single photons that are highly indistinguishable – that is, as identical as possible. Current single-photon sources using semiconductor quantum dots inserted into photonic structures produce photons that are ultrabright but have limited indistinguishability due to charge noise, which results in a fluctuating electric field. [14]*

*A method to produce significant amounts of semiconducting nanoparticles for light-emitting displays, sensors, solar panels and biomedical applications has gained momentum with a demonstration by researchers at the Department of Energy's Oak Ridge National Laboratory. [13]*

*A source of single photons that meets three important criteria for use in quantum-information systems has been unveiled in China by an international team of physicists. Based on a quantum dot, the device is an efficient source of photons that emerge as solo* *particles that are indistinguishable from each other. The researchers are now trying to use the source to create a quantum computer based on "boson sampling". [11]*

*With the help of a semiconductor quantum dot, physicists at the University of Basel have developed a new type of light source that emits single photons. For the first time, the researchers have managed to create a stream of identical photons. [10]*

*Optical photons would be ideal carriers to transfer quantum information over large distances. Researchers envisage a network where information is processed in certain nodes and transferred between them via photons. [9]*

*While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer using Quantum Information.*

*In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods.*

*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 Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass rate and the Weak and Strong Interactions by the diffraction patterns. The Weak Interaction changes the diffraction patterns by moving the electric charge from one side to the other side of the diffraction pattern, which violates the CP and Time reversal symmetry.*

*The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the Relativistic Quantum Theory and making possible to build the Quantum Computer with the help of Quantum Information.*

## Contents

Author: George Rajna

## Preface

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer.

Australian engineers detect in real-time the quantum spin properties of a pair of atoms inside a silicon chip, and disclose new method to perform quantum logic operations between two atoms. [5]

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

I think that we have a simple bridge between the classical and quantum mechanics by understanding the Heisenberg Uncertainty Relations. It makes clear that the particles are not point like but have a dx and dp uncertainty.

## Master equation to boost quantum technologies

As the size of modern technology shrinks down to the nanoscale, weird quantum effects—such as quantum tunneling, superposition, and entanglement—become prominent. This opens the door to a new era of quantum technologies, where quantum effects can be exploited. Many everyday technologies make use of feedback control routinely; an important example is the pacemaker, which must monitor the user's heartbeat and apply electrical signals to control it, only when needed. But physicists do not yet have an equivalent understanding of feedback control at the quantum level. Now, physicists have developed a "master equation" that will help engineers understand feedback at the quantum scale. Their results are published in the journal *Physical Review Letters*.

"It is vital to investigate how feedback control can be used in quantum technologies in order to develop efficient and fast methods for controlling quantum systems, so that they can be steered in real time and with high precision," says co-author Björn Annby-Andersson, a quantum physicist at Lund University, in Sweden.

An example of a crucial feedback-control process in quantum computing is quantum error correction. A quantum computer encodes information on physical qubits, which could be photons of light, or atoms, for instance. But the quantum properties of the qubits are fragile, so it is likely that the encoded information will be lost if the qubits are disturbed by vibrations or fluctuating electromagnetic fields. That means that physicists need to be able to detect and correct such errors, for instance by using feedback control. This error correction can be implemented by measuring the state of the qubits and, if a deviation from what is expected is detected, applying feedback to correct it.

But feedback control at the quantum level presents unique challenges, precisely because of the fragility physicists are trying to mitigate against. That delicate nature means that even the feedback process itself could destroy the system. "It is necessary to only interact weakly with the measured system, preserving the properties we want to exploit," says Annby-Andersson.

It is thus important to develop a full theoretical understanding of quantum feedback control, to establish its fundamental limits. But most existing theoretical models of quantum feedback control require computer simulations, which typically only provide quantitative results for specific systems. "It is difficult to draw general, qualitative conclusions," Annby-Andersson says. "The few models that can provide qualitative understanding are only applicable on a narrow class of feedback controlled systems—this type of feedback is typically referred to as linear feedback."

## 'Pen and paper'

Annby-Andersson and his colleagues have now developed a master equation, called a "Quantum Fokker-Planck equation," that enables physicists to track the evolution of any quantum system with feedback control over time. "The equation can describe scenarios that go beyond linear feedback," says Annby-Andersson. "In particular, the equation can be solved with pen and paper, rather than having to rely on computer simulations."

The team tested their equation by applying it to a simple feedback model. This confirmed that the equation provides physically sensible results and also demonstrated how energy can be harvested in microscopic systems, using feedback control. "The equation is a promising starting point for future studies of how energy may be manipulated with the help of information on a microscopic level," says Annby-Andersson.

The team is now investigating a system that makes use of feedback to manipulate energy in "quantum dots"—tiny semiconducting crystals just billionths of a meter across. "An important future direction is to use the equation as a tool for inventing novel feedback protocols that can be used for quantum technologies," says Annby-Andersson. [42]

# New quantum technology combines free electrons and photons

Faster computers, tap-proof communication, better car sensors—quantum technologies have the potential to revolutionize our lives just as the invention of computers or the internet once did. Experts worldwide are trying to implement findings from basic research into quantum technologies. To this end, they often require individual particles, such as photons—the elementary particles of light—with tailored properties.

However, obtaining individual particles is complicated and requires intricate methods. In a study recently published in the journal *Science*, researchers now present a new method that simultaneously generates two individual particles in form of a pair.

## Fundamental quantum physics in electron microscopes

The international team from the Göttingen Max Planck Institute (MPI) for Multidisciplinary Sciences, the University of Göttingen, and the Swiss Federal Institute of Technology in Lausanne (EPFL) succeeded in coupling single free electrons and photons in an electron microscope. In the Göttingen experiment, the beam from an electron microscope passes through an integrated optical chip, fabricated by the Swiss team. The chip consists of a fiber-optic coupling and a ring-shaped resonator that stores light by keeping moving photons on a circular path.

"When an electron scatters at the initially empty resonator, a photon is generated," explains Armin Feist, scientist at the MPI and one of the study's first authors. "In the process, the electron loses exactly the amount of energy that the photon requires to be created virtually from nothing in the resonator. As a result, the two particles are coupled through their interaction and form a pair." With an improved measurement method, the physicists could precisely detect the individual particles involved and their simultaneous manifestation.

## Future quantum technology with free electrons

"With the electron-photon pair, we only need to measure one particle to obtain information about the energy content and temporal appearance of the second one," says Germaine Arend, a Ph.D. candidate at the MPI and also first author of the study. This allows researchers to use one quantum particle in an experiment while, at the same time, confirming its presence by detecting the other particle, in a so-called heralding scheme. Such a feature is necessary for many applications in quantum technology.

Max Planck Director Claus Ropers sees electron-photon pairs as a new opportunity for quantum research. "The method opens up fascinating new possibilities in electron microscopy. In the field of quantum optics, entangled photon pairs already improve imaging. With our work, such concepts can now be explored with electrons," Roper says.

Tobias Kippenberg, professor at EPFL, adds, "For the first time, we bring free electrons into the toolbox of quantum information science. More broadly, coupling free electrons and light using integrated photonics could open the way to a new class of hybrid quantum technologies." [41]

# Quantum-tunnelling time is measured using ultracold atoms

The time it takes for an atom to quantum-mechanically tunnel through an energy barrier has been measured by Aephraim Steinberg of the University of Toronto and colleagues. The team observed ultracold atoms tunnelling through a laser beam, and their experiment provides important clues in a long-standing mystery in quantum physics.

Quantum tunnelling involves a particle passing through an energy barrier despite lacking the energy required to overcome the barrier, as required by classical physics. The phenomenon is not fully understood theoretically, yet it underpins practical technologies ranging from scanning tunnelling microscopy to flash memories.

There has been a long controversy about the length of time taken to cross the barrier – a process that cannot be described as a classical trajectory. This problem arises because quantum mechanics itself provides no prescription for it, explains Karen Hatsagortsyan of the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. “Many definitions have been invented, but they describe the tunnelling process from different points of view”, he says, “and the relationship between them is not simple and straightforward.”

## Angular streaking

Hatsagortsyan was involved in one of several recent experiments that looked at electrons escaping from atoms by light-induced ionization in a strong electric field – a process that involves the electrons tunnelling through a barrier as “wave packets” with a range of velocities. These experiments use a phenomenon called angular streaking, which establishes a kind of “clock” that can measure tunnelling with a precision of attoseconds ($10^{-18}$ s).

Because the peak of the wave packet is produced by interference effects, its behaviour does not follow our classical intuitions: it can seem to move from one side of the barrier to the other faster than light, in defiance of special relativity. This is because “there is ‘no law’ connecting an incoming and an outgoing peak”, says Steinberg. “Even if the peak appears at the output before the input even arrives, that doesn’t mean anything travelled faster than light.”

The method does not, however, really correspond to any previously defined picture of what the tunnelling time is, says Alexandra Landsman of the Max Planck Institute for the Physics of Complex Systems in Dresden, who led some of the other “attoclock” ionization studies of tunnelling. Rather, it was a way to “pick out a ‘correct’ physical definition of tunnelling time among a number of competing proposals”, she says.

## More controversy than consensus

But these experiments seem to have created more controversy than consensus – partly because it is not clear how to define the time at which tunnelling “starts”. Recently a team based mostly at Griffith University in Nathan, Australia, concluded from the same approach that particles might tunnel more or less instantaneously.

It may all be a question of definitions. “Sometimes”, says Steinberg, “there’s a quantity you can measure a number of different ways, and since they all give the same answer classically, we think these different measurements are probing the same thing.” But they’re not necessarily – in which case “two different measurements both of which we expected to reveal ‘*the* tunnelling time’ can have different results.”

But “even if there isn’t *one* tunnelling time, neither is there an infinite number of options”, Steinberg adds. “There are maybe two or three timescales, and we need to work to understand what each one describes.”

Steinberg’s team approached the problem by measuring a definition of the tunnelling time determined by a kind of internal clock in the particles themselves. For particles, they use a cloud of about five to ten thousand ultracold atoms of rubidium propelled gently towards a barrier induced by a light beam.

## Spinning clocks

The atoms each have a spin that, when placed in a magnetic field, will rotate (precess) at a known frequency, which is the ticking clock. The apparatus is arranged so that the particles will only experience an effective magnetic field inside the barrier itself. By measuring how much the orientation of their spin has changed when atoms exit the barrier, they obtain a measure of how long the particles spent “inside” the barrier.

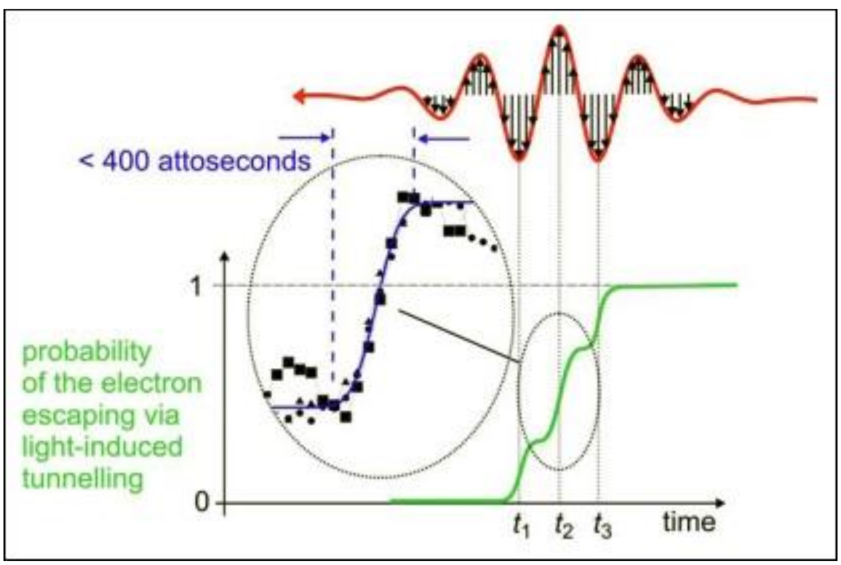
Proposed more than 50 years ago by two Russian physicists, Steinberg’s team created the experiment using atoms that adopt a collective state called a Bose-Einstein condensate (BEC), described by quantum mechanics. The atoms have relatively long quantum wavelengths – a micron or so, which means they can penetrate relatively wide barriers, with long passage times of about a millisecond or so – which can be measured precisely. “We want particles with a well-controlled starting state and a very long wavelength”, says Steinberg. “A BEC is an ideal way to produce this.”

"Honestly, when we started these experiments", he adds, "partly I just wanted to see with our own eyes that a composite particle with 87 nucleons and 37 electrons [that is, rubidium atoms] could really tunnel all the way across a barrier 10,000 times larger than an atom itself".

## Laser tweezer

To create the barrier and have the atoms impinge on it, the team used two laser beams. "We Bose-condense them inside an attractive 'laser tweezer' beam, which acts as an optical waveguide", says Steinberg. Then they use a magnetic field to give the atoms a little push towards the barrier, moving at a few millimetres per second.

The barrier is created by a blue laser beam, focused to be about a micron wide, with a frequency slightly greater than that of one of the resonances in the atoms. Inside this laser's intense electromagnetic field, the atoms will interact with it. But "the atoms can't keep up, oscillate out of phase with the field, and end up in a higher-energy state", says Steinberg. This means that the blue laser acts as a repulsive potential, about 1.3 micron wide, through which just a few percent of the atoms can tunnel. To reduce their random thermal motions, the researchers chill the system to a temperature of about 1 nK.




**Electron tunnelling seen in real time**

Deducing the tunnelling time is then a matter of measuring how the spin angles of the atoms in the trap have changed when they exit it. In this way, says Steinberg, "we are probing the dwell time of transmitted atoms in the barrier." They find that this is about 0.62 ms.

"This is a remarkable experiment," says Hatsagortsyan. It is "especially nice because the quantity [tunnelling time] it measures is well defined", says Landsman. "The findings may have practical implications for tunnelling devices, since the measured time seems to correspond to the time the electron actually spends inside the barrier".

Steinberg adds that the technique could reveal something about the trajectory within the barrier itself. "We hope in the future to restrict our effective magnetic field to regions even smaller than the barrier", he says, "so that when we look at the final spin, we're measuring not how much time the atom spent somewhere ill-defined in the barrier, but in one particular region." According to one theoretical description, he says, it looks as though a particle "appears on the far side without ever crossing the middle. This is what we'd like to test."

The research is described in Nature. [40]

## Scientists discover a topological magnet that exhibits exotic quantum effects

An international team led by researchers at Princeton University has uncovered a new class of magnet that exhibits novel quantum effects that extend to room temperature.

The researchers discovered a quantized topological phase in a pristine magnet. Their findings provide insights into a 30-year-old theory of how electrons spontaneously quantize and demonstrate a proof-of-principle method to discover new topological magnets. Quantum magnets are promising platforms for dissipationless current, high storage capacity and future green technologies. The study was published in the journal *Nature* this week.

The discovery's roots lie in the workings of the quantum Hall effect- a form of topological effect which was the subject of the Nobel Prize in Physics in 1985. This was the first time that a branch of theoretical mathematics, called topology, would start to fundamentally change how we describe and classify matter that makes up the world around us. Ever since, topological phases have been intensely studied in science and engineering. Many new classes of quantum materials with topological electronic structures have been found, including topological insulators and Weyl semimetals. However, while some of the most exciting theoretical ideas require magnetism, most materials explored have been nonmagnetic and show no quantization, leaving many tantalizing possibilities unfulfilled.

"The discovery of a magnetic topological material with quantized behavior is a major step forward that could unlock new horizons in harnessing quantum topology for future fundamental physics and next-generation device research" said M. Zahid Hasan, the Eugene Higgins Professor of Physics at Princeton University, who led the research team.

While experimental discoveries were rapidly being made, theoretical physics excelled at developing ideas leading to new measurements. Important theoretical concepts on 2-D topological insulators were put forward in 1988 by F. Duncan Haldane, the Thomas D. Jones Professor of Mathematical Physics and the Sherman Fairchild University Professor of Physics at Princeton, who in 2016 was awarded the Nobel Prize in Physics for theoretical discoveries of topological phase transitions and topological phases of matter. Subsequent theoretical developments showed that topological insulator-hosting magnetism in a special atomic arrangement known as a kagome lattice can host some of the most bizarre quantum effects.

Hasan and his team has been on a decade-long search for a topological magnetic quantum state that may also operate at room temperature since their discovery of the first examples of three dimensional topological insulators. Recently, they found a materials solution to Haldane's conjecture in a kagome lattice magnet that is capable of operating at room temperature, which also exhibits the much desired quantization. "The kagome lattice can be designed to possess relativistic band crossings and strong electron-electron interactions. Both are essential for novel magnetism. Therefore, we realized that kagome magnets are a promising system in which to search for topological magnet phases as they are like the topological insulators that we studied before," said Hasan.

For so long, direct material and experimental visualization of this phenomenon has remained elusive. The team found that most of the kagome magnets were too difficult to synthesize, the magnetism was not sufficiently well understood, no decisive experimental signatures of the topology or quantization could be observed, or they operate only at very low temperatures.

"A suitable atomic chemistry and magnetic structure design coupled to first-principles theory is the crucial step to make Duncan Haldane's speculative prediction realistic in a high-temperature setting," said Hasan. "There are hundreds of kagome magnets, and we need both intuition, experience, materials-specific calculations, and intense experimental efforts to eventually find the right material for in-depth exploration. And that took us on a decade-long journey."

The arrows represent the electron spins pointing up from a kagome lattice. The chirality is represented by the counterclockwise circle of fire, which represents the propagating electrons/current on the edge of the magnet. The two cones demonstrate that the bulk of the magnet contains Dirac fermions (linear or conical dispersion of bands) with an energy gap (Chern gap), making it topological. Credit: M. Zahid Hasan group, Princeton University

Through several years of intense research on several families of topological magnets (Nature 562, 91 (2018); Nature Phys 15, 443 (2019), Phys. Rev. Lett. 123, 196604 (2019), Nature Commun. 11, 559 (2020), Phys. Rev. Lett. 125, 046401 (2020)), the team gradually realized that a material made of the elements terbium, magnesium and tin (TbMn6Sn6) has the ideal crystal structure with chemically pristine, quantum mechanical properties and spatially segregated kagome lattice layers. Moreover, it uniquely features a strong out-of-plane magnetization. With this ideal kagome magnet successfully synthesized at the large single crystal level by collaborators from Shuang Jia's group at Peking University, Hasan's group began systematic state-of-the-art measurements to check whether the crystals are topological and, more important, feature the desired exotic quantum magnetic state.

The Princeton team of researchers used an advanced technique known as scanning tunneling microscopy, which is capable of probing the electronic and spin wavefunctions of a material at the sub-atomic scale with sub-millivolt energy resolution. Under these fine-tuned conditions, the researchers identified the magnetic kagome lattice atoms in the crystal, findings that were further confirmed by state-of-the-art angle-resolved photoemission spectroscopy with momentum resolution.

"The first surprise was that the magnetic kagome lattice in this material is super clean in our scanning tunneling microscopy," said Songtian Sonia Zhang, a co-author of the study who earned her Ph.D. at Princeton earlier this year. "The experimental visualization of such a defect-free magnetic kagome lattice offers an unprecedented opportunity to explore its intrinsic topological quantum properties."

The real magical moment was when the researchers turned on a magnetic field. They found that the electronic states of the kagome lattice modulate dramatically, forming quantized energy levels in a way that is consistent with Dirac topology. By gradually raising the magnetic field to 9 Tesla, which is hundreds of thousands of times higher than the earth's magnetic field, they systematically mapped out the complete quantization of this magnet. "It is extremely rare—there has not been one found yet—to find a topological magnetic system featuring the quantized diagram. It requires a nearly defect-free magnetic material design, fine-tuned theory and cutting-edge spectroscopic measurements" said Nana Shumiya, a graduate student and co-author of the study.

The quantized diagram that the team measured provides precise information revealing that the electronic phase matches a variant of the Haldane model. It confirms that the crystal features a spin-polarized Dirac dispersion with a large Chern gap, as expected by the theory for topological magnets. However, one piece of the puzzle was still missing. "If this is truly a Chern gap, then based on the fundamental topological bulk-boundary principle, we should observe chiral (one-way traffic) states at the edge of the crystal," Hasan said.

The final piece fell into place when the researchers scanned the boundary or the edge of the magnet. They found a clear signature of an edge state only within the Chern energy gap. Propagating along the side of the crystal without apparent scattering (which reveals its dissipationless character), the state was confirmed to be the chiral topological edge state. Imaging of this state was unprecedented in any previous study of topological magnets.

The researchers further used other tools to check and reconfirm their findings of the Chern gapped Dirac fermions, including electrical transport measurements of anomalous Hall scaling, angle-resolved photoemission spectroscopy of the Dirac dispersion in momentum space, and first-principles calculations of the topological order in the material family. The data provided a complete spectrum of inter-linked evidence all pointing to the realization of a quantum-limit Chern phase in this kagome magnet. "All the pieces fit together into a textbook demonstration of the physics of Chern-gapped magnetic Dirac fermions," said Tyler A. Cochran, a graduate student and co-first author of the study.

Now the theoretical and experimental focus of the group is shifting to the dozens of compounds with similar structures to TbMn6Sn6 that host kagome lattices with a variety of magnetic structures, each with its individual quantum topology. "Our experimental visualization of the quantum limit Chern phase demonstrates a proof-of-principle methodology to discover new topological magnets," said Jia-Xin Yin, a senior postdoctoral researcher and another co-first author of the study.

"This is like discovering water in an exoplanet—it opens up a new frontier of topological quantum matter research our laboratory at Princeton has been optimized for," Hasan said. [39]

## Research reveals exotic quantum states in double-layer graphene

Researchers from Brown and Columbia Universities have demonstrated previously unknown states of matter that arise in double-layer stacks of graphene, a two-dimensional nanomaterial. These new states, known as the fractional quantum Hall effect, arise from the complex interactions of electrons both within and across graphene layers.

"The findings show that stacking 2-D materials together in close proximity generates entirely new physics," said Jia Li, assistant professor of physics at Brown, who initiated this work while a post-doc at Columbia working with Cory Dean, professor of physics, and Jim Hone, professor of mechanical engineering. "In terms of materials engineering, this work shows that these layered systems could be viable in creating new types of electronic devices that take advantage of these new quantumHall states."

The research is published in the journal *Nature Physics*.

Importantly, says Hone, Wang Fong-Jen Professor of Mechanical Engineering at Columbia Engineering, several of these new quantum Hall states "may be useful in making fault-tolerant quantum computers."

The Hall effect emerges when a magnetic field is applied to a conducting material in a perpendicular direction to a current flow. The magnetic field causes the current to deflect, creating a voltage in the transverse direction, called the Hall voltage. The strength of the Hall voltage increases with the strength of the magnetic field. The quantum version of the Hall effect was first discovered in experiments performed in 1980 at low temperatures and strong magnetic fields. The experiments showed that rather than increasing smoothly with magnetic field strength, the Hall voltage increases in step-wise (or quantized) fashion. These steps are integer multiples of fundamental constants of nature and are entirely independent of the physical makeup of the material used in the experiments. The discovery was awarded the 1985 Nobel Prize in Physics.

A few years later, researchers working at temperatures near absolute zero and with very strong magnetic fields found new types of quantum Hall states in which the quantum steps in Hall voltage correspond to fractional numbers, hence the name fractional quantum Hall effect. The discovery of the fractional quantum Hall effect won another Nobel Prize, in 1998. Theorists later posited that the fractional quantum Hall effect is related to the formation of quasi-particles called composite fermions. In this state, each electron combines with a quantum of magnetic flux to form a composite fermion carrying a fraction of an electron charge giving rise to the fractional values in Hall voltage.

The composite fermion theory has been successful in explaining a myriad of phenomena observed in single quantum well systems. This new research used double-layer graphene to investigate what happens when two quantum wells are brought close together. Theory had suggested that the interaction between two layers would lead to a new type of composite fermion, but this had never been observed in experiment.

For the experiments, the team built on many years of work at Columbia to improve the quality of graphene devices, creating ultra-clean devices entirely from atomically flat 2-D materials. The core of the structure consists of two graphene layer separated by a thin layer of hexagonal boron nitride as an insulating barrier. The double-layer structure is encapsulated by hexagonal boron nitride as a protective insulator, and graphite as a conductive gate to change the charge carrier density in the channel.

"Once again the incredible versatility of graphene has allowed us to push the boundaries of device structures beyond what was previously possible." says Dean, a professor of physics at Columbia University. "The precision and tunability with which we can make these devices is now allowing us to explore an entire realm of physics that was just recently thought to be totally inaccessible."

The graphene structures were then exposed to strong magnetic fields—millions of times stronger than Earth's magnetic field. The research produced a range of fractional quantum Hall states, some of which demonstrate excellent agreement with the composite fermion model, and some that had never been predicted or seen.

"Apart from the interlayer composite fermions, we observed other features that cannot be explained within the composite fermion model," said Qianhui Shi, the paper's co-first author and postdoctoral researcher at Columbia. "A more careful study revealed that, to our surprise, these new states result from pairing between composite fermions. Pairing interaction between adjacent layers and within the same layer give rise to a variety of new quantum phenomena, making double-layer graphene an exciting platform to study."

"Of particular interest," says Hone, "are several new states that have the potential of hosting non-Abelian wave functions—states that don't quite fit the traditional composite fermion model." In non-Abelian states, electrons maintain a kind of "memory" of their past positions relative to each other. That has potential in enabling quantum computers that do not require error correction, which is currently a major stumbling block in the field.

"These are the first new candidates for non-Abelian states in 30 years," Dean said. "It's really exciting to see new physics emerge from our experiments."

The study is titled "Pairing states of composite fermions in double-layer graphene." [38]

## Tiny motion is measured by quantum squeezing and amplification

A quantum squeezing and amplification technique has been used to measure the position of a trapped ion to subatomic precision. The method was developed by Shaun Burd and colleagues at the US's National Institute of Standards and Technology (NIST) in Boulder, Colorado and could be used to develop quantum sensors and quantum computers.

Heisenberg's uncertainty principle puts a fundamental restriction on how precise a measurement can be made on a quantum object such as a single ion. It requires that the product of the measurement uncertainties in the position and momentum of the ion must be larger than a specific value. The only way to decrease the uncertainty in the position of the ion is to boost the uncertainty in the momentum. This process is called squeezing because much like a balloon, squeezing along one direction in position-momentum space creates a bulge in the other direction.

Squeezing is not a new idea and squeezed light is currently used by LIGO and Virgo to measure extremely small changes in length that occur when gravitational waves pass through the detectors.

## Caught in a trap

In the NIST experiment, a magnesium ion is trapped using electric fields and then cooled to its ground state by applying a sequence of laser and microwave pulses. Even in this ultracold and confined environment, the uncertainty in the position of the ion (the extent of its "zero-point oscillation" within the trap) is about 70 times the size of the ion itself.

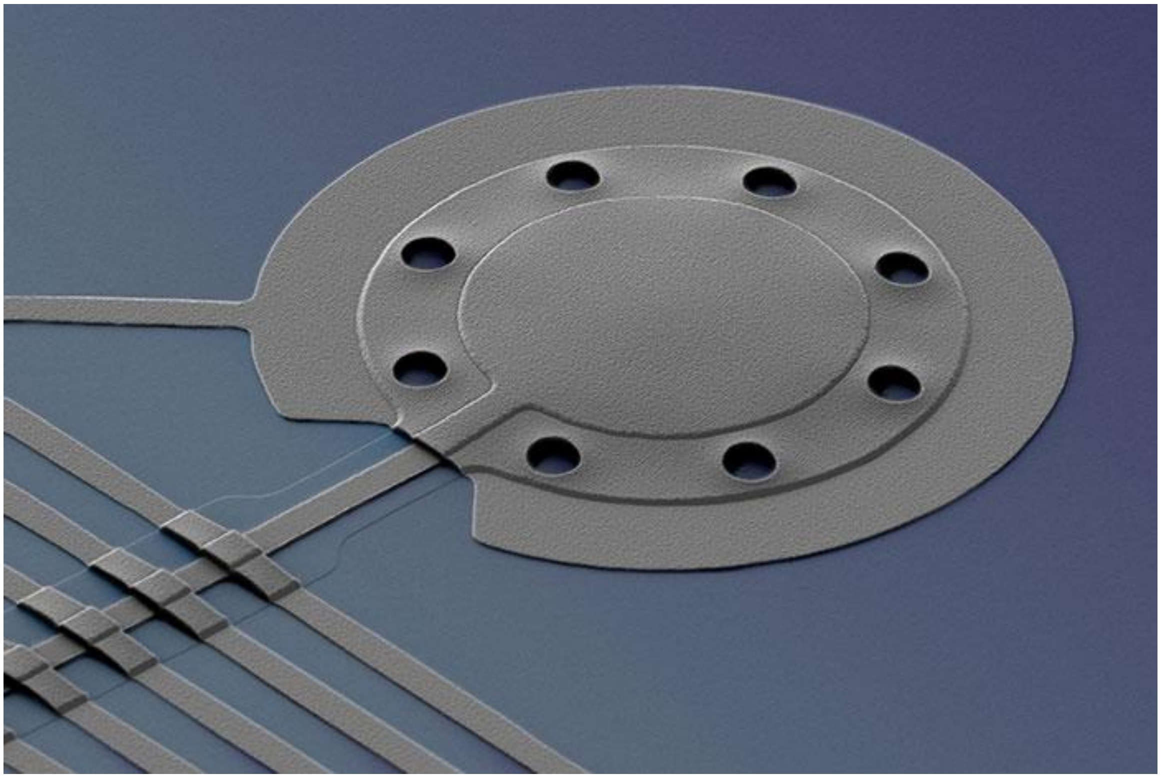
Making a more precise measurement of the position of the ion requires squeezing, which is done by oscillating one of the trapping fields at twice the oscillation frequency of the ion. This has the effect of amplifying the uncertainty in the momentum of the ion whilst shrinking the uncertainty in position.

The team then apply an oscillating "test" field that displaces the position of the ion within the trap. Next, a third oscillating field that is 180° out of phase with the initial squeezing field is applied. This "unsqueezes" the ion and amplifies the displacement caused by the test field. Finally, the amplified displacement is measured by shining light on the ion and observing its fluorescence.

## Repeat for smaller displacements

The result is that the measurement is about 7.3 times more sensitive to small displacements of the ion compared to when squeezing and amplification are not implemented. This allowed the team to measure ion displacements of just 50 pm, which is about 10% of the diameter of a hydrogen atom. Even smaller displacements can be measured by repeating the process several times.

Monitoring the displacement of a trapped ion provides a very sensitive way of measuring acceleration and external fields so the technique could find use in quantum sensors. With further improvements, such sensors could be used to study the effects of gravity on quantum objects.



**Squeezed light plays a quantum drum**

Trapped ions also function as qubits in quantum computers and the squeezing and amplification process could be used to transmit quantum information between ions.

Another possible application is photon recoil spectroscopy, which involves measuring the tiny change in momentum that occurs when an ion absorbs a photon. Such studies could reveal that fundamental constants vary over space or time – thereby pointing to new physics beyond the Standard Model.

The research is described in *Science*. [37]

## The right squeeze for quantum computing

A new theoretical model involves squeezing light to just the right amount to accurately transmit information using subatomic particles. Scientists at Hokkaido University and Kyoto University report that this theoretical approach to quantum computing is 10 billion times more tolerant to errors than current theoretical models. Their method has application in quantum computers that use the diverse properties of subatomic particles to transmit, process and store extremely large amounts of complex information, enabling the modeling of complex chemical processes far better and faster than modern computers.

Computers currently store data by coding it into "bits." A bit can exist in one of two states: zero and one. Scientists have been investigating ways to employ subatomic particles, called "quantum bits," which can exist in more than two states, for the storage and processing of much vaster amounts of information. Quantum bits are the building blocks of quantum computers.

One such approach involves using the inherent properties in photons of light, encoding information as quantum bits into a light beam by digitizing patterns of the electromagnetic field. But the encoded information can be lost from light waves during quantum computation, leading to an accumulation of errors. To reduce information loss, scientists have been experimenting with "squeezing" light. Squeezing is a process that removes tiny quantum-level fluctuations, referred to as noise, from an electromagnetic field. Noise introduces a certain level of uncertainty into the amplitude and phase of the electromagnetic field. Squeezing is thus an efficient tool for the optical implementation of quantum computers, but the current usage is inadequate.

In a paper published in the journal *Physical Review X*, Akihisa Tomita, an applied physicist at Hokkaido University, and his colleagues suggested a novel way to dramatically reduce errors when using this approach. They developed a theoretical model that uses both the properties of quantum bits and the modes of the electromagnetic field in which they exist. The approach involves squeezing light by removing error-prone quantum bits, when quantum bits cluster together.

This model is 10 billion times more tolerant to errors than current experimental methods, meaning that it tolerates up to one error every 10,000 calculations. "The approach is achievable using currently available technologies, and could further advance developments in quantum computing research," says Akihisa Tomita of Hokkaido University. [36]

## New quantum computer design to predict molecule properties

The standard approach to building a quantum computer with majoranas as building blocks is to convert them into qubits. However, a promising application of quantum computing—quantum chemistry—would require these qubits to be converted again into so-called fermions. Physicists from Leiden and Delft propose to turn majoranas directly into fermions, making computations more efficient. Their research was published in *Physical Review Letters*.

Everything in the universe is either matter or energy. Energy consists of only one type of particle: bosons. Matter consists of the other fundamental particle type, fermions. One of the major questions in science is how to predict the properties of matter on the molecular level. Because molecules are governed by quantum mechanics, this field is called quantum chemistry. Efficient simulation of quantum chemistry is a task beyond the reach of classical computers, with quantum computers being a promising alternative. However, the standard equivalent for bits in quantum computing are qubits, which are bosons. Trying to simulate fermions (matter) using bosons (qubits) is inefficient, because of the differences between these particle types.

An exotic proposal for building qubits relies on using so-called Majorana zero modes. These are useful for quantum computation because of their intrinsic robustness against noise. Quantum computation with majoranas previously relied on combining four or six majoranas into a single qubit. But you don't necessarily have to make majoranas into qubits, as originally they are neither fermions nor bosons.

Leiden physicist Tom O'Brien and Piotr Rożek and Anton Akhmerov from Delft have now devised a method to solve quantum chemistry problems by converting majoranas directly into fermions. This approach is a win-win situation. On the one hand, their new scheme requires using fewer majoranas to simulate the same molecule, since you only need two majoranas to make a fermion instead of four or six for a qubit. On the other hand, the proposal avoids the complication of using bosons (qubits) to simulate fermions (matter), and therefore uses a simpler and more direct algorithm. [35]

## Scientists use a photonic quantum simulator to make virtual movies of molecules vibrating

Scientists have shown how an optical chip can simulate the motion of atoms within molecules at the quantum level, which could lead to better ways of creating chemicals for use as pharmaceuticals.

An optical chip uses light to process information, instead of electricity, and can operate as a quantum computing circuit when using single particles of light, known as photons. Data from the chip allows a frame-by-frame reconstruction of atomic motions to create a virtual movie of a molecule's quantum vibrations, which is what lies at the heart of the research published today in *Nature*.

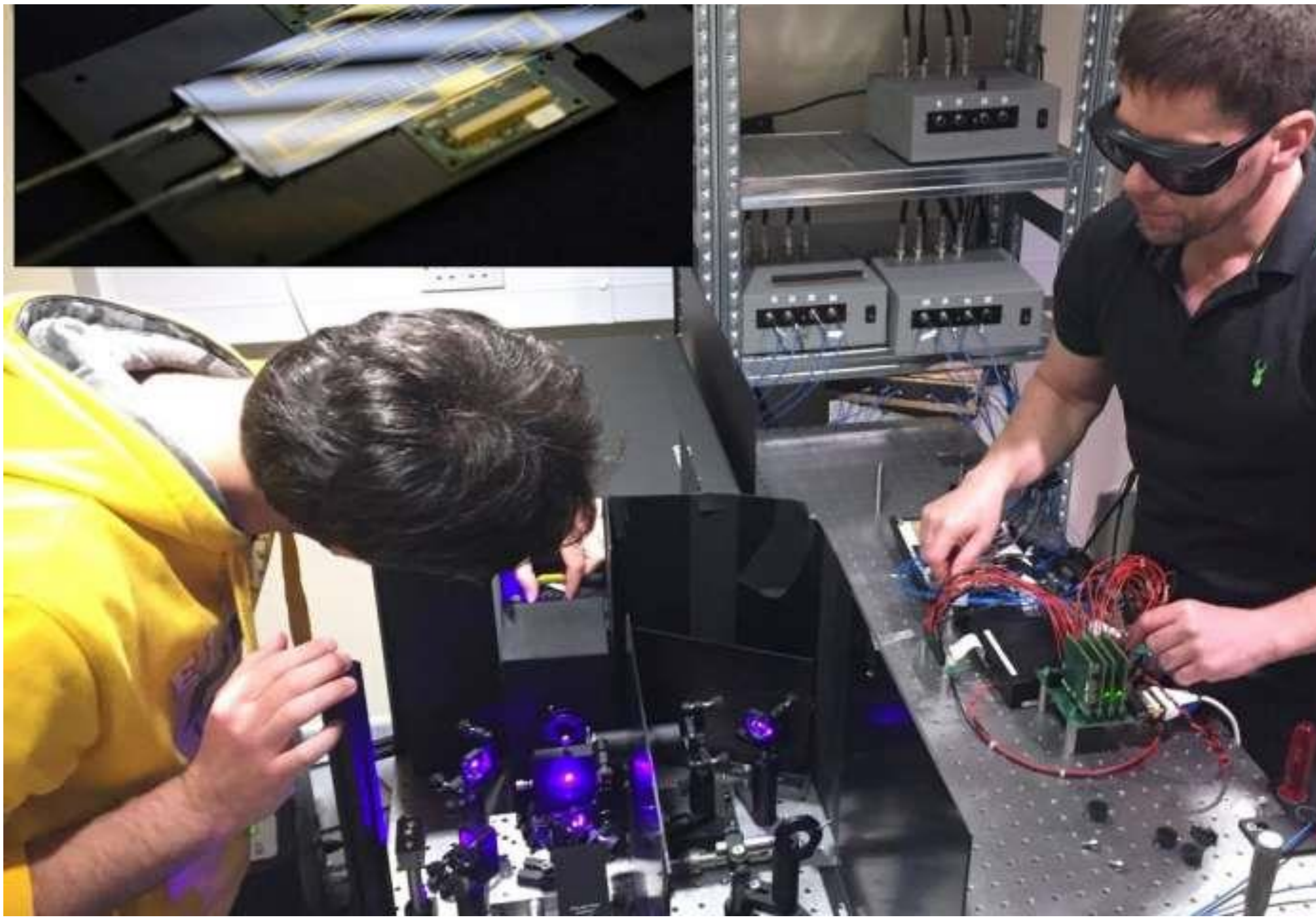
These findings are the result of a collaboration between researchers at the University of Bristol, MIT, IUPUI, Nokia Bell Labs, and NTT. As well as paving the way for more efficient pharmaceutical developments, the research could prompt new methods of molecular modelling for industrial chemists.

When lasers were invented in the 1960s, experimental chemists had the idea of using them to break apart molecules. However, the vibrations within molecules rapidly redistribute the laser energy before the intended molecular bond is broken. Controlling the behaviour of molecules requires an understanding of how they vibrate at the quantum level. But modelling these dynamics requires massive computational power, beyond what we can expect from coming generations of supercomputers.

The Quantum Engineering and Technology Labs at Bristol have pioneered the use of optical chips, controlling single photons of light, as basic circuitry for quantum computers. Quantum computers are expected to be exponentially faster than conventional supercomputers at solving certain problems. Yet constructing a quantum computer is a highly challenging long-term goal.

As reported in *Nature*, the team demonstrated a new route to molecular modelling that could become an early application of photonic quantum technologies. The new methods exploit a similarity between the vibrations of atoms in molecules and photons of light in optical chips.

Bristol physicist Dr. Anthony Laing, who led the project, explained: "We can think of the atoms in molecules as being connected by springs. Across the whole molecule, the connected atoms will collectively vibrate, like a complicated dance routine. At a quantum level, the energy of the dance goes up or down in well-defined levels, as if the beat of the music has moved up or down a notch. Each notch represents a quantum of vibration.



Dr Laing's laboratory where the experiments were performed. Single photons of light are generated using a powerful Ti-Sapphire laser, to pump a series of nonlinear crystals, operated by Ph.D. student and co-author Nicola Maraviglia (left). …more

"Light also comes in quantised packets called photons. Mathematically, a quantum of light is like a quantum of molecular vibration. Using integrated chips, we can control the behaviour of photons very precisely. We can program a photonic chip to mimic the vibrations of a molecule.

"We program the chip, mapping its components to the structure of a particular molecule, say ammonia, then simulate how a particular vibrational pattern evolves over some time interval. By taking many time intervals, we essentially build up a movie of the molecular dynamics."

First author Dr. Chris Sparrow, who was a student on the project, spoke of the simulator's versatility: "The chip can be reprogrammed in a few seconds to simulate different molecules. In these experiments we simulated the dynamics of ammonia and a type of formaldehyde, and other more exotic molecules. We simulated a water molecule reaching thermal equilibrium with its environment, and energy transport in a protein fragment.

"In this type of simulation, because time is a controllable parameter, we can immediately jump to the most interesting points of the movie. Or play the simulation in slow motion. We can even rewind the simulation to understand the origins of a particular vibrational pattern."

Joint first author, Dr. Enrique Martín-Lopéz, now a Senior Researcher with Nokia Bell Labs, added: "We were also able to show how a machine learning algorithm can identify the type of vibration that best breaks apart an ammonia molecule. A key feature of the photonic simulator that enables this is its tracking of energy moving through the molecule, from one localised vibration to another. Developing these quantum simulation techniques further has clear industrial relevance."

The photonic chip used in the experiments was fabricated by Japanese Telecoms company NTT.

Dr. Laing explained the main directions for the future of the research: "Scaling up the simulators to a size where they can provide an advantage over conventional computing methods will likely require error correction or error mitigation techniques. And we want to further develop the sophistication of molecular model that we use as the program for the simulator. Part of this study was to demonstrate techniques that go beyond the standard harmonic approximation of molecular dynamics. We need to push these methods to increase the real-world accuracy of our models.

"This approach to quantum simulation uses analogies between photonics and molecular vibrations as a starting point. This gives us a head start in being able to implement interesting simulations. Building on this, we hope that we can realise quantum simulation and modelling tools that provide a practical advantage in the coming years." [34]

## Largest-ever 3-D quantum chip for boosting analog quantum computing

Chinese scientists Xianmin Jin and his colleagues from Shanghai Jiao Tong University have successfully fabricated the largest-scaled quantum chip and demonstrated the first two-dimensional quantum walks of single photons in real spatial space, which may provide a powerful platform to boost analog quantum computing for quantum supremacy.

Since early last year, IBM, Google, Intel and rivals have competed to set new records on the achieved number of qubits in quantum computer development. However, universal quantum computers are far from feasible until error correction and full connections between the increasing number of qubits can be realized. In contrast, analog quantum computers, or quantum simulators, can be built in a straightforward way to solve practical problems directly without error correction, and potentially beat the computational power of classical computers in the near future.

As a powerful and straightforward approach to analog quantum computing, the quantum walk in a two-dimensional array maps certain computing tasks into the coupling matrix of the quantum paths, and provides efficient solutions to even classically intractable problems. Prominent quantum advantages are achievable as long as the scale of quantum systems goes above a considerably large level. Xianmin Jin et al are now able to fabricate a three-dimensional photonic chip with a scale up to 49×49 nodes using a technique called femtosecond direct writing. It is the largest-scaled chip reported so far that allows for the realization of this two-dimensional quantum walk in real spatial space, and allows researchers to explore many new quantum computing tasks.

This work demonstrates that the dimension and scale of quantum system can be employed as new resources for boosting quantum computing power. During the past two decades, increasing the photon number has posed a challenge, resulting in probabilistic generation of single photons and multiplicative loss. This ingenious alternative method of increasing the external physics dimension and complexity of the quantum evolution system may accelerate future analog quantum computing. [33]

## Engineers invent smart microchip that can self-start and operate when battery runs out

The Internet of Things (IoT), while still in its infancy, is shaping the future of many industries and will also impact daily life in significant ways. One of the key challenges of moving IoT devices from concept to reality is to have long-lasting operation with tightly constrained energy sources, and thus extreme power efficiency. IoT devices such as sensors are often deployed on a massive scale and in places that are usually remote and difficult to service regularly, thus making their self-sufficiency essential.

Currently, batteries in IoT devices are much larger and up to three times more expensive than the single chip they power. Their size is determined by the sensor node lifetime, which directly affects how often they need to be changed. This has an important bearing on maintenance cost and impact on the environment when batteries are disposed. To extend the overall lifetime, the battery is usually recharged slowly by harvesting some limited power from the environment, such as using a solar cell. However, existing IoT devices cannot operate without battery, and small batteries are fully discharged more frequently. Hence, battery miniaturisation often results in highly discontinuous operation of IoT devices, as they stop functioning every time the battery runs out of energy.

To address this technology gap, a team of engineers from the National University of Singapore (NUS) has developed an innovative microchip, named BATLESS, that can continue to operate even when the battery runs out of energy. BATLESS is designed with a novel power management technique that allows it to self-start and continue to function under dim light without any battery assistance, using a very small on-chip solar cell. This research breakthrough substantially reduces the size of batteries required to power IoT sensor nodes, making them 10 times smaller and cheaper to produce. The breakthrough has been presented at the International Solid-State Circuits Conference (ISSCC) 2018 conference in San Francisco, the premier global forum for presenting advances in solid-state circuits and systems-on-a-chip.

The leader of the NUS research team, Associate Professor Massimo Alioto at the NUS Faculty of Engineering, said, "We have demonstrated that batteries used for IoT devices can be shrunk substantially, as they do not always need to be available to maintain continuous operation. Tackling this fundamental problem is a major advancement towards the ultimate vision of IoT sensor nodes without the use of batteries, and will pave the way for a world with a trillion IoT devices."

Battery indifference is the ability for IoT devices to continue operations even when the battery is exhausted. It is achieved by operating in two modes—minimum energy and minimum power. When the battery energy is available, the chip runs in minimum-energy mode to maximise the battery lifetime. However, when the battery is exhausted, the chip switches to the minimum-power mode and operates with very low power consumption of about half a nano-Watt—this is about a billion times lower than the power consumption of a smartphone during a phone call. Power can be provided by a very small on-chip solar cell that is about half a square millimetre in area, or other forms of energy available from the environment, such as vibration or heat.

The chip's ability to switch between minimum energy and minimum power mode translates into aggressive miniaturisation of batteries from centimetres down to a few millimetres. The BATLESS microchip enables the uncommon capability to uninterruptedly sense, process, capture and timestamp events of interest, and for such valuable data to be wirelessly transmitted to the cloud when the battery becomes available again. Despite being in minimum-power mode when battery is not available, the reduced speed of the microchip is still adequate for numerous IoT applications that need to sense parameters that vary slowly in time, including temperature, humidity, light, and pressure. Among many other applications, BATLESS is very well suited for smart buildings, environmental monitoring, energy management, and adaptation of living spaces to occupants' needs.

Assoc Prof Alioto added, "BATLESS is the first example of a new class of chips that are indifferent to battery charge availability. In minimum-power mode, it uses 1,000 to 100,000 times less power, compared to the best existing microcontrollers designed for fixed minimum-energy operation. At the same time, our 16-bit microcontroller can also operate 100,000 times faster than others that have been recently designed for fixed minimum-power operation. In short, the BATLESS microchip covers a very wide range of possible energy, power, and speed trade-offs, as allowed by the flexibility offered through the two different modes."

BATLESS is also equipped with a new power management technique that enables self-starting operations while powered directly by the tiny on-chip solar cell, with no battery assistance. The team demonstrated this at 50-lux indoor light intensity, which is equivalent to the dim light available at twilight, and corresponds to nano-Watts of power. This makes BATLESS indifferent to battery availability, addressing a previously unsolved challenge in battery-less chips.

The NUS Engineering team is now exploring new solutions to build complete battery-indifferent systems that cover the entire signal chain from sensor to wireless communications, thus expanding the current work on microcontrollers and power management. The research team aims to demonstrate a solution that shrinks the battery to millimetre scale, with the long-term goal of completely eliminating the need for it. This will be a major step toward the realisation of the IoT vision worldwide, and also make the planet greener and smarter. [32]

## Researchers develop water-based battery to store solar and wind energy

Stanford researchers have developed a water-based battery that could provide a cheap way to store wind or solar energy generated when the sun is shining and wind is blowing so it can be fed back into the electric grid and be redistributed when demand is high.

The prototype manganese-hydrogen battery, reported today in *Nature Energy*, stands just three inches tall and generates a mere 20 milliwatt hours of electricity, which is on par with the energy levels of LED flashlights one might hang a key ring.

Despite the prototype's diminutive output, the researchers are confident they can take this table-top technology up to an industrial-grade system that could charge and recharge up to 10,000 times, creating a grid-scale battery with a useful lifespan well in excess of a decade.

Yi Cui, a professor of materials science at Stanford and senior author on the paper, said manganese-hydrogen battery technology could be one of the missing pieces in the nation's energy puzzle - a way to store unpredictable wind or solar energy so as to lessen the need to burn reliable but carbon-emitting fossil fuels when the renewable sources aren't available.

"What we've done is thrown a special salt into water, dropped in an electrode, and created a reversible chemical reaction that stores electrons in the form of hydrogen gas," Cui said.

### Clever chemistry

The team that dreamed up the concept and built the prototype was led by Wei Chen, a postdoctoral scholar in Cui's lab. In essence the researchers coaxed a reversible electron-exchange between water and manganese sulfate, a cheap, abundant industrial salt used to make dry cell batteries, fertilizers, paper and other products.

To mimic how a wind or solar source might feed power into the battery, the researchers attached a power source to the prototype. The electrons flowing in reacted with the manganese sulfate dissolved in the water to leave particles of manganese dioxide clinging to the electrodes. Excess electrons bubbled off as hydrogen gas thus storing that energy for future use. Engineers know how to recreate electricity from the energy stored in hydrogen gas so the important next step was to prove was that the water-based battery can be recharged.

The researchers did this by re-attaching their power source to the depleted prototype, this time with the goal of inducing the manganese dioxide particles clinging to the electrode to combine with water, replenishing the manganese sulfate salt. Once this salt was restored, incoming electrons became surplus, and excess power could bubble off as hydrogen gas, in a process that can be repeated again and again and again.

Cui estimated that, given the water-based battery's expected lifespan, it would cost a penny to store enough electricity to power a 100 watt lightbulb for twelve hours.

"We believe this prototype technology will be able to meet Department of Energy (DOE) goals for utility-scale electrical storage practical," Cui said.

The DOE has recommended batteries for grid-scale storage should store and then discharge at least 20 kilowatts of power over a period of an hour, be capable of at least 5,000 recharges, and have a useful lifespan of 10 years or more. To make it practical such a battery system should cost $2,000 or less, or $100 per kilowatt hour.

Former Department of Energy Secretary and Nobel laureate Steven Chu, now a professor at Stanford, has a long-standing interest in encouraging technologies to help the nation transition to renewable energy.

"While the precise materials and design still need development, this prototype demonstrates the type of science and engineering that suggest new ways to achieve low-cost, long-lasting utility-scale batteries," said Chu, who was not a member of research team.

## Shifting away from carbon

According to DOE estimates, about 70 percent of U.S. electricity is generated by coal or natural gas plants, which account for 40 percent of carbon dioxide emissions. Shifting to wind and solar generation is one way to reduce those emissions but it creates new challenge involving the variability of power supply. Most obviously, the sun only shines by day and, sometimes, the wind doesn't blow.

But another less-well understood but import form of variability come from surges of demand on the grid - that network of high-tension wires that distribute electricity over regions and ultimately to homes. On a hot day, when people come home from work and crank up the air conditioning, utilities must have load-balancing strategies to meet peak demand: some way to boost power generation within minutes to avoid brownouts or blackouts that might otherwise bring down the grid.

Today utilities often accomplish this by firing up on-demand or "dispatchable" power plants that may lay idle much of the day, but can come online within minutes - producing quick energy but boosting carbon emissions. Some utilities have developed short-term load balancing that does not rely on fossil-fuel burning plants. The most common and cost effect such strategy is pumped hydroelectric storage: using excess power to send water uphill, then letting it flow back down to generate energy during peak demand. However, hydroelectric storage only works in regions with the water and the space, so to make wind and solar more useful DOE has encouraged high capacity batteries as an alternative.

## High capacity, low cost

Cui said there are several types of rechargeable battery technologies on the market, but it isn't clear which approaches will meet DOE requirements and prove their practicality to the utilities, regulators and other stakeholders who maintain the nation's electrical grid.

For instance, Cui said rechargeable lithium ion batteries, which store the small amounts of energy needed to run phones and laptops, are based on rare materials and are thus too pricey to store power for a neighborhood or city. Cui said grid-scale storage requires a low-cost, high-capacity, rechargeable battery and the manganese-hydrogen process seems promising.

"Other rechargeable battery technologies are easily more than 5 times of that cost over the life time," Cui added.

Chen said novel chemistry, low cost materials and relative simplicity made the manganese-hydrogen battery ideal for low-cost grid-scale deployment.

"The breakthrough we report in *Nature Energy* has the potential to meet DOE's grid-scale criteria," Chen said.

The prototype needs development work to prove itself. For one thing it uses platinum as a catalyst to spur the crucial chemical reactions at the electrode that make the recharge process efficient, and the cost of that component would be prohibitive for large-scale deployment. But Chen said the team is already working on cheaper ways to coax the manganese sulfate and water to perform the reversible electron exchange.

"We have identified catalysts that could bring us below the $100 per kilowatt hour DOE target," he said.

The researchers reported doing 10,000 recharges of the prototypes, which is twice the DOE requirements, but say it will be necessary to test the manganese-hydrogen battery under actual electric grid storage conditions in order to truly assess its lifetime performance and cost.

Cui said he has sought to patent process through the Stanford Office of Technology Licensing, and plans to form a company to commercialize the system.

Yi Cui is also a professor in the Photon Science Directorate at SLAC National Accelerator Laboratory, and a Senior Fellow of the Precourt Institute for Energy, a member of Stanford Bio-X and the Stanford Neurosciences Institute. Additional coauthors include Guodong Li, a visiting scholar in materials science and engineering and now with the Chinese Academy of Sciences; postdoctoral scholars Hongxia Wang, Jiayu Wan, Lei Liao, Guangxu Chen and Jiangyan Wang; visiting scholar Hao Zhang; and graduate students Zheng Liang, Yuzhang Li and Allen Pei. [31]

## A microscopic roundabout for light—team develops a magnet-free optical circulator

Circulators are important components in communication technology. Their unique way of routing light usually requires centimeter-sized magnets, which are difficult to miniaturize for use on optical chips. Researchers at AMOLF and the University of Texas have circumvented this problem with a vibrating glass ring that interacts with light. They thus created a microscale circulator that directionally routes light on an optical chip without using magnets. The researchers published their work in *Nature Communications* on 4 May 2018.

Circulators allow the transmission of information without loss among more than two nodes in a network, which is why they are widely used in optical networks. Circulators have several entrance and exit ports between which they route light in a special way: light entering a particular port is forced to exit in a second port, but light entering that second port exits in a third port, and so on.

"Light propagation is symmetric in nature, which means if light can propagate from A to B, the reverse path is equally possible. We need a trick to break the symmetry," says AMOLF group leader Ewold Verhagen. "Usually this trick is using centimeter-sized magnets to impart directionality and break the symmetric nature of light propagation. Such systems are difficult to miniaturize for use on photonic chips."

Verhagen and his colleagues created circulating behavior using a microscale glass ring resonator with a different trick. They let light in the ring interact with the ring's mechanical vibrations. The researchers used this principle in earlier work to demonstrate one-way optical transmission. "By shining light of a 'control' laser in the ring, light of a different color can excite vibrations through a force known as radiation pressure, but only if it propagates in the same direction as the control light wave," Verhagen explains. "Since light propagates differently through a vibrating structure than through a structure that is standing still, the optical force breaks symmetry in the same way as a magnetic field would."

Animated video of the light circulator Credit: Henk-Jan Boluijt (AMOLF)

## Roundabout for light

Turning the 'one-way street for light' into a useful optical 'roundabout' was not as straightforward as it may seem, as postdoc John Mathew points out: "The challenge is to dictate the particular exit to which light can be routed, such that it always takes the next port."

The researchers found the solution in optical interference. Careful control of the optical paths in the structure ensures that light from each input constructively interferes in exactly the right output. "We demonstrated this circulation in experiments, and showed that it can be actively tuned. The frequency and power of the control laser allow the circulation to be turned on and off and change handedness," says Mathew.

## Information networks

The AMOLF 'roundabout' for light is actually the first magnet-free, on-chip optical circulator. Although the research is fundamental in nature, it has many possible applications. Verhagen: "Devices like this could form building blocks for chips that use light instead of electrons to carry information, as well as for future quantum computers and communication networks. The fact that the circulator can be actively controlled provides additional functionality as the optical circuits can be reconfigured at will." [30]

## Three distinct variants of magnetic domain walls discovered in helimagnet iron germanium (FeGe)

Researchers have discovered three distinct variants of magnetic domain walls in the helimagnet iron germanium (FeGe). Their results have been published in *Nature Physics*. Researcher Dennis Meier, an associate professor at the Norwegian University of Science and Technology (NTNU), says understanding the creation of magnetic fields is key to understanding the significance of the discovery.

An electric current can generate a magnetic field, as in electromagnets. The second source of an electric field is spin, which is the magnetic moment of an atom's elementary particles. The most widely known type of magnetism is ferromagnetism. This type of magnetic order occurs when the magnetic moments of the atoms in a substance are essentially aligned—that is, they point in the same direction and attract or repel other magnetic objects.

With helimagnets, the atoms' magnetic moments arrange themselves in spiral or helical patterns. Iron germanium (FeGe) is a mixture of iron and the metalloid germanium. It has a crystalline structure similar to that found in a diamond, in which the same pattern of atoms repeats itself. In reality, this material is not as uniform as it looks. The crystal may be close to perfect, but the magnetic structure can simultaneously have its own organization.

In other words, an apparently perfect crystalline structure in a solid is divided into separate areas, each with its own special magnetic properties. These magnetic regions are called domains. In ferromagnets, the atoms in each of these domains have magnetic moments pointing in the same direction, but the direction varies between neighboring areas. Helimagnets have domains with spiral patterns instead. The transitions between these areas are called domain walls, which are what Meier and his colleagues are studying.

The international research group discovered three new classes of domain walls in helimagnets. "The special patterns occur because of so-called topological defects. The researchers were lucky to find them," Meier says. "But you have to know when you're lucky."

Their discoveries are completely new to science. Domain walls can have exotic magnetic properties that the regions which they separate don't reveal. The walls, for example, may interact more strongly with an electric current and could possibly be used for data transfer and storage in the future. This discovery may someday provide an alternative to today's computers, which flip the magnetic field and toggle the voltage between one and zero. This method is far more energy intensive than moving topological magnetic structures along so-called racetrack memory.

"The next thing we're going to do is try to influence these new domain walls," says Meier. The researchers will attempt to direct these walls with an electric current—that is, control them. For this project, Meier and his team at the Department of Materials Science and Engineering will collaborate with colleagues from the NTNU's new Center of Excellence QuSpin (Center for Quantum Spintronics). [29]

## Unusual magnetic structure may support next-generation technology

Magnetic materials that form helical structures—coiled shapes comparable to a spiral staircase or the double helix strands of a DNA molecule—occasionally exhibit exotic behavior that could improve information processing in hard drives and other digital devices.

A research team from Colorado State University is using neutrons at the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL) to study one such material, Fe3PO7. Although helical structures are typically formed by magnetic moments that wind around an axis in a set direction, the researchers discovered that Fe3PO7 does not pick a particular direction and allows only short-range helical structures to form. These structures may provide novel technological capabilities.

"Because the direction of the helix is varying in space, it has what we call a partial order, which means there is no set direction for the helical axis to point," said assistant professor Kate Ross, who is also a former chair of ORNL's SNS-HFIR User Group.

By determining Fe3PO7's magnetic structure using the Four-Circle Diffractometer instrument, beamline HB-3A at ORNL's High Flux Isotope Reactor (HFIR), the researchers hope to identify the underlying factors contributing to this unusual helical magnetic structure. Neutrons have their own "spin" (an intrinsic momentum), making them sensitive to magnetism inside materials, which means they are the ideal tool for the task.

The team's small crystal sample is antiferromagnetic, meaning that each spin on the atomic lattice attempts to face in the opposite direction of its neighboring spin. However, Fe3PO7 forms a lattice based on triangular units that makes this arrangement impossible, resulting in an atomic deadlock called "frustration." These key qualities may inform the team's investigation of the unconventional magnetic structure.

"We think there is one exciting possibility that could potentially explain this material's partial helical order and short-range correlations, both of which are unusual to see in a solid-state material," Ross said.

This phenomenon could be caused by twisted regions of magnetization called "skyrmions" that disrupt magnetic spin patterns. According to Ross, these antiferromagnetic, "hedgehog-like" defects could advance the field of spintronics, which involves manipulating electron spin to improve magnetic information storage and other applications.

After analyzing their data, the researchers plan to conduct additional studies focused on the dynamics of Fe3PO7to confirm this scenario.

Ross has studied frustrated magnetism since her undergraduate years, and the subject continues to fascinate and inspire her today. She describes her team as explorers seeking interesting magnetic phases who often arrive at unexpected conclusions.

"That's what really keeps me interested in doing these sorts of projects," she said. "You can head in one direction based on a good idea and then be diverted to learn about something entirely different." [28]

## Invisible magnetic sensors measure magnetic fields without disturbing them

Currently, most of the magnetic sensors used in today's computers, airplanes, cars, and other systems distort the magnetic fields that they are measuring. These distortions can cause major problems for some applications, in particular biomedical techniques, that require highly accurate measurements, and can also cause cross-talk in sensor arrays.

In a new study, researchers have designed "invisible" magnetic sensors—sensors that are magnetically invisible so that they can still detect but do not distort the surrounding magnetic fields. The researchers, Rosa Mach-Batlle, Carles Navau, and Alvaro Sanchez at the Autonomous University of Barcelona, have published a paper on the invisible magnetic sensors in a recent issue of *Applied Physics Letters*.

"This is the first proposal to render a magnetic sensor invisible," Mach-Batlle told *Phys.org*. "The invisibility can even be made exact in some cases, something never achieved before, to our knowledge."

Many magnetic sensors are made of ferromagnetic materials, which have the advantage of enhanced sensor detectability compared to other materials. However, the downside of ferromagnetic materials is that they attract magnetic fields, causing distortions in the same magnetic fields that the sensors are detecting.

The challenging part of making invisible magnetic sensors is to simultaneously cancel these distortions while still allowing the sensors to detect the magnetic fields. Previously, researchers have designed magnetic cloaks for cloaking magnetic objects that make it impossible to magnetically detect them from the outside. However, these cloaks work both ways, so that the cloaked magnetic objects are completely isolated from and unable to detect any external magnetic fields. So a cloaked sensor could no longer function as a sensor.

In the new study, the researchers have proposed a method for making a sensor magnetically invisible while maintaining its ability to sense. Their strategy uses a spherical magnetic shell that cancels out the leading term of the distortion that the sensor creates in response to external magnetic fields. The shell is also designed with tiny "air gaps" that allow a fraction of the external magnetic field to arrive at the sensor. Theoretically, the invisibility can be made perfect under certain conditions—specifically, when the sensor is spherical and the magnetic field is uniform.

According to the researchers' model, the proposed spherical shell must be made of a material with certain properties (in particular, a precise diamagnetic permeability) that do not exist in nature. Nevertheless, the researchers expect that these properties can be emulated with metamaterials made of high-temperature superconductors. In the future, the researchers plan to further explore these possibilities as well as variations on magnetic cloaking.

"We are developing ideas such as exploring cloaking properties for AC fields or incorporating the intriguing concept of negative static permeability for creating novel shapes of magnetic fields," Sanchez said. [27]

## Magnetic materials increase energy density in power transformation

Power transformation. Electrification of vehicles. Creating motors that are efficient. Some of the biggest technologies of the future rest on finding ways to efficiently transform energy. And the backbone that enables the development of these technologies is the field of advanced materials.

At Carnegie Mellon University, Materials Science and Engineering Professor Mike McHenry and his research group are developing metal amorphous nanocomposite materials (MANC), or magnetic materials whose nanocrystals have been grown out of an amorphous matrix to create a two phase magnetic material that exploits both the attractive magnetic inductions of the nanocrystals and the large electrical resistance of a metallic glass. When operated at high frequencies, these MANC materials offer very high energy efficiency, due to their low losses of energy—an essential component for transforming energy.

Different MANC compositions can be applied to various applications but have most recently been adopted in power transformers that will be used to bring renewable energy to the grid. These transformers need magnetic materials to harvest solar or wind energy, then transform it to a power that can be stored and fed to the grid.

Typically, silicon steels used to transform energy are lossy at high frequencies, meaning they lose energy when excited with high frequency alternating current fields. But McHenry's material doesn't suffer from this problem. It is highly efficient and loses little energy, even at frequencies reaching tens of kHz. The lossless nature of the material allows for high power density applications such as power grid inductors and transformers, electric vehicle motors, and even potentially for motors that propel aircraft and rockets in space.

To synthesize these materials, McHenry's team weighs alloy components combining iron, cobalt, and nickel, mixed with glass formers in ratios optimized to achieve desirable magnetic, electrical and mechanical properties. Next, they use a crucible to melt the material and cast the molten metal onto a rotating copper wheel using a technique called planar flow casting. The molten alloy forms a melt pool on the copper alloy casting wheel. The large thermal mass of the wheel quickly extracts heat out of the material, cooling the liquid metal at about 1 million degrees per second. At those solidification rates, atoms do not have time to find positions in a crystalline lattice. The resulting metastable material is a metallic glass—a material whose isotropic structure makes it easy to switch the magnetization without losing energy, perfect for use in high power applications.

"In every one of the projects we work on, we learn something more," said McHenry.

McHenry's lab is strong in this method of synthesis, called rapid solidification, which is part of the synthesis stage of the materials science paradigm (synthesis, structure, properties, and performance). His lab is able to create these materials, or discover the best method for creating these materials, then works with others at national laboratories and industry to scale it up for use in real-world applications.

Currently, McHenry and his team are collaborating with the National Energy Technology Laboratory (NETL), NASA Glenn Research Center, North Carolina State University, and Eaton Corporation on a Department of Energy-funded project to create high-density transformers to bring renewable energy to the power grid. The project, a three-port photovoltaic converter, increases power density and enables the photovoltaic energy source to connect directly to the transformer that connects to the storage device.

"We work on a myriad of geometries," said McHenry. "Our job is to create materials, then hand it off to the people who will use it in their products. It's really the materials that are enabling power and energy applications; everyone is riding the materials' development horse." [26]

## Controlling quantum interactions in a single material

The search and manipulation of novel properties emerging from the quantum nature of matter could lead to next-generation electronics and quantum computers. But finding or designing materials that can host such quantum interactions is a difficult task.

"Harmonizing multiple quantum mechanical properties, which often do not coexist together, and trying to do it by design is a highly complex challenge," said Northwestern University's James Rondinelli.

But Rondinelli and an international team of theoretical and computational researchers have done just that. Not only have they demonstrated that multiple quantum interactions can coexist in a single material, the team also discovered how an electric field can be used to control these interactions to tune the material's properties.

This breakthrough could enable ultrafast, low-power electronics and quantum computers that operate incredibly faster than current models in the areas of data acquisition, processing, and exchange.

Supported by the US Army Research Office, National Science Foundation of China, German Research Foundation, and China's National Science Fund for Distinguished Young Scholars, the research was published online today in the journal *Nature Communications*. James Rondinelli, the Morris E. Fine Junior Professor in Materials and Manufacturing in Northwestern's McCormick School of Engineering, and Cesare Franchini, professor of quantum materials modeling at the University of Vienna, are the paper's co-corresponding authors. Jiangang He, a postdoctoral fellow at Northwestern, and Franchini served as the paper's co-first authors.

Quantum mechanical interactions govern the capability of and speed with which electrons can move through a material. This determines whether a material is a conductor or insulator. It also controls whether or not the material exhibits ferroelectricity, or shows an electrical polarization.

"The possibility of accessing multiple order phases, which rely on different quantum-mechanical interactions in the same material, is a challenging fundamental issue and imperative for delivering on the promises that quantum information sciences can offer," Franchini said.

Using computational simulations performed at the Vienna Scientific Cluster, the team discovered coexisting quantum-mechanical interactions in the compound silver-bismuth-oxide. Bismuth, a post-transition metal, enables the spin of the electron to interact with its own motion—a feature that has no analogy in classical physics. It also does not exhibit inversion symmetry, suggesting that ferroelectricity should exist when the material is an electrical insulator. By applying an electric field to the material, researchers were able to control whether the electron spins were coupled in pairs (exhibiting Weyl-fermions) or separated (exhibiting Rashba-splitting) as well as whether the system is electrically conductive or not.

"This is the first real case of a topological quantum transition from a ferroelectric insulator to a non-ferroelectric semi-metal," Franchini said. "This is like awakening a different kind of quantum interactions that are quietly sleeping in the same house without knowing each other." [25]

## Scientists discover chiral phonons in a 2-D semiconductor crystal

A research team from the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) has found the first evidence that a shaking motion in the structure of an atomically thin (2-D) material possesses a naturally occurring circular rotation.

This rotation could become the building block for a new form of information technology, and for the design of molecular-scale rotors to drive microscopic motors and machines.

The monolayer material, tungsten diselenide ($WSe_2$), is already well-known for its unusual ability to sustain special electronic properties that are far more fleeting in other materials.

It is considered a promising candidate for a sought-after form of data storage known as valleytronics, for example, in which the momentum and wavelike motion of electrons in a material can be sorted into opposite "valleys" in a material's electronic structure, with each of these valleys representing the ones and zeroes in conventional binary data.

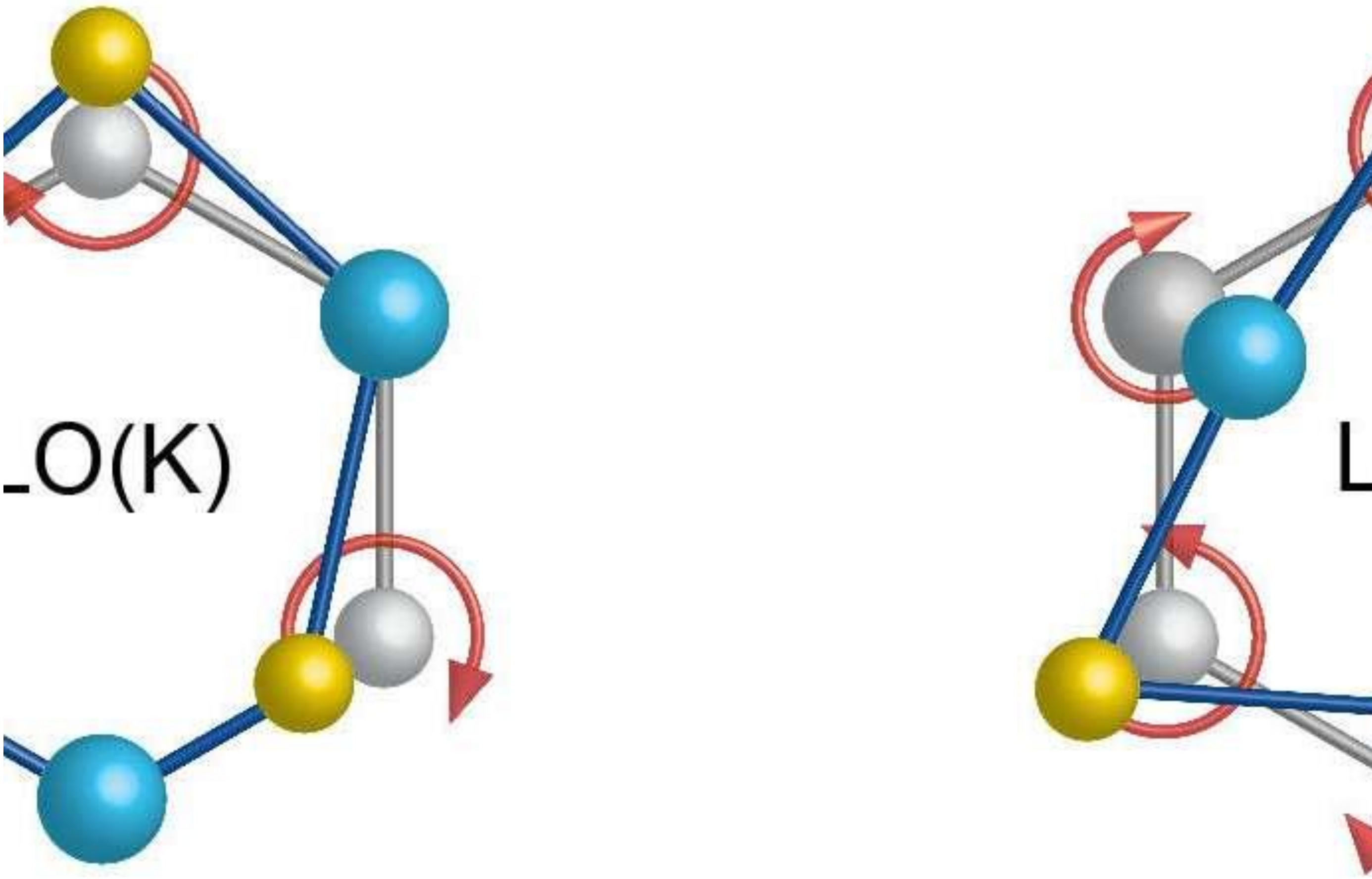
Modern electronics typically rely on manipulations of the charge of electrons to carry and store information, though as electronics are increasingly miniaturized they are more subject to problems associated with heat buildup and electric leaks.

The latest study, published online this week in the journal *Science*, provides a possible path to overcome these issues. It reports that some of the material's phonons, a term describing collective vibrations in atomic crystals, are naturally rotating in a certain direction.

This property is known as chirality – similar to a person's handedness where the left and right hand are a mirror image of each other but not identical. Controlling the direction of this rotation would provide a stable mechanism to carry and store information.

"Phonons in solids are usually regarded as the collective linear motion of atoms," said Xiang Zhang, the corresponding author of the study and senior scientist of the Materials Science Division at

Lawrence Berkeley National Laboratory and professor at UC Berkeley. "Our experiment discovered a new type of so-called chiral phonons where atoms move in circles in an atomic monolayer crystal of tungsten diselenide."




This diagram maps out atomic motion in separate phonon modes. At left ("LO" represents a longitudinal optical mode), selenium atoms exhibit a clockwise rotation while tungsten atoms stand still. At right ("LA" represents a longitudinal …more

Hanyu Zhu, the lead author of the study and a postdoctoral researcher at Zhang's group, said, "One of the biggest advantage of chiral phonon is that the rotation is locked with the particle's momentum and not easily disturbed."

In the phonon mode studied, the selenium atoms appear to collectively rotate in a clockwise direction, while the tungsten atoms showed no motion. Researchers prepared a "sandwich" with four sheets of centimeter-sized monolayer WSe2 samples placed between thin sapphire crystals. They synced ultrafast lasers to record the time-dependent motions.

The two laser sources converged on a spot on the samples measuring just 70 millionths of a meter in diameter. One of the lasers was precisely switched between two different tuning modes to sense the difference of left and right chiral phonon activity.

A so-called pump laser produced visible, red-light pulses that excited the samples, and a probe laser produced mid-infrared pulses that followed the first pump pulse within one trillionth of a second. About one mid-infrared photon in every 100 million is absorbed by $WSe_2$ and converted to a chiral phonon.

The researchers then captured the high-energy luminescence from the sample, a signature of this rare absorption event. Through this technique, known as transient infrared spectroscopy, researchers not only confirmed the existence of a chiral phonon but also accurately obtained its rotational frequency.

So far, the process only produces a small number of chiral phonons. A next step in the research will be to generate larger numbers of rotating phonons, and to learn whether vigorous agitations in the crystal can be used to flip the spin of electrons or to significantly alter the valley properties of the material. Spin is an inherent property of an electron that can be thought of as its compass needle – if it could be flipped to point either north or south it could be used to convey information in a new form of electronics called spintronics.

"The potential phonon-based control of electrons and spins for device applications is very exciting and within reach," Zhu said. "We already proved that phonons are capable of switching the electronic valley. In addition, this work allows the possibility of using the rotating atoms as little magnets to guide the spin orientation."

The chiral properties found in the study likely exist across a wide range of 2-D materials based on a similar patterning in their atomic structure, Zhu also noted, adding that the study could guide theoretical investigations of electron-phonon interactions and the design of materials to enhance phonon-based effects.

"The same principle works in all 2-D periodic structures with three-fold symmetry and inversion asymmetry" Zhu said. "The same principle covers a huge family of natural materials, and there are almost infinite possibilities for creating rotors at the molecular scale." [24]

## New exotic phenomena seen in photonic crystals

Topological effects, such as those found in crystals whose surfaces conduct electricity while their bulk does not, have been an exciting topic of physics research in recent years and were the subject of the 2016 Nobel Prize in physics. Now, a team of researchers at MIT and elsewhere has found novel topological phenomena in a different class of systems—open systems, where energy or material can enter or be emitted, as opposed to closed systems with no such exchange with the outside.

This could open up some new realms of basic physics research, the team says, and might ultimately lead to new kinds of lasers and other technologies.

The results are being reported this week in the journal *Science*, in a paper by recent MIT graduate Hengyun "Harry" Zhou, MIT visiting scholar Chao Peng (a professor at Peking University), MIT graduate student Yoseob Yoon, recent MIT graduates Bo Zhen and Chia Wei Hsu, MIT Professor Marin Soljačić, the Francis Wright Davis Professor of Physics John Joannopoulos, the Haslam and Dewey Professor of Chemistry Keith Nelson, and the Lawrence C. and Sarah W. Biedenharn Career Development Assistant Professor Liang Fu.

In most research in the field of topological physical effects, Soljačić says, so-called "open" systems—in physics terms, these are known as non-Hermitian systems—were not studied much in experimental work. The complexities involved in measuring or analyzing phenomena in which energy or matter can be added or lost through radiation generally make these systems more difficult to study and analyze in a controlled fashion.

But in this work, the team used a method that made these open systems accessible, and "we found interesting topological properties in these non-Hermitian systems," Zhou says. In particular, they found two specific kinds of effects that are distinctive topological signatures of non-Hermitian systems. One of these is a kind of band feature they refer to as a bulk Fermi arc, and the other is an unusual kind of changing polarization, or orientation of light waves, emitted by the photonic crystal used for the study.

Photonic crystals are materials in which billions of very precisely shaped and oriented tiny holes are made, causing light to interact in unusual ways with the material. Such crystals have been actively studied for the exotic interactions they induce between light and matter, which hold the potential for new kinds of light-based computing systems or light-emitting devices. But while much of this research has been done using closed, Hermitian systems, most of the potential real-world applications involve open systems, so the new observations made by this team could open up whole new areas of research, the researchers say.

Fermi arcs, one of the unique phenomena the team found, defy the common intuition that energy contours are necessarily closed curves. They have been observed before in closed systems, but in those systems they always form on the two-dimensional surfaces of a three-dimensional system. In the new work, for the first time, the researchers found a Fermi arc that resides in the bulk of a system. This bulk Fermi arc connects two points in the emission directions, which are known as exceptional points—another characteristic of open topological systems.

The other phenomenon they observed consists of a field of light in which the polarization changes according to the emission direction, gradually forming a half-twist as one follows the direction along a loop and returns back to the starting point. "As you go around this crystal, the polarization of the light actually flips," Zhou says.

This half-twist is analogous to a Möbius strip, he explains, in which a strip of paper is twisted a half-turn before connecting it to its other end, creating a band that has only one side. This Möbius-like twist in light polarization, Zhen says, could in theory lead to new ways of increasing the amount of data that could be sent through fiber-optic links.

The new work is "mostly of scientific interest, rather than technological," Soljačić says. Zhen adds that "now we have this very interesting technique to probe the properties of non-Hermitian systems." But there is also a possibility that the work may ultimately lead to new devices, including new kinds of lasers or light-emitting devices, they say.

The new findings were made possible by earlier research by many of the same team members, in which they found a way to use light scattered from a photonic crystal to produce direct images that reveal the energy contours of the material, rather than having to calculate those contours indirectly.

"We had a hunch" that such half-twist behavior was possible and could be "quite interesting," Soljačić says, but actually finding it required "quite a bit of searching to figure out, how do we make it happen?"

"Perhaps the most ingenious aspect of this work is that the authors use the fact that their system must necessarily lose photons, which is usually an obstacle and annoyance, to access new topological physics," says Mikael Rechtsman, an assistant professor of physics at Pennsylvania State University who was not involved in this work. "Without the loss … this would have required highly complex 3-D fabrication methods that likely would not have been possible." In other words, he says, the technique they developed "gave them access to 2-D physics that would have been conventionally thought impossible." [23]

## Photonic crystals reveal their internal characteristics with new method

A new technique developed by MIT researchers reveals the inner details of photonic crystals, synthetic materials whose exotic optical properties are the subject of widespread research.

Photonic crystals are generally made by drilling millions of closely spaced, minuscule holes in a slab of transparent material, using variations of microchip-fabrication methods. Depending on the exact orientation, size, and spacing of these holes, these materials can exhibit a variety of peculiar optical properties, including "superlensing," which allows for magnification that pushes beyond the normal theoretical limits, and "negative refraction," in which light is bent in a direction opposite to its path through normal transparent materials.

But to understand exactly how light of various colors and from various directions moves through photonic crystals requires extremely complex calculations. Researchers often use highly simplified approaches; for example they may only calculate the behavior of light along a single direction or for a single color.

Instead, the new technique makes the full range of information directly visible. Researchers can use a straightforward laboratory setup to display the information—a pattern of so-called "iso-frequency contours"—in a graphical form that can be simply photographed and examined, in many cases eliminating the need for calculations. The method is described this week in the journal Science Advances, in a paper by MIT postdoc Bo Zhen, recent Wellesley College graduate and MIT affiliate Emma Regan, MIT professors of physics Marin Soljacic and John Joannopoulos, and four others.

The discovery of this new technique, Zhen explains, came about by looking closely at a phenomenon that the researchers had noticed and even made use of for years, but whose origins they hadn't previously understood. Patterns of scattered light seemed to fan out from samples of photonic materials when the samples were illuminated by laser light. The scattering was surprising, since the underlying crystalline structure was fabricated to be almost perfect in these materials.

"When we would try to do a lasing measurement, we would always see this pattern," Zhen says. "We saw this shape, but we didn't know what was happening." But it did help them to get their experimental setup properly aligned, because the scattered light pattern would appear as soon as the laser beam was properly lined up with the crystal. Upon careful analysis, they realized the scattering patterns were generated by tiny defects in the crystal—holes that were not perfectly round in shape or that were slightly tapered from one end to the other.

"There is fabrication disorder even in the best samples that can be made," Regan says. "People think that the scattering would be very weak, because the sample is nearly perfect," but it turns out that at certain angles and frequencies, the light scatters very strongly; as much as 50 percent of the incoming light can be scattered. By illuminating the sample in turn with a sequence of different colors, it is possible to build up a full display of the relative paths light beams take, all across the visible spectrum. The scattered light produces a direct view of the iso-frequency contours—a sort of topographic map of the way light beams of different colors bend as they pass through the photonic crystal.

"This is a very beautiful, very direct way to observe the iso-frequency contours," Soljacic says. "You just shine light at the sample, with the right direction and frequency," and what comes out is a direct image of the needed information, he says.

The finding could potentially be useful for a number of different applications, the team says. For example, it could lead to a way of making large, transparent display screens, where most light would pass straight through as if through a window, but light of specific frequencies would be scattered to produce a clear image on the screen. Or, the method could be used to make private displays that would only be visible to the person directly in front of the screen.

Because it relies on imperfections in the fabrication of the crystal, this method could also be used as a quality-control measure for manufacturing of such materials; the images provide an indication of not only the total amount of imperfections, but also their specific nature—that is, whether the dominant disorder in the sample comes from noncircular holes or etches that aren't straight—so that the process can be tuned and improved.

The team also included researchers at MIT Research Laboratory of Electronics, including Yuichi Igarashi (now at NEC Corporation in Japan), Ido Kaminer, Chia Wei Hsu (now at Yale University), and

Yichen Shen. The work was supported by the Army Research Office through the Institute for Soldier Nanotechnologies at MIT, and by the U.S. Department of Energy through S3TEC, an Energy Frontier Center. [22]

## New tabletop technique probes outermost electrons of atoms deep inside solids

It may be unwise to judge a book by its cover, but you can tell a lot about a material from the outermost electrons in its atoms.

"These outermost electrons, known as valence electrons, are the most important players in forming chemical bonds and actually define almost every property of a solid – electrical, thermal, conductive," said Shambhu Ghimire, an associate staff scientist at the Department of Energy's SLAC National Accelerator Laboratory.

Now Ghimire and two colleagues at the Stanford PULSE Institute have invented a new way to probe the valence electrons of atoms deep inside a crystalline solid.

In a report today in Nature Physics, they describe using laser light to excite some of the valence electrons, steer them around inside the crystal and bounce them off other atoms. This produces high-energy bursts of light that are invisible to our eyes, but carry clues to the material's atomic structure and function.

"This will change the world of imaging the inside of crystalline solids," Ghimire said, "much as scanning tunneling microscopy, or STM, changed the atomic-scale imaging of surfaces."

### A New Way to Look at Atoms in Solids

Invented in the early 1980s, STM was a revolutionary method that allowed scientists to make the first images of individual atoms and their bonds. It was honored with the 1986 Nobel Prize in physics.

But STM senses valence electrons from only the top two or three layers of atoms in a material. A flow of those electrons into the instrument's tip creates a current that allows it to measure the distance between the tip and the surface, tracing the bumps where atoms poke up and the valleys between them. This creates an image of the atoms and yields information about the bonds that hold them together.

Now the new technique will give scientists the same level of access to the valence electrons deep inside the solid.

The experiments, carried out in a SLAC laser lab by PULSE postdoctoral researcher Yong Sing You, involved crystals of magnesium oxide or magnesia, a common mineral used to make cement, preserve library books and clean up contaminated soil, among a host of other things.

These crystals also have the ability to shift incoming laser light to much shorter wavelengths and higher energies – much as pressing down on a guitar string produces a higher note – through a process called high harmonic generation, or HHG.

### Steering Electrons to Generate Light

In this case, the scientists carefully adjusted the incoming infrared laser beam so it would excite valence electrons in the crystal's oxygen atoms. Those electrons oscillated, like vibrating guitar strings, and generated light of much shorter wavelengths – in the extreme ultraviolet range – through HHG.

But when they adjusted the polarization of the laser beam to steer the excited electrons along different trajectories within the crystal, they discovered that HHG only took place when an electron hit a neighboring atom, and was most efficient when it hit the atom dead center. Further, the wavelength of the harmonically generated light coming out – which was 13 to 21 times shorter than the light that went in – revealed the density of the neighboring atom's valence electrons, the size of the atom and even whether it was an atom of oxygen or magnesium.

"It's difficult to home in on the valence electrons with current methods of measuring electron charge density, which typically use X-ray or electron diffraction," said study co-author David Reis, an associate professor at SLAC and Stanford and deputy director of PULSE. "So demonstrating that we can do that with atomic-scale sensitivity in a tabletop laser experiment is an important milestone."

Alan Fry, division director for laser science and technology at SLAC's Linac Coherent Light Source Xray laser, was not involved in the experiment but offered kudos "to the team that developed this technique and who continue to do exciting and interesting research with it."

While this approach may be limited to materials that can generate light through HHG, he said, "it can still tell you a lot about the electronic structure inside those solids, and in principle could give us a better understanding of other materials that don't have same response. Understanding simple systems like this builds a foundation for understanding more complex systems." [21]

## X-ray laser glimpses how electrons dance with atomic nuclei in materials

From hard to malleable, from transparent to opaque, from channeling electricity to blocking it: Materials come in all types. A number of their intriguing properties originate in the way a material's electrons "dance" with its lattice of atomic nuclei, which is also in constant motion due to vibrations known as phonons.

This coupling between electrons and phonons determines how efficiently solar cells convert sunlight into electricity. It also plays key roles in superconductors that transfer electricity without losses, topological insulators that conduct electricity only on their surfaces, materials that drastically change their electrical resistance when exposed to a magnetic field, and more.

At the Department of Energy's SLAC National Accelerator Laboratory, scientists can study these coupled motions in unprecedented detail with the world's most powerful X-ray laser, the Linac Coherent Light Source (LCLS). LCLS is a DOE Office of Science User Facility.

"It has been a long-standing goal to understand, initiate and control these unusual behaviors," says LCLS Director Mike Dunne. "With LCLS we are now able to see what happens in these materials and to model complex electron-phonon interactions. This ability is central to the lab's mission of developing new materials for next-generation electronics and energy solutions."

LCLS works like an extraordinary strobe light: Its ultrabright X-rays take snapshots of materials with atomic resolution and capture motions as fast as a few femtoseconds, or millionths of a billionth of a second. For comparison, one femtosecond is to a second what seven minutes is to the age of the universe.

Two recent studies made use of these capabilities to study electron-phonon interactions in lead telluride, a material that excels at converting heat into electricity, and chromium, which at low temperatures has peculiar properties similar to those of high-temperature superconductors.

## Turning Heat into Electricity and Vice Versa

Lead telluride, a compound of the chemical elements lead and tellurium, is of interest because it is a good thermoelectric: It generates an electrical voltage when two opposite sides of the material have different temperatures.

"This property is used to power NASA space missions like the Mars rover Curiosity and to convert waste heat into electricity in high-end cars," says Mariano Trigo, a staff scientist at the Stanford PULSE Institute and the Stanford Institute for Materials and Energy Sciences (SIMES), both joint institutes of Stanford University and SLAC. "The effect also works in the opposite direction: An electrical voltage applied across the material creates a temperature difference, which can be exploited in thermoelectric cooling devices."

Mason Jiang, a recent graduate student at Stanford, PULSE and SIMES, says, "Lead telluride is exceptionally good at this. It has two important qualities: It's a bad thermal conductor, so it keeps heat from flowing from one side to the other, and it's also a good electrical conductor, so it can turn the temperature difference into an electric current. The coupling between lattice vibrations, caused by heat, and electron motions is therefore very important in this system. With our study at LCLS, we wanted to understand what's naturally going on in this material."

In their experiment, the researchers excited electrons in a lead telluride sample with a brief pulse of infrared laser light, and then used LCLS's X-rays to determine how this burst of energy stimulated lattice vibrations.

"Lead telluride sits at the precipice of a coupled electronic and structural transformation," says principal investigator David Reis from PULSE, SIMES and Stanford.

"It has a tendency to distort without fully transforming – an instability that is thought to play an important role in its thermoelectric behavior.  With our method we can study the forces involved and literally watch them change in response to the infrared laser pulse."

The scientists found that the light pulse excites particular electronic states that are responsible for this instability through electron-phonon coupling. The excited electrons stabilize the material by weakening certain long-range forces that were previously associated with the material's low thermal conductivity.

"The light pulse actually walks the material back from the brink of instability, making it a worse thermoelectric," Reis says. "This implies that the reverse is also true – that stronger long-range forces lead to better thermoelectric behavior."

The researchers hope their results, published July 22 in Nature Communications, will help them find other thermoelectric materials that are more abundant and less toxic than lead telluride.

## Controlling Materials by Stimulating Charged Waves

The second study looked at charge density waves – alternating areas of high and low electron density across the nuclear lattice – that occur in materials that abruptly change their behavior at a certain threshold. This includes transitions from insulator to conductor, normal conductor to superconductor, and from one magnetic state to another.

These waves don't actually travel through the material; they are stationary, like icy waves near the shoreline of a frozen lake.

"Charge density waves have been observed in a number of interesting materials, and establishing their connection to material properties is a very hot research topic," says Andrej Singer, a postdoctoral fellow in Oleg Shpyrko's lab at the University of California, San Diego. "We've now shown that there is a way to enhance charge density waves in crystals of chromium using laser light, and this method could potentially also be used to tweak the properties of other materials."

This could mean, for example, that scientists might be able to switch a material from a normal conductor to a superconductor with a single flash of light. Singer and his colleagues reported their results on July 25 in Physical Review Letters.

The research team used the chemical element chromium as a simple model system to study charge density waves, which form when the crystal is cooled to about minus 280 degrees Fahrenheit. They stimulated the chilled crystal with pulses of optical laser light and then used LCLS X-ray pulses to observe how this stimulation changed the amplitude, or height, of the charge density waves.

"We found that the amplitude increased by up to 30 percent immediately after the laser pulse," Singer says. "The amplitude then oscillated, becoming smaller and larger over a period of 450 femtoseconds, and it kept going when we kept hitting the sample with laser pulses. LCLS provides unique opportunities to study such process because it allows us to take ultrafast movies of the related structural changes in the lattice."

Based on their results, the researchers suggested a mechanism for the amplitude enhancement: The light pulse interrupts the electron-phonon interactions in the material, causing the lattice to vibrate. Shortly after the pulse, these interactions form again, which boosts the amplitude of the vibrations, like a pendulum that swings farther out when it receives an extra push.

## A Bright Future for Studies of the Electron-Phonon Dance

Studies like these have a high priority in solid-state physics and materials science because they could pave the way for new materials and provide new ways to control material properties.

With its 120 ultrabright X-ray pulses per second, LCLS reveals the electron-phonon dance with unprecedented detail. More breakthroughs in the field are on the horizon with LCLS-II – a nextgeneration X-ray laser under construction at SLAC that will fire up to a million X-ray flashes per second and will be 10,000 times brighter than LCLS.

"LCLS-II will drastically increase our chances of capturing these processes," Dunne says. "Since it will also reveal subtle electron-phonon signals with much higher resolution, we'll be able to study these interactions in much greater detail than we can now." [20]

## A 'nonlinear' effect that seemingly turns materials transparent is seen for the first time in X-rays at SLAC's LCLS

Imagine getting a medical X-ray that comes out blank – as if your bones had vanished. That's what happened when scientists cranked up the intensity of the world's first X-ray laser, at the Department of Energy's SLAC National Accelerator Laboratory, to get a better look at a sample they were studying: The X-rays seemed to go right through it as if it were not there.

This result was so weird that the leader of the experiment, SLAC Professor Joachim Stöhr, devoted the next three years to developing a theory that explains why it happened. Now his team has published a paper in Physical Review Letters describing the 2012 experiment for the first time.

What they saw was a so-called nonlinear effect where more than one photon, or particle of X-ray light, enters a sample at the same time, and they team up to cause unexpected things to happen.

"In this case, the X-rays wiggled electrons in the sample and made them emit a new beam of X-rays that was identical to the one that went in," said Stöhr, who is an investigator with the Stanford Institute for Materials and Energy Sciences at SLAC. "It continued along the same path and hit a detector. So from the outside, it looked like a single beam went straight through and the sample was completely transparent."

This effect, called "stimulated scattering," had never been seen in X-rays before. In fact, it took an extremely intense beam from SLAC's Linac Coherent Light Source (LCLS), which is a billion times brighter than any X-ray source before it, to make this happen.

### A Milestone in Understanding How Light Interacts with Matter

The observation is a milestone in the quest to understand how light interacts with matter, Stöhr said.

"What will we do with it? I think we're just starting to learn. This is a new phenomenon and I don't want to speculate," he said. "But it opens the door to controlling the electrons that are closest to the core of atoms – boosting them into higher orbitals, and driving them back down in a very controlled manner, and doing this over and over again."

Nonlinear optical effects are nothing new. They were discovered in the1960s with the invention of the laser – the first source of light so bright that it could send more than one photon into a sample at a time, triggering responses that seemed all out of proportion to the amount of light energy going in. Scientists use these effects to shift laser light to much higher energies and focus optical microscopes on much smaller objects than anyone had thought possible.

The 2009 opening of LCLS as a DOE Office of Science User Facility introduced another fundamentally new tool, the X-ray free-electron laser, and scientists have spent a lot of time since then figuring out exactly what it can do. For instance, a SLAC-led team recently published the first report of nonlinear effects produced by its brilliant pulses.

"The X-ray laser is really a quantum leap, the equivalent of going from a light bulb to an optical laser," Stöhr said. "So it's not just that you have more X-rays. The interaction of the X-rays with the sample is very different, and there are effects you could never see at other types of X-ray light sources."

## A Most Puzzling Result

Stöhr stumbled on this latest discovery by accident. Then director of LCLS, he was working with Andreas Scherz, a SLAC staff scientist, who is now with the soon-to-open European XFEL in Hamburg, Germany, and Stanford graduate student Benny Wu to look at the fine structure of a common magnetic material used in data storage.

To enhance the contrast of their image, they tuned the LCLS beam to a wavelength that would resonate with cobalt atoms in the sample and amplify the signal in their detector. The initial results looked great. So they turned up the intensity of the laser beam in the hope of making the images even sharper.

That's when the speckled pattern they'd been seeing in their detector went blank, as if the sample had disappeared.

"We thought maybe we had missed the sample, so we checked the alignment and tried again," Stöhr said. "But it kept happening. We knew this was strange – that there was something here that needed to be understood."

Stöhr is an experimentalist, not a theorist, but he was determined to find answers. He and Scherz dove deeply into the scientific literature. Meanwhile Wu finished his PhD thesis, which described the experiment and its unexpected result, and went on to a job in industry. But the team held off on publishing their experimental results in a scientific journal until they could explain what happened. Stöhr and Scherz published their explanation last fall in Physical Review Letters.

"We are developing a whole new field of nonlinear X-ray science, and our study is just one building block in this field," Stöhr said. "We are basically opening Pandora's box, learning about all the different nonlinear effects, and eventually some of those will turn out to be more important than others." [19]

# Researchers use quantum dots to manipulate light

Leiden physicists have manipulated light with large artificial atoms, so-called quantum dots. Before, this has only been accomplished with actual atoms. It is an important step toward light-based quantum technology. The study was published on August 30th in Nature Communications.

When you point a laser pointer at the screen during a presentation, an immense number of light particles races through the air at a billion kilometers per hour. They don't travel in a continuous flow, but in packages containing varying numbers of particles. Sometimes as many as four so-called photons pass by, and other times none at all. You won't notice this during your presentation, but for light-based quantum technology, it is crucial that scientists have control over the number of photons per package.

### Quantum dots

In theory, you can manipulate photons with real individual atoms, but because of their small size, it is extremely hard to work with them. Now, Leiden physicists have discovered that the same principle goes for large artificial atoms—so-called quantum dots—that are much easier to handle. In fact, they managed to filter light beams with one photon per package out of a laser. "Another big advantage of quantum dots is that the system already works within nanoseconds," says first author Henk Snijders. "With atomic systems, you need microseconds, so a thousand times longer. This way, we can manipulate photons much faster."

### Quantum cryptography

The ultimate goal for the research group led by Prof. Dirk Bouwmeester is to entangle many photons using quantum dots. This is essential, for example, in techniques like quantum cryptography. Snijders: "This research shows that we are already able to manipulate individual photons with our system. And the beauty is that in principle, we don't need large experimental setups. We can just integrate our quantum dots in small microchips." [18]

## 'Artificial atom' created in graphene

In a tiny quantum prison, electrons behave quite differently as compared to their counterparts in free space. They can only occupy discrete energy levels, much like the electrons in an atom - for this reason, such electron prisons are often called "artificial atoms". Artificial atoms may also feature properties beyond those of conventional ones, with the potential for many applications for example in quantum computing. Such additional properties have now been shown for artificial atoms in the carbon material graphene. The results have been published in the journal Nano Letters, the project was a collaboration of scientists from TU Wien (Vienna, Austria), RWTH Aachen (Germany) and the University of Manchester (GB).

### Building Artificial Atoms

"Artificial atoms open up new, exciting possibilities, because we can directly tune their properties", says Professor Joachim Burgdörfer (TU Wien, Vienna). In semiconductor materials such as gallium arsenide, trapping electrons in tiny confinements has already been shown to be possible. These structures are often referred to as "quantum dots". Just like in an atom, where the electrons can only circle the nucleus on certain orbits, electrons in these quantum dots are forced into discrete quantum states.

Even more interesting possibilities are opened up by using graphene, a material consisting of a single layer of carbon atoms, which has attracted a lot of attention in the last few years. "In most materials, electrons may occupy two different quantum states at a given energy. The high symmetry of the graphene lattice allows for four different quantum states. This opens up new pathways for quantum information processing and storage" explains Florian Libisch from TU Wien. However, creating well-controlled artificial atoms in graphene turned out to be extremely challenging.

### Cutting edge is not enough

There are different ways of creating artificial atoms: The simplest one is putting electrons into tiny flakes, cut out of a thin layer of the material. While this works for graphene, the symmetry of the material is broken by the edges of the flake which can never be perfectly smooth. Consequently, the special four-fold multiplicity of states in graphene is reduced to the conventional two-fold one.

Therefore, different ways had to be found: It is not necessary to use small graphene flakes to capture electrons. Using clever combinations of electrical and magnetic fields is a much better option. With the tip of a scanning tunnelling microscope, an electric field can be applied locally. That way, a tiny region is created within the graphene surface, in which low energy electrons can be trapped. At the same time, the electrons are forced into tiny circular orbits by applying a magnetic field. "If we would only use an electric field, quantum effects allow the electrons to quickly leave the trap" explains Libisch.

The artificial atoms were measured at the RWTH Aachen by Nils Freitag and Peter Nemes-Incze in the group of Professor Markus Morgenstern. Simulations and theoretical models were developed at TU Wien (Vienna) by Larisa Chizhova, Florian Libisch and Joachim Burgdörfer. The exceptionally clean graphene sample came from the team around Andre Geim and Kostya Novoselov from Manchester (GB) - these two researchers were awarded the Nobel Prize in 2010 for creating graphene sheets for the first time.

The new artificial atoms now open up new possibilities for many quantum technological experiments: "Four localized electron states with the same energy allow for switching between different quantum states to store information", says Joachim Burgdörfer. The electrons can preserve arbitrary superpositions for a long time, ideal properties for quantum computers. In addition, the new method has the big advantage of scalability: it should be possible to fit many such artificial atoms on a small chip in order to use them for quantum information applications. [17]

## Two atoms in an optical cavity can absorb one photon

When two atoms are placed in a small chamber enclosed by mirrors, they can simultaneously absorb a single photon. So says an international team of researchers, which has found that the reverse process – two excited atoms emitting a single photon – is also possible. According to the team, this process could be used to transmit information in a quantum circuit or computer.

Physicists have long known that a single atom can absorb or emit two photons simultaneously. These two-photon, one-atom processes are widely used for spectroscopy and for the production of entangled photons used in quantum devices. However, Salvatore Savasta of the University of Messina in Italy, together with colleagues at the RIKEN Institute in Japan, wondered if two atoms could absorb one photon. Savasta asked his PhD student at the time, Luigi Garziano, to simulate the process. When Garziano's simulation showed that the phenomenon was possible, Savasta was so excited that he "punched the wall," he told physicsworld.com.

### One for two?

Their simulation found that the phenomenon occurs when the resonant frequency of the optical cavity containing the atoms is twice the transition frequency of an individual atom. For example, in a cavity whose resonant frequency is three times that of the atomic transition, three atoms can simultaneously absorb or emit a single photon. The optical-cavity's dimensions are determined by this resonant frequency, which must be a standing wave. According to the researchers' calculations, the two atoms would oscillate back and forth between their ground and excited states. Indeed, the atoms would first jointly absorb the photon, ending up in their excited states, before jointly emitting a single photon to return to their ground states. The cycle would then repeat. In addition, they found that the joint absorption and emission can occur with more than just two atoms.

### Quantum switch

A two-atom, one-photon system could be used as a switch to transmit information in a quantum circuit, Savasta says. One atom would act as a qubit, encoding information as a superposition of the ground and excited states. To transmit the information outside of the cavity, the qubit would need to transfer the information to a photon in the cavity. The second atom would be used to control whether the qubit transmits the information. If the second atom's transition frequency is tuned to half the resonance frequency of the cavity, the two atoms could jointly absorb and emit a single photon, which would contain the encoded information to be transmitted.

To ensure that the atoms do not re-adsorb the photon, the atom's resonant frequency can be changed by applying an external magnetic field.

Savasta's group has begun to look for experimental collaborators to produce its theoretical prediction in the lab. While the experiment could be performed using actual atoms, Savasta plans to use artificial atoms: superconducting particles that have quantized energy levels and behave analogously as atoms, but whose transition energies can be more easily tuned by the experimentalist. In addition, controlling real atoms involves expensive technology, while artificial atoms can be created cheaply on solid-state chips. "Real atoms are only good for proof-of-principle experiments," he says.

Savasta anticipates that their collaborators will be able to successfully perform the experiment in about a year. "We think that, especially if using superconducting qubits, that this experiment is well within the reach of present technology," he says.

According to Tatjana Wilk at the Max Planck Institute for Quantum Optics in Garching, who was not involved in the current research, speaking to the American Physical Society's Physics Focus, she cautions that the excited states of the atoms may not last long enough to be useful in an actual quantum device.

The research is published in Physical Review Letters. [16]

## Quantum processor for single photons

"Nothing is impossible!" In line with this motto, physicists from the Quantum Dynamics Division of Professor Gerhard Rempe (director at the Max Planck Institute of Quantum Optics) managed to realise a quantum logic gate in which two light quanta are the main actors. The difficulty of such an endeavour is that photons usually do not interact at all but pass each other undisturbed. This makes them ideal for the transmission of quantum information, but less suited for its processing. The scientists overcame this steep hurdle by bringing an ancillary third particle into play: a single atom trapped inside an optical resonator that takes on the role of a mediator. "The distinct feature of our gate implementation is that the interaction between the photons is deterministic", explains

Dr. Stephan Ritter. "This is essential for future, more complex applications like scalable quantum computers or global quantum networks."

In all modern computers, data processing is based on information being binary-coded and then processed using logical operations. This is done using so-called logic gates which assign predefined output values to each input via deterministic protocols. Likewise, for the information processing in quantum computers, quantum logic gates are the key elements. To realise a universal quantum computer, it is necessary that every input quantum bit can cause a maximal change of the other quantum bits. The practical difficulty lies in the special nature of quantum information: in contrast to classical bits, it cannot be copied. Therefore, classical methods for error correction cannot be applied, and the gate must function for every single photon that carries information.

Because of the special importance of photons as information carriers – for example, for communicating quantum information in extended quantum networks – the realisation of a deterministic photon-photon gate has been a long-standing goal. One of several possibilities to encode photonic quantum bits is the use of polarisation states of single photons. Then the states "0" and "1" of a classical bit correspond to two orthogonal polarisation states. In the two-photon gate, the polarisation of each photon can influence the polarisation of the other photon. As in the classical logic gate it is specified beforehand which input polarisation leads to which output polarisation. For example, a linear polarisation of the second photon is rotated by 90° if the first one is in the logic state "1", and remains unchanged if the first one is in "0". In contrast to classical logic gates, which would be fully specified by such a description, a quantum gate can take on an infinite number of possible input states. The quantum logic gate has to create the correct combination of output states for each one of these.

In the experiment presented here two independently polarised photons impinge, in quick succession, onto a resonator which is made of two high-reflectivity mirrors.

Inside a single rubidium atom is trapped forming a strongly coupled system with the resonator. The resonator amplifies the light field of the impinging photon at the position of the atom enabling a direct atom-photon interaction. As a result, the atomic state gets manipulated by the photon just as it is being reflected from the mirror. This change is sensed by the second photon when it arrives at the mirror shortly thereafter.

After their reflection, both photons are stored in a 1.2-kilometre-long optical fibre for some microseconds. Meanwhile, the atomic state is measured. A rotation of the first photon's polarisation conditioned on the outcome of the measurement enables the back action of the second photon on the first one. "The two photons are never at the same place at the same time and thus they do not see each other directly. Nevertheless, we achieve a maximal interaction between them", explains Bastian Hacker, PhD student at the experiment.

The scientists could prove experimentally that – depending on the choice of the photons' polarisations – either the first photon affects the second or vice versa. To this end, they measured the polarisation states of the two outgoing photons for different input states. From these, they generated "truth tables" which correspond to the expected gate operations and thus demonstrate the diverse operational modes of the photon-photon gate.

The case when the input polarisation of the two photons is chosen such that they influence each other is of particular interest: Here the two outgoing photons form an entangled pair. "The possibility to generate entanglement fundamentally distinguishes a quantum gate from its classical counterpart. One of the applications of entangled photons is in the teleportation of quantum states", explains Stephan Welte, PhD student at the experiment.

The scientists envision that the new photon-photon gate could pave the way towards all-optical quantum information processing. "The distribution of photons via an optical quantum network would allow linking any number of network nodes and thus enable the setup of a scalable optical quantum computer in which the photon-photon gate plays the role of a central processing unit (CPU)", explains Professor Gerhard Rempe. [15]

## The path to perfection: Quantum dots in electrically-controlled cavities yield bright, nearly identical photons

Optical quantum technologies are based on the interactions of atoms and photons at the singleparticle level, and so require sources of single photons that are highly indistinguishable – that is, as identical as possible. Current single-photon sources using semiconductor quantum dots inserted into photonic structures produce photons that are ultrabright but have limited indistinguishability due to charge noise, which results in a fluctuating electric field. Conversely, parametric down conversion sources yield photons that while being highly indistinguishable have very low brightness. Recently, however, scientists at CNRS - Université Paris-Saclay, Marcoussis, France; Université Paris Diderot, Paris, France; University of Queensland, Brisbane, Australia; and Université Grenoble Alpes, CNRS, Institut Néel, Grenoble, France; have developed devices made of quantum dots in electricallycontrolled cavities that provide large numbers of highly indistinguishable photons with strongly reduced charge noise that are 20 times brighter than any source of equal quality. The researchers state that by demonstrating efficient generation of a pure single photon with near-unity indistinguishability, their novel approach promises significant advances in optical quantum technology complexity and scalability.

Dr. Pascale Senellart and Phys.org discussed the paper, Near-optimal single-photon sources in the solid state, that she and her colleagues published in Nature Photonics, which reports the design and fabrication of the first optoelectronic devices made of quantum dots in electrically controlled cavities that provide bright source generating near-unity indistinguishability and pure single photons. "The ideal single photon source is a device that produces light pulses, each of them containing exactly one, and no more than one, photon. Moreover, all the photons should be identical in spatial shape, wavelength, polarization, and a spectrum that is the Fourier transform of its temporal profile," Senellart tells Phys.org. "As a result, to obtain near optimal single photon sources in an optoelectronic device, we had to solve many scientific and technological challenges, leading to an achievement that is the result of more than seven years of research."

While quantum dots can be considered artificial atoms that therefore emit photons one by one, she explains, due to the high refractive index of any semiconductor device, most single photons emitted by the quantum dot do not exit the semiconductor and therefore cannot be used. "We solved this problem by coupling the quantum dot to a microcavity in order to engineer the electromagnetic field around the emitter and force it to emit in a well-defined mode of the optical field," Senellart points out. "To do so, we need to position the quantum dot with nanometer-scale accuracy in the microcavity."

Senellart notes that this is the first challenge that the researchers had to address since targeting the issue of quantum dots growing with random spatial positions.

"Our team solved this issue in 2008[1] by proposing a new technology, in-situ lithography, which allows measuring the quantum dot position optically and drawing a pillar cavity around it. With this technique, we can position a single quantum dot with 50 nm accuracy at the center of a micronsized pillar." In these cavities, two distributed Bragg reflectors confine the optical field in the vertical direction, and the contrast of the index of refraction between the air and the semiconductor provides the lateral confinement of the light. "Prior to this technology, the fabrication yield of quantum dot cavity devices was in the 10-4 – but today it is larger than 50%." The scientists used this technique to demonstrate the fabrication of bright single photon sources in 2013[2], showing that the device can generate light pulses containing a single photon with a probability of 80% – but while all photons had the same spatial shape and wavelength, they were not perfectly identical.

"Indeed, for the photons to be fully indistinguishable, the emitter should be highly isolated from any source of decoherence induced by the solid-state environment.

However, our study showed that collisions of the carriers with phonons and fluctuation of charges around the quantum dot were the main limitations." To solve this problem, the scientists added an electrical control to the device, such that the application of an electric field stabilized the charges around the quantum dot by sweeping out any free charge. This in turn removed the noise. Moreover, she adds, this electrical control allows tuning the quantum dot wavelength – a process that was previously done by increasing temperature at the expense of increasing vibration.

"I'd like to underline here that the technology described above is unique worldwide," Senellart stresses. "Our group is the only one with such full control of all of the quantum dot properties. That is, we control emission wavelength, emission lifetime and coupling to the environment, all in a fully deterministic and scalable way."

Specifically, implementing control of the charge environment for quantum dots in connected pillar cavities, and applying an electric field on a cavity structure optimally coupled to a quantum dot, required significant attention. "We had strong indications back in 2013 that the indistinguishability of our photons was limited by some charge fluctuations around the quantum dot: Even in the highest-quality semiconductors, charges bound to defects fluctuate and create a fluctuating electric field[3]. In the meantime, several colleagues were observing very low charge noise in structures where an electric field was applied to the quantum dot – but this was not combined with a cavity structure." The challenge, Senellart explains, was to define a metallic contact on a microcavity (which is typically a cylinder with a diameter of 2-3 microns) without covering the pillar's top surface.

"We solved this problem by proposing a new kind of cavity – that is, we showed that we can actually connect the cylinder to a bigger frame using some one-dimensional bridges without modifying too much the confinement of the optical field." This geometry, which the researchers call connected pillars, allows having the same optical confinement as an isolated pillar while defining the metallic contact far from the pillar itself. Senellart says that the connected pillars geometry was the key to both controlling the quantum wavelength of dot and efficiently collecting its emission4.

In demonstrating the efficient generation of a pure single photon with near-unity indistinguishability, Senellart continues, the researchers had one last step – combining high photon extraction efficiency and perfect indistinguishability – which they did by implementing a resonant excitation scheme of the quantum dot. "In 2013, Prof. Chao-Yang Lu's team in Hefei, China showed that one could obtain photons with 96% indistinguishability by exciting the quantum dot state in a strictly resonant way5. Their result was beautiful, but again, not combined with an efficient extraction of the photons. The experimental challenge here is to suppress the scattered light from the laser and collect only the single photons radiated by the quantum dot."

Senellart adds that while removing scattered photons when transmitting light in processed microstructures is typically complicated, in their case this step was straightforward. "Because the quantum dot is inserted in a cavity, the probability of the incident laser light to interact with the quantum dot is actually very high. It turns out that we send only a few photons – that is, less than 10 – on the device to have the quantum dot emitting one photon. This beautiful efficiency, also demonstrated in the excitation process, which we report in another paper6, made this step quite easy."

The devices reported in the paper have a number of implications for future technologies, one being the ability to achieve strongly-reduced charge noise by applying an electrical bias. "Charge noise has been extensively investigated in quantum dot structures," Senellart says, "especially by Richard Warburton's group."

Warburton and his team demonstrated that in the best quantum dot samples, the charge noise could take place on a time scale of few microseconds – which is actually very good, since the quantum dot emission lifetime is around 1 nanosecond7. However, this was no longer the case in etched structures, where a strong charge noise is always measured on very short time scale – less than 1 ns – that prevents the photon from being indistinguishable. "I think the idea we had – that this problem would be solved by applying an electric field – was an important one," Senellart notes. "The time scale of this charge noise does not only determine the degree of indistinguishability of the photons, it also determines how many indistinguishable photon one can generate with the same device. Therefore, this number will determine the complexity of any quantum computation or simulation scheme one can implement." Senellart adds that in a follow-up study7 the scientists generated long streams of photons that can contain more than 200 being indistinguishable by more than 88%.

In addressing how these de novo devices may lead to new levels of complexity and scalability in optical quantum technologies, Senellart first discusses the historical sources used develop optical quantum technologies. She makes the point that all previous implementations of optical quantum simulation or computing have been implemented using Spontaneous Parametric Down Conversion (SPDC) sources, in which pairs of photons are generated by the nonlinear interaction of a laser on a nonlinear crystal, wherein one photon of the pair is detected to announce the presence of the other photon. This so-called heralded source can present strongly indistinguishable photons, but only at the cost of extremely low brightness. "Indeed, the difficulty here is that the one pulse does not contain a single pair only, but some of the time several pairs," Senellart explains. "To reduce the probability of having several pairs generated that would degrade the fidelity of a quantum simulation, calculation or the security of a quantum communication, the sources are strongly attenuated, to the point where the probability of having one pair in a pulse is below 1%. Nevertheless, with these sources, the quantum optics community has demonstrated many beautiful proofs of concept of optical quantum technologies, including long-distance teleportation, quantum computing of simple chemical or physical systems, and quantum simulations like BosonSampling." (A BosonSampling device is a quantum machine expected to perform tasks intractable for a classical computer, yet requiring minimal non-classical resources compared to full-scale quantum computers.) "Yet, the low efficiency of these sources limits the manipulation to low photon numbers: It takes typically hundreds of hours to manipulate three photons, and the measurement time increases exponentially with the number of photons. Obviously, with the possibility to generate more many indistinguishable photons with an efficiency more than one order of magnitude greater than SPDC sources, our devices have the potential to bring optical quantum technologies to a whole new level."

Other potential applications of the newly-demonstrated devices will focus on meeting near-future challenges in optical quantum technologies, including scalability of photonic quantum computers and intermediate quantum computing tasks. "The sources presented here can be used immediately to implement quantum computing and intermediate quantum computing tasks. Actually, very recently – in the first demonstration of the superiority of our new single photon sources – our colleagues in Brisbane made use of such bright indistinguishable quantum dot-based single photon sources to demonstrate a three photon BosonSampling experiment8, where the solid-state multiphoton source was one to two orders-of-magnitude more efficient than downconversion sources, allowing to complete the experiment faster than those performed with SPDC sources. Moreover, this is a first step; we'll progressively increase the number of manipulated photons, in both quantum simulation and quantum computing tasks."

Another target area is quantum communications transfer rate. "Such bright single photon sources could also drastically change the rate of quantum communication protocols that are currently using attenuated laser sources or SPDC sources. Yet, right now, our sources operate at 930 nm when 1.3 µm or 1.55 µm sources are needed for long distance communications. Our technique can be transferred to the 1.3 µm range, a range at which single photon emission has been successfully demonstrated – in particular by the Toshiba research group – slightly changing the quantum dot material. Reaching the 1.55 µm range will be more challenging using quantum dots, as it appears that the single photon emission is difficult to obtain at this wavelength. Nevertheless, there's a very promising alternative possibility: the use of a 900 nm bright source, like the one we report here, to perform quantum frequency conversion of the single photons. Such efficient frequency conversion of single photons has recently been demonstrated, for example, in the lab of Prof. Yoshie Yamamoto at Stanford9."

Regarding future research, Senellart says "There are many things to do from this point. On the technology side, we will try to improve our devices by further increasing the source brightness. For that, a new excitation scheme will be implemented to excite the device from the side, as was done by Prof. Valia Voliotis and her colleagues on the Nanostructures and Quantum Systems team at

Pierre and Marie Curie University in Paris and Prof. Glenn Solomon's group at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. Applying this technique to our cavities should allow gaining another factor of four on source brightness. In addition, operating at another wavelength would be another important feature for our devices, since as discussed above, this would allow using the source for quantum telecommunication. For example, a shorter wavelength, in the visible/near infrared range, would open new possibilities to interconnect various quantum systems, including ions or atoms through their interaction with photons, as well as applications in quantum imaging and related fields."

The researchers also want to profit from the full potential of these sources and head to high photon number manipulation in, for instance, quantum simulation schemes. "We're aiming at performing BosonSampling measurements with 20-30 photons, with the objective of testing the extended Church Turing thesis and proving the superiority of a quantum computer over a classical one." The original Church Turing thesis, based on investigations of Alonzo Church and Alan Turing into computable functions, states that, ignoring resource limitations, a function on the natural numbers is computable by a human being following an algorithm, if and only if it is computable by a Turing machine.

Another promising impact on future optical quantum technologies is the generation of entangled photon pairs. "A quantum dot can also generate entangled photon pairs, and in 2010 we demonstrated that we could use the in situ lithography to obtain the brightest source of entangled photon pairs10. That being said, photon indistinguishability needs to be combined with high pair brightness – and this is the next challenge we plan to tackle. Such a device would play an important role in developing quantum relays for long distance communication and quantum computing tasks."

Senellart tells Phys.org that other areas of research might well benefit from their findings, in that devices similar to the one the scientists developed to fabricate single photon sources could also provide nonlinearities at the low photon count scale. This capability could in turn allow the implementation of deterministic quantum gates, a new optical quantum computing paradigm in which reversible quantum logic gates – for example, Toffoli or CNOT (controlled NOT) gates– can simulate irreversible classical logic gates, thereby allowing quantum computers to perform any computation which can be performed by a classical deterministic computer. "Single photons can also be used to probe the mechanical modes of mechanical resonator and develop quantum sensing with macroscopic objects. Other applications," she concludes, "could benefit from the possibility to have very efficient single photon sources, such as an imaging system with single photon sources that could allow dramatically increased imaging sensitivity. Such technique could have applications in biology where the lower the photon flux, the better for exploring in vivo samples." [14]

## Team demonstrates large-scale technique to produce quantum dots

A method to produce significant amounts of semiconducting nanoparticles for light-emitting displays, sensors, solar panels and biomedical applications has gained momentum with a demonstration by researchers at the Department of Energy's Oak Ridge National Laboratory.

While zinc sulfide nanoparticles - a type of quantum dot that is a semiconductor - have many potential applications, high cost and limited availability have been obstacles to their widespread use. That could change, however, because of a scalable ORNL technique outlined in a paper published in Applied Microbiology and Biotechnology.

Unlike conventional inorganic approaches that use expensive precursors, toxic chemicals, high temperatures and high pressures, a team led by ORNL's Ji-Won Moon used bacteria fed by inexpensive sugar at a temperature of 150 degrees Fahrenheit in 25- and 250-gallon reactors. Ultimately, the team produced about three-fourths of a pound of zinc sulfide nanoparticles - without process optimization, leaving room for even higher yields.

The ORNL biomanufacturing technique is based on a platform technology that can also produce nanometer-size semiconducting materials as well as magnetic, photovoltaic, catalytic and phosphor materials. Unlike most biological synthesis technologies that occur inside the cell, ORNL's biomanufactured quantum dot synthesis occurs outside of the cells. As a result, the nanomaterials are produced as loose particles that are easy to separate through simple washing and centrifuging.

The results are encouraging, according to Moon, who also noted that the ORNL approach reduces production costs by approximately 90 percent compared to other methods.

"Since biomanufacturing can control the quantum dot diameter, it is possible to produce a wide range of specifically tuned semiconducting nanomaterials, making them attractive for a variety of applications that include electronics, displays, solar cells, computer memory, energy storage, printed electronics and bio-imaging," Moon said.

Successful biomanufacturing of light-emitting or semiconducting nanoparticles requires the ability to control material synthesis at the nanometer scale with sufficiently high reliability, reproducibility and yield to be cost effective. With the ORNL approach, Moon said that goal has been achieved.

Researchers envision their quantum dots being used initially in buffer layers of photovoltaic cells and other thin film-based devices that can benefit from their electro-optical properties as light-emitting materials. [13]

## Superfast light source made from artificial atom

All light sources work by absorbing energy – for example, from an electric current – and emit energy as light. But the energy can also be lost as heat and it is therefore important that the light sources emit the light as quickly as possible, before the energy is lost as heat. Superfast light sources can be used, for example, in laser lights, LED lights and in single-photon light sources for quantum technology. New research results from the Niels Bohr Institute show that light sources can be made much faster by using a principle that was predicted theoretically in 1954. The results are published in the scientific journal, Physical Review Letters.

Researchers at the Niels Bohr Institute are working with quantum dots, which are a kind of artificial atom that can be incorporated into optical chips. In a quantum dot, an electron can be excited (i.e. jump up), for example, by shining a light on it with a laser and the electron leaves a 'hole'. The stronger the interaction between light and matter, the faster the electron decays back into the hole and the faster the light is emitted.

But the interaction between light and matter is naturally very weak and it makes the light sources very slow to emit light and this can reduce energy efficiency.

Already in 1954, the physicist Robert Dicke predicted that the interaction between light and matter could be increased by having a number of atoms that 'share' the excited state in a quantum superposition.

## Quantum speed up

Demonstrating this effect has been challinging so far because the atoms either come so close together that they bump into each other or they are so far apart that the quantum speed up does not work. Researchers at the Niels Bohr Institute have now finally demonstrated the effect experimentally, but in an entirely different physical system than Dicke had in mind. They have shown this so-called superradiance for photons emitted from a single quantum dot.

"We have developed a quantum dot so that it behaves as if it was comprised of five quantum dots, which means that the light is five times stronger. This is due to the attraction between the electron and the hole. But what is special is that the quantum dot still only emits a single photon at a time. It is an outstanding single-photon source," says Søren Stobbe, who is an associate professor in the Quantum Photonic research group at the Niels Bohr Institute at the University of Copenhagen and led the project. The experiment was carried out in collaboration with Professor David Ritchie's research group at the University of Cambridge, who have made the quantum dots.

Petru Tighineanu, a postdoc in the Quantum Photonics research group at the Niels Bohr Institute, has carried out the experiments and he explains the effect as such, that the atoms are very small and light is very 'big' because of its long wavelength, so the light almost cannot 'see' the atoms – like a lorry that is driving on a road and does not notice a small pebble. But if many pebbles become a larger stone, the lorry will be able to register it and then the interaction becomes much more dramatic. In the same way, light interacts much more strongly with the quantum dot if the quantum dot contains the special superradiant quantum state, which makes it look much bigger.

## Increasing the light-matter interaction

"The increased light-matter interaction makes the quantum dots more robust in regards to the disturbances that are found in all materials, for example, acoustic oscillations. It helps to make the photons more uniform and is important for how large you can build future quantum computers," says Søren Stobbe.

He adds that it is actually the temperature, which is only a few degrees above absolute zero, that limits how fast the light emissions can remain in their current experiments. In the long term, they will study the quantum dots at even lower temperatures, where the effects could be very dramatic. [12]

## Single-photon source is efficient and indistinguishable

Devices that emit one – and only one – photon on demand play a central role in light-based quantum-information systems. Each photon must also be emitted in the same quantum state, which makes each photon indistinguishable from all the others. This is important because the quantum state of the photon is used to carry a quantum bit (qubit) of information.

Quantum dots are tiny pieces of semiconductor that show great promise as single-photon sources. When a laser pulse is fired at a quantum dot, an electron is excited between two distinct energy levels. The excited state then decays to create a single photon with a very specific energy. However, this process can involve other electron excitations that result in the emission of photons with a wide range of energies – photons that are therefore not indistinguishable.

### Exciting dots

This problem can be solved by exciting the quantum dot with a pulse of light at the same energy as the emitted photon. This is called resonance fluorescence, and has been used to create devices that are very good at producing indistinguishable single photons. However, this process is inefficient, and only produces a photon about 6% of the time.

Now, Chaoyang Lu, Jian-Wei Pan and colleagues at the University of Science and Technology of China have joined forces with researchers in Denmark, Germany and the UK to create a resonancefluorescence-based source that emits a photon 66% of the time when it is prompted by a laser pulse.

Of these photons, 99.1% are solo and 98.5% are in indistinguishable quantum states – with both figures of merit being suitable for applications in quantum-information systems.

Lu told physicsworld.com that nearly all of the laser pulses that strike the source produce a photon, but about 34% of these photons are unable to escape the device. The device was operated at a laser-pulse frequency of 81 MHz and a pulse power of 24 nW, which is a much lower power requirement than other quantum-dot-based sources.

### Quantum sandwich

The factor-of-ten improvement in efficiency was achieved by sandwiching a quantum dot in the centre of a "micropillar" created by stacking 40 disc-like layers (see figure). Each layer is a "distributed Bragg reflector", which is a pair of mirrors that together have a thickness of one quarter the wavelength of the emitted photons.

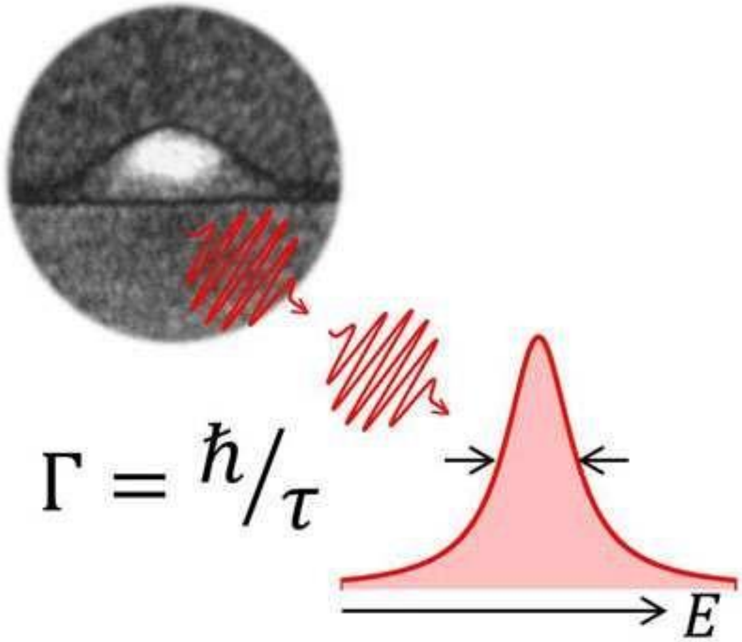
The micropillar is about 2.5 µm in diameter and about 10 µm tall, and it allowed the team to harness the "Purcell effect", whereby the rate of fluorescence is increased significantly when the emitter is placed in a resonant cavity.

Lu says that the team is already thinking about how the photon sources could be used to perform boson sampling (see "'Boson sampling' offers shortcut to quantum computing"). This involves a network of beam splitters that converts one set of photons arriving at a number of parallel input ports into a second set leaving via a number of parallel outputs. The "result" of the computation is the probability that a certain input configuration will lead to a certain output. This result cannot be easily calculated using a conventional computer, and this has led some physicists to suggest that boson sampling could be used to solve practical problems that would take classical computers vast amounts of time to solve.

Other possible applications for the source are the quantum teleportation of three properties of a quantum system – the current record is two properties and is held by Lu and Pan – or quantum cryptography.

The research is described in Physical Review Letters. [11]

## Semiconductor quantum dots as ideal single-photon source




A single-photon source never emits two or more photons at the same time. Single photons are important in the field of quantum information technology where, for example, they are used in quantum computers. Alongside the brightness and robustness of the light source, the indistinguishability of the photons is especially crucial. In particular, this means that all photons must be the same color. Creating such a source of identical single photons has proven very difficult in the past.

However, quantum dots made of semiconductor materials are offering new hope. A quantum dot is a collection of a few hundred thousand atoms that can form itself into a semiconductor under certain conditions. Single electrons can be captured in these quantum dots and locked into a very small area. An individual photon is emitted when an engineered quantum state collapses.

### Noise in the semiconductor

A team of scientists led by Dr. Andreas Kuhlmann and Prof. Richard J. Warburton from the University of Basel have already shown in past publications that the indistinguishability of the photons is reduced by the fluctuating nuclear spin of the quantum dot atoms. For the first time ever, the scientists have managed to control the nuclear spin to such an extent that even photons sent out at very large intervals are the same color.

Quantum cryptography and quantum communication are two potential areas of application for single-photon sources. These technologies could make it possible to perform calculations that are far beyond the capabilities of today's computers. [10]

## How to Win at Bridge Using Quantum Physics

Contract bridge is the chess of card games. You might know it as some stuffy old game your grandparents play, but it requires major brainpower, and preferably an obsession with rules and strategy. So how to make it even geekier? Throw in some quantum mechanics to try to gain a competitive advantage. The idea here is to use the quantum magic of entangled photons–which are essentially twins, sharing every property–to transmit two bits of information to your bridge partner for the price of one. Understanding how to do this is not an easy task, but it will help elucidate some basic building blocks of quantum information theory. It’s also kind of fun to consider whether or not such tactics could ever be allowed in professional sports. [6]

## Quantum Information

In quantum mechanics, quantum information is physical information that is held in the "state" of a quantum system. The most popular unit of quantum information is the qubit, a two-level quantum system. However, unlike classical digital states (which are discrete), a two-state quantum system can actually be in a superposition of the two states at any given time.

Quantum information differs from classical information in several respects, among which we note the following:

However, despite this, the amount of information that can be retrieved in a single qubit is equal to one bit. It is in the processing of information (quantum computation) that a difference occurs.

The ability to manipulate quantum information enables us to perform tasks that would be unachievable in a classical context, such as unconditionally secure transmission of information. Quantum information processing is the most general field that is concerned with quantum information. There are certain tasks which classical computers cannot perform "efficiently" (that is, in polynomial time) according to any known algorithm. However, a quantum computer can compute the answer to some of these problems in polynomial time; one well-known example of this is Shor's factoring algorithm. Other algorithms can speed up a task less dramatically - for example, Grover's search algorithm which gives a quadratic speed-up over the best possible classical algorithm.

Quantum information, and changes in quantum information, can be quantitatively measured by using an analogue of Shannon entropy. Given a statistical ensemble of quantum mechanical systems with the density matrix S, it is given by.

Many of the same entropy measures in classical information theory can also be generalized to the quantum case, such as the conditional quantum entropy. [7]

## Heralded Qubit Transfer

Optical photons would be ideal carriers to transfer quantum information over large distances. Researchers envisage a network where information is processed in certain nodes and transferred between them via photons. However, inherent losses in long-distance networks mean that the information transfer is subject to probabilistic errors, making it hard to know whether the transfer of a qubit of information has been successful. Now Gerhard Rempe and colleagues from the Max Planck Institute for Quantum Optics in Germany have developed a new protocol that solves this problem through a strategy that “heralds” the accurate transfer of quantum information at a network node.

The method developed by the researchers involves transferring a photonic qubit to an atomic qubit trapped inside an optical cavity. The photon-atom quantum information transfer is initiated via a quantum “logic-gate” operation, performed by reflecting the photon from the atom-cavity system, which creates an entangled atom-photon state. The detection of the reflected photon then collapses the atom into a definite state. This state can be one of two possibilities, depending on the photonic state detected: Either the atom is in the initial qubit state encoded in the photon and the transfer process is complete, or the atom is in a rotated version of this state. The authors were able to show that the roles of the atom and photon could be reversed. Their method could thus be used as a quantum memory that stores (photon-to-atom state transfer) and recreates (atom-to-photon state transfer) a single-photon polarization qubit. [9]

## Quantum Teleportation

Quantum teleportation is a process by which quantum information (e.g. the exact state of an atom or photon) can be transmitted (exactly, in principle) from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location. Because it depends on classical communication, which can proceed no faster than the speed of light, it cannot be used for superluminal transport or communication of classical bits. It also cannot be used to make copies of a system, as this violates the no-cloning theorem. Although the name is inspired by the teleportation commonly used in fiction, current technology provides no possibility of anything resembling the fictional form of teleportation. While it is possible to teleport one or more qubits of information between two (entangled) atoms, this has not yet been achieved between molecules or anything larger. One may think of teleportation either as a kind of transportation, or as a kind of communication; it provides a way of transporting a qubit from one location to another, without having to move a physical particle along with it.

The seminal paper first expounding the idea was published by C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters in 1993. Since then, quantum teleportation has been realized in various physical systems. Presently, the record distance for quantum teleportation is 143 km (89 mi) with photons, and 21 m with material systems. In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

## Quantum Computing

A team of electrical engineers at UNSW Australia has observed the unique quantum behavior of a pair of spins in silicon and designed a new method to use them for "2-bit" quantum logic operations.

These milestones bring researchers a step closer to building a quantum computer, which promises dramatic data processing improvements.

Quantum bits, or qubits, are the building blocks of quantum computers. While many ways to create a qubits exist, the Australian team has focused on the use of single atoms of phosphorus, embedded inside a silicon chip similar to those used in normal computers.

The first author on the experimental work, PhD student Juan Pablo Dehollain, recalls the first time he realized what he was looking at.

"We clearly saw these two distinct quantum states, but they behaved very differently from what we were used to with a single atom. We had a real 'Eureka!' moment when we realized what was happening – we were seeing in real time the `entangled' quantum states of a pair of atoms." [5]

## Quantum Entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

## The Bridge

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. [1]

### Accelerating charges

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field. In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion.  The same thing happens on the atomic scale giving a dp impulse difference and a dx way difference between the different part of the not point like particles.

### Relativistic effect

Another bridge between the classical and quantum mechanics in the realm of relativity is that the charge distribution is lowering in the reference frame of the accelerating charges linearly: ds/dt = at (time coordinate), but in the reference frame of the current it is parabolic: $s = a/2\ t^2$ (geometric coordinate).

## 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 that 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.

## The Relativistic Bridge

Commonly accepted idea that the relativistic effect on the particle physics it is the fermions' spin - another unresolved problem in the classical concepts. If the electric charges can move only with accelerated motions in the self maintaining electromagnetic field, once upon a time they would reach the velocity of the electromagnetic field. The resolution of this problem is the spinning particle, constantly accelerating and not reaching the velocity of light because the acceleration is radial. One origin of the Quantum Physics is the Planck Distribution Law of the electromagnetic oscillators, giving equal intensity for 2 different wavelengths on any temperature. Any of these two wavelengths will give equal intensity diffraction patterns, building different asymmetric constructions, for example proton - electron structures (atoms), molecules, etc. Since the particles are centers of diffraction patterns they also have particle – wave duality as the electromagnetic waves have. [2]

## The weak interaction

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 Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

Another important issue of the quark model is when one quark changes its flavor such that a linear oscillation transforms into plane oscillation or vice versa, changing the charge value with 1 or -1. This kind of change in the oscillation mode requires not only parity change, but also charge and time changes (CPT symmetry) resulting a right handed anti-neutrino or a left handed neutrino.

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions, the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

The neutrino is a 1/2spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with ½ spin. The weak interaction changes the entropy since more or less particles will give more or less freedom of movement. The entropy change is a result of temperature change and breaks the equality of oscillator diffraction intensity of the Maxwell–Boltzmann statistics. This way it changes the time coordinate measure and

makes possible a different time dilation as of the special relativity.

The limit of the velocity of particles as the speed of light appropriate only for electrical charged particles, since the accelerated charges are self maintaining locally the accelerating electric force. The neutrinos are CP symmetry breaking particles compensated by time in the CPT symmetry, that is the time coordinate not works as in the electromagnetic interactions, consequently the speed of neutrinos is not limited by the speed of light.

The weak interaction T-asymmetry is in conjunction with the T-asymmetry of the second law of thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes the weak interaction, for example the Hydrogen fusion.

Probably because it is a spin creating movement changing linear oscillation to 2 dimensional oscillation by changing d to u quark and creating anti neutrino going back in time relative to the proton and electron created from the neutron, it seems that the anti neutrino fastest then the velocity of the photons created also in this weak interaction?

A quark flavor changing shows that it is a reflection changes movement and the CP- and T-symmetry breaking!!! This flavor changing oscillation could prove that it could be also on higher level such as atoms, molecules, probably big biological significant molecules and responsible on the aging of the life.

Important to mention that the weak interaction is always contains particles and antiparticles, where the neutrinos (antineutrinos) present the opposite side. It means by Feynman's interpretation that these particles present the backward time and probably because this they seem to move faster than the speed of light in the reference frame of the other side.

Finally since the weak interaction is an electric dipole change with ½ spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

## The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. A good example of this is the neutron decay, creating more particles with less known information about them.

The neutrino oscillation of the Weak Interaction shows that it is a general electric dipole change and it is possible to any other temperature dependent entropy and information changing diffraction pattern of atoms, molecules and even complicated biological living structures.

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater then subatomic matter structures as an electric dipole change.

There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.

The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. So the Weak Interaction has two directions, samples for one direction is the Neutron decay, and Hydrogen fusion is the opposite direction.

## Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing.

## Van Der Waals force

Named after the Dutch scientist Johannes Diderik van der Waals – who first proposed it in 1873 to explain the behaviour of gases – it is a very weak force that only becomes relevant when atoms and molecules are very close together. Fluctuations in the electronic cloud of an atom mean that it will have an instantaneous dipole moment. This can induce a dipole moment in a nearby atom, the result being an attractive dipole–dipole interaction.

## Electromagnetic inertia and mass

### Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

### Relativistic change of mass

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.

### The frequency dependence of mass

Since $E = hv$ and $E = mc^2$, $m = hv / c^2$ that is the $m$ depends only on the $v$ 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 $m_o$ 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.

### Electron – Proton mass rate

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 a gravitational force. [2]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## Gravity from the point of view of quantum physics

### The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass rate Mp=1840 Me. In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have +

parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

Since the Higgs boson is necessary to the W and Z bosons, the dipole change of the Weak interaction and the change in the magnetic effect caused gravitation must be conducted. The Wien law is also important to explain the Weak interaction, since it describes the $T_{max}$ change and the diffraction patterns change. [2]

## Higgs mechanism and Quantum Gravity

The magnetic induction creates a negative electric field, causing an electromagnetic inertia. Probably it is the mysterious Higgs field giving mass to the charged particles? We can think about the photon as an electron-positron pair, they have mass. The neutral particles are built from negative and positive charges, for example the neutron, decaying to proton and electron. The wave – particle duality makes sure that the particles are oscillating and creating magnetic induction as an inertial mass, explaining also the relativistic mass change. Higher frequency creates stronger magnetic induction, smaller frequency results lesser magnetic induction. It seems to me that the magnetic induction is the secret of the Higgs field.

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The spontaneous symmetry breaking of the underlying local symmetry triggers conversion of components of this Higgs field to Goldstone bosons which interact with (at least some of) the other fields in the theory, so as to produce mass terms for (at least some of) the gauge bosons. This mechanism may also leave behind elementary scalar (spin-0) particles, known as Higgs bosons.

In the Standard Model, the phrase "Higgs mechanism" refers specifically to the generation of masses for the $W^{\pm}$, and Z weak gauge bosons through electroweak symmetry breaking. The Large Hadron Collider at CERN announced results consistent with the Higgs particle on July 4, 2012 but stressed that further testing is needed to confirm the Standard Model.

### What is the Spin?

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particles like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

### The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [3]

## Conclusions

The method developed by the researchers involves transferring a photonic qubit to an atomic qubit trapped inside an optical cavity. The photon-atom quantum information transfer is initiated via a quantum “logic-gate” operation, performed by reflecting the photon from the atom-cavity system, which creates an entangled atom-photon state. [9]

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

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 they movement .

The accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also. [1]

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. The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves. [2]

The key breakthrough to arrive at this new idea to build qubits was to exploit the ability to control the nuclear spin of each atom. With that insight, the team has now conceived a unique way to use the nuclei as facilitators for the quantum logic operation between the electrons. [5]

Basing the gravitational force on the accelerating Universe caused 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 also.

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