

# Quantum Origins of the Universe

---

*By demonstrating a stable method for formulating the no-boundary proposal, the results may lead to a rethinking of the idea as a description for the origins of the universe. [40]*

*A pair of researchers, one at the Massachusetts Institute of Technology (MIT) and another at California Institute of Technology (Caltech) and the University of Tokyo, have recently investigated a set of old conjectures about symmetries in quantum gravity. [39]*

*In conventional holography a photographic film can record the interference pattern of monochromatic light scattered from the object to be imaged with a reference beam of un-scattered light. [38]*

*The scientists used the quantum nature of the electron-light interaction to separate the electron-reference and electron-imaging beams in energy instead of space. [37]*

*A holographic acoustic tweezers (HAT) system has been used to suspend up to 25 objects in mid-air simultaneously. [36]*

*Holography is a powerful tool that can reconstruct wavefronts of light and combine the fundamental wave properties of amplitude, phase, polarization, wave vector and frequency. [35]*

*Physicist Artem Rudenko from Kansas State University and his colleagues pondered how to improve the images of viruses and microparticles that scientists get from X-rays. [34]*

*A team of materials scientists from Penn State, Cornell and Argonne National Laboratory have, for the first time, visualized the 3-D atomic and electron density structure of the most complex perovskite crystal structure system decoded to date. [33]*

*Hydrogen-powered electronics, travel, and more may be a step closer thanks to the work of a collaborative team of scientists in Japan. [32]*

*"The realization of such all-optical single- [HYPERLINK](#) ["https://phys.org/tags/information+processing/"](https://phys.org/tags/information+processing/) information processing," says Tanji-Suzuki. [31]*

*Researchers at ETH have now used attosecond laser pulses to measure the time evolution of this effect in molecules. [30]*

*A new benchmark quantum chemical calculation of C<sub>2</sub>, Si<sub>2</sub>, and their hydrides reveals a qualitative difference in the topologies of core electron orbitals of organic molecules and their silicon analogues. [29]*

*A University of Central Florida team has designed a nanostructured optical sensor that for the first time can efficiently detect molecular chirality—a property of molecular spatial twist that defines its biochemical properties. [28]*

*UCLA scientists and engineers have developed a new process for assembling semiconductor devices. [27]*

*A new experiment that tests the limit of how large an object can be before it ceases to behave quantum mechanically has been proposed by physicists in the UK and India. [26]*

*Phonons are discrete units of vibrational energy predicted by quantum mechanics that correspond to collective oscillations of atoms inside a molecule or a crystal. [25]*

*This achievement is considered as an important landmark for the realization of practical application of photon upconversion technology. [24]*  
*Considerable interest in new single-photon detector technologies has been scaling in this past decade. [23]*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## **Contents**

Preface .....	7
Stabilizing the no-boundary proposal sheds light on the universe's quantum origins.....	8
Researchers demonstrate constraints on symmetries from holography .....	9
Holographic imaging of electromagnetic fields using electron-light quantum interference.....	11
New holographic technique opens the way for quantum computation .....	17
Holographic acoustic tweezers could be used to create 3D displays.....	18
Intricate sound field.....	19
The wonderful world of ultrasound .....	19
Multichannel vectorial holographic display and encryption .....	20
Blasting molecules with extreme X-rays .....	25
Can We Trust What We See?.....	25
The Only Spot in the World.....	25
The Moment of Truth .....	26
Revealing the Why.....	27
A 3-D imaging technique unlocks properties of perovskite crystals .....	27
Seeing the light: Researchers offer solution for efficiency problem of artificial photosynthesis.....	29

Controlling photons with a photon .....	30
The photoelectric effect in stereo .....	30
Core electron topologies in chemical bonding .....	32
New optical sensor can determine if molecules are left or right 'handed' .....	33
Tiny defects in semiconductors created 'speed bumps' for electrons—researchers cleared the path .....	35
How to measure quantum behaviour in nanocrystals .....	37
Caught in a trap .....	37
“That’s pretty tricky” .....	38
Detecting the birth and death of a phonon.....	38
Sustainable solvent platform for photon upconversion increases solar utilization efficiency.....	39
Graphene single photon detectors .....	41
Engineers develop key mathematical formula for driving quantum experiments.....	41
New tool for characterizing quantum simulators .....	42
A collaborative effort .....	43
More efficient measurements.....	43
New gold standard.....	44
Flip-flop qubits: Radical new quantum computing design invented.....	44
New quantum memory device small enough to fit on a chip .....	46
How to store data on magnets the size of a single atom .....	47
The quest for atomic magnets.....	48
Raising the temperature.....	48
Future uses.....	49
Optical control of magnetic memory—New insights into fundamental mechanisms.....	49
Making precise measurements in tiny laser spots .....	49
The crucial thing occurs in the boundary ring.....	50
Surprising influence of the layer thickness .....	50
Photosensitive perovskites change shape when exposed to light .....	50
Conformal metasurface coating eliminates crosstalk and shrinks waveguides .....	51

A nano-roundabout for light.....	52
Signal processing using light instead of electronics .....	53
Two glass fibers and a bottle for light.....	53
Researchers create hidden images with commercial inkjet printers.....	54
For the first time, magnets are be made with a 3-D printer .....	56
Designed on a computer.....	56
Tiny magnetic particles in the polymer matrix .....	57
A whole world of new possibilities .....	57
New method to make permanent magnets more stable over time .....	57
New method for generating superstrong magnetic fields.....	58
Inverse spin Hall effect: A new way to get electricity from magnetism .....	59
A new way to get electricity from magnetism .....	59
From spin current to electric current .....	60
New electron spin secrets revealed: Discovery of a novel link between magnetism and electricity.....	60
Simple Experiment.....	62
Uniformly accelerated electrons of the steady current .....	62
Magnetic effect of the decreasing U electric potential.....	63
The work done on the charge and the Hamilton Principle .....	65
The Magnetic Vector Potential .....	65
The Constant Force of the Magnetic Vector Potential .....	66
Electromagnetic four-potential .....	66
Magnetic induction .....	66
Lorentz transformation of the Special Relativity.....	67
Heisenberg Uncertainty Relation.....	68
Wave – Particle Duality .....	68
Atomic model .....	68
Fermions' spin.....	69
Fine structure constant.....	69
Planck Distribution Law.....	70

Electromagnetic inertia and Gravitational attraction .....	70
Conclusions .....	71
References .....	72

Author: George Rajna

## Preface

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

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

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

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

## Stabilizing the no-boundary proposal sheds light on the universe's quantum origins

One idea for how the universe began is that the universe may have appeared out of nothing due to some quantum effect, such as quantum tunneling. In the 1980s, Stephen Hawking and James Hartle further elaborated on this idea by suggesting that time did not exist before the beginning of the universe, leading them to conclude that the universe has no initial boundary conditions on either time or space. The idea is called the "no-boundary proposal" or the "Hawking-Hartle state."

However, precisely describing how a physical system can transition from zero size to a finite size has been challenging. To describe the quantum effects involved, physicists use the path integral formulation, which involves rewriting a single classical trajectory as an integral over many possible trajectories, resulting in a quantum amplitude.

Although the path integral formulation is successful at describing how something can emerge from nothing, one major problem is that it predicts unstable perturbations, implying that the universe is highly non-homogenous and non-isotropic. As the universe is known to be approximately both homogenous and isotropic (meaning that it looks the same in all locations and from all directions), as stated by the cosmological principle, the path integral formulation doesn't accurately describe the observed universe. This has led some scientists to conclude that the no-boundary proposal cannot provide an accurate description of the universe's origins.

Now in a new paper, physicists Alice Di Tucci and Jean-Luc Lehners at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Potsdam, Germany, have shown that the path integral formulation can be used in a way that avoids instabilities, while still providing a consistent definition of the no-boundary proposal.

"I think that the biggest significance is that our new definition does not describe the emergence of the universe from a complete absence of space and time," Lehners told *Phys.org*. "Rather, the new mathematical conditions, that we had to impose to avoid instabilities, can be interpreted as saying that there existed already fluctuations of space and time. This is in fact what one might expect from quantum theory in any case, as the quantum uncertainty principle implies that there should always be fluctuations, presumably even of space and time."

The new proposal combines several ideas that have previously been suggested to overcome the problem with instabilities. Their work essentially changes the geometry of the space over which the path integral is defined. The path integral, which represents the state of the universe at a certain time, passes through certain critical points called saddle points, which correspond to possible Hawking-Hartle states.

However, most of these saddle points are unstable. One of the most important changes the physicists made in the new paper was to modify the boundary conditions on the entire geometry (by using Robin boundary conditions) to remove the unstable saddle points from the path of the path integral. In the new geometry, the path integral passes through only one saddle



point, which is stable, therefore avoiding the problem with instabilities. At this stable saddle point, there exists a Hawking-Hartle state that satisfies the no-boundary proposal.

By demonstrating a stable method for formulating the no-boundary proposal, the results may lead to a rethinking of the idea as a description for the origins of the universe. Still, there are many questions that remain.

"In the future we plan to see how robust our new definition is when incorporating aspects from string theory, which is the most advanced attempt at a full theory of quantum gravity," Lehnert said. "Also, we plan to explore whether other stable definitions of the no-boundary proposal might exist, or whether our new one is in some sense unique. And a big question that remains is whether we could deduce any testable/observable consequences." [40]

## Researchers demonstrate constraints on symmetries from holography

A pair of researchers, one at the Massachusetts Institute of Technology (MIT) and another at California Institute of Technology (Caltech) and the University of Tokyo, have recently investigated a set of old conjectures about symmetries in quantum gravity. The specific conjectures of focus: (1) Quantum gravity does not allow for global symmetries; (2) For gauge symmetry, all possible charges must be realized; (3) Internal gauge groups must be compact. Their paper, [published in \*Physical Review Letters\*](#), shows that these old assumptions hold within the anti-de Sitter/conformal field theory (AdS-CFT) correspondence.

"Historically, the concept of symmetry has played important roles in physics, both in identifying and formulating fundamental laws of nature, and in using these laws to understand and predict natural phenomena such as dynamics and phases of matters," Hiroshi Ooguri, one of the researchers who carried out the study, told Phys.org. "However, there has been theoretical evidence to suggest that, once we combine gravity and quantum mechanics (the two fundamental ideas in modern physics), all global symmetries are gone."

In physics, symmetries can be of two kinds: gauge and global. For several decades, researchers have proposed the idea that global symmetries should not be possible in quantum gravity, as the unified theory of gravity and quantum mechanics would not allow for any symmetry. This is a profound claim with important consequences. For instance, it predicts that a proton would not be stable against decaying into other particles.

"The standard model of particle physics has both kinds of symmetries, so we are predicting that the global ones must only be approximate," Daniel Harlow, the other researcher involved in the study, told Phys.org. "So far, this idea has had some circumstantial support, but there was no convincing argument. In our paper, we gave what we think is a rather convincing argument in the special case of the AdS/CFT correspondence. This correspondence gives our best-understood

theories of quantum gravity, and we were able to show that it does not allow global symmetries."

Prior to Ooguri and Harlow's paper, other researchers made arguments supporting the claim that quantum gravity (the unification of quantum mechanics and gravity) cannot have any symmetry. Nonetheless, these arguments often presented logical gaps or loopholes, for instance failing to address some important cases (e.g. discrete symmetry).

"Our new paper provides a rigorous proof of this claim in the context of the AdS/CFT correspondence, where quantum gravity is defined in a mathematically precise way, and we have done so in the most general way, excluding all possible global symmetries from quantum gravity," Ooguri said.

The proof presented by Ooguri and Harlow is based on two important ideas: the holographic principle of quantum gravity and quantum error correcting codes. The holographic principle was first introduced by [Gerard 't Hooft](#) and [Leonard Susskind](#) in the early '90s, yet it has since been widely built upon. One of its most crucial developments was the discovery of the AdS/CFT correspondence by [Juan Maldacena](#) in 1997.

Ooguri and Harlow wished to prove a mathematical theorem on quantum gravity, so they required a precise definition of the holographic principle. They decided to adopt the AdS/CFT correspondence, as this was the only way they felt they could achieve their goal.

"Our basic tools are quantum error correction, the AdS/CFT correspondence, and quantum field theory," Harlow said. "Probably the most important point to convey here is that although AdS/CFT is a beautiful theory of quantum gravity, it is not the theory of quantum gravity in our world. It is a toy model of the type that physicists like to study (such as the famous spherical cow). We believe, however, that lessons we learn in this toy model should carry over to our world provided that we are careful."

A few years ago, a different research group that also included Harlow showed that holography works in quantum gravity in a similar way to how quantum error correction works in quantum computing. In the AdS/CFT correspondence, spacetime geometry in the anti-de Sitter Space emerges from quantum entanglement in the conformal field theory. Harlow and his colleagues showed that the emergent geometric data is, in fact, quantum error correcting codes, from a CFT standpoint.

The insight from this previous research was essential to prove the theorem in the researchers' recent study. In their new study, Ooguri and Harlow found that the way quantum error correction works is not compatible with any symmetry. Thus, once quantum mechanics and gravity are merged, no symmetry is exact.

"It has generally been believed that symmetry is a fundamental concept in nature," Ooguri said. "Many physicists believe that there must be a beautiful set of laws in nature, and that one way to quantify beauty is by symmetry. Some of the symmetry may be hidden in our world (or

'spontaneously broken," in physics terms), but they may manifest themselves if we look at nature at a more fundamental level. We showed that the belief expressed in the above is wrong. The laws of nature at the most fundamental level, where quantum mechanics and gravity is unified, have no global symmetry."

The study carried out by Ooguri and Harlow brings key insight to the physics field, ruling out the possibility of global symmetries in a wide class of quantum gravity theories. Their findings have implications for numerous areas of study, for instance predicting the instability of protons.

"Our findings predict that the proton should not be stable," Harlow said. "It isn't obvious, but it also predicts the existence of magnetic monopoles: isolated objects which carry magnetic charge. So far, we have never seen such an object, but people are still searching for them. Unfortunately, our results are not strong enough to say how many monopoles should exist, where they should be, or how long we have to wait to see a proton decay."

In their future work, Harlow and Ooguri would like to quantify how symmetry is broken. So far, they have merely proved that quantum gravity cannot have any symmetry without clarifying how it is taken apart. For instance, their findings suggest that the proton should decay, yet they do not clarify how it decays or how long it can live for before it does. These are very important questions, which the researchers hope to address in their future research.

"The Kavli Institute for the Physics and Mathematics of the Universe at the University of Tokyo, of which I am the director, is involved in the Hyper-Kamiokande project to be built in the Kamioka zinc mine in the central mountain area in Japan," Ooguri added. "One of the aims of the project is to see whether the proton decays and to do this experimenters will build a large water tank in the mine. According to our theorem, the protons should decay. But, we cannot tell experimenters how big the water tanks should be for them to be able to see the protons decay within a reasonable period of time. This is one example of why quantifying how symmetry is broken would be crucial. Daniel and I have some idea on how to quantify the way symmetry is broken and we are now continuing our investigation in this direction." [39]

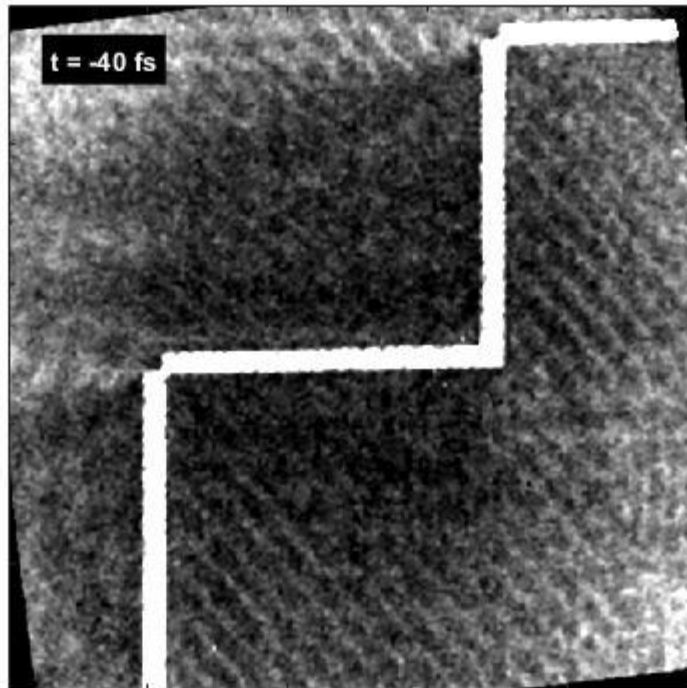
## **Holographic imaging of electromagnetic fields using electron-light quantum interference**

In [conventional holography](#) a photographic film can record the interference pattern of monochromatic light scattered from the object to be imaged with a reference beam of un-scattered light. Scientists can then illuminate the developed image with a replica of the reference beam to create a virtual image of the original object. [Holography](#) was originally proposed by the physicist [Dennis Gabor in 1948](#) to improve the resolution of an electron microscope, demonstrated using light optics. A [hologram](#) can be formed by capturing the phase and amplitude distribution of a signal by superimposing it with a known reference. The original

concept was followed by [holography with electrons](#), and after the invention of lasers optical holography became a popular technique for 3-D imaging macroscopic objects, [information encryption](#) and [microscopy imaging](#).

However, extending holograms to the [ultrafast domain](#) currently remains a challenge with electrons, although developing the technique would allow the highest possible combined [spatiotemporal resolution](#) for [advanced imaging applications](#) in condensed matter physics. In a recent study now published in *Science Advances*, Ivan Madan and an interdisciplinary research team in the departments of Ultrafast Microscopy and Electron Scattering, Physics, Science and Technology in Switzerland, the U.K. and Spain, detailed the development of a hologram using local [electromagnetic fields](#). The scientists obtained the electromagnetic holograms with combined [attosecond/nanometer](#) resolution in an [ultrafast transmission electron microscope](#) (UEM).

In the [new method](#), the scientists relied on electromagnetic fields to split an electron wave function in a quantum [coherent superposition](#) of different energy states. The technique deviated from the conventional method, where the signal of interest and reference spatially separated and recombined to reconstruct the amplitude and phase of a signal of interest to subsequently form a hologram. The principle can be extended to any kind of detection configuration involving a periodic signal capable of undergoing interference, including sound waves, [X-rays](#) or [femtosecond pulse waveforms](#).



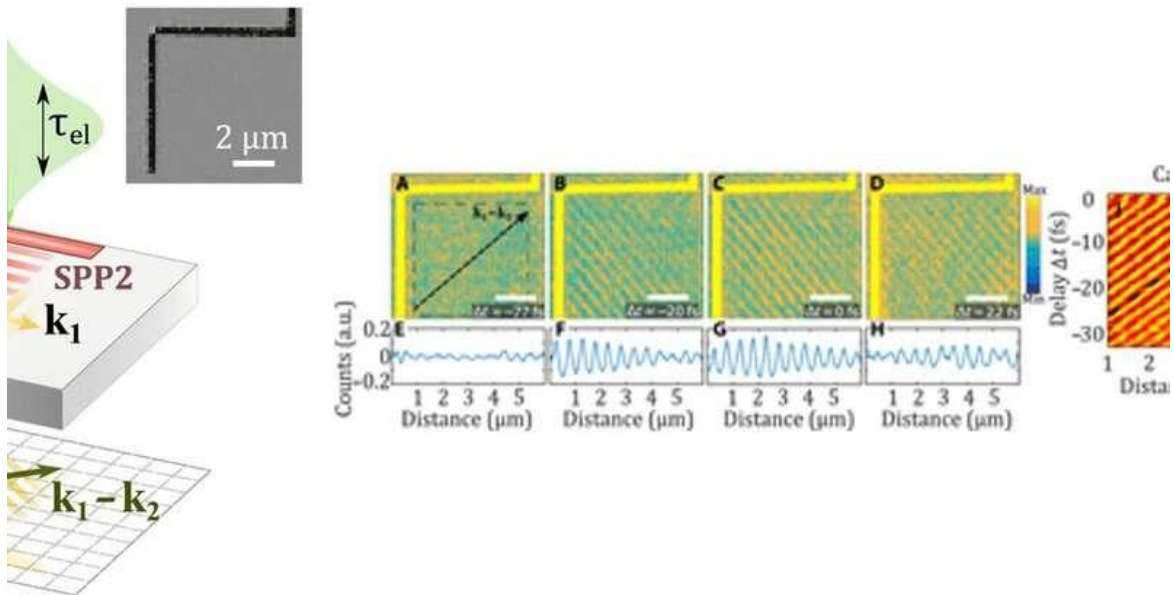
Plasmon hologram evolution with 0.33-fs time step. Credit: Science Advances, doi: 10.1126/sciadv.aav8358.

Further advances in the study of holography resulted in [time-resolved optical holography](#), successfully realized in the femtosecond regime for enhanced spatial resolution in time-resolved [photoemission electron spectroscopy](#) (tr-PEEM). Reaching the ultrafast domain can also become a reality, due to recent developments in ultrafast transmission electron microscopy using femtosecond lasers to [create ultrafast electron pulses](#). The developments have allowed real-time filming of [collective electronic modes](#), [strain fields](#) and [magnetic textures](#) at a resolution of a few hundred femtoseconds.

In the new work, Madan et al. demonstrated a time-domain holography imaging technique in an ultrafast transmission electron microscope (UEM). They based the technique on quantum coherent interaction of electron wave packets with multiple optical fields. To illustrate the method, Madan et al. captured attosecond/nanometer-resolved phase-sensitive movies of rapidly evolving electromagnetic fields in plasmonic structures. The scientists implemented two key experimental methods in the study in an approach to parallelly access the quantum coherence of generic electronic states. The work will be relevant for further electron quantum optics applications.

As a simple implementation of the holographic UEM, the scientists based the local interference of two fields on two propagating [surface plasmon polaritons](#) (SPPs) (i.e. a collective oscillation wave of free electrons along a metal). They described the interaction mechanism of the electron pulse with a single SPP using conventional photon-induced, near-field electron microscopy (PINEM) and then comparatively examined the holograms produced via the interference between two SPPs in a local holographic PINEM. During conventional PINEM, electrons can inelastically absorb or emit photon energy [quanta](#) and filter inelastically scattered electrons to allow the formation of real-space images of the plasmon fields.

## PINEM

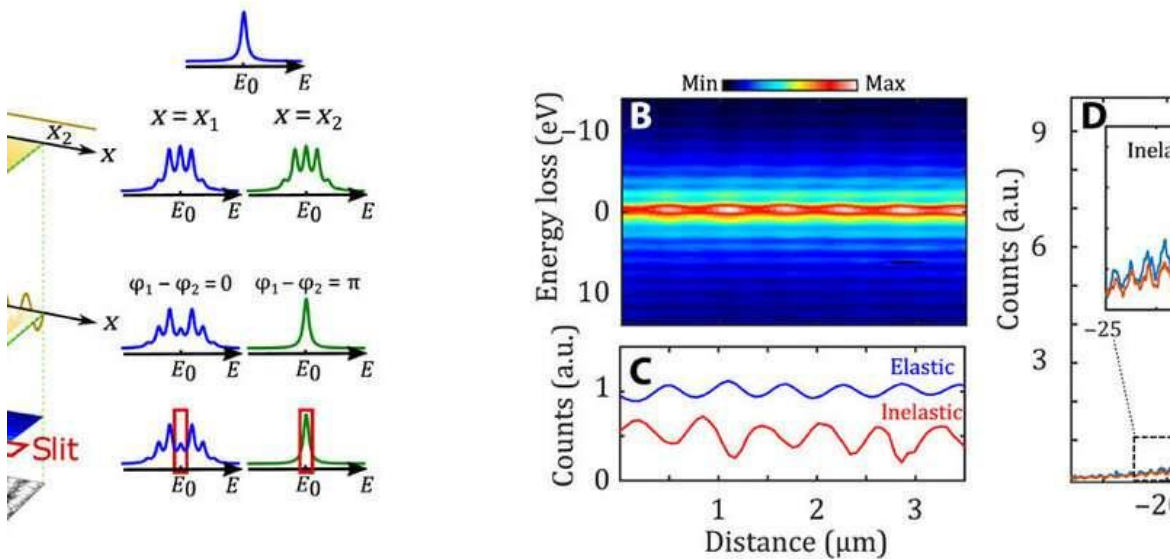


LEFT: Schematic illustration of local holographic PINEM, where two SPPs propagate with orthogonal wave vectors  $k_1$  and  $k_2$  forming a standing wave pattern along the direction  $k_1 - k_2$ , which is imaged as a periodic modulation in PINEM (the hologram). The interference contrast appears only when the two pulses overlap in space and time. Inset: SEM image of a fabricated structure. RIGHT: Holographic images formed by two pulses of orthogonal polarization at different delays. (A to D) Micrographs of PINEM images for different values of the relative time delay  $\Delta t$  between the photo-exciting pulses, as indicated in each image. Scale bars,  $2 \mu\text{m}$ . The SPP emitted from the vertical slit propagates from left to right. Correspondingly, the interference pattern moves from the bottom-left to the top-right corner. (E to H) Modulation of the electron counts along the  $k_1 - k_2$  direction indicated in (A), calculated as the average of counts along the direction orthogonal to  $k_1 - k_2$ , taken within the dashed square indicated in (A). (I) Evolution of the profiles shown in (E) to (H) as a function of delay between the two pulses; because of the experimentally adopted sample orientation, retardation effects cause the slope of the fringes (see dashed line as a guide) to be decreased by a factor of 0.71 with respect to the SPP phase velocity. (J) Envelope of the interference pattern as a function of delay between the two pulses, with the slope of the peak (see dashed line as a guide) also decreased by a factor of 0.71 with respect to the SPP group velocity. Envelope data have been acquired in a separate measurement

over a longer delay span and with larger time steps. a.u., arbitrary units. Credit: Science Advances, doi: 10.1126/sciadv.aav8358.

To implement the holographic PINEM concept, Madan et al. used an experimental nanostructure composed of two perpendicular slits, composed of silver (Ag) film fabricated by gallium (Ga) ion milling, deposited on a silicon nitride membrane ( $\text{Si}_3\text{N}_4$ ). They conducted the experiments in a [modified transmission electron microscope](#). In the work, the scientists used a second SPP wave as a reference and created an interference pattern with the SPP of interest to form a hologram when both waves overlapped in space and time. The scientists observed holograms formed by the 2 SPPs with relative pulse delays of -77, -20, 0 and 22 femtoseconds by energy filtering inelastically scattered electrons.

Madan et al. generalized the holographic approach using the coherence between different energy states of the quantum ladder, where the [electron wave function split upon interacting with light](#). Since [electrons carry information](#) about the amplitude and phase of the optical field, even after completing the interaction, the scientists exploited this fact to enable quantum holography. In the experiments, they made use of a semi-infinite light field created by the reflection of the optical beam from an electron transparent optical mirror, to create a material-independent reference field. The setup allowed nearly constant spatial amplitude and phase to prepare an optimum reference field for holography in the study.

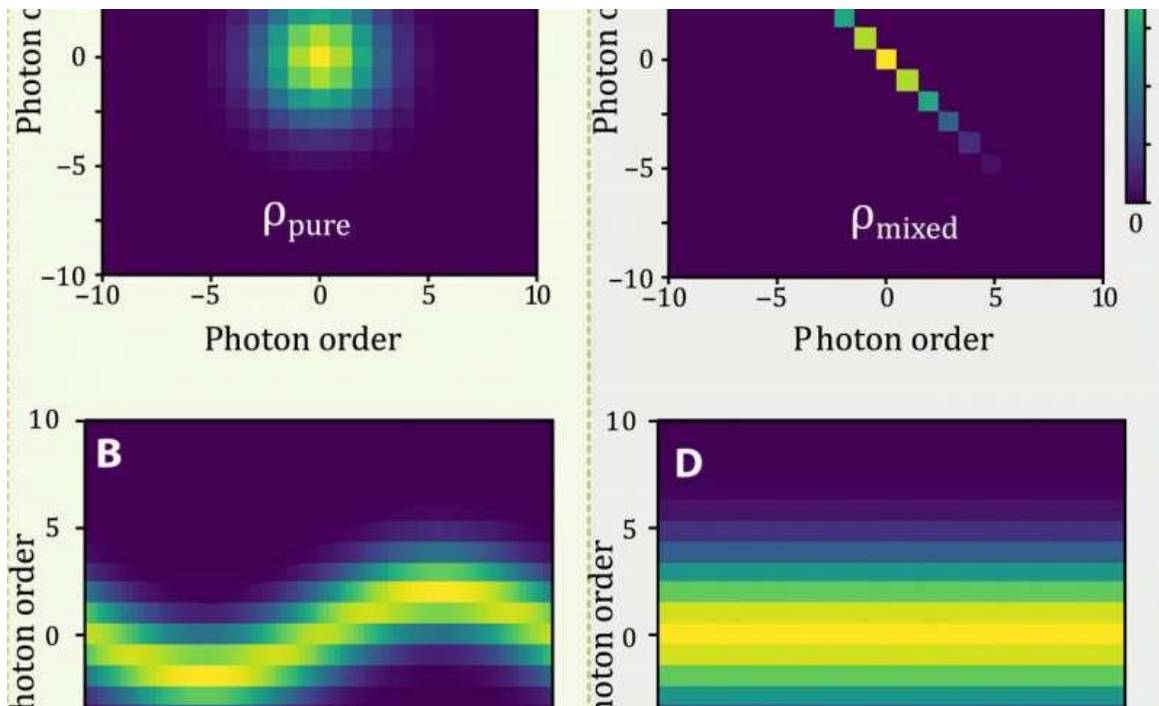


Principle of spatially separated electron holography. (A) The initial energy distribution of the electron beam is a function of energy that is singly peaked at  $E = E_0$  (right). Interaction with the reference field produces coherent superposition states with energies  $E = E_0 \pm n\hbar\omega$ . The ensuing interaction with an SPP depends on the relative phase between SPP and reference fields, which results in a position-dependent electron energy distribution. The elastic part of the electron spectrum is then used to form the 2D hologram. The spectra on the right are simulations from an analytical model. (B) Hybrid energy-space map (spectrogram) of the electrons after interaction

with the two fields, as schematized in (A). (C) Spatial profiles of the normalized intensity for elastic (blue curve) and inelastic (red curve) electrons, as obtained from (B) by energy-averaging from  $-1$  to  $1$  eV for the elastic contribution and from  $-27$  to  $-12$  eV for the inelastic one. (D) Energy profiles at the maximum and minimum of the spatial modulation shown in (B), averaged over four periods. Credit: Science Advances, doi: 10.1126/sciadv.aav8358.

In the context of this study, quantum coherence of an electron state did not refer to the coherence between electrons, but to a measure of the [monochromaticity](#) (singularity) and phase stability of the electron plane wave. Madan et al. used the term to determine if an electron was in a pure state or entangled state in the environment. In the quantum sense, therefore, the phase between different energy states was determined by the time evolution operator and not at random.

The scientists then reconstructed the complex electric field distribution around 3-D particles or nanostructures. They showed that the mathematical equivalence of local plasmon holography and spatially separated quantum holography allowed the recorded holograms to be treated with the same formalism of propagating standing waves. Madan et al. thus presented an observation of this effect by recording holograms formed by the tilted wavefront of the light reflected from a silver mirror and a plasmon wave emitted from a hole carved in the silver layer. The resulting pattern exhibited a periodicity that was naturally absent from an untilted hologram.



Proposal for the determination of the coherence of photoemitted electrons. (A) Density matrix of a fully coherent (pure) state created by photoemission. (B) Spatially dependent spectrogram formed after interaction of the pure state with an SPP. (C) Density matrix of the completely mixed state. (D) Spectrogram formed after interaction of the mixed state with an SPP. Credit: Science Advances, doi: 10.1126/sciadv.aav8358.



Using model calculations, Madan et al. discriminated between a highly coherent (pure) and fully incoherent (completely mixed) electron distribution. For this, they modelled the density matrix of photoelectrons generated, for example, using UV illumination of a solid target. They then coordinated the electron states to interact with a traveling plasmon polariton in the experimental setup. By observing the electron energy distribution, the scientists were able to establish if there was partial coherence in the photoemitted electrons. Based on the observation, they proposed a further extension of the UEM holographic imaging to practically realize quantum holographic UEM. The scientists envision using the technique to study potential objects of interest such as atomic polarizabilities, excitons, phonons, Higgs and other collective and quasiparticle excitations in condensed matter systems in the future.

The present work provided sufficient information to reconstruct the complete density matrix of an unknown electronic state, similar to a [previous approach](#) on quantum state reconstruction with attosecond pulse trains. But unlike previous work, this method can also use well-controlled SPP fields to realize a number of projective measurements in parallel.

In this way Madan et al. demonstrated both local and spatially separated holographic approaches based on [ultrafast transmission electron microscopy](#) (UEM). The scientists showed that the nonlocal character of the technique allowed to completely decouple the reference and probe fields, which was not previously possible with near-field optical or photoemission microscopy techniques. The work offers a unique perspective to achieve atomic and sub-femtosecond combined resolution within a transmission microscope. The method will allow a spatially resolved detection method of coherences in electron quantum states with great potential for electron quantum holography and additional applications. [38]

## **New holographic technique opens the way for quantum computation**

Photography measures how much light of different color hits the photographic film. However, light is also a wave, and is therefore characterized by the phase. Phase specifies the position of a point within the wave cycle and correlates to depth of information, meaning that recording the phase of light scattered by an object can retrieve its full 3-D shape, which cannot be obtained with a simple photograph. This is the basis of optical holography, popularized by fancy holograms in sci-fi movies like Star Wars.

But the problem is that the spatial resolution of the photo/hologram is limited by the wavelength of light, around or just-below 1  $\mu\text{m}$  (0.001 mm). That's fine for macroscopic objects, but it starts to fail when entering the realm of nanotechnology.

Now researchers from Fabrizio Carbone's lab at EPFL have developed a method to see how light behaves on tiniest scale, well beyond wavelength limitations. The researchers used the most

unusual photographic media: freely propagating electrons. Used in their ultrafast electron microscope, the method can encode quantum information in a holographic light pattern trapped in a nanostructure, and is based on an exotic aspect of electron and light interaction.

The scientists used the quantum nature of the electron-light interaction to separate the electron-reference and electron-imaging beams in energy instead of space. This makes it now possible to use light pulses to encrypt information on the electron wave function, which can be mapped with ultra-fast transmission electron microscopy.

Credit: Ecole Polytechnique Federale de Lausanne

The new method can provide us with two important benefits: First, information on light itself, making it a powerful tool for imaging electromagnetic fields with attosecond and nanometer precision in time and space. Second, the method can be used in quantum computing applications to manipulate the quantum properties of free electrons.

"Conventional holography can extract 3-D information by measuring the difference in distance that light travels from different parts of the object," says Carbone. "But this needs an additional reference beam from a different direction to measure the interference between the two. The concept is the same with electrons, but we can now get higher spatial resolution due to their much shorter wavelength. For example, we were able to record holographic movies of quickly moving objects by using ultrashort electron pulses to form the holograms."

Beyond quantum computations, the technique has the highest spatial resolution compared to alternatives, and could shift the way we think about light in everyday life. "So far, science and technology have been limited to freely propagating photons, used in macroscopic optical devices," says Carbone. "Our new technique allows us to see what happens with light at the nanoscale, the first step for miniaturization and integration of light devices onto integrated circuits." [37]

## Holographic acoustic tweezers could be used to create 3D displays

A holographic acoustic tweezers (HAT) system has been used to suspend up to 25 objects in mid-air simultaneously. The feat was achieved by [Bruce Drinkwater](#) at the University of Bristol in the UK and [Asier Marzo](#) at the Public University of Navarra in Spain, who used a complex array of loudspeakers to create an intricate, controllable field of sound waves. The duo believes that their setup could have important medical applications in the near future, and could also be used to create physical 3D hologram displays.

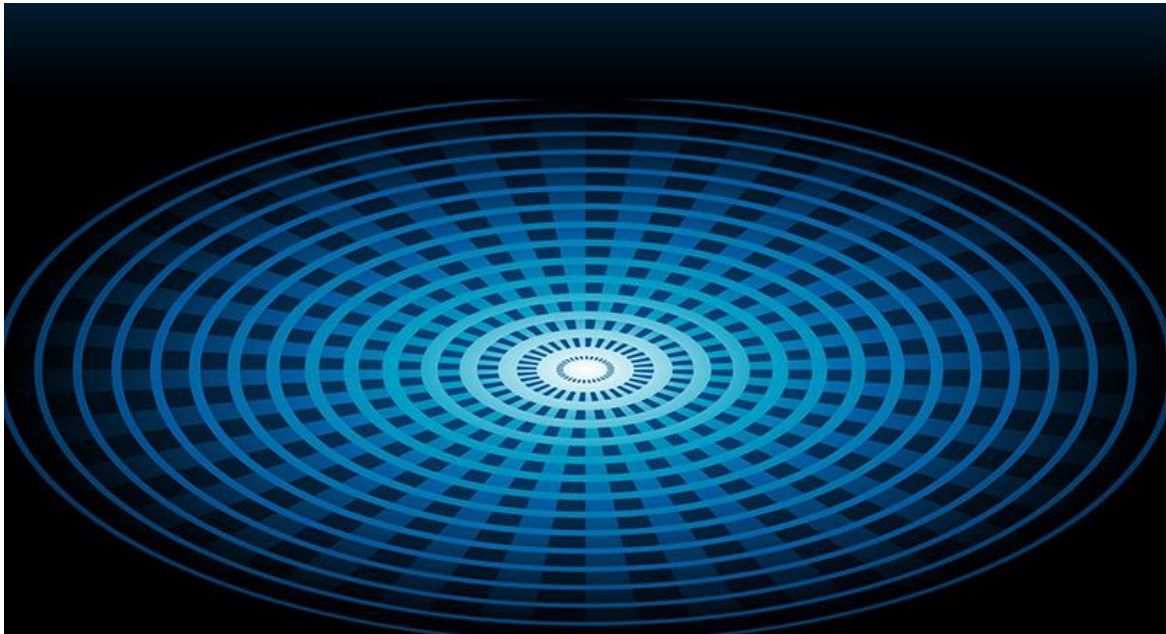
Optical tweezers were invented in 1986 by [Arthur Ashkin](#), who shared the 2018 Nobel Prize for showing that small dielectric objects including bacteria and viruses can be levitated and

manipulated with a focussed beam of laser light. Since then, holographic optical tweezers (HOTs) have been developed to manipulate multiple objects and assemble 3D microstructures. However, HOTs have several shortcomings. Since light can only travel through transparent media, HOTs are unable to operate within more opaque media, including human tissues. Another problem is that the lasers used to create HOTs deliver a significant amount of energy, which can damage objects such as living cells.

In contrast, HATs allow for manipulations of objects within a wide variety of liquid and solid media. HATs operate with over 100,000 times greater power efficiency than HOTs, which means that far less energy is delivered to the objects – resulting in less damage to the objects being manipulated. Furthermore, HATs are able to manipulate larger objects (up to the centimetre scale) than HOTs.

### **Intricate sound field**

Drinkwater and Marzo have built a HAT system that offers the benefits of a HOT, while using far less energy. Their system is directed by an algorithm that creates an intricate sound field by the precise control of the phases of 40 kHz sound waves emitted by an array of 256 small loudspeakers.



### **The wonderful world of ultrasound**

They tested the setup, firstly by suspending up to 25 millimetre-sized polystyrene spheres in mid-air simultaneously. The researchers were also able to sew a length of thread into a piece of fabric, simply by attaching a polystyrene sphere to each end and precisely controlling their movements.

Drinkwater and Marzo are confident that HATs could soon be used to assemble objects on micron and millimetre scales. By creating yet more intricate fields of sound waves, their technology could be used to suspend large arrays of physical 3D pixels. This could be used to create tangible hologram displays in mid-air.

The duo will now work towards adapting their existing setup to manipulate objects within water; aiming to demonstrate the technology in around a year's time. Soon after this demonstration, they hope that their methods will be adapted further, enabling the manipulation of objects within biological tissues, potentially allowing for intricate, non-invasive cell positioning and targeted drug delivery. [36]

## **Multichannel vectorial holographic display and encryption**

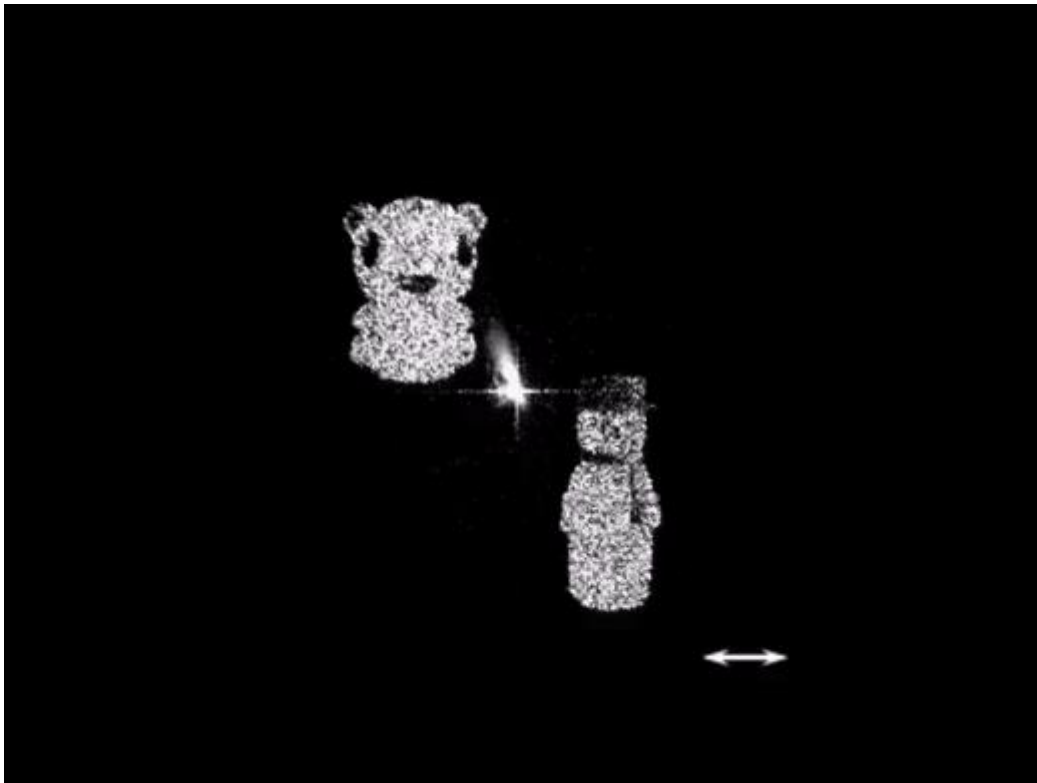
Holography is a powerful tool that can reconstruct wavefronts of light and combine the fundamental wave properties of amplitude, phase, polarization, wave vector and frequency. Smart multiplexing techniques (multiple signal integration) together with [metasurface designs](#) are currently in high demand to explore the capacity to engineer information storage systems and enhance optical encryption security using such metasurface holograms.

Holography based on metasurfaces is a promising candidate for applications in optical displays/storage with enormous [information bearing capacity](#) alongside a [large field of view](#) compared to traditional methods. To practically realize [metasurface](#) holograms, holographic profiles should be encoded on [ultrathin nanostructures](#) that possess [strong light-matter interactions](#) ([plasmonic](#) interactions) in an ultrashort distance. Metasurfaces can control light and acoustic waves in a manner not seen in nature to provide a flexible and compact platform and realize a variety of vectorial holograms, with high dimensional information that surpass the limits of [liquid crystals](#) or optical photoresists.

Among the existing techniques employed to achieve highly desired optical properties, [polarization multiplexing](#) (multiple signal integration) is an attractive method. The strong cross-talk associated with such platforms can, however, be prevented with [birefringent metasurfaces](#) (two-dimensional surfaces with two different refractive indices) composed of a single meta-atom per unit-cell for optimized [polarization](#) multiplexing.

Nevertheless, the full capacity of all polarization channels remains to be explored for improved information storage capacity within metasurface holograms and in holographic optical devices. In a recent study, Ruizhe Zhao and co-workers demonstrated a new method to realize multichannel vectorial holography for dynamic display and high-security applications. In the study, birefringent metasurfaces were explored to control polarization channels and process very different

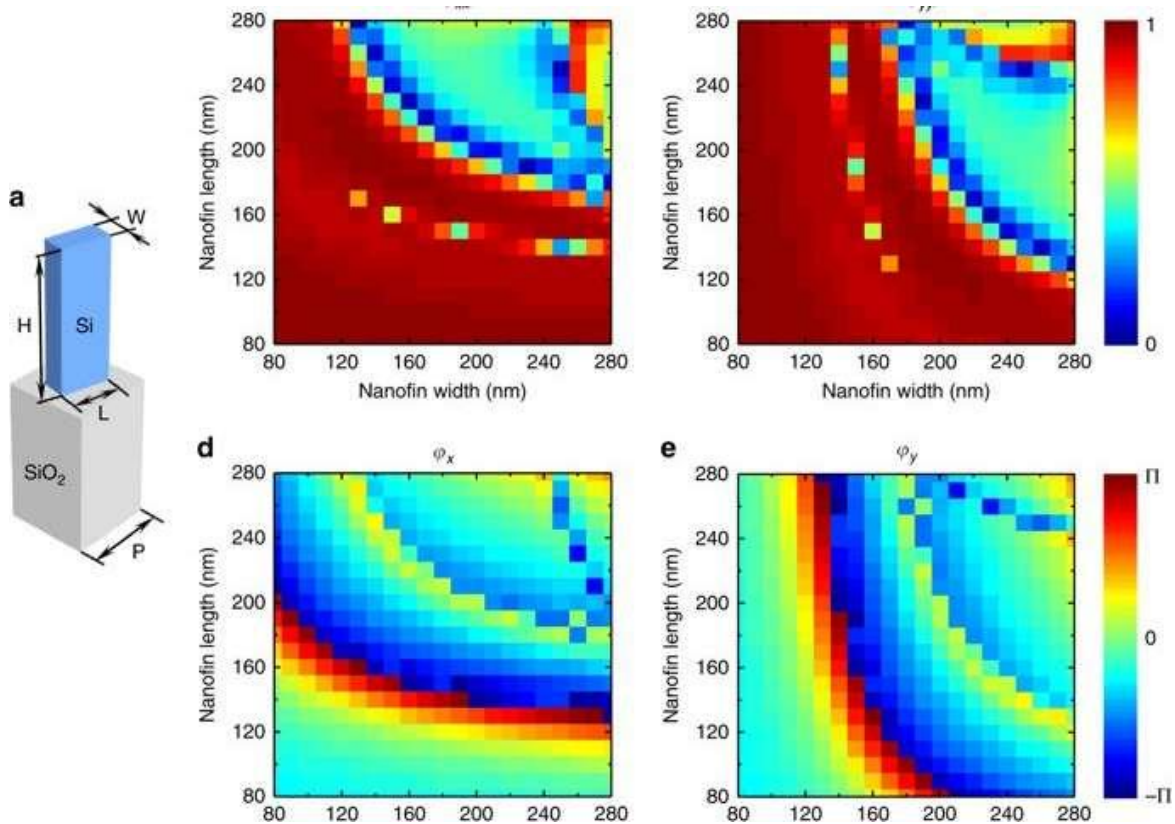
information through rotation. The reconstructed vectorial images could be switched from one form to another with negligible cross-talk by selecting a combination of input/output polarization states. The results are now published in *Light: Science & Applications*.



The two-channel polarization and angle-multiplexed hologram represents a cartoon tiger, cartoon snowman, teapot and teacup. Credit: *Light: Science & Applications*, doi: 10.1038/s41377-018-0091-0.

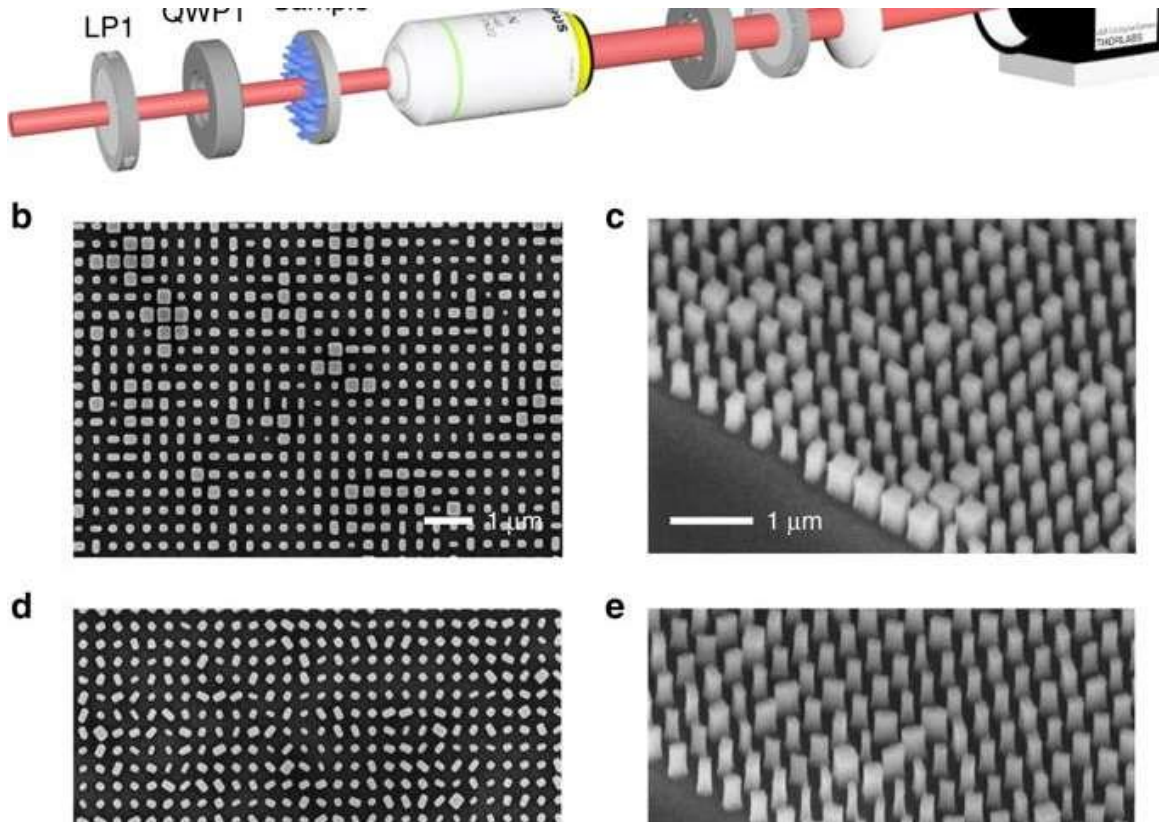
The scientists first derived a multiplexing algorithm to support the dynamic vectorial holographic display and encryption process. By using the correct polarization keys, the receiver could obtain the exact information delivered. By increasing the complexity of such images, even higher flexibility was obtained alongside detailed analysis of the reconstructed vectorial image properties. Since the device containing metasurfaces is compact in size, in practice, it can be easily transported with encoded information.

To pattern the design of interest, Zhao et al. engineered several dielectric silicon metasurfaces on top of a glass substrate using plasma etching, followed by electron beam lithography. The metasurfaces were composed of 1000 x 1000 nanofins, i.e. nanostructures with the ability to augment heat transfer via surface area enhancement and liquid-solid-interactions. The researchers studied two schemes of multiple polarization channels; with or without rotation using the birefringent dielectric metasurfaces—to realize the holograms.



a) Schematic illustration of an amorphous silicon nanofin positioned on a glass substrate. The metasurface will be composed of a periodic arrangement of such unit-cells. b–e) Simulation results for the amplitude and phase of the ...[more](#)

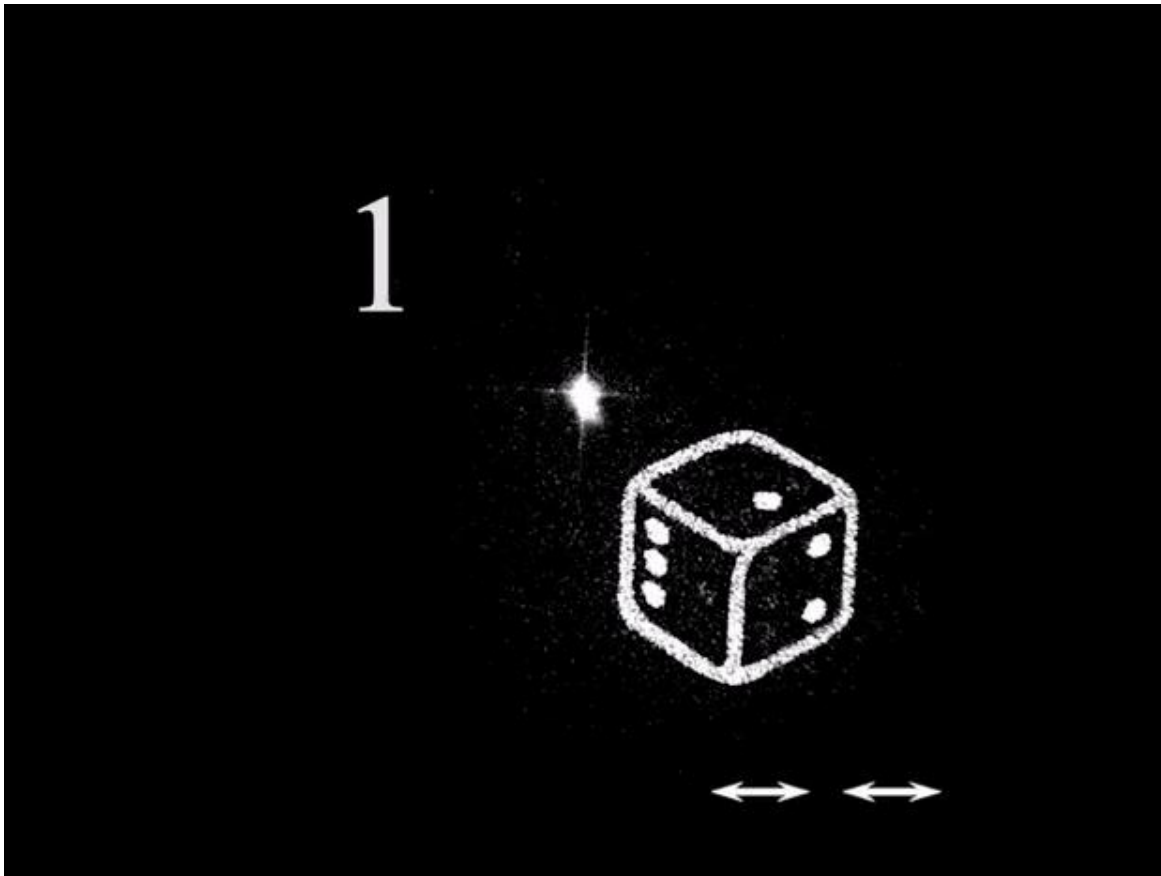
The birefringent dielectric metasurfaces were designed using silicon nanofins on top of a glass substrate. To achieve the desired phase shifts, 2-D parameter optimization was conducted using a rigorous coupled wave analysis (RCWA) method. The RCWA semi-analytical method is typically applied in computational electromagnetics to solve scattering from periodic dielectric structures. The length  $L$  and width  $W$  of the nanofin were in the range of 80 to 280 nm, height at 600 nm and period size  $P$  at 400 nm. The values were carefully selected to ensure the phase of the output light eliminated any undesired orders of diffraction. For the simulation, the nanofin was placed on a glass substrate and subjected to a fixed wavelength of incident light at 800 nm. Simulation results indicated the amplitude of transmission for most nanofins with diverse cross-sections were beyond 90 percent efficiency. The scientists determined orientation angles of the nanofins using equations derived in the study to experimentally demonstrate multichannel polarization multiplexing.



Experimental setup and scanning electron microscopy images of the fabricated metasurface samples. a) The experimental setup for the observation of the holographic images. The two linear polarizers (LP1, LP2) and two quarter-wave plates ...[more](#)

For optical characterization of the metasurface holograms, Zhao et al. used an [experimental setup](#). The magnifying ratio and numerical aperture of the objective lens were carefully chosen to collect all the diffraction light from the sample and reconstruct holographic images in the Fourier plane. The scientists used a second objective/lens to capture the Fourier plane on a CCD camera. They also separately observed two scanning electron microscopy images of the samples with or without rotation to characterize the engineered surface.

As a proof-of-principle, using the metasurfaces, Zhao et al. constructed holographic images of a cartoon tiger and a snowman that appeared with high fidelity and high resolution when illuminated by x-polarized light. When the incident light was switched to y-polarization, the reconstructed images changed to a teapot and a teacup. In this experiment, only two polarization channels were available in the setup, with both pairs of the holographic images reconstructed and made to disappear simultaneously by rotating the polarizer behind the sample. The [experimental results](#) were in agreement with the simulation to confirm the study's fundamental design principle. The net diffraction efficiency of the hologram was defined as the ratio of intensity of the single reconstructed image to the power of incident light.



Multichannel polarization-multiplexed holograms (“Dice”). Credit: Light: Science & Applications, doi: 10.1038/s41377-018-0091-0.

The scientists were able to design and construct more complex multiplexing functionalities with 12 channels using the same principles of design thereafter. The vectorial images were viewed as holographic reconstructions with the input/output polarization combinations developed as proposed. The technique could also be used to encrypt different images at the same spatial location. In encryption, such superposition can convey a different meaning on reconstruction. As an example, the scientists chose the image of a die with six representative surfaces, and by using different combinations of input/output polarization states, encoded up to six images for viewing.

The multiplexing algorithm derived in the study aided the dynamic vectorial holographic display and the encryption of images encoded on birefringent dielectric metasurfaces. By using the correct polarization keys, a receiver could obtain the exact information delivered. Higher flexibility could be obtained by increasing the complexity of the image and changing the medium of encryption to titanium dioxide (TiO<sub>2</sub>) or silicon nitride (SiN). The correct polarization combination secured the information for enhanced complexity during decryption.

The multichannel hologram maintained a relatively large working bandwidth since the reconstructed images could be observed away from the designed wavelength of 800 nm. The study established a design and engineering technique that combined birefringent properties of



simple nanofins used as the building blocks, with extra-design freedom of rotation matrix and smart multiplexing algorithms. The results enabled high-dimensional multichannel polarization multiplexed holograms, with up to 12 polarization channels. In this way, efficient light-based encryption and integrated multichannel holographic display techniques can pave the way for advanced communication in high security applications. [35]

## Blasting molecules with extreme X-rays

Reading these words, your eyes let you see each letter and the spaces between them. But if you need reading glasses, the letters may be fuzzy or incomprehensible. Scientists face a similar challenge. Gathering the right data depends on having tools that can provide accurate, comprehensive measurements. After all, scientists want to have the clearest sight possible.

Physicist Artem Rudenko from Kansas State University and his colleagues pondered how to improve the images of viruses and microparticles that scientists get from X-rays. To dig into the issue, they shot the most powerful X-ray laser in the world—located at the Department of Energy (DOE) Office of Science's Linac Coherent Light Source (LCLS)—at a series of [atoms](#) and molecules.

## Can We Trust What We See?

Scientists regularly use X-ray light sources to take pictures and videos of biological and chemical processes and objects. For example, a recent study at the LCLS looked at how antibiotics and the parts of the body that produce proteins interact.

But like a farsighted person's eyes, these instruments can affect scientists' perception. In less time than it takes light to travel a millimeter, the X-ray obliterates the sample. But the X-ray damages the sample long before it's annihilated—even while scientists are trying to capture their images.

This means the images captured are of a damaged sample, not the original. That can distort the data and how scientists interpret it.

Scientists have done quite a bit of work studying the effects of lower energy "soft" X-rays. They concluded images from soft X-rays provide a good reproduction of the original structures despite the damage.

But most imaging research uses higher energy "hard" X-rays because they often provide more detail. Scientists had less data about the damage very intense hard X-rays cause. They had no equivalent to an eye chart to estimate the extent of the problem or what might need to be adjusted. Rudenko and his colleagues aimed to change that.

## The Only Spot in the World

It was obvious where they needed to go—the LCLS.

"That was the only spot in the world that we could focus this [amount of] light," said Rudenko.

The team looked at how X-rays affect heavy atoms with lots of protons, neutrons, and electrons. Many heavy atoms play important functions in biological reactions, such as iodine's role in producing hormones. Because heavy atoms interact more with X-rays than light ones, scientists often use heavy atoms to get clearer images.

Like everyone else, the team had to compete for time at the LCLS, an Office of Science user facility hosted by DOE's SLAC National Accelerator Laboratory. They rewrote and resubmitted their proposal three times before it was accepted. Compared to medical research, it was a tough sell. "We just wanted to blast the heck out of a molecule," said Daniel Rolles, an assistant professor at Kansas State University. "Our argument was, 'Hey look, you guys can only understand what you're doing if you let us do our stuff first.'"

### **The Moment of Truth**

It was finally time to turn on the X-ray.

"It was just all knobs to the right," said Rolles. "We basically went all-out in terms of intensity."

First, they hit a xenon atom with the LCLS's full power.

That reaction went as expected. The X-ray ionized electrons close to the nucleus, blasting them out of the atom. As the closest spaces emptied out, electrons further away moved inward. Then the new electrons became energized and zoomed out of the atom as well. Within a millionth of a billionth of a second, that process repeated itself until only a few electrons were left. Overall, a single xenon atom ejected 48 of its 54 electrons.

Satisfied, the team ran the entire experiment again. This time, they pointed the X-ray at an iodine atom surrounded by a few others in a molecule.

That's when things got weird.

"It was clear that there was something happening under these experimental conditions that we hadn't seen anywhere else, so that was very exciting," said Rebecca Boll, a scientist on the study who works at the European X-Ray Free Electron Laser facility.

The team expected the iodine to eject, suck in, and then eject more electrons the way the xenon did. But when iodine ran out of electrons, it didn't stop. Instead, the iodine slurped up electrons from surrounding carbon and hydrogen atoms. After ejecting 47 of its own electrons, it cycled through seven more. By the end, the iodine fundamentally altered the carbon and hydrogen's electron structures.

The team wanted to see if the same thing would happen with a bigger molecule. Sticking another iodine-containing molecule under the X-ray, they watched as it spit out so many fragments that it was difficult to keep track of them. They estimated it ejected more than 60 electrons.

## Revealing the Why

While the researchers knew what happened, they didn't know why. An iodine atom losing two electrons could result in a huge number of possible electron structures. Not only did the iodine atom lose more than 50 electrons, its structure completely changed after each loss.

To help explain this process, they turned to their colleagues in theoretical physics at the Center for Free-Electron Laser Science in Germany. Modeling revealed that under lower intensities, both the atom by itself and the atom within the molecule absorb just a few photons at a time. At the LCLS, the molecule absorbed up to 20 photons—far more than an atom. That super-charged the system.

Finding out X-rays can strongly affect atoms besides the one directly hit by the X-ray showed that scientists have to take a second look at their images. In the future, the team predicts they will be able to plot out an X-ray's effects on a particular molecule. Just as reading glasses adjust a farsighted person's sight, scientists will be able to better account for radiation's influence on their results. That knowledge will help them see a clearer picture than ever before. [34]

## A 3-D imaging technique unlocks properties of perovskite crystals

A team of materials scientists from Penn State, Cornell and Argonne National Laboratory have, for the first time, visualized the 3-D atomic and electron density structure of the most complex perovskite crystal structure system decoded to date.

Perovskites are minerals that are of interest as electrical insulators, semiconductors, metals or superconductors, depending on the arrangement of their atoms and electrons.

Perovskite crystals have an unusual grouping of oxygen atoms that form an octahedron—an eight-sided polygon. This arrangement of oxygen atoms acts like a cage that can hold a large number of the elemental atoms in the periodic table. Additionally, other atoms can be fixed to the corners of a cube outside of the cage at precise locations to alter the material's properties, for instance in changing a metal into an insulator, or a non-magnet into a ferromagnet.

In their current work, the team grew the very first discovered perovskite crystal, called calcium titanate, on top of a series of other perovskite crystal substrates with similar but slightly different oxygen cages at their surfaces. Because the thin film perovskite on top wants to conform to the structure of the thicker substrate, it contorts its cages in a process known as tilt epitaxy. The researchers found this tilt epitaxy of calcium titanate caused a very ordinary material to become ferroelectric—a spontaneous polarization—and to remain ferroelectric up to 900 Kelvin, around three times hotter than room temperature. They were also able to visualize the three-dimensional electron density distribution in calcium titanate thin film for the first time.

"We have been able to see atoms for quite some time, but not map them and their electron distribution in space in a crystal in three dimensions," said Venkat Gopalan, professor of [materials](#) science and physics, Penn State. "If we can see not just where [atomic nuclei](#) are

located in space, but also how their electron clouds are shared, that will tell us basically everything we need to know about the material in order to infer its properties."

That was the challenge the team set for itself over five years ago when Gopalan gave the project to his student and lead author of a new report in *Nature Communications*, Yakun Yuan,. Based on a rarely used X-ray visualization technique called COBRA, (coherent Bragg rod analysis) originally developed by a group in Israel, Yuan figured out how to expand and modify the technique to analyze one of the most complicated, least symmetrical material systems studied to date. This system is a strained three-dimensional perovskite crystal with octahedral tilts in all directions, grown on another equally complex crystal structure.

"To reveal 3-D structural details at the [atomic level](#), we had to collect extensive datasets using the most brilliant synchrotron X-ray source available at Argonne National Labs and carefully analyze them with the COBRA analysis code modified for accommodating the complexity of such low symmetry," said Yuan.

Gopalan went on to explain that very few perovskite oxygen cages are perfectly aligned throughout the material. Some rotate counterclockwise in one layer of atoms and clockwise in the next. Some cages are squeezed out of shape or tilt in directions that are in or out of plane to the substrate surface. From the interface of a film with the substrate it is grown on, all the way to its surface, each atomic layer may have unique changes in their structure and pattern. All of these distortions make a difference in the material properties, which they can predict using a computational technique called density functional theory (DFT).

"The predictions from the DFT calculations provide insights that complement the experimental data and help explain the way that material properties change with the alignment or tilting of the [perovskite](#) oxygen cages," said Susan Sinnott, head and professor of Materials Science and Engineering, whose group performed the theoretical calculations.

The team also validated their advanced COBRA technique against multiple images of their material using the powerful Titan transmission electron microscope in the Materials Research Institute at Penn State. Since the electron microscopes image extremely thin electron transparent samples in a 2-D projection, not all of the 3-D image could be captured even with the best microscope available today and with multiple sample orientations. This is an area where 3-D dimensional imaging by the COBRA technique outperformed the electron microscopy in such complex structures.

The researchers believe their COBRA technique is applicable to the study of many other 3-D, low-symmetry atomic crystals. [33]

## Seeing the light: Researchers offer solution for efficiency problem of artificial photosynthesis

Hydrogen-powered electronics, travel, and more may be a step closer thanks to the work of a collaborative team of scientists in Japan. The researchers have developed an efficient method to produce a key component needed to convert solar energy and water into hydrogen fuel, a process called photoelectrochemical water splitting. They published their results in October in *Applied Energy Materials*, a journal of the American Chemical Society.

"With the abundance of solar energy and water, photoelectrochemical water splitting is a promising way to ease [global environment](#) and energy-storage issues," said lead author Katsuya Teshima, a professor of the Department of Materials Chemistry and the director of the Center for Energy and Environmental Science at Shinshu University. Teshima is also affiliated with the Nagano Prefecture Nanshin Institute of Technology.

In water splitting, a photo anode, which is a semiconductor and a metal cathode, absorbs sunlight. The semiconductor absorbs high-energy photons from that light, which forces splitting of the molecules around the semiconductor. This causes oxygen to divorce from hydrogen and combine with other free oxygen molecules. Hydrogen pairs and oxygen pairs can then be separately funneled through to the appropriate cathodes to be stored and used as energy.

The problem, however, according to Teshima and coworker, Suzuki, is that the first proposed photo anodes could only absorb UV light, which accounts for about five percent of the solar spectrum. Made of titanium oxide, these photo anodes are highly efficient at converting the solar energy they do capture, but they're not a viable option for industrial use because they capture so little [solar energy](#).

Teshima and his team have turned to tantalum nitride, one of the most promising light-responsive materials available for use in water splitting. Not only can it absorb visible light, but it can also absorb light with a wavelength up to 600 nanometers, which allows for even more light absorption. The researchers previously fabricated the tantalum nitride crystals, but the process was complicated and the resulting crystal layer varied in thickness and coverage. Such unevenness can lead to inefficient or even completely ineffective water splitting efforts.

In this new attempt, Teshima placed the metal tantalum samples on top of powder sodium compounds, and heated them with ammonia gas at high temperatures. The researchers could control how evenly the sodium compounds reacted with the tantalum, as well as how thick the crystal layer grew by altering the ratio of the sodium compounds, the temperature, and the time.

"Our ultimate goal is to efficiently produce hydrogen and oxygen gases from natural [water](#) by use of our flux-grown photo anode," Teshima said. "As environment and energy problems are global issues, we want to contribute to their solutions." [32]

## Controlling photons with a photon

Photons are considered to be ideal information carriers and expected to play important roles in quantum communication and information processing, where quantum mechanics allows for absolutely secure cryptographic key distribution as well as computation much faster than conventional computers. In order to take full advantage of quantum information carried by photons, it is important to make them directly interact with each other for information processing.

However, photons generally do not interact with one another. So it is necessary to mediate such interactions with matter to realize effective photon-photon interaction, but light-matter interaction is usually extremely weak in normal media.

Haruka Tanji-Suzuki and colleagues at the Institute for Laser Science, the University of Electro-Communications, Tokyo, are currently working to develop all-optical quantum devices that are sensitive to a single photon input, such as a single photon switch in which an incoming photon switches the state of another photon.

In order to realize the strong [light-matter interaction](#) that is necessary for such devices, Tanji-Suzuki uses a laser-cooled ensemble of 87Rb atoms (~10 uK) trapped within a high-finesse optical resonator (finesse ~50000) in an ultrahigh-vacuum chamber. Notably, in order to switch a photon with a photon in such a system, the researchers use an effect known as 'vacuum-induced transparency' observed recently by Tanji-Suzuki et al., in which an electromagnetic field as weak as a vacuum field (light with no photons) is shown to alter the optical properties of atoms.

"The realization of such all-optical single-[photon](#) devices will be a large step towards deterministic multi-mode entanglement generation as well as high-fidelity photonic quantum gates that are crucial for all-optical [quantum information processing](#)," says Tanji-Suzuki. [31]

## The photoelectric effect in stereo

In the photoelectric effect, a photon ejects an electron from a material. Researchers at ETH have now used attosecond laser pulses to measure the time evolution of this effect in molecules. From their results they can deduce the exact location of a photoionization event.

When a photon hits a material, it can eject an electron from it provided it has enough energy. Albert Einstein found the theoretical explanation of this phenomenon, which is known as the photoelectric effect, in Bern during his "year of wonders" 1905. That explanation was a crucial contribution to the development of quantum mechanics, which was under way at the time, and it earned him the Nobel Prize in Physics in 1921. An international team of physicists led by Ursula

Keller at the Institute for Quantum Electronics of the ETH Zurich has now added a new dimension to the experimental investigation of this important effect. Using attosecond laser pulses they were able to measure a tiny time difference in the ejection of the electron from a molecule depending on the position of the electron inside the molecule.

"For quite some time, people have studied the [time evolution](#) of the photoelectric effect in [atoms](#)", says Ph.D. student Jannie Vos, "but very little has so far been published on [molecules](#)." That is mainly due to the fact that molecules are considerably more complex than single atoms. In an atom, the outermost electron moving around the atomic nucleus is essentially catapulted out of its orbit. In a molecule, by contrast, two or more nuclei share the same electron. Where it is located depends on the interplay between the different attractive potentials. Exactly how the [photoelectric effect](#) happens under such conditions could only now be studied in detail.

To do so, Keller and her co-workers used carbon monoxide molecules, which consist of two atoms – one carbon and one oxygen atom. Those molecules were exposed to an extreme ultraviolet laser pulse that only lasted for a few attoseconds. (An attosecond is the billionth part of a billionth of a second). The energy of the ultraviolet photons ripped an electron out of the molecules, which subsequently broke up into their constituent atoms. One of those atoms turned into a positively charged ion in the process. Using a special instrument, the researchers then measured the directions in which the electrons and ions flew away. A second laser pulse, which acted as a kind of measuring stick, also allowed them to determine the precise instant at which the electron left the molecule.

"In this way we were able, for the first time, to measure the so-called Stereo Wigner time delay," explains Laura Cattaneo, who works as a postdoctoral researcher in Keller's group. The stereo Wigner time delay measures how much earlier or later an electron leaves the molecule if it is located close to the [oxygen atom](#) or to the carbon atom when photoionization occurs. The extremely short laser pulses make it possible to measure that instant to within a few attoseconds. From that information, in turn, it is possible to determine the location of the ionization event inside the molecule to within a tenth of a nanometre. The experimental results agree well with theoretical predictions that describe the most likely position of an electron at the time of photoionization.

Next, the ETH researchers want to take a closer look at larger molecules, starting with the laughing gas N<sub>2</sub>O. The extra atom in that molecule already makes the theoretical description quite a bit more difficult, but at the same time the physicists hope to obtain new insights, for example into the so-called charge migration inside molecules, which plays an important role in chemical process.

In principle it should even be possible to use attosecond laser pulses not just to study those processes, but also to deliberately steer them and thus to control chemical reactions in detail. Right now, however, such atto-chemistry is still a long way off, as Jannie Vos points out: "In theory that's all very exciting, but a lot remains to be done before we get there." [30]

## Core electron topologies in chemical bonding

YNU researchers have solved the age-old mystery of why silicon cannot replace carbon in organic compounds. A new benchmark quantum chemical calculation of  $C_2$ ,  $Si_2$ , and their hydrides reveals a qualitative difference in the topologies of core electron orbitals of organic molecules and their silicon analogues. The researchers propose other elements with carbon's propensity to reshape their core electron nodal structures upon chemical bonding.

Since the discovery of [silicon](#) and Wöhler's success in the mid-19th century with synthesizing organic compounds, Wöhler himself was among the first to suggest replacing carbon by silicon in [organic compounds](#). It became clear in the early 20th century that silicon does not have a chemistry similar to carbon, and dreams of silicon-based life only survive in science fiction. We know empirically that carbon has the capability to form a variety of unsaturated compounds, which silicon does not. However, the root cause of why only carbon has this capability has remained a mystery.

Quantum chemical calculations of unprecedented accuracy carried out at YNU reveal that [core electrons](#) (which were not supposed to participate in [chemical bonding](#)) have a very different role in the unsaturated compounds of carbon and silicon. Carbon has the propensity to alter the topology (nodal structure) of its core electrons, which, for  $C_2$ , results in the formation of a torus-like ring in the  $1\sigma_g$  orbital formed of  $C1s$  electrons (see Figure).  $Si_2$ , however, maintains the spherical like core orbitals centered at each atomic site in all its molecules. This flexibility of carbon's core orbitals allows [carbon](#) to form a cornucopia of different valence bond structures, whereas silicon is restricted to bond structures orthogonal to the atomic like spherical core orbitals.

The impact of this discovery is far-reaching. Core electrons have thus far been assumed more or less inert, but perhaps it becomes necessary to reassess their contribution to [chemical bonding](#)—at least in the case of unsaturated bonds. Finally, the study suggests that other elements, such as nitrogen, phosphorous, and fluorine, exhibit similar flexibility to modify their core electron topologies, and thus, exhibit similarly rich chemistries.

The paper, "Core Electron Topologies in Chemical Compounds: Case Study of Carbon versus Silicon," is published in *Angewandte Chemie International Edition* vol 57(24) on June 6th, 2018. [29]



## **New optical sensor can determine if molecules are left or right 'handed'**

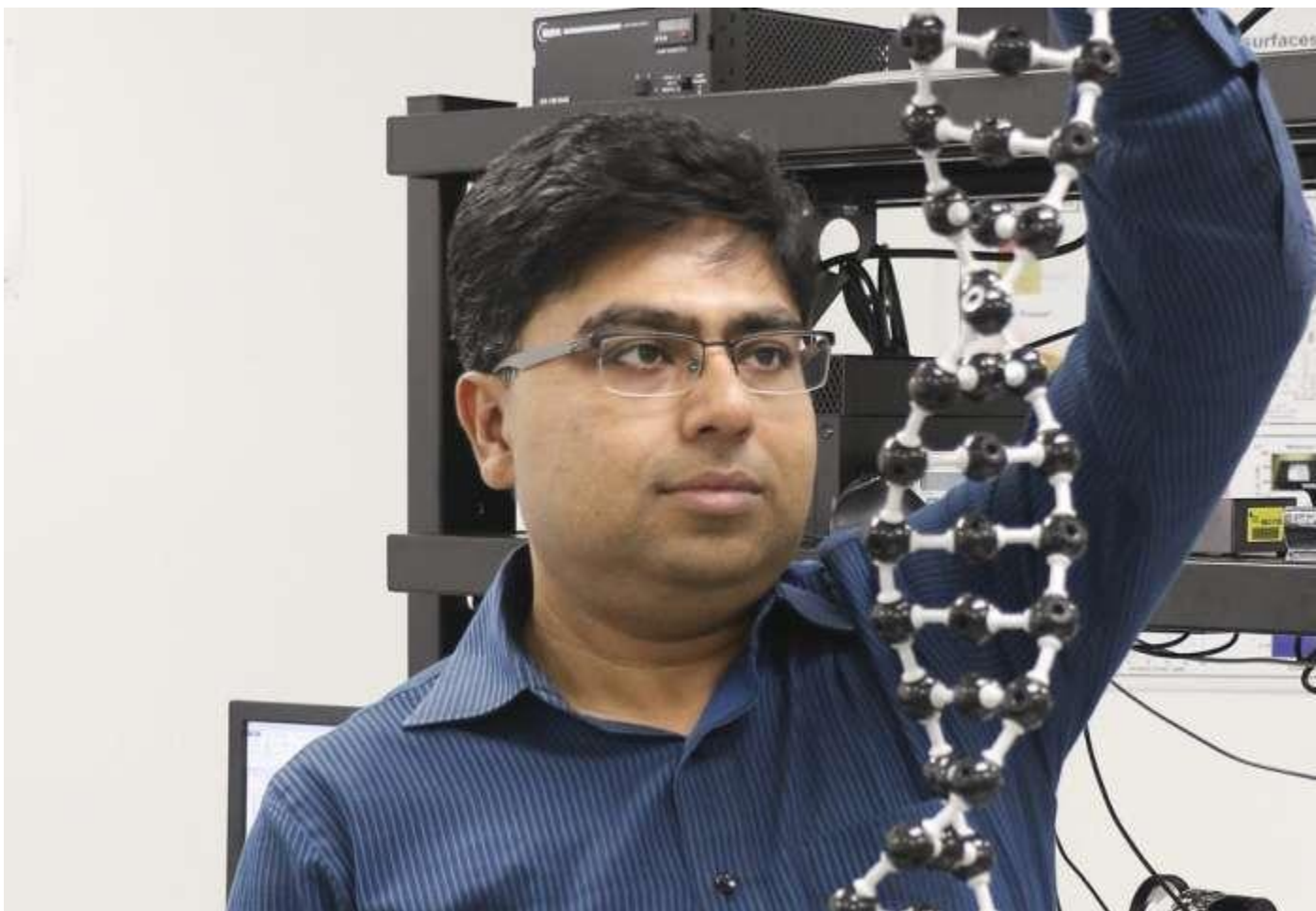
A University of Central Florida team has designed a nanostructured optical sensor that for the first time can efficiently detect molecular chirality—a property of molecular spatial twist that defines its biochemical properties.

Determining chirality is critical for new drug development.

Think of molecules as having little hands. They are not identical, but they serve almost undistinguishable functions. You can grip, pinch, punch and open your hands, regardless of whether you use your left or right hand. But when you get to some functions, such as writing, it matters if you are right-handed or left-handed.

Scientists have struggled to determine if molecules have unique left- or right-hand functions because their physical attributes such as length, weight, density, elasticity, etc. appear to be identical.

UCF's NanoScience Technology Center Associate Professor Debashis Chanda and Ph.D. student Abraham Vazquez-Guardado have figured out a unique way to do it. The interaction between light and the specially designed nanostructure they built creates a strong chiral light field—called superchiral light. Such a nanostructure does not have geometrical chirality yet it creates two opposite light chirality (left or right) on demand. When light and matter's chirality match, just as hand-shaking with our right hand, successful identification happens. Therefore, this rotating light field has the ability to probe and identify any chiral molecule like drugs, proteins or DNAs. The light field lets scientist see the tiny hands, so to speak.



UCF's NanoScience Technology Center Associate Professor Debashis Chanda. Credit: University of Central Florida: Karen Norum

Their findings were recently published in the *Physical Review Letters* journal.

"Chirality detection is vital in the drug-development industry, where newly synthesized chiral drugs also have two-handed strands and always form with the same likeliness during the synthesis process," Chanda said. "But while one chiral strand constitutes the active element in the drug, its opposite can turn out to be toxic or render detrimental side effects. Consequently, pharmacological and toxicological characterization of chirality plays a crucial role in the pharmaceutical drug industry and FDA approval process."

By being able to detect chirality at this level, scientists will have a better way to identify what may be causing bad side effects or perhaps finding places to upload life-saving drugs.

In this preliminary study, the UCF team demonstrated chiral molecule-detection sensitivity that is four times higher compared to the conventional technique, but without the extensive and tedious sample preparation and at much lower sample volume.

The single optical element thin-film [chirality](#) sensor, when fabricated based on low cost and large-area nanoimprinting technique, will immensely benefit [drug](#) design and protein-conformation identification, both of paramount importance in treating and understanding several diseases, Chanda added. [28]

## **Tiny defects in semiconductors created 'speed bumps' for electrons—researchers cleared the path**

UCLA scientists and engineers have developed a new process for assembling semiconductor devices. The advance could lead to much more energy-efficient transistors for electronics and computer chips, diodes for solar cells and light-emitting diodes, and other semiconductor-based devices.

A paper about the research was published in *Nature*. The study was led by Xiangfeng Duan, professor of chemistry and biochemistry in the UCLA College, and Yu Huang, professor of materials science and engineering at the UCLA Samueli School of Engineering. The lead author is Yuan Liu, a UCLA postdoctoral fellow.

Their method joins a [semiconductor](#) layer and a metal electrode layer without the atomic-level defects that typically occur when other processes are used to build semiconductor-based devices. Even though those defects are minuscule, they can trap electrons traveling between the semiconductor and the adjacent metal electrodes, which makes the devices less efficient than they could be. The electrodes in semiconductor-based devices are what enable electrons to travel to and from the semiconductor; the electrons can carry computing information or energy to power a device.

Generally, metal electrodes in [semiconductor devices](#) are built using a process called physical vapor deposition. In this process, metallic materials are vaporized into atoms or atomic clusters that then condense onto the semiconductor, which can be silicon or another similar material. The metal atoms stick to the semiconductor through strong [chemical bonds](#), eventually forming a thin film of electrodes atop the semiconductor.

One issue with that process is that the metal atoms are usually different sizes or shapes from the atoms in the semiconductor materials that they're bonding to. As a result, the layers cannot form perfect one-to-one atomic connections, which is why small gaps or defects occur.

"It is like trying to fit one layer of Lego brand blocks onto those of a competitor brand," Huang said. "You can force the two different blocks together, but the fit will not be perfect. With semiconductors, those imperfect chemical bonds lead to gaps where the two layers join, and those gaps could extend as defects beyond the interface and into the materials."

Those defects trap electrons traveling across them, and the electrons need extra energy to get through those spots.

The UCLA method prevents the defects from forming, by joining a thin sheet of metal atop the semiconductor layer through a simple lamination process. And instead of using chemical bonds to hold the two components together, the new procedure uses van der Waals forces—weak electrostatic connections that are activated when atoms are very close to each other—to keep the molecules "attached" to each other. Van der Waals forces are weaker than chemical bonds, but they're strong enough to hold the materials together because of how thin they are—each layer is around 10 nanometers thick or less.

"Even though they are different in their geometry, the two layers join without defects and stay in place due to the van der Waals forces," Huang said.

The research is also the first work to validate a scientific theory that originated in the 1930s. The Schottky-Mott rule proposed the minimum amount of energy electrons need to travel between metal and a semiconductor under ideal conditions.

Using the theory, engineers should be able to select the metal that allows electrons to move across the junction between metal and semiconductor with the smallest amount of energy. But because of those tiny defects that have always occurred during manufacturing, semiconductor devices have always needed electrons with more energy than the theoretical minimum.

The UCLA team is the first to verify the theory in experiments with different combinations of metals and semiconductors. Because the electrons didn't have to overcome the usual defects, they were able to travel with the minimum amount of energy predicted by the Schottky-Mott rule.

"Our study for the first time validates these fundamental limits of [metal](#)-semiconductor interfaces," Duan said. "It shows a new way to integrate metals onto other surfaces without introducing defects. Broadly, this can be applied to the fabrication of any delicate material with interfaces that were previously plagued by defects."

For example, besides electrode contacts on semiconductors, it could be used to assemble ultra-energy-efficient nanoscale electronic components, or optoelectronic devices such as solar cells.

The paper's other UCLA authors are graduate students Jian Guo, Enbo Zhu and Sung-Joon Lee, and postdoctoral scholar Mengning Ding. Researchers from Hunan University, China; King Saud University, Saudi Arabia; and Northrop Grumman Corporation also contributed to the study.

The study builds off of nearly a decade of work by Duan and Huang on using van der Waals forces to integrate materials. A [study they led](#), published in *Nature* in March 2018, described their use of van der Waals forces to create a new class of 2-D materials called monolayer atomic crystal molecular superlattices. In an earlier study, which was published in *Nature* in 2010, they described their use of van der Waals forces to build high-speed transistors using graphene. [27]

## How to measure quantum behaviour in nanocrystals

A new experiment that tests the limit of how large an object can be before it ceases to behave quantum mechanically has been proposed by physicists in the UK and India. The measurement involves trapping a nanocrystal with light and then measuring its position to see if its behaviour violates the Leggett-Garg inequality – which is a test of the quantum nature of a system. While the team is keen to have their proposal tested in the lab, not all physicists believe that it could be implemented.

A crucial important feature of quantum mechanics is Heisenberg's uncertainty principle. Whereas in classical mechanics, both the position and momentum of an object can be determined at arbitrarily high precision at the same time, the principle states that it is impossible to measure both position and momentum in quantum mechanics beyond a certain degree of accuracy. Furthermore, the more you know about one measurement, the more uncertain the other becomes.

The proposed experiment tests how large an object can be before the rules of quantum measurement do not apply. [Sougato Bose](#) of University College London and colleagues at the Bose Institute and the SN Bose National Centre for Basic Sciences in Kolkata studied the behaviour of a quantum linear harmonic oscillator, which bears a strong resemblance to its classical counterpart. "The uncertainties in position and momentum are both as low as they can get," explains Bose.

### Caught in a trap

Bose and colleagues have done an analysis of a hypothetical experiment involving a cooled nanocrystal oscillating in a trap that is created by an optical harmonic potential. The experiment can detect which side of the trap is occupied by the nanocrystal at any instant by focusing a beam of light on one side of the trap. The light causes fluorescence in the nanocrystal, and if fluorescent light is not detected it can be concluded that the nanocrystal is in the other side of the trap – a procedure called negative result measurement.

The experiment begins with a position measurement and then the system evolves for about a microsecond before the position is measured again. If the nanocrystal is a purely classical object, the researchers reasoned, a negative result in the first measurement would not affect the nanocrystal's position in the second measurement. This is because the nanocrystal would have been in the other half of the trap, and therefore would not have interacted with the beam. If there were quantum uncertainty in the position and momentum of the nanocrystal, however, the null result at the start of the experimental run could still affect its measured position at the second measurement. This is because the nanocrystal's position would not be well defined until it was actually measured. Therefore, the nanocrystal could have interacted with the light beam in one half of the trap despite not being detected there.

The team calculated the Leggett-Garg inequality for the systems. This is analogous to Bell's inequality, which is famously used to rule out hidden variable explanations of quantum mechanics. Bell's inequality quantifies the maximum statistical correlation that is possible between properties of independent particles separated by distances so great that information could not pass between them without travelling faster than light.

The Leggett-Garg inequality uses similar reasoning to calculate the maximum statistical correlation between two results that had not influenced each other. Violation of the inequality, therefore, would show that the nanocrystal's state could be influenced by the earlier negative result, and therefore that the nanocrystal is a quantum, rather than a classical, object. Crunching the numbers, the researchers calculated that it should be feasible to detect non-classical behaviour in objects with masses up to around  $10^{10}$  amu or about  $10^{-14}$  g. Bose says experimentalists are planning to test this.

### **“That’s pretty tricky”**

Bose and colleagues report their results in [Physical Review Letters](#). Theoretical physicist [Clive Emary](#) of Newcastle University in the UK says “if someone goes on to do these experiments, we’ll all look back and say it was a significant paper”. He cautions, however, that: “it looks like it needs very high time resolution to do the proposed measurements and in my experience that looks like the kind of thing you propose to experimentalists and they come back and say ‘that’s pretty tricky’.” Quantum information theorist [Renato Renner](#) of ETH Zurich is more optimistic: “We can now do experiments in quantum technologies that, five or ten years ago, people would have said were not possible,” he says, “I’m optimistic that most quantum experiments we can think of will at some point be feasible.”

Emary and Renner agree, however, that, whereas in Bell's inequality, the two measurements are isolated classically by the fact that nothing that can travel faster than the speed of light, the Leggett-Garg inequality relies on proving there can be no classical explanation for the earlier measurement disturbing the later one. “That’s just not possible,” says Emary, “There’s always a loophole: you could disturb the air molecules in the lab next door and they could come back and disturb your system, for example.” [26]

### **Detecting the birth and death of a phonon**

Phonons are discrete units of vibrational energy predicted by quantum mechanics that correspond to collective oscillations of atoms inside a molecule or a crystal. When such vibrations are produced by light interacting with a material, the vibrational energy can be transferred back and forth between individual phonons and individual packets of light energy, the photons. This process is called the Raman effect.

In a new study, the lab of Christophe Galland at EPFL's Institute of Physics has developed a technique for measuring, in real time and at room-temperature, the creation and destruction of individual phonons, opening up exciting possibilities in various fields such as spectroscopy and quantum technologies.

The technique uses [ultra-short laser pulses](#), which are bursts of light that last less than  $10^{-13}$  seconds (a fraction of a trillionth of a second). First, one such [pulse](#) is shot onto a diamond crystal to excite a single [phonon](#) inside it. When this happens, a partner photon is created at a new wavelength through the Raman effect and is observed with a specialized detector, heralding the success of the preparation step.

Second, to interrogate the crystal and probe the newly created phonon, the scientists fire another laser pulse into the diamond. Thanks to another detector, they now record photons that have reabsorbed the energy of the vibration. These photons are witnesses that the phonon was still alive, meaning that the crystal was still vibrating with exactly the same energy.

This is in strong contradiction with our intuition: we are used to seeing vibrating objects progressively lose their energy over time, like a guitar string whose sound fades away. But in [quantum mechanics](#) this is "all or nothing": the crystal either vibrates with a specific energy or it is in its resting state; there is no state allowed in between. The decay of the phonon over time is therefore observed as a decrease of the probability of finding it in the excited state instead of having jumped down to the rest state.

Through this approach, the scientists could reconstruct the birth and death of a single phonon by analyzing the output of the two photon detectors. "In the language of quantum mechanics, the act of measuring the system after the first pulse creates a well-defined quantum state of the phonon, which is probed by the second pulse," says Christophe Galland. "We can therefore map the phonon decay with very fine time resolution by changing the time delay between the pulses from zero to a few trillionths of a second ( $10^{-12}$  seconds or picoseconds)."

The new technique can be applied to many different types of materials, from bulk crystals down to single molecules. It can also be refined to create more exotic vibrational quantum states, such as entangled states where [energy](#) is "delocalized" over two vibrational modes. And all this can be performed in ambient conditions, highlighting that exotic [quantum](#) phenomena may occur in our daily life—we just need to watch very fast. [25]

## **Sustainable solvent platform for photon upconversion increases solar utilization efficiency**

The conversion of solar energy into electricity is currently restricted by a concept known as the Shockley-Queisser limit. This limitation allows only photons that have higher energies than those of the bandgap to be used, while those with lower energies are wasted. In an effort to obtain a solution to this problem and make solar energy conversion more efficient, researchers have developed a process of converting photons with lower energies into ones with higher energies, called photon upconversion.

In the past decade, a method of photon upconversion that uses triplet-triplet annihilation (TTA) of organic molecules has drawn attention because it is presently the only method applicable to weak light such as sunlight. This method combines two kinds of organic molecules or chromophores, a sensitizer and an emitter. The sensitizer will absorb a photon and convert it to its excited triplet state. The excitation energy is then transferred to the emitter. When two emitters with excitation energy collide, one will convert to its lowest excited singlet state and release an upconverted photon that can be harvested for energy conversion.

While many studies into photon upconversion have been carried out in organic solvents, their practical use is limited due to the high vapor pressures, vapor toxicity, flammability, and lack of thermal stability of the solvent mixtures. Multiple approaches have been proposed to overcome these limitations, including the use of viscous fluidic media like ionic liquids that have low vapor pressures and high thermal stability. Ionic liquids are also limited in practicality, however, due to the relatively high costs of starting materials and synthetic processes, as well as their poor biodegradability.

To fundamentally resolve these previous problems, scientists at Tokyo Tech developed a TTA photon upconversion using a new class of liquids known as deep eutectic solvents (DESs). DESs are a potential alternative to ionic fluids, because they possess desirable properties similar to those of ionic fluids and can be created through a simple mixing of two substances, a hydrogen bond donor and a hydrogen bond acceptor, without the need for synthetic processes. The starting substances for the generation of DESs are also generally much cheaper, safer and more biodegradable than those needed for the creation of ionic liquids, making them an ideal alternative.

Photographs of the DESs and photon upconverters are shown in Fig. 1. The prepared DES was optically transparent and colorless and used as the solvent for the sensitizer and emitter chromophores. The sample converts weak incident green light (wavelength: 532 nm; power: 2-3 mW) into blue emission (wavelength: ~440 nm). The expected high thermal stability was confirmed by the absence of ignition and fuming during exposure to a burner flame for 1 min.

Notably, the photon upconversion quantum yield of the samples reached 0.21 (where the maximum quantum yield is defined as 0.5; one higher-energy photon is created by using two lower-energy photons at maximum in photon upconversion). This corresponds to the upconversion quantum efficiency of 42 percent (whose maximum is defined as 100 percent). This is a relatively high efficiency.

The scientists developed a novel material platform for TTA photon upconversion using cheaper, less toxic, and thermally stable DESs. This achievement is considered as an important landmark for the realization of practical application of photon upconversion technology. [24]



## Graphene single photon detectors

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

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

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

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

The results of the study confirm that we can expect a rapid progress in integrating graphene and other 2-D materials with conventional electronics platforms, such as in CMOS-chips, and shows a promising path towards single-photon-resolving imaging arrays, quantum information processing applications of optical and microwave photons, and other applications that would benefit from the quantum-limited detection of low-energy photons. [23]

## Engineers develop key mathematical formula for driving quantum experiments

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

work, he has developed a formula that researchers can use to generate that information themselves.

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

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

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

For more than a decade, Li has sought a better way for pulse design using the similarity between spins and springs by applying numerical experiments. Spin is a form of angular momentum carried by elementary particles. Spin systems are nonlinear and difficult to work with, Li said, while spring systems, or harmonic oscillators, are linear and easier to work with. While a doctoral student at Harvard University, Li found a solution by projecting the nonlinear spin system onto the linear spring system, but was unable to prove it mathematically until recently.

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

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

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

## **New tool for characterizing quantum simulators**

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

quantum simulators. The technique, called matrix product state tomography, could become a new standard tool for characterizing quantum simulators.

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

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

### **A collaborative effort**

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

### **More efficient measurements**

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

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

### **New gold standard**

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

### **Flip-flop qubits: Radical new quantum computing design invented**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

"This means we can now place the single-atom qubits much further apart than previously thought possible," he continued. "So there is plenty of space to intersperse the key classical

components such as interconnects, control electrodes and readout devices, while retaining the precise atom-like nature of the quantum bit."

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

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

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

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

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

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

## **New quantum memory device small enough to fit on a chip**

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

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

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

To operate the device, the researchers fired laser pulses at it, causing photons to assemble in the comb, which forced them to be absorbed—the configuration also caused the photons to emerge from the comb after 75 nanoseconds. During the time period when the photons were absorbed, the researchers fired dual laser pulses at the comb to delay the reemergence of the photons for 10 nanoseconds, which allowed for on-demand retrieval of data. During the time period when the photons were held, they existed as dual pulses—early and late.

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

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

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

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

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

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

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

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

### **The quest for atomic magnets**

Current magnetic data storage technologies – those used in traditional hard disks with spinning platters, the standard until a few years ago and still common today – are built using “top-down” methods. This involves making thin layers from a large piece of ferromagnetic material, each containing the many magnetic domains that are used to hold data. Each of these magnetic domains is made of a large collection of magnetised atoms, whose magnetic polarity is set by the hard disk’s read/write head to represent data as either a binary one or zero.

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

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

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

### **Raising the temperature**

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



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

### **Future uses**

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

### **Optical control of magnetic memory—New insights into fundamental mechanisms**

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

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

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

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

### **Making precise measurements in tiny laser spots**

The HZB scientists together with those of Freie Universität Berlin and Universität Regensburg studied the microscopic processes at extremely high resolution while irradiating a thin layer of magnetic material using circularly polarised laser light. To do this, they directed the light of an infrared laser onto a nanometre-thick layer of alloy made from the metals terbium and iron (TbFe). What was special about the experimental set-up was that the narrowly focussed spot of

laser light had a diameter of only three microns. "That is far less than was usual in prior experiments", says HZB scientist Ashima Arora, first author of the study. And it provided the researchers with unsurpassed detail resolution for studying the phenomena. The images of the magnetic domains in the alloy that the team created with the help of X-rays from the BESSY II synchrotron radiation source revealed fine features that themselves were only 30 nanometres in size.

### **The crucial thing occurs in the boundary ring**

The results of the measurements prove that a ring-shaped region forms around the tiny laser spot and separates the two magnetically contrasting domains from one another. The extant magnetisation pattern inside the ring is completely erased by the thermal energy of the laser light. Outside the ring, however, it remains in its original state. Within the boundary zone itself, a temperature distribution arises that facilitates a change in magnetisation by displacing the domain boundaries. "It is only there that the toggling of magnetic properties can proceed, permitting a device to store re-writable data", explains Arora.

### **Surprising influence of the layer thickness**

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

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

### **Photosensitive perovskites change shape when exposed to light**

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

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

KAUST electrical engineer Jr-Hau He and his colleagues have looked for photostriction in a new family of materials, the perovskites. "Perovskites are one of the hottest optical materials," says He. His work now shows there's more to their interesting optical properties than solar energy

harvesting. The researchers tested a perovskite called MAPbBr<sub>3</sub> and revealed it had strong and robust photostriction behavior.

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

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

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

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

## **Conformal metasurface coating eliminates crosstalk and shrinks waveguides**

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

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

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

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

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

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

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

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

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

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

## **A nano-roundabout for light**

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

still valid even if the light consists merely of individual photons. Such a roundabout will consequently be installed in integrated optical chips - an important step for optical signal processing.

### **Signal processing using light instead of electronics**

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

"These components have long been used for freely propagating light beams," says Arno Rauschenbeutel from the Vienna Center for Quantum Science and Technology at the Institute of Atomic and Subatomic Physics of TU Wien. "Such optical circulators are mostly based on the so-called Faraday effect: a strong magnetic field is applied to a transparent material, which is located between two polarization beam splitters which are rotated with respect to each other. The direction of the magnetic field breaks the symmetry and determines in which direction the light is redirected."

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

### **Two glass fibers and a bottle for light**

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

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

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

case it rotates clockwise. The direction of circulation and the polarization of the light are therefore locked together.

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

"Because we use only a single atom, we can subtly control the process," says Rauschenbeutel. "The atom can be prepared in a state in which both traffic rules apply at the same time: all light particles then travel together through the circulator in both clockwise and counterclockwise direction." Luckily, this is impossible according to the rules of classical physics, as it would result in chaos in road traffic. In quantum physics however, such superpositions of different states are permitted which opens up entirely new and exciting possibilities for the optical processing of quantum information. [14]

## **Researchers create hidden images with commercial inkjet printers**

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

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

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

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

## Printing metamaterials

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

Nahata and his colleagues previously developed a simple method to use an off-the-shelf inkjet printer to apply inks made with silver and carbon, which can be purchased from specialty stores online. They wanted to see if their ink-jet printing technique could create various conductivities, a parameter that is typically difficult to modify because it requires changing the type of metal applied at each spatial location. To do this using standard lithography would be time consuming and expensive because each metal would have to be applied in a separate process.

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

## Creating hidden images

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

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

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

With the very inexpensive (under \$60) printers used in the paper, the technique can produce images with a resolution of about 100 microns. With somewhat more expensive but still commercially available printers, 20-micron resolution should be achievable. Although the

researchers used QR codes that are relatively simple and small, the technique could be used to embed information into more complex and detailed images using a larger canvas.

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

The researchers are also exploring the possibility of developing additional capabilities that could make the embedded information even more secure. For example, they could make inks that might have to be heated or exposed to light of a certain wavelength before the information would be visible using the appropriate terahertz radiation. [13]

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

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

### **Designed on a computer**

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

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

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



## **Tiny magnetic particles in the polymer matrix**

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

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

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

## **A whole world of new possibilities**

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

[12]

## **New method to make permanent magnets more stable over time**

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

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

To design magnets that retain their magnetic stability, the authors altered the chemical composition of a RE-TM-B magnet. Their method consists in inserting small amounts of Samarium atoms at random places within the crystalline sub-lattice of the magnet's rare-earth

component. They observed a multi-fold increase in the magnet's stability over time with as little as 1% Samarium. The advantage of using such low quantity of additives to stabilise the magnet is that it does not alter the magnetic properties.

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

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

## **New method for generating superstrong magnetic fields**

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

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

According to physicist Sergey Popruzhenko, it will be possible to check the calculations in the near future. Several new laser facilities of record power will be completed in the next several years. Three such lasers are now under construction within the European project Extreme Light Infrastructure (ELI) in the Czech Republic, Romania and Hungary. The Exawatt Center for Extreme Light Studies – XCELS is under the development at the Applied Physics Institute RAS at Nizhny Novgorod. These laser facilities will be capable of the intensities required for the

generation of superstrong magnetic fields due to radiation friction and also for the observation of many other fundamental strong-field effects. [10]

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

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

"This paper is the first to demonstrate the inverse spin Hall effect in a range of organic semiconductors with unprecedented sensitivity," although a 2013 study by other researchers demonstrated it with less sensitivity in one such material, says Christoph Boehme, a senior author of the study published April 18 in the journal Nature Materials.

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

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

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

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

### **A new way to get electricity from magnetism**

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

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

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

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

### **From spin current to electric current**

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

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

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

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

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

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

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

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

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

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

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

"Much of the progress in spintronics has resulted from exploiting the coupling between the electron spin and its orbital motion, but our understanding of these interactions is still immature. We need to know more so that we can fully explore and exploit these forces," says Arne Brataas, professor at NTNU and the corresponding author for the paper.

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

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

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

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

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

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

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

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

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

## Simple Experiment

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

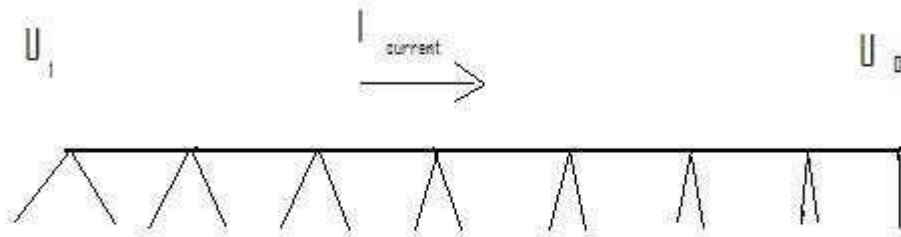


Figure 1.) Aluminium folios shows the charge distribution on the electric wire

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

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

## Uniformly accelerated electrons of the steady current

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

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

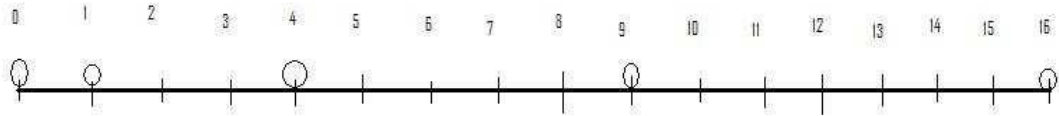


Figure 2.) The accelerating electrons created charge distribution on the electric wire

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

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

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

### **Magnetic effect of the decreasing $\mathbf{U}$ electric potential**

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

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

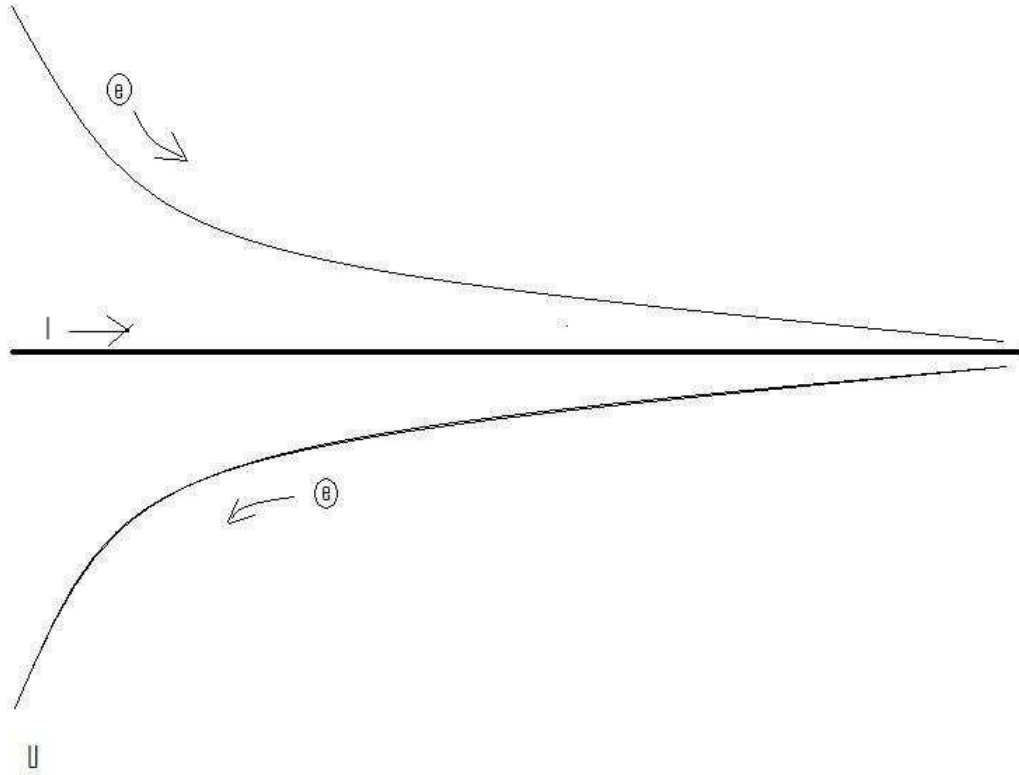


Figure 3.) Concentric parabolic equipotential surfaces around the electric wire causes the magnetic effect on the external moving charges

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

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



## The work done on the charge and the Hamilton Principle

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

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

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

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

## The Magnetic Vector Potential

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

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

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

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

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

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

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

### The Constant Force of the Magnetic Vector Potential

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

### Electromagnetic four-potential

The electromagnetic four-potential defined as:

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

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

### Magnetic induction

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

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

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

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

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

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

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

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

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

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

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

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

Or

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

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

## Lorentz transformation of the Special Relativity

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

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

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

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

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

## Heisenberg Uncertainty Relation

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

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

## Wave – Particle Duality

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

## Atomic model

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

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

## Fermions' spin

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

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

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

## Fine structure constant

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

$$E = h\nu .$$

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

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

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

The expression of the fine-structure constant becomes the abbreviated

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

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

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

## Planck Distribution Law

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

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

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

## Electromagnetic inertia and Gravitational attraction

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

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

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

Since  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu / c^2$  that is the  $m$  depends only on the  $\nu$  frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the  $m_0$  inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the

atom and the proton, their masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

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

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

## Conclusions

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

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

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

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

## References

- [1] 3 Dimensional String Theory  
Author: George Rajna  
Publisher: academia.edu  
[http://www.academia.edu/3834454/3\\_Dimensional\\_String\\_Theory](http://www.academia.edu/3834454/3_Dimensional_String_Theory)
- [2] Magnetic forces on moving charges  
[http://theory.uwinnipeg.ca/mod\\_tech/node93.html](http://theory.uwinnipeg.ca/mod_tech/node93.html)
- [3] Equipotential surface [http://en.wikipedia.org/wiki/Equipotential\\_surface](http://en.wikipedia.org/wiki/Equipotential_surface)
- [4] Hamilton Principle [http://en.wikipedia.org/wiki/Hamilton%27s\\_principle](http://en.wikipedia.org/wiki/Hamilton%27s_principle)
- [5] Magnetic Vector Potential <http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magvec.html>
- [6] Electromagnetic four-potential [http://en.wikipedia.org/wiki/Electromagnetic\\_four-potential](http://en.wikipedia.org/wiki/Electromagnetic_four-potential)
- [7] [http://en.wikipedia.org/wiki/Electrical\\_resistivity\\_and\\_conductivity](http://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity)
- [8] New electron spin secrets revealed: Discovery of a novel link between magnetism and electricity <http://phys.org/news/2014-11-electron-secrets-revealed-discovery-link.html>
- [9] Inverse spin Hall effect: A new way to get electricity from magnetism  
<http://phys.org/news/2016-04-inverse-hall-effect-electricity-magnetism.html>
- [10] New method for generating superstrong magnetic fields <http://phys.org/news/2016-08-method-superstrong-magnetic-fields.html> [11] New method to make permanent magnets more stable over time <http://phys.org/news/2016-10-method-permanent-magnets-stable.html> [12] For the first time, magnets are be made with a 3-D printer <http://phys.org/news/2016-10-magnets-d-printer.html>
- [13] Researchers create hidden images with commercial inkjet printers  
<http://phys.org/news/2016-12-hidden-images-commercial-inkjet-printers.html>
- [14] A nano-roundabout for light <http://phys.org/news/2016-12-nano-roundabout.html>



- [15] Conformal metasurface coating eliminates crosstalk and shrinks waveguides  
<https://phys.org/news/2017-08-conformal-metasurface-coating-crosstalk-waveguides.html>
- [16] Photosensitive perovskites change shape when exposed to light  
<https://phys.org/news/2017-08-photosensitive-perovskites-exposed.html>
- [17] Optical control of magnetic memory—New insights into fundamental mechanisms  
<https://phys.org/news/2017-08-optical-magnetic-memorynew-insights-fundamental.html>
- [18] How to store data on magnets the size of a single atom  
<https://cosmosmagazine.com/technology/how-to-store-data-on-magnets-the-size-of-a-singleatom>
- [19] New quantum memory device small enough to fit on a chip <https://phys.org/news/2017-09-quantum-memory-device-small-chip.html> [20] Flip-flop qubits: Radical new quantum computing design invented <https://phys.org/news/2017-09-flip-flop-qubits-radical-quantum.html>
- [21] New tool for characterizing quantum simulators <https://phys.org/news/2017-09-tool-characterizing-quantum-simulators.html> [22] Engineers develop key mathematical formula for driving quantum experiments  
<https://phys.org/news/2017-09-key-mathematical-formula-quantum.html>
- [23] Graphene single photon detectors <https://phys.org/news/2017-09-graphene-photon-detectors.html>
- [24] Sustainable solvent platform for photon upconversion increases solar utilization efficiency  
<https://phys.org/news/2017-12-sustainable-solvent-platform-photon-upconversion.html>
- [25] Detecting the birth and death of a phonon  
<https://phys.org/news/2018-06-birth-death-phonon.html>
- [26] How to measure quantum behaviour in nanocrystals  
<https://physicsworld.com/a/how-to-measure-quantum-behaviour-in-nanocrystals/>
- [27] Tiny defects in semiconductors created 'speed bumps' for electrons—researchers cleared the path

<https://phys.org/news/2018-06-tiny-defects-semiconductors-electronsresearchers-path.html>

[28] New optical sensor can determine if molecules are left or right 'handed'

<https://phys.org/news/2018-06-optical-sensor-molecules-left.html>

[29] Core electron topologies in chemical bonding

<https://phys.org/news/2018-06-core-electron-topologies-chemical-bonding.html>

[30] The photoelectric effect in stereo

<https://phys.org/news/2018-06-photoelectric-effect-stereo.html>

[31] Controlling photons with a photon

<https://phys.org/news/2018-06-photons-photon.html>

[32] Seeing the light: Researchers offer solution for efficiency problem of artificial photosynthesis

<https://phys.org/news/2018-12-solution-efficiency-problem-artificial-photosynthesis.html>

[33] A 3-D imaging technique unlocks properties of perovskite crystals

<https://phys.org/news/2018-12-d-imaging-technique-properties-perovskite.html>

[34] Blasting molecules with extreme X-rays

<https://phys.org/news/2018-12-blasting-molecules-extreme-x-rays.html>

[35] Multichannel vectorial holographic display and encryption

<https://phys.org/news/2018-12-multichannel-vectorial-holographic-encryption.html>

[36] Holographic acoustic tweezers could be used to create 3D displays

<https://physicsworld.com/a/holographic-acoustic-tweezers-could-be-used-to-create-3d-displays/>

[37] New holographic technique opens the way for quantum computation

<https://phys.org/news/2019-05-holographic-technique-quantum.html>

[38] Holographic imaging of electromagnetic fields using electron-light quantum interference

<https://phys.org/news/2019-05-holographic-imaging-electromagnetic-fields-electron-light.html>

[39] Researchers demonstrate constraints on symmetries from holography

<https://phys.org/news/2019-05-constraints-symmetries-holography.html>

[40] Stabilizing the no-boundary proposal sheds light on the universe's quantum origins

<https://phys.org/news/2019-05-stabilizing-no-boundary-universe-quantum.html>