

# Navigating Terahertz Gap

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*The terahertz range has been barely exploited compared to the rest of the electromagnetic spectrum. [37]*

*A new terahertz imaging technique could help slow the spread of these infestations by detecting insect damage inside wood before it becomes visible on the outside. [36]*

*A research team led by Osaka University showed how multiple overlapping laser beams are better at accelerating electrons to incredibly fast speeds, as compared with a single laser. [35]*

*In a major step toward developing portable scanners that can rapidly measure molecules in pharmaceuticals or classify tissue in patients' skin, researchers have created an imaging system that uses lasers small and efficient enough to fit on a microchip. [34]*

*A new study, "Wavelength-encoded laser particles for massively multiplexed cell tagging," by scientists in the Wellman Center for Photomedicine has been published in Nature Photonics. [33]*

*"This is just a wonderful example of the unexpected ways projects can develop when a team of diverse scientists from around the world come together to try and understand new and interesting phenomena," said team member Jim Cleaves, also of ELSI. [32]*

*In a recent study now published on Light: Science & Applications, Yuchao Li and colleagues at the Institute of Nanophotonics in China, developed an optical microscope system using living cells as tiny lenses to image and manipulate objects smaller than the wavelength of light. [31]*

*A team of researchers affiliated with several institutions in Japan has developed a way to create catenanes and a molecular trefoil knot out of para-connected benzene rings. [30]*

*Scientists at the U.S. Naval Research Laboratory have devised a new process for using nano-particles to build powerful lasers that are more efficient and safer for your eyes. [29]*

*Lawrence Livermore National Laboratory (LLNL) researchers are working to make better electronic devices by delving into the way nanocrystals are arranged inside of them. [28]*

*Self-assembly and crystallisation of nanoparticles (NPs) is generally a complex process, based on the evaporation or precipitation of NP-building blocks. [27]*

*New nanoparticle-based films that are more than 80 times thinner than a human hair may help to fill this need by providing materials that can holographically archive more than 1000 times more data than a DVD in a 10-by-10-centimeter piece of film. [26]*

*Researches of scientists from South Ural State University are implemented within this area. [25]*

*Following three years of extensive research, Hebrew University of Jerusalem (HU) physicist Dr. Uriel Levy and his team have created technology that will enable computers and all optic communication devices to run 100 times faster through terahertz microchips. [24]*

*When the energy efficiency of electronics poses a challenge, magnetic materials may have a solution. [23]*

*An exotic state of matter that is dazzling scientists with its electrical properties, can also exhibit unusual optical properties, as shown in a theoretical study by researchers at A\*STAR. [22]*

*The breakthrough was made in the lab of Andrea Alù, director of the ASRC's Photonics Initiative. Alù and his colleagues from The City College of New York, University of Texas at Austin and Tel Aviv University were inspired by the seminal work of three British researchers who won the 2016 Noble Prize in Physics for their work, which teased out that particular properties of matter (such as electrical conductivity) can be preserved in certain materials despite continuous changes in the matter's form or shape. [21]*

*Researchers at the University of Illinois at Urbana-Champaign have developed a new technology for switching heat flows 'on' or 'off'. [20]*

*Thermoelectric materials can use thermal differences to generate electricity. Now there is an inexpensive and environmentally friendly way of producing them with the simplest tools: a pencil, photocopy paper, and conductive paint. [19]*

*A team of researchers with the University of California and SRI International has developed a new type of cooling device that is both portable and efficient.*

*[18]*

*Thermal conductivity is one of the most crucial physical properties of matter when it comes to understanding heat transport, hydrodynamic evolution and energy balance in systems ranging from astrophysical objects to fusion plasmas. [17]*

*Researchers from the Theory Department of the MPSD have realized the control of thermal and electrical currents in nanoscale devices by means of quantum local observations. [16]*

*Physicists have proposed a new type of Maxwell's demon—the hypothetical agent that extracts work from a system by decreasing the system's entropy—in which the demon can extract work just by making a measurement, by taking advantage of quantum fluctuations and quantum superposition. [15]*

*Pioneering research offers a fascinating view into the inner workings of the mind of 'Maxwell's Demon', a famous thought experiment in physics. [14]*

*For more than a century and a half of physics, the Second Law of Thermodynamics, which states that entropy always increases, has been as close to inviolable as any law we know. In this universe, chaos reigns supreme.*

*[13]*

*Physicists have shown that the three main types of engines (four-stroke, twostroke, and continuous) are thermodynamically equivalent in a certain quantum regime, but not at the classical level. [12]*

*For the first time, physicists have performed an experiment confirming that thermodynamic processes are irreversible in a quantum system—meaning that, even on the quantum level, you can't put a broken egg back into its shell. The results have implications for understanding thermodynamics in quantum systems and, in turn, designing quantum computers and other quantum information technologies. [11]*

*Disorder, or entropy, in a microscopic quantum system has been measured by an international group of physicists. The team hopes that the feat will shed light on the "arrow of time": the observation that time always marches towards the future. The experiment involved continually flipping the spin of carbon atoms with an oscillating magnetic field and links the emergence of the arrow of time to quantum fluctuations between one atomic spin state and another. [10]*

*Mark M. Wilde, Assistant Professor at Louisiana State University, has improved this theorem in a way that allows for understanding how quantum measurements can be approximately reversed under certain circumstances. The new results allow for understanding how quantum information that has been lost during a measurement can be nearly recovered, which has potential implications for a variety of quantum technologies. [9]*

*Today, we are capable of measuring the position of an object with unprecedented accuracy, but quantum physics and the Heisenberg uncertainty principle place fundamental limits on our ability to measure. Noise that arises as a result of the quantum nature of the fields used to make those measurements imposes what is called the "standard quantum limit." This same limit influences both the ultrasensitive measurements in nanoscale devices and the kilometer-scale gravitational wave detector at LIGO. Because of this troublesome background noise, we can never know an object's exact location, but a recent study provides a solution for rerouting some of that noise away from the measurement. [8]*

*The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the Wave-Particle Duality and the electron's spin also, building the Bridge between the Classical and Quantum Theories.*

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

*The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the relativistic quantum theory.*

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## Preface

Physicists are continually looking for ways to unify the theory of relativity, which describes largescale phenomena, with quantum theory, which describes small-scale phenomena. In a new proposed experiment in this area, two toaster-sized "nanosatellites" carrying entangled condensates orbit around the Earth, until one of them moves to a different orbit with different gravitational field strength. As a result of the change in gravity, the entanglement between the condensates is predicted to degrade by up to 20%. Experimentally testing the proposal may be possible in the near future. [5]

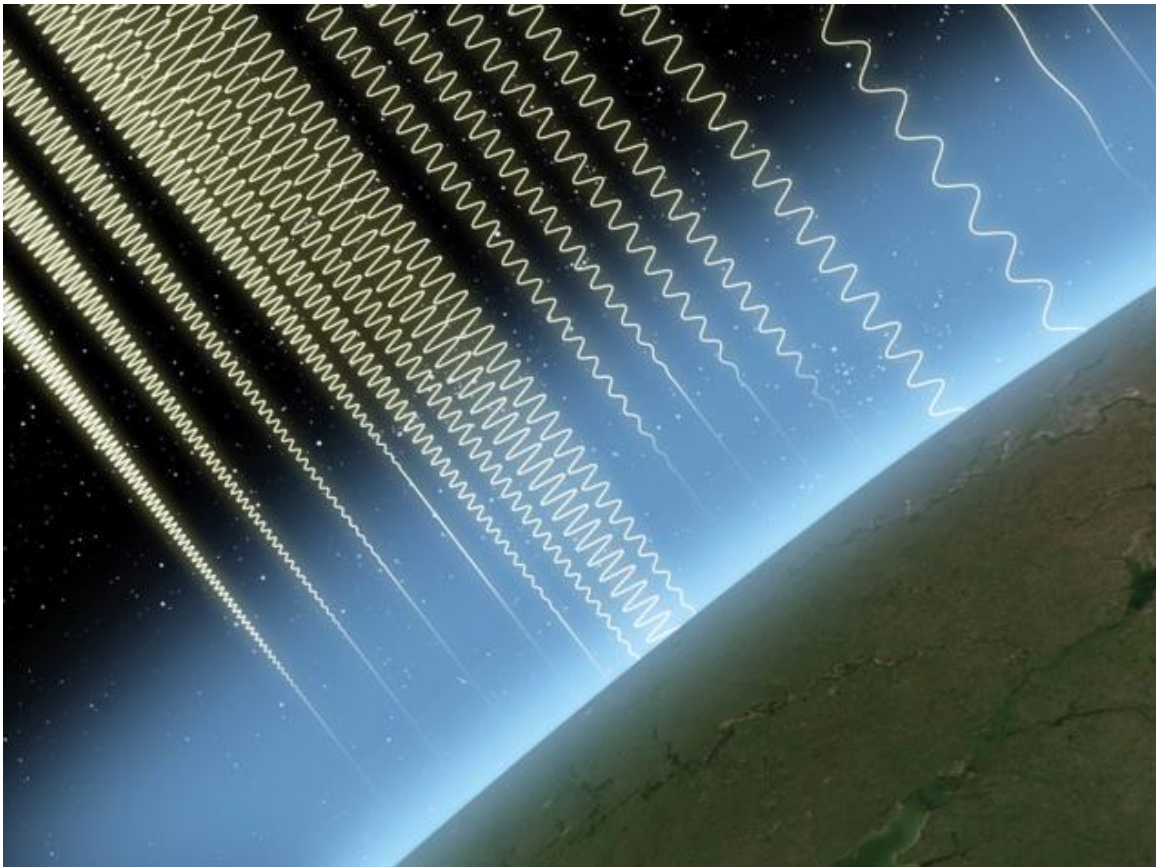
Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

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

### Navigating the terahertz gap

Taken from the March 2020 issue of *Physics World*. Members of the Institute of Physics can enjoy the full issue [via the \*Physics World\* app](#).

The terahertz range has been barely exploited compared to the rest of the electromagnetic spectrum. But as **Sidney Perkowitz** argues, our ability to detect radiation at these wavelengths has proved vital in many areas of astronomy and cosmology



[\(Courtesy: Equinox Graphics/Science Photo Library\)](#)

Look carefully at one of those classroom posters that shows the sweep of the electromagnetic spectrum, from gamma rays to radio waves, and you'll find a small patch squeezed in between the infrared and microwave. Called the far-

infrared, submillimetre or terahertz region, it is nominally defined as spanning wavelengths from 30  $\mu\text{m}$  (10 THz) in the mid-infrared, to 1–3 mm (0.1–0.3 THz) in the microwave domain. Although hardly prominent in these educational posters, this region is a rich research area for physics on and beyond the Earth.

While there are microwave and infrared sources that can produce thousands of watts of power at those frequencies, there is a lack of sources that work well across the terahertz range, which is why it is often referred to as the “terahertz gap”. Hot blackbodies only emit microwatts at terahertz frequencies, whereas microwave technology is not easily pushed below millimetre wavelengths, so standard spectroscopic methods do not apply. Yet the gap is well worth exploring. It is the right range to probe electronic, lattice and quantum properties in condensed matter, and to examine massive molecules. It supports applications in biomedicine, in security systems and in the study of artworks. Outside the lab, terahertz radiation is relevant to the cosmic microwave background (CMB) and other astrophysical phenomena, and is helping in the search for the origins of life in space.

#### **Making do with microwatts and milliwatts**

Fortunately, when scientists see a gap in understanding, they dive right in. Since the 1960s researchers have found ways to obtain high-quality terahertz spectra by using a Fourier-transform spectrometer. In this device, a hot source sends microwatts of terahertz power to a solid, liquid or gaseous sample where it is reflected or transmitted through. Next, the beam is split into two and each part is reflected from a mirror. The beams are then recombined, and a detector measures the resulting interference signal as one mirror moves relative to the other. Fourier analysis of this interferogram yields the frequency spectrum specific to the sample with a higher signal-to-noise ratio than in a conventional spectrometer.

Another common method of creating a terahertz source – which provides greater power – is by optically pumping the vibrational states of a molecular organic medium, such as methanol ( $\text{CH}_3\text{OH}$ ), with a  $\text{CO}_2$  laser. This excites molecular rotational sub-levels that emit discrete terahertz laser lines. Different media supply hundreds of lines at milliwatt powers, which yield precise data over broad ranges.



Since the 1960s and 1970s, in my lab and others, such terahertz Fourier spectrometers and pumped lasers have probed semiconductors and their nanostructures, superconductors, inhomogeneous materials, water in liquid and vapour form, and biomolecules. But more recently, lab research has been enhanced by powerful new terahertz sources based on semiconductor technology ([see June 2016](#)), and on synchrotrons and free electron lasers (see box, below). Indeed, according to a 2014 bibliometric study by Roger Lewis of the University of Wollongong in Australia, the number of papers published containing “terahertz” in the abstract, title or keywords grew exponentially between 1975 and 2013 ([J. Phys. D: Appl. Phys. 47 374001](#)).

### Power for the terahertz gap



[New source: The NCLS-II at Brookhaven National Laboratory in New York has terahertz capability. \(Courtesy: Brookhaven National Laboratory\)](#)

Spacecraft-based astrophysical and cosmological research at terahertz frequencies – such as measuring the fluctuations in the cosmic microwave background – is made possible thanks to

sensitive detectors that have been cryogenically cooled to reduce noise, as in the [COBE](#) and [Planck](#) projects. Sensitive detectors are also important for terahertz Fourier-transform spectroscopy in the lab that uses microwatts from a hot source.

Another approach for terahertz spectroscopy is to develop more powerful sources. Optically pumped lasers (see main text) generate milliwatts, which is ample for many uses, but they require a CO<sub>2</sub> laser and, unlike a blackbody, do not offer continuous frequency coverage. Other powerful sources have different limitations. Quantum cascade lasers (QCLs, [see June 2016 pp28–31](#)) are semiconductor nanostructures that produce higher powers, but at fixed frequencies and under cryogenic cooling. One recent paper ([L H Li et al. 2017 \*Electronics Letters\* 53 799](#)) describes a QCL that emits 1.8 W and 2.4 W at 4.4 THz, cooled to 77 K and 10 K, respectively.

High powers for demanding applications such as terahertz microscopy are also available at central facilities. One type of source generates powerful terahertz waves in a free-electron laser, where a beam of relativistic electrons moves past an arrangement of magnets with alternating poles. This gives the electrons a transverse wiggling motion, which produces monochromatic photons whose frequency can be tuned by changing the electron velocity or the magnetic field, and that are made coherent by confinement in a cavity. The free-electron laser at the [University of California, Santa Barbara](#), for example, generates kilowatts from 0.1 THz to 4.8 THz. Another unit at the [Budker Institute of Nuclear Physics](#) in Novosibirsk, Russia, operates from 1.2 to 8.2 THz.

High-power terahertz radiation is also generated by electrons circulating in a synchrotron storage ring. The [National Synchrotron Light Source](#) at the Brookhaven National Laboratory in New York maintains a terahertz beamline that provides 100 mW of broadband power at frequencies above 0.15 THz, covering the terahertz range and beyond and acting as a source for a Fourier-transform spectrometer. A beamline at another synchrotron, the [Canadian Light Source](#) at the University of Saskatchewan in Saskatoon, also covers the terahertz range at high brightness as a source for Fourier-transform spectrometry and terahertz microscopy.

With judicious choice of detectors, sources or both, scientists have found footholds in the terahertz gap and perform research of the highest quality. But the ideal terahertz source – producing milliwatts or more, tunable over the entire range, compact and operating at room temperature – remains elusive. This is a major stumbling block to carrying out applications in security systems and biomedicine.

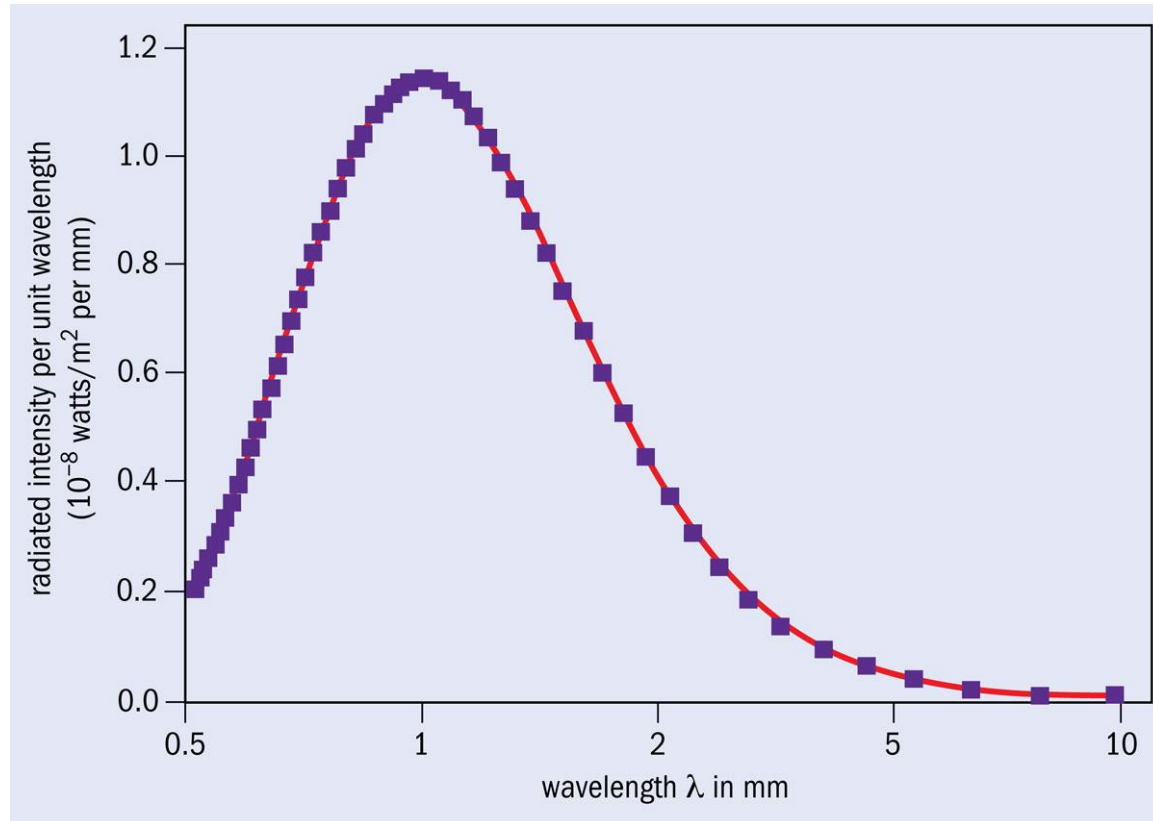
### **Terahertz physics takes to the skies**

Back in 1964, terahertz physics also received a powerful push out of the lab and into the universe. That was when Arno Penzias and Robert Wilson, working with an antenna at Bell Labs designed for satellite communications, unexpectedly found a constant signal at the microwave wavelength of 7.35 cm that seemed evenly distributed across the heavens.

The definitive measurement of this unknown radiation was made aboard NASA's [Cosmic Background Explorer](#) (COBE) satellite, which launched in 1989. Using a Fourier-transform spectrometer, COBE's result was in near-perfect agreement with the emission curve of a blackbody at  $2.725 \pm 0.002$  K. With peak intensity at 1.07 mm, this

spectrum spans the terahertz range (figure 1), and Penzias and Wilson had picked up the tail end of the curve. Separately, COBE also compared millimetre-wave radiation from different sky directions and found that the CMB is slightly anisotropic, representing temperature fluctuations of 1 part in  $10^5$  ([see February 2020](#)).

### 1 Close curve



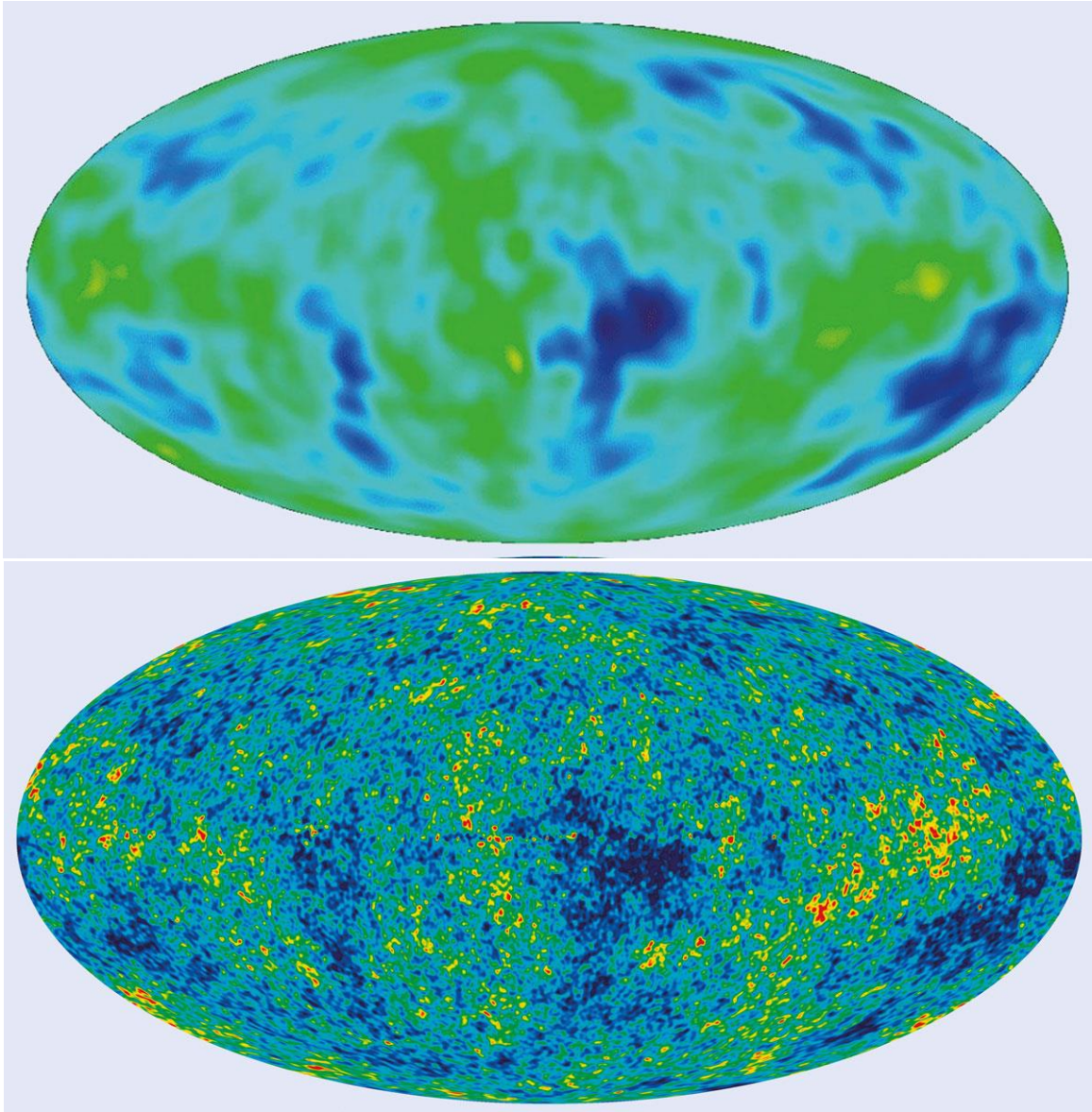
The cosmic microwave background data from COBE, which shows a remarkably close fit to the emission curve of a blackbody at 2.7 K, actually enters the terahertz range.

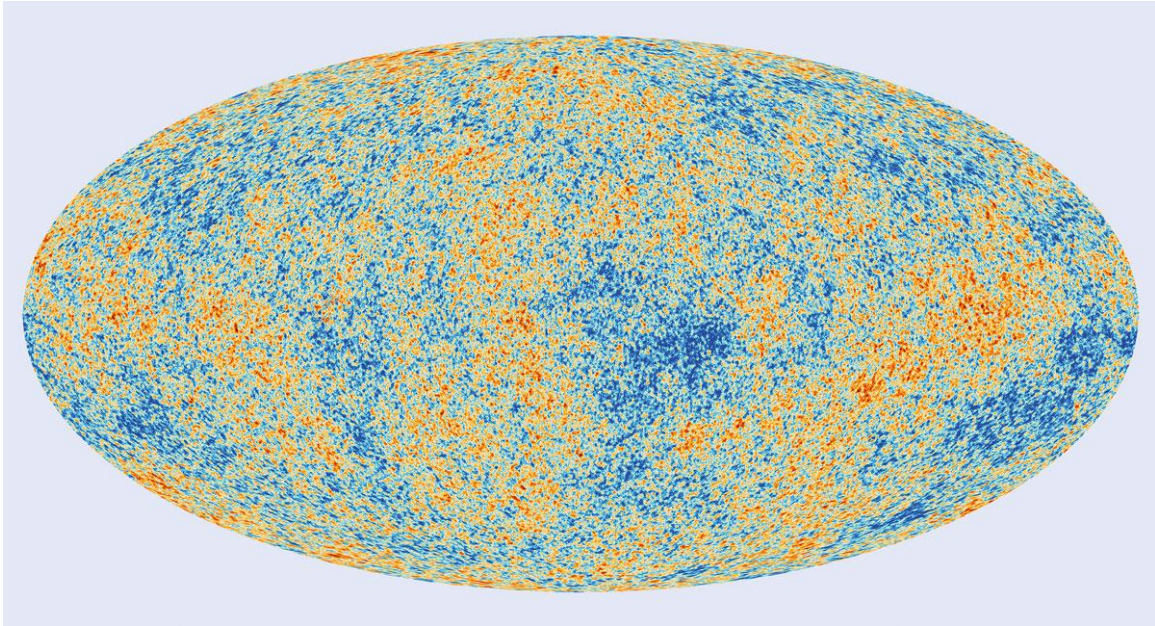
The blackbody data matched a 1965 prediction by the cosmologists [Robert Dicke](#), [Philip Peebles](#) and colleagues that as the universe cooled after the Big Bang, it would be filled with residual blackbody radiation at  $\sim 3$  K. This agreement provided strong support for the Big Bang theory and the results gave deep insights into the history of the universe. Indeed, when [George Smoot](#) and [John Mather](#) received the [2006 Nobel Prize for Physics](#) for their work on COBE, the Nobel Committee noted that COBE can be “regarded as the starting point for cosmology as a precision science”.

The CMB temperature fluctuations are also significant; they represent density variations in the hydrogen making up the universe 380,000

years after the Big Bang. These evolved into today's cosmic structure, with filaments of galaxies surrounded by enormous voids. After COBE, the fluctuations were studied from space by NASA's [Wilkinson Microwave Anisotropy Probe](#) (WMAP) launched in 2001, and the [Planck spacecraft](#), launched by the European Space Agency in 2009. Advances in detection methods and space technology improved each subsequent mission. Planck sensed weak signals with heat detectors cooled to 0.1 K, giving attowatt noise levels, and covered the widest frequency range at nine values from 0.03 THz (10 mm) to 0.857 THz (0.35 mm). The spacecraft measured cosmic temperature differences of 5  $\mu$ K or less at angular resolutions down to 4 arcmin, compared to 7° for COBE and 0.5° for WMAP (figure 2).

## 2 All in the detail





Successively higher resolution of temperature variations in the early universe as seen in the terahertz range by the COBE, WMAP and Planck spacecraft.

The terahertz data from Planck was analysed with the so-called lambda cold dark matter model ( $\Lambda$ CDM), the cosmological “standard model”.  $\Lambda$ CDM assumes that physics, including general relativity, is the same throughout the universe; that the universe was initially hot and dense and has always been expanding; and that it includes dark energy, dark matter, ordinary matter, photons and neutrinos. In 2018 the final results from Planck showed that the universe is 13.8 billion years old; it contains 31.5% matter (4.9% normal matter and 26.6% dark matter) and 68.5% dark energy; it most probably contains only three species of neutrinos, whose masses sum to less than 0.12 eV; and it is expanding with a Hubble constant  $H_0$  of 67.4 km/s/Mpc.

These results provide our most accurate and comprehensive picture of the universe to date and terahertz detection technology played an important role. However, with an uncertainty of only 1%, the Planck value of  $H_0$  is at variance with the value 73 km/s/Mpc derived from other supposedly reliable astrophysical data – a difference that perhaps points to new physics.

### **Seeing a black hole with millimetre waves**

Another terahertz astrophysical project required far higher resolution than Planck attained. In April 2019 the international [Event Horizon Telescope](#) (EHT) collaboration presented the [first ever image of a black](#)

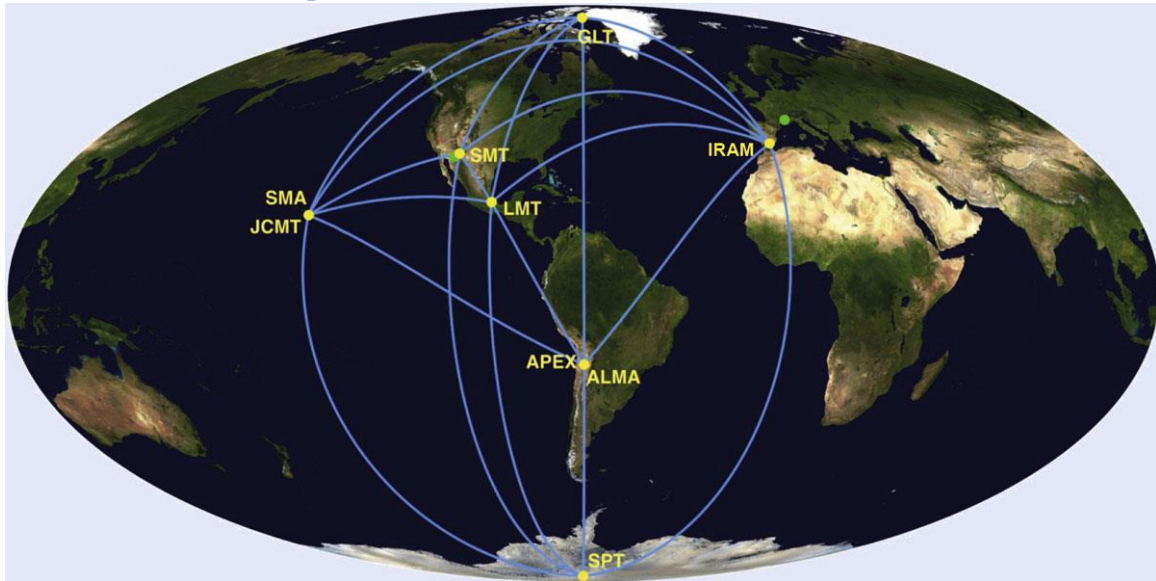
[hole](#) – the supermassive black hole at the centre of the elliptical galaxy M87, 55 million light-years away.

The aim had been to study the region near the event horizon by observing the black hole's "shadow", a dark area within the glow emitted by hot accretion material flowing into the black hole. The shadow, caused by the gravitational bending and capture of light near the event horizon, has a diameter about five times the Schwarzschild radius (the radius of the black hole) as predicted by general relativity. It would subtend only a tiny angle of  $\sim 40 \mu\text{arcsec}$ .

Terahertz photons delineate a black hole because they come from deep within its gravitational well. Earlier studies of M87 at wavelengths from 1.3 mm to 7 mm had shown signs of a central  $40 \mu\text{arcsec}$  structure but could not image it. These results did, however, show that the shorter the millimetre wavelength, the more closely the photons represented the actual site of the black hole within the bright region. But no individual radio telescope installation, single-dish or multi-dish, could provide the required angular resolution at millimetre wavelengths.

The answer was for the EHT to link eight separate installations around the Earth, including the [Atacama Large Millimeter/submillimeter Array](#) (ALMA) in the Chilean desert, the [South Pole Telescope](#) (SPT) in Antarctica, and the [IRAM 30-metre telescope](#) in Spain (figure 3). The resulting virtual telescope gave an angular resolution of the order of the 1.3 mm wavelength divided by the Earth's diameter. After an intricate process of co-ordinating the telescopes and analysing petabytes of data, the composite network produced a striking image at a resolution of  $20 \mu\text{arcsec}$ . It clearly shows the dark shadow within the bright emission region  $42 \mu\text{arcsec}$  across, which itself displays details. Analysis of the data gave a central mass of  $6.5 \times 10^6$  solar masses, definitively establishing the existence of a supermassive black hole in M87 and supporting the supposition that black holes of this size lie at the centre of galaxies.

### 3 Worldwide telescope



The system of telescopes in the Event Horizon Telescope array, forming an Earth-sized virtual telescope to achieve ultrahigh angular resolution of the order of 1.3 mm wavelength divided by the Earth's diameter. Green dots indicate future sites.

### Seeking the molecules of life

Besides research in space to explore the origin and development of the universe, terahertz methods can also examine a different set of fundamental questions. How did life begin on Earth? Was it a unique process, meaning we are alone in the universe? Or did it seed life elsewhere?

One possible answer to these big questions is that the complex molecules of life, or their precursors, originated in the interstellar medium, and came to Earth and other planets via meteorites. According to what we know about earthly life, this means finding organic molecules in space that contain carbon along with hydrogen, oxygen and nitrogen. Some of these molecules – including the amino acids necessary to build proteins – have already been found in meteorites that landed on Earth, and now terahertz astronomical spectroscopy is being used to seek such biotic or pre-biotic molecules in space.

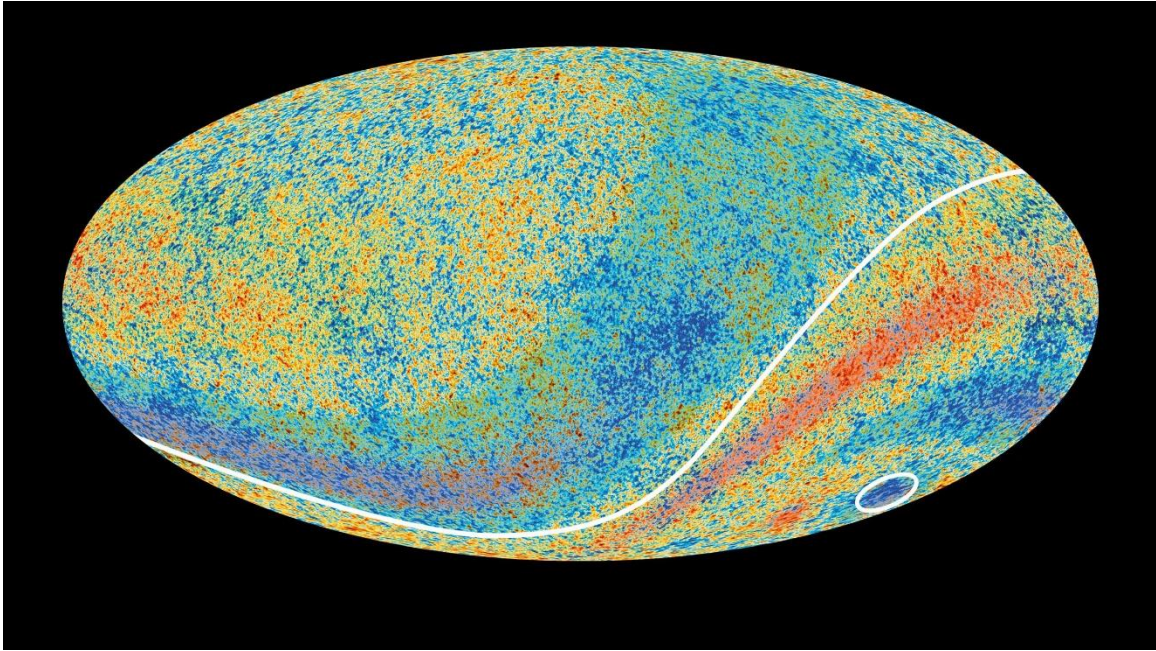
The universe seems to support active carbon-based chemical processes – indeed, the first molecule found in space was CH in 1937, and organic molecules still dominate the more than 200 species found since by ultraviolet to centimetre-wavelength spectroscopy. These results mostly come from radio astronomy at frequencies below 2 THz, where transitions between the



energy levels associated with molecular rotations provide many identifying spectral features in emission or absorption. This is the same mechanism that in the lab generates terahertz laser lines from compounds like methanol,  $\text{CH}_3\text{OH}$  (which has also been found in space).

The known astronomical organic molecules contain up to 13 atoms (excluding the non-biotic fullerenes  $\text{C}_{60}$  and  $\text{C}_{70}$ ), a level of complexity associated with biological function. In 2003 the simple amino acid glycine ( $\text{NH}_2\text{CH}_2\text{COOH}$ ) was reportedly detected in space, but later measurements have not confirmed this. Other relevant findings are the sugar-related molecule glycolaldehyde ( $\text{CH}_2\text{OHCHO}$ ), and formamide ( $\text{NH}_2\text{CHO}$ ), a possible biotic precursor with the appropriate properties to form sugars and amino acids.

The high angular resolution offered by arrays like ALMA aids the search for complexity beyond the straight-chain carbon backbone found in most big organic molecules in space. In 2014 a team under [Arnaud Belloche](#) at the [Max Planck Institute for Radio Astronomy](#) in Bonn, Germany, used ALMA at 3 mm wavelength to find the first space molecule with a branched carbon chain, iso-propyl cyanide ( $i\text{-C}_3\text{H}_7\text{CN}$ ). This feature is characteristic of the amino acids that have been seen in meteorites on Earth. The molecule was observed in the giant star-forming gas cloud Sagittarius B2 in our galaxy, suggesting that active areas in space tend to make complex compounds. Deeper physical and chemical understanding of how molecules form in diverse places, from interstellar and circumstellar regions to protoplanetary discs, will further focus the hunt for biotic molecules.



The enduring enigma of the cosmic cold spot

Lab measurements of complex molecular spectra are essential as well to guide astronomical research and interpret its results. [Susanna Widicus Weaver](#), for example, is a chemist at [Emory University](#) who works on improving terahertz Fourier-transform spectroscopy and other methods, for these purposes and to study new areas in interstellar chemistry, such as molecular reactions with ice. These approaches, she wrote in a recent review article ([Ann. Rev. Astron. Astrophys. 57 79](#)), are “poised to fill the terahertz gap...offering analytical techniques that rival those used in the microwave and infrared regions of the electromagnetic spectrum”.

Researchers have extended microwave and infrared methods on and off the Earth to make the terahertz gap navigable and carry out innovative studies in both locales. This breadth illustrates the interdisciplinary nature of terahertz science as it explores the beginnings of the universe, the properties of matter in space and on Earth, and the fascinating, still-mysterious intersection where non-living molecules make the leap into life. [37]

## Terahertz imaging technique reveals subsurface insect damage in wood

Insect infestation is becoming an increasingly costly problem to the forestry industry, especially in areas experiencing increased droughts and hot spells related to climate change. A new terahertz imaging technique could help slow the spread of these infestations by detecting insect damage inside wood before it becomes visible on the outside.

"Our approach could be used to detect early-stage [insect infestation](#) on the trunks of trees, in imported [wood](#) or on [wood products](#) in an early infestation stage," said research team member Kirsti Krügener, from HAWK University of Applied Science and Arts in Germany. "This could help keep out damaging insects from other countries and stop infestation before it spreads throughout a forest."

In the Optical Society journal *Applied Optics*, the researchers report how they used [terahertz](#) time-of-flight tomography to noninvasively identify wood samples with otherwise invisible damage from the typographer beetle, which infects spruce and other coniferous trees in Europe. They were also able to reconstruct the internal structure of wood samples.

"Detecting the boreholes of wood-destroying insects is typically done by manually inspecting the wood, and the infested area of the forest to be removed is then estimated," said Krügener. "To our knowledge, this is the first time a technical method has been used to detect insect boreholes."

Incorporating the new approach into a portable instrument could allow assessment of individual trees in a forest so that only infested trees would need to be removed. Because it does not damage the sample being imaged, the technique might also be useful for investigating mummies, studying and restoring art or for quality control in industry.

### Seeing beneath the surface

The terahertz region of the electromagnetic spectrum lies between microwave and infrared regions. It is used for applications such as the full-body scanners found in many airports because it doesn't harm people or materials being examined and can see through materials such as clothing, plastics and plant material.

Terahertz time-of-flight tomography works much like ultrasonic measurement in that each interface within the wood sample reflects a certain amount of the terahertz radiation that is detected and analyzed in respect to its time-dependent order. Each subsurface tunnel made by the insects leads to a new interface on which the radiation is reflected.

"An infested sample will reflect more terahertz radiation than one that is not infested because there will be fewer interfaces," said Krügener. "In addition, the individual reflected terahertz signals can be used to form a picture of an entire area so that the [inner structure](#) of infested wood can be visualized."

### Beyond flat surfaces

Although terahertz time-of-flight tomography has been used for almost 20 years, until recently it could only be applied to flat samples. Two years ago, the researchers developed new procedures to

use a robotic arm to scan an arbitrarily shaped sample point by point while keeping the emitter-receiver-head perpendicular to, and at defined distance from, the sample surface.

The researchers applied those methods to image wood samples with both known and unknown inner structures. They compared the results to conventional tomographic techniques and found that the inner structure reconstructed from terahertz signals matched well with what can be achieved with X-ray or computed tomography. They were able to distinguish between infested and non-infested samples by detecting typographer beetle burrows that were up to 1 centimeter beneath the wood's surface.

"The depth resolution of the terahertz measurements is higher than that of conventional X-ray techniques and comparable to micro-CT," said Krügener. "However, unlike micro-CT, the terahertz system can be used with any size sample."

The researchers are now working to improve the speed of the measurement and data analysis and also develop more complex data analysis to make the method more practical for detecting infested wood. They also want to develop a portable instrument that could be used in the field. [36]

## **Balancing beams: Multiple laser beamlets show better electron and ion acceleration**

A research team led by Osaka University showed how multiple overlapping laser beams are better at accelerating electrons to incredibly fast speeds, as compared with a single laser. This method can lead to more powerful and efficient X-ray and ion generation for laboratory astrophysics, cancer therapy research, as well as a path toward controlled nuclear fusion.

High-[energy](#) density physics is a field of study that deals with conditions much closer the chaotic moments immediately following the Big Bang than those commonly encountered on Earth. However, being able to produce and control intense beams of light, or very fast-moving electrons, has many practical benefits. These include the ability to make very bright X-rays needed for visualizing ultrafast deformation of matter, or conducting experiments that mimic the cosmological conditions near the surface of a star.

However, it is often tricky to keep efficiently accelerating electron beams with intense [laser beams](#) because of [complex interactions](#) between the laser and electrons. Previously, very expensive optics or patterned targets were required to transfer laser energy to the electron beam energy. In a new study, researchers at Osaka University showed how splitting the laser beam into four coherent smaller beams, called beamlets, allows more energy to be transferred to electrons. This was accomplished by creating specific light interference patterns that keep the electrons on track.

"Just like overlapping ripples in a pond can create complex wave structures, we can use four laser beamlets to precisely control the environment to best accelerate the electrons," explains first author Morace. They found that the simultaneous irradiation of multiple laser beams at a single

point allows for highly efficient [laser](#)-driven particle acceleration. Using light interference patterns instead of physical targets allows for better control and increased energy transfer.

The team sees this as just the beginning of the new technique. "This research shows how new, high-performance lasers systems utilizing multi-[beam](#) coupling can be developed," says senior author Kodama. "This means that the method may soon appear in biology departments or fusion power plants." [35]

## Closing the terahertz gap: Tiny laser is an important step toward new sensors

In a major step toward developing portable scanners that can rapidly measure molecules in pharmaceuticals or classify tissue in patients' skin, researchers have created an imaging system that uses lasers small and efficient enough to fit on a microchip.

The system emits and detects [electromagnetic radiation](#) at [terahertz frequencies](#)—higher than radio waves but lower than the long-wave infrared light used for thermal imaging. Imaging using [terahertz](#) radiation has long been a goal for engineers, but the difficulty of creating practical systems that work in this frequency range has stymied most applications and resulted in what engineers call the "terahertz gap."

"Here, we have a [revolutionary technology](#) that doesn't have any moving parts and uses direct emission of terahertz radiation from semiconductor chips," said Gerard Wysocki, an associate professor of electrical engineering at Princeton University and one of the leaders of the research team.

Terahertz radiation can penetrate substances such as fabrics and plastics, is non-ionizing and therefore safe for medical use, and can be used to view materials difficult to image at other frequencies. The new system, described in a paper published in the June issue of the journal *Optica*, can quickly probe the identity and arrangement of molecules or expose structural damage to materials.

The device uses stable beams of radiation at precise frequencies. The setup is called a frequency comb because it contains multiple "teeth" that each emit a different, well-defined frequency of radiation. The radiation interacts with molecules in the sample material. A dual-comb structure allows the instrument to efficiently measure the reflected radiation. Unique patterns, or spectral signatures, in the reflected [radiation](#) allow researchers to identify the molecular makeup of the sample.

While current terahertz imaging technologies are expensive to produce and cumbersome to operate, the new system is based on a semiconductor design that costs less and can generate many images per second. This speed could make it useful for real-time quality control of pharmaceutical tablets on a [production line](#) and other fast-paced uses.

"Imagine that every 100 microseconds a tablet is passing by, and you can check if it has a consistent structure and there's enough of every ingredient you expect," said Wysocki.

As a proof of concept, the researchers created a tablet with three zones containing common inert ingredients in pharmaceuticals—forms of glucose, lactose and histidine. The terahertz imaging system identified each ingredient and revealed the boundaries between them, as well as a few spots where one chemical had spilled over into a different zone. This type of "hot spot" represents a frequent problem in pharmaceutical production that occurs when the active ingredient is not properly mixed into a tablet.

The team also demonstrated the system's resolution by using it to image a U.S. quarter. Fine details like the eagle's [wing feathers](#), as small as one-fifth of a millimeter wide, were clearly visible.

While the technology makes the industrial and [medical use](#) of terahertz imaging more feasible than before, it still requires cooling to a low temperature, a major hurdle for practical applications. Many researchers are now working on lasers that will potentially operate at room temperature. The Princeton team said its dual-comb hyperspectral imaging technique will work well with these new room-temperature laser sources, which could then open many more uses.

Because it is non-ionizing, [terahertz radiation](#) is safe for patients and could potentially be used as a diagnostic tool for skin cancer. In addition, the technology's ability to image metal could be applied to test airplane wings for damage after being struck by an object in flight.

In addition to Wysocki, the paper's Princeton authors are former visiting graduate student Lukasz Sterczewski (currently a postdoctoral scholar at NASA's Jet Propulsion Laboratory) and associate research scholar Jonas Westberg. Other co-authors are Yang Yang, David Burghoff and Qing Hu of the Massachusetts Institute of Technology; and John Reno of Sandia National Laboratories. Support for the research was provided in part by the Defense Advanced Research Projects Agency and the U.S. Department of Energy. [34]

## **Wavelength-encoded laser particles for massively multiplexed cell tagging**

A new study, "Wavelength-encoded laser particles for massively multiplexed cell tagging," by scientists in the Wellman Center for Photomedicine has been published in *Nature Photonics*.

According to the study's researchers, "We have developed a new class of probes, [laser](#) particles, which are tiny lasers that can be inserted inside living cells. These laser particles are biocompatible, occupy only 0.1% of the volume of a typical cell and don't interfere with its normal behavior. We use the light emitted by these probes to tag and track cells as they move throughout complex biological samples. They can be thought as barcodes that can be used to distinguish cells from one another.

Conventional probes used to tag cells are based on fluorescence emission; scientists use different fluorescent molecules with different colors to distinguish different cells. Due to intrinsic limitations,

however, fluorescence can only provide a handful of distinguishable colors, usually up to 4-5. Our new probes emit [laser light](#), which can produce many more distinguishable colors, around 400 in this work.

We have used these laser particles to tag [tumor cells](#) and track their individual movement for days in a tumor spheroid (a system which mimics the growth of a tumor). In the future, we will be able to use this information to understand how tumors grow and identify specific cells with a higher potential of forming metastasis. It will be possible to single out these [cells](#) and perform further studies on them, like sequencing of their genetic profile. This will allow us to target [specific genes](#) with more intentionality, improving the options with which we can treat tumors in order to stop their spreading and formation of metastases." [33]

## Scientists discover new chemistry that may help explain the origins of cellular life

Before life began on Earth, the environment likely contained a massive number of chemicals that reacted with each other more or less randomly, and it is unclear how the complexity of cells could have emerged from such chemical chaos. Now, a team led by Tony Z. Jia at the Tokyo Institute of Technology and Kuhan Chandru of the National University of Malaysia has shown that simple  $\alpha$ -hydroxy acids, like glycolic and lactic acid, spontaneously polymerize and self-assemble into polyester microdroplets when dried at moderate temperatures followed by rehydration. This could be what happened along primitive beaches and river banks, or in drying puddles. These form a new type of cell-like compartment that can trap and concentrate biomolecules like nucleic acids and proteins. These droplets, unlike most modern cells, are able to merge and reform easily, and thus could have hosted versatile early genetic and metabolic systems potentially critical for the origins of life.

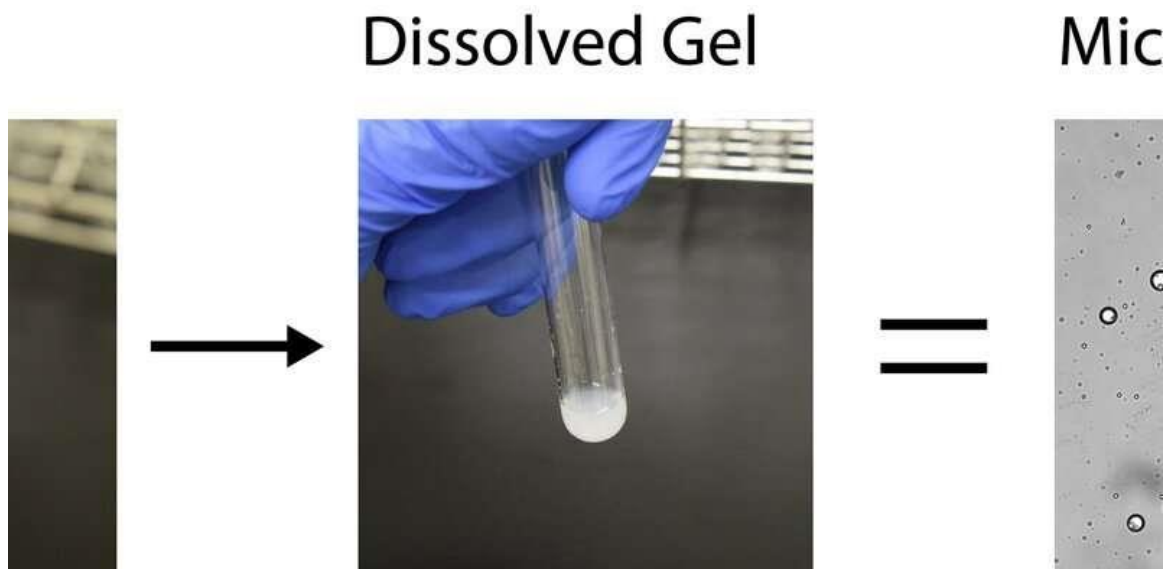
All life on Earth is made up of [cells](#). Cells are composed of lipids, proteins and nucleic acids, with the lipid forming the [cell membrane](#), an enclosure that keeps the other components together and interfaces with the environment, exchanging food and waste. How molecular assemblages as complex as cells originally formed remains a mystery.

Most origins of life research focuses on how the molecules and structures of life were produced by the environment, and then assembled into structures that led to the first cells. However, there were likely many other types of molecules that formed alongside biomolecules on early Earth, and it is possible that life started using very simple chemistry unrelated to modern biomolecules, then evolved through increasingly complex stages to give rise to the structures found in modern cells.

Previous work conducted at ELSI showed that moderate temperature drying of the simple organic compounds known as alpha-hydroxy acids, which are found in meteorites and many simulations of prebiological chemistry, spontaneously polymerizes them into mixtures of long polyesters. Building on this work, Jia and colleagues took the next step and examined these reactions under the

microscope, and found that these mixed polyester systems form a gel phase and spontaneously self-assemble when rewetted to form simple cell-like structures.

The most challenging aspect of this work was devising new methods to characterize the droplets' properties and functions, as no one had analyzed such systems before. Jia noted that the team was fortunate to have such a diversity of multidisciplinary expertise, including chemists, biochemists, materials scientists and geologists. After determining their composition and showing their propensity to self-assemble, the next question was whether these cell-like structures might be able to do something chemically useful. Modern cell membranes perform many crucial functions that help maintain the cell, for example, retaining macromolecules and metabolites in one place, as well as providing a constant internal environment, which can be very different from the one outside the cell. They first measured how stable these structures were and found they could persist for very long periods depending on the environmental conditions, but could also be made to merge and coalesce.



Alpha-hydroxy acid monomers are dried, resulting in the synthesis of a polyester gel. This gel is then rehydrated, resulting in the assembly of microdroplets. Credit: ELSI

They then tested the ability of these structures to sequester molecules from the environment and found they accumulated large dye molecules to a remarkable degree. They then showed that these droplets could also host RNA and protein molecules and still permit them to be functionally catalytic. Further, the team showed that the droplets could assist in the formation of a lipid layer on their surface, suggesting they could have helped scaffold protocell formation.

Jia and colleagues are not certain these structures are the direct ancestors of cells, but they think it is possible such droplets could have enabled the assembly of protocells on Earth. The new compartmentalization system they have found is extremely simple, they note, and could form easily in primitive environments throughout the universe. Says Jia, "This allows us to imagine non-[biological systems](#) on early Earth that could still have had a hand in the origins of life. This suggests there may be many other non-biological systems that should be targets of future investigations of this type." He thinks the development of these or similar model systems could



allow better study of the evolution of diverse chemical systems representative of the complex chemistries likely to be found on primitive planetary bodies.

"The early Earth was certainly a messy place chemically," Jia explains, "and often, most origins of [life](#) studies focus on modern biomolecules under relatively 'clean' conditions. Perhaps it is important to take these 'messy' mixtures and see if there are interesting functions or structures that can arise from them spontaneously." The authors now think that by systematically increasing the chemical complexity of such systems, they will be able to observe how they evolve over time and possibly discover divergent and emergent properties.

"We have this new experimental system we can now play with, so we can start to study phenomena like evolution and evolvability of these droplets. The possible combinations of structures or functions these droplets might have are almost endless. If the physical rules that govern the formation of droplets are fairly universal in nature, then we hope to study similar systems to discover whether they also can form microdroplets with novel properties," adds Jia.

Finally, while the team is presently focused on understanding the [origins of life](#), they note this basic research could have applications in other areas, for example, drug delivery and personalized medicine. "This is just a wonderful example of the unexpected ways projects can develop when a team of diverse scientists from around the world come together to try and understand new and interesting phenomena," said team member Jim Cleaves, also of ELSI. [32]

## Seeing smaller through cells: A natural single-cell biomagnifier for subwavelength imaging

Optical microscopes and tweezers can image and manipulate objects at the microscale for applications in cellular and molecular biology. The optical resolution is, however, hampered by the [diffraction limit](#) and therefore both microscopes and tweezers are unable to image and manipulate nano-objects directly. Emerging techniques in plasmonic/photonic nanoscopes and [nanotweezers](#) aim to achieve nanometer-scale resolution, although high-index material structures can easily cause mechanical and photothermal damage to the nanoscale biospecimens.

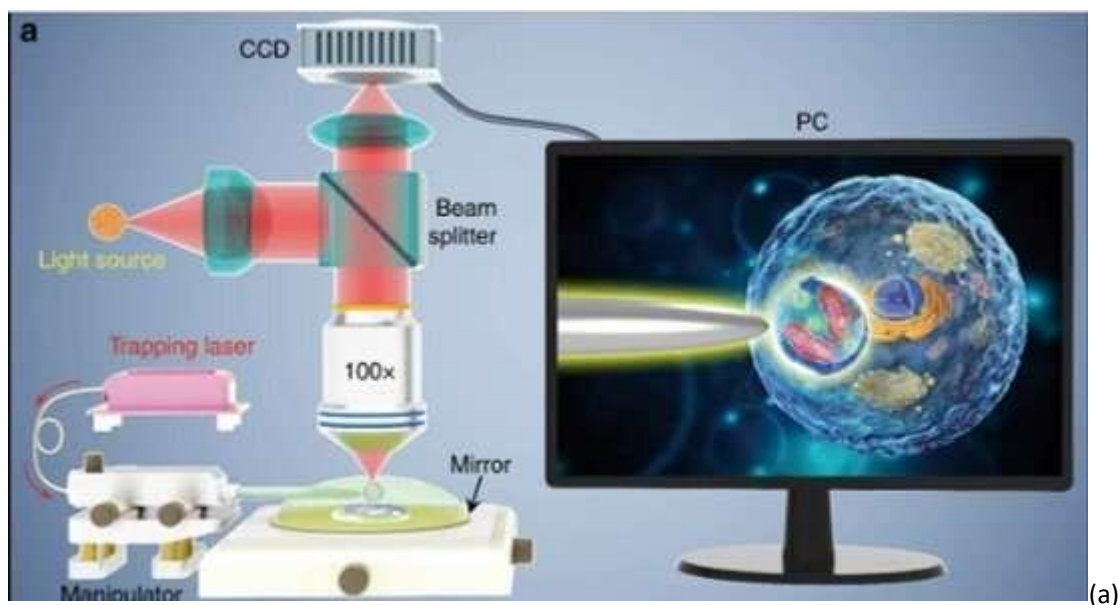
In a recent study now published on *Light: Science & Applications*, Yuchao Li and colleagues at the Institute of Nanophotonics in China, developed an optical microscope system using living cells as tiny lenses to image and manipulate objects smaller than the [wavelength of light](#). They showed sub-diffraction-limit imaging and manipulation of nano-objects with a non-invasive device, which they constructed by trapping a cell on a fiber tip. The trapped cell formed a biomagnifier that could magnify nanostructures with a resolution of 100 nm, under white light microscopy. Using the biomagnifier, Li et al. formed a nano-optical trap to precisely manipulate an individual nanoparticle with a 50 nm radius. The technique provides a high-precision tool for [optical imaging](#), sensing and assembly of bio-nanomaterials without mechanical or photothermal damage.

Optical imaging to manipulate small objects is crucial for [medical diagnosis](#), [biological sensing](#), [cellular exploration](#), [molecular training](#) and [materials assembly](#).

Tweezers and microscopes are [standard devices for noncontact imaging](#) and manipulation of minute samples ranging from a few nanometers to several microns. Nevertheless, it is challenging to use the technology [to image at the nanoscale](#), since optical resolution is restricted to approximately half the illumination wavelength.

Scientists have achieved dramatic progress of near-field nanoscopes and nanotweezers in the past few decades to achieve [optical imaging at nanometer resolution](#). These [imaging techniques](#) were withheld by high-index inorganic materials such as [noble metals and semiconductors](#) used for their fabrication—that can mechanically damage samples of biological cells or tissue during near-field imaging and manipulation.

Scientists therefore investigated [simpler optical imaging schemes](#) based on dielectric microspheres to overcome the [diffraction limit](#) common to conventional microscopes. While the technique is label-free and feasible, such microspheres are based on artificial inorganic materials such as silicon dioxide ( $\text{SiO}_2$ ), titanium dioxide ( $\text{TiO}_2$ ) and barium titanate ( $\text{BaTiO}_3$ ). Researchers are therefore interested in developing a natural biomaterial to construct a biocompatible device for bioimaging, manipulation and biomagnification at nanoscale spatial resolution.

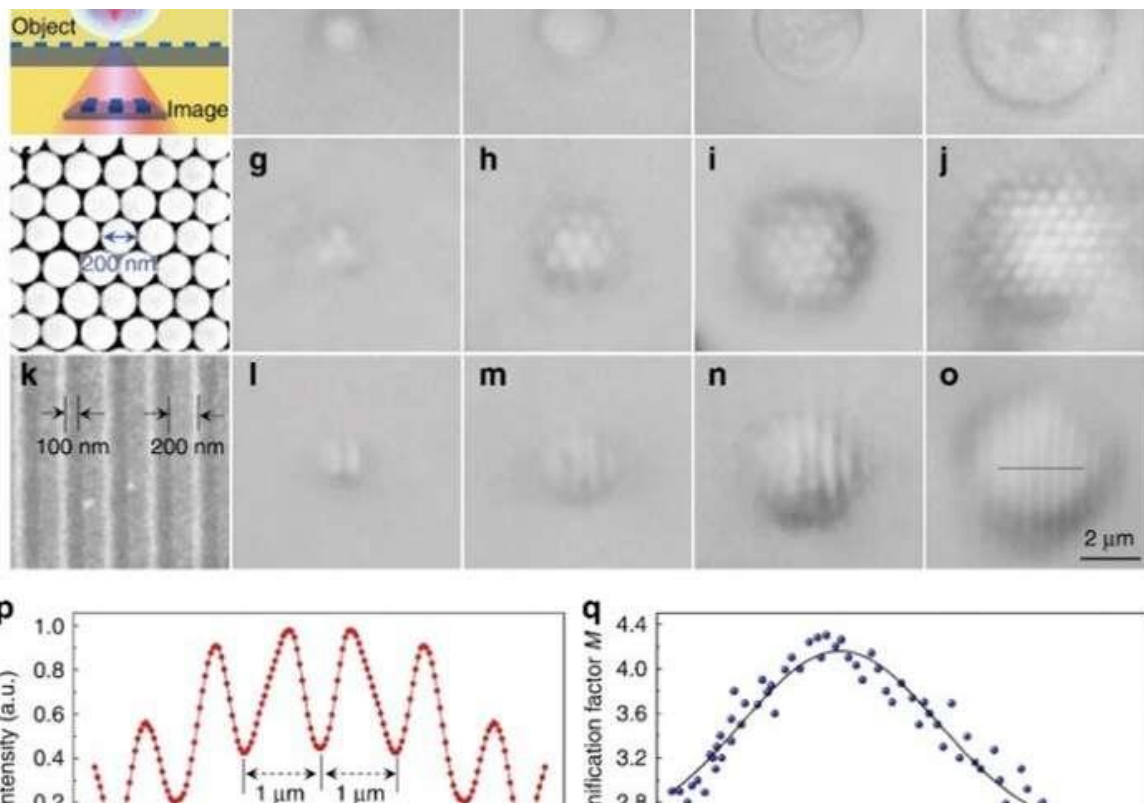


Schematic illustration of the experimental setup. A conventional reflection-mode microscope equipped with a CCD camera and  $\times 100$  objective lens was used to observe samples and record images. The inset shown in a PC screen schematically depicting how the biomagnifier is used to magnify and image the subcellular structures inside a bio sample. Credit: Light: Science & Applications, doi: 10.1038/s41377-019-0168-4

Li et al. selected biological cells to replace microspheres since cells are both abundant and biocompatible in contact with biological systems. For instance, scientists can use living cells to manipulate light in biological environments and act as [optofluidic microlenses](#), [optical probes](#) and even incorporate *E.coli* as [biophotonic waveguides](#). In the present work, Li

et al. enhanced the index contrast of living cells by using a spherical shape semi-immersed in a medium to achieve focusing at the sub-wavelength. The scientists captured biological [images](#) using the subdiffraction light spot to illuminate targeted samples along with white-light microscopy. The nano-sized light spot exerted a strong optical gradient force to trap and manipulate a single nanoparticle enabling the biomagnifier to also function as an optical nanotweezer.

The scientists conducted all experiments under a reflection-mode optical microscope coupled to a charge-coupled device (CCD) camera and objective lens. They used light sources at 390 nm, 560 nm and 808 nm for excitation, illumination and trapping respectively. Using an optical fiber with a tapered tip, Li et al. trapped the biomagnifier at the end of the fiber, which they controlled by moving the tip using a micromanipulator. Li et al. selected smooth and spherical cells to minimize image aberration and noted the cells to exhibit better focusing performance when semi-immersed in solution to maintain cell viability.

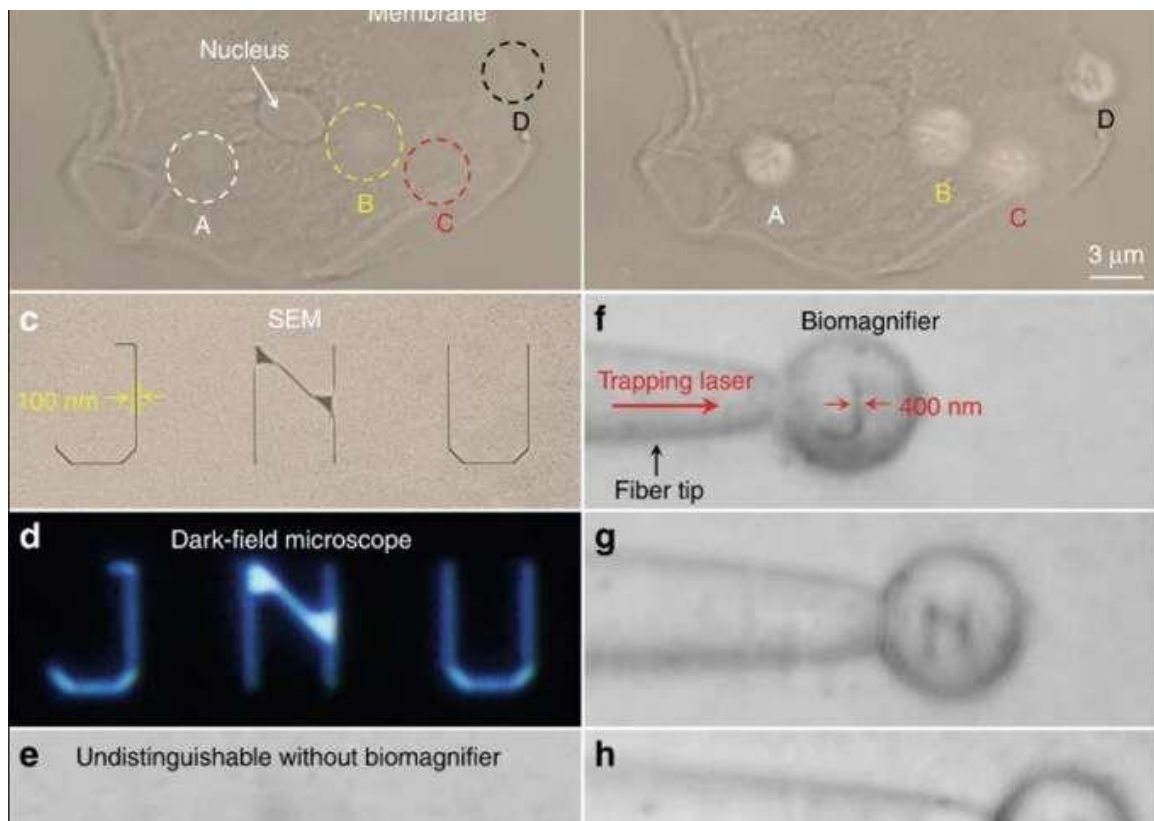


Experimental imaging performance of different biomagnifiers. (a) Schematic diagram showing that the biomagnifier collects the near-field nanostructures from an object and forms a virtually magnified image that can be captured by a conventional optical microscope. (b–e) Optical images of different biomagnifiers constructed from bacterial (b), yeast (c), red blood (d), and stem cells (e) that are partially submerged in cell suspension. f SEM image of a two-dimensional hexagonal close-packed silica nanosphere array assembled by a photophoresis technique. (g–j) Optical images of the silica nanosphere array magnified through biomagnifiers based on bacterial (g), yeast (h), red blood (i), and stem cells (j). (k) SEM image of the surface of a Blu-ray disk grating with a line width of 200 nm and spacing of 100 nm. l–o Optical images of the Blu-ray grating structure magnified through biomagnifiers based on bacterial (l), yeast (m), red blood (n), and stem cells (o). p Intensity

profile along the dotted line across the Blu-ray grating structure indicated in o. q Blue dots showing the magnification factor  $M$  of the images obtained by the biomagnifiers as a function of the biomagnifier diameter. Credit: Light: Science & Applications, doi: 10.1038/s41377-019-0168-4

During experimental imaging, the scientists positioned a semi-submerged biomagnifier on top of a test sample and collected the underlying near-field information from the sample, to form a [virtual image](#) as detected by an optical microscope. Li et al. prepared a variety of biomagnifiers using diverse cells including bacteria, yeast, red blood cells and stem cells. For the first imaging sample, they used a two-dimensional hexagonal silica nanosphere array with a 200 nm diameter on a glass substrate using a [photophoretic technique](#).

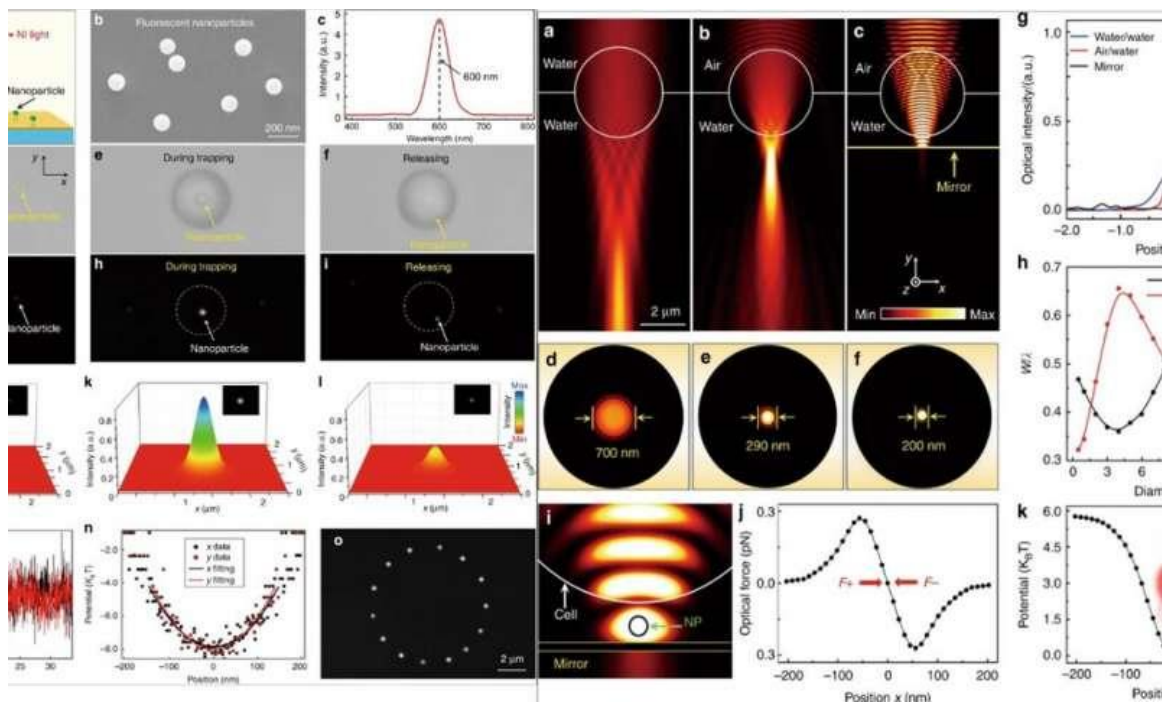
Only nanospheres with biomagnifiers on top of them could be resolved during imaging, whereas nanospheres without biomagnifiers could not be resolved using a conventional microscope. The magnification factor  $M$  of the stem-cell based biomagnifiers was determined to be 3.3 times larger ( $\times 3.3$ ), and the scientists showed the experimental  $M$  depended on the biomagnifier's diameter. Subsequently, Li et al. performed all experiments using biomagnifiers of this diameter.



Nano-optical imaging of subcellular structures and nanopatterned letters. (a, b) Optical images of the subcellular structures of a human epithelial cell using a conventional optical microscope (a) and biomagnifiers (b). The positions of four biomagnifiers are marked as A–D. For comparison, the biomagnifiers can resolve the fibrous cytoskeleton (indicated as A–C) inside the cell and two-layer structures (indicated as D) on the cell membrane, which are indistinguishable by the conventional microscope. c–e SEM (c), dark-field (d), and optical images (e) of nanopatterned letters JNU representing the acronym of Jinan University. The line width of the nanopatterned letters is

100 nm, which is smaller than the diffraction-limit resolution of the conventional optical microscope. f–h Optical images showing that the biomagnifier trapped on the fiber tip can scan and image the nanopatterned letters J (f), N (g), and U (h) by moving the fiber. The line width of the nanopatterned letters was magnified from 100 to 400 nm. Credit: Light: Science & Applications, doi: 10.1038/s41377-019-0168-4

To investigate the applications of biomagnifiers, Li et al. imaged [human epithelial cells](#) as imaging targets by growing epithelial cells on a mirror substrate for enhanced light-matter interactions via the interference of the illumination light and reflection light. While it was difficult to distinguish the [fibrous cytoskeleton](#) and bilayer structures under a conventional optical microscope, after positioning a biomagnifier on top of the epithelial [cells](#) the scientists were able to resolve both structures. To improve the imaging field of view (FOV), they trapped the biomagnifier on a fiber tip and moved it to scan the samples. For example, Li et al. used the setup to scan nanopatterned letters that stood for an acronym of Jinan University—JNU, which they first created on silicon using [electron-beam lithography](#).



LEFT: Optical manipulation of a single fluorescent nanoparticle. (a) Schematic diagram showing a fluorescent nanoparticle suspended on the surface of a mirror and trapped by the biomagnifier. (b) SEM image showing the PS fluorescent nanoparticles with an average radius of 50 nm. (c) Emission spectrum showing the central emission wavelength of the fluorescent nanoparticles located at 600 nm. (d–f) Optical images show the trapping process of a single PS nanoparticle with the biomagnifier. The process consisted of three successive steps: before trapping (d), during trapping (e), and after release (f). g–i Fluorescence images showing the fluorescence spot of the PS nanoparticle before being trapped (g), during trapping (h), and after release (i). j–l Three-dimensional color mapping of the fluorescence spots of the nanoparticle as shown in g–i. m Real-time trace of the position of the trapped nanoparticle in the x and y directions. (n) Trapping potential of the trapped nanoparticle in the x and y directions with parabola fittings. (o) Composite

fluorescence images show the movement trace of the trapped nanoparticle in the x–y plane by controlled movement of the biomagnifier. RIGHT: Numerical simulation and calculation. (a–c) Optical intensity distributions of light focusing by a 4- $\mu\text{m}$  biomagnifier fully immersed in water (a), semi-immersed in water (b), and suspended on the surface of a mirror (c). The illumination light source was set as a Gaussian beam with a wavelength of 560 nm. (d–f) Optical intensity distributions of the light spots from the biomagnifier corresponding to (a–c) in the x–z plane. (g) Optical intensity profiles at the focal planes of the output light from the biomagnifiers in the x direction. (h) FEM simulation results for the normalized waist of the light spot  $w/\lambda$  ( $w$  is the waist radius of the light spot and  $\lambda$  is the wavelength of the input light) and the ratio  $D/d$  (the width of the linear region where light enters the biomagnifier at its front surface is referred to as  $D$ , and the width of the output light beam at the rear surface is  $d$ ) as a function of the biomagnifier diameter. (i) Simulated intensity distribution of near-infrared trapping light showing that a nanoparticle (radius: 50 nm) is trapped in the gap between the biomagnifier and mirror. The input optical power of the trapping light was set to 10 mW. (j) Simulated optical forces of the nanoparticle trapped in the light spot as a function of the nanoparticle position along the x direction. (k) Calculated trapping potential of the trapped nanoparticle as a function of the position along the x direction. Credit: Light: Science & Applications, doi: 10.1038/s41377-019-0168-4

Thereafter, when they simultaneously irradiated near infrared (IR) and UV laser beams on the biomagnifier through an objective lens, they could trap and excite the nanoparticles. For these experiments, the scientists used fluorescent nanoparticles with a 50 nm average radius. When they trapped a single nanoparticle in the focus of a biomagnifier, they observed both optical and fluorescent images of the sample of interest. Li et al. then calculated the trapping stiffness of the particle in real-time using standard optical tweezers. The ability to manipulate a single nanoparticle without contact and precisely via optics will be useful to assemble well-regulated nanostructures. When Li et al. numerically investigated the imaging mechanism and trapping stiffness of biomagnifiers using 3-D simulation and [COMSOL software](#). They observed the subdiffraction-limit light focusing ability resulted from a combined "photonic nanojet" effect and coherent interference enhancement by the mirror.

Limitations of the method included imaging aberration and distortion due to the inhomogeneous intracellular structures of the natural biomagnifier, compared to dielectric microspheres with uniform refractive indices. Fortunately, intracellular materials were optically transparent to visible and near-infrared light and the optical interactions were relatively weak inside a single cell. Intracellular activities could also change the partial refractive index distribution in a cell to cause light distortion during trapping and imaging, but most intracellular activities were ultrafast and did not influence the imaging scheme.

In this way, Yuchao Li and colleagues developed a new experimental imaging technique and verified the experimental capabilities with FEM simulations. Li et al. integrated optical nanoscopes and nanotweezers in a single device to image and manipulate nanostructures simultaneously for the first time in the present work. They promoted the resolution of the technique to 100 nm and proposed a label-free imaging procedure. The scientists envision the living biomagnifier to open new opportunities in super-resolution imaging, real-time sensing and precise nano-assembly of bionanomaterials to form nanoarchitectures of interest. [31]

## Making catenanes and a molecular trefoil knot out of para-connected benzene rings

A team of researchers affiliated with several institutions in Japan has developed a way to create catenanes and a molecular trefoil knot out of para-connected benzene rings. In their paper published in the journal *Science*, the group describes their process and possible uses of their results. Jeff Van Raden, and Ramesh Jasti with the University of Oregon, have published a Perspective piece on the work done by the team in the same journal issue.

In recent years, carbon-based materials such as graphene, fullerenes and carbon nanotubes have captured the imagination of scientists—such materials have a wide range of unique physical properties that make them useful for certain applications. Graphene, for example, is a zero-gap semiconductor. Scientists have also been looking at ways in which such structures can be formed. In this new effort, the researchers have found a way to get benzene rings to form into two kinds of catenanes, and also a trefoil knot. Catenanes are a type of molecular architecture with two or more interlocking macrocycles. And a trefoil knot, as its name suggests, is a molecular structure that that resembles a knot with three crossings. By creating these structures, the researchers have added molecules that are mechanically bonded to the list of carbon nanostructures.

To create their structures, the researchers built on prior work that involved synthesizing benzene rings—but this time around, they introduced a silicon template on adjoining fragments of nanorings. After the fragments had cyclized into rings, the researchers removed the silicon, which left behind small rings interlocked with larger rings, structures called catenanes. They used a similar process to create the trefoil knot, but note that it was more difficult—only 0.3 percent of attempts worked out as planned.

The researchers also note that during testing of the nanocarbons they had created, they found something surprising—the chains in the structures moved around when exposed to magnetic resonance. They had expected all of the structures would be rigid. They suggest that the ability to control the topology of such nanocarbons could lead to the development of products that take advantage of their unique configurations. [30]

## Researchers use nano-particles to increase power, improve eye safety of fiber lasers

Scientists at the U.S. Naval Research Laboratory have devised a new process for using nano-particles to build powerful lasers that are more efficient and safer for your eyes.

They're doing it with what's called "rare-earth-ion-doped fiber." Put simply, it's laser [light](#) pumping a silica fiber that has been infused with rare earth ions of holmium. According to Jas S. Sanghera, who heads the Optical Materials and Devices Branch, they have achieved an 85 percent efficiency with their new process.

"Doping just means we're putting rare earth ions into the core of the fiber, which is where all the action happens," Sanghera explained. "That's how we've produced this world record efficiency, and it's what we need for a high-energy, eye-safer laser."

According to Colin Baker, research chemist with the Optical Materials and Devices Branch, the lasing process relies on a pump source—most often another laser—which excites the rare earth ions, which then emit photons to produce a high quality light for lasing at the desired wavelength.

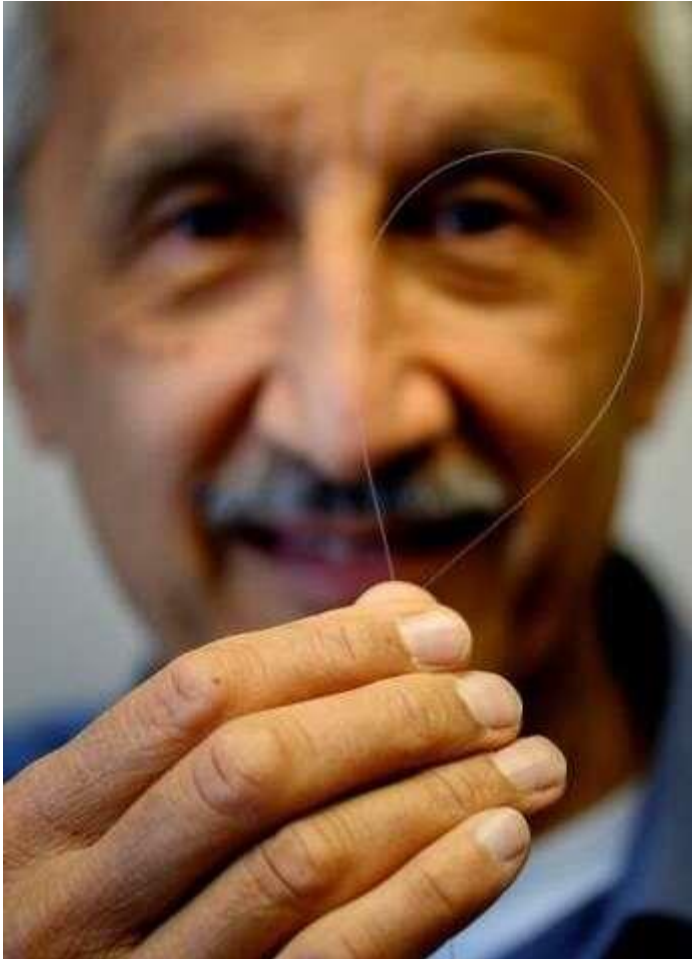
"But this process has a penalty," Baker said. "It's never 100 percent efficient. What you're putting in is pump energy, not the high quality light at the wavelength you want. What's coming out is a much higher quality of light at the specific wavelength that you want, but the remaining energy that isn't converted into laser light is wasted and converted into heat."

That loss of energy, Baker said, ultimately limits power scaling and the quality of the [laser light](#), which makes efficiency especially important.

With the aid of a nano-particle 'dopant,' they're able to achieve the 85 percent level of efficiency with a laser that operates at a 2 microns wavelength, which is considered an "eye-safer" wavelength, rather than the traditional 1 micron. Of course, Baker pointed out, no laser can be said to be safe when it comes to the human eye.

The danger arises from the potential of scattered light to be reflected into the eye during a laser's operation. Scattered light from the path of a 100-kilowatt laser operating at 1 micron can cause significant damage to the retina, leading to blindness. With an eye-safer laser, operated at wavelengths beyond 1.4 micron, however, the danger from scattered light is considerably lessened.





Jas Sanghera, U.S. Naval Research

Laboratory branch head for Optical Materials and Devices, holds up optical fiber that will be used to produce eye safer lasers at U.S. NRL, DC on March 26, 2019. Credit: U.S. Navy/Jonathan Steffen

According to Baker, the nano-particle doping also solves several other problems, such as that it shields the rare earth ions from the silica. At 2 microns, the silica's glassy structure can reduce the light output from the rare earth ions. The nanoparticle doping also separates the rare earth ions from each other, which is helpful since packing them closely together can also reduce the light output.

Traditional lasers that operate at 1 micron, using an ytterbium dopant, aren't nearly as affected by these factors, Baker said.

"The solution was some very clever chemistry that dissolved holmium in a nano-powder of lutetia or lanthanum oxide or lanthanum fluoride to create a suitable crystal environment [for the rare earth ions]," Sanghera said. "Using bucket chemistry to synthesize this nano-powder was key in keeping the cost down."

The particles of the nano-particle powder, which Sanghera's team had originally synthesized for a previous project, are typically less than 20 nanometers, which is 5,000 times smaller than a human hair.

"Additionally, we had to be able to successfully dope these nano-powders into the silica fiber in quantities that would be suitable to achieve lasing," he added.

At the Optical Materials and Devices Branch, Sanghera's team of scientists are working with a room-sized, glass-working lathe, where the glass that will eventually become the fiber is cleaned with fluorine gases, molded with a blow torch and infused with the nano-particle mixture—what the scientists call a "nanoparticle slurry." The result is a rare-earth-ion-doped, one-inch diameter glass rod, or "optical preform."

Next door, scientists use a fiber pulling system—a tower so massive that it takes up two large rooms and the height of two floors of the building—to soften the preform with a furnace and elongate it, in a process akin to pulling taffy, into an optical fiber about as thin as a human hair, which then spools onto a nearby large spindle.

Sanghera's team has already submitted a patent application for the process. Among the potential applications they envision for the new specialty fiber laser are high powered lasers and amplifiers for defense, telecommunications and even welding and [laser](#)-cutting.

"From a fundamental perspective, the whole process is commercially viable," Sanghera said. "It's a low-cost process to make the powder and incorporate it into the fiber. The process is very similar to making telecom fiber." [29]

## Nanocrystals arrange to improve electronics

Lawrence Livermore National Laboratory (LLNL) researchers are working to make better electronic devices by delving into the way nanocrystals are arranged inside of them.

Nanocrystals are promising building blocks for new and improved electronic devices, due to their size-tunable properties and ability to integrate into devices at low-cost.

While the structure of nanocrystals has been extensively studied, no one has been able to watch the full assembly process.

That's where LLNL scientists Christine Orme, Yixuan Yu, Babak Sadigh and a colleague from the University of California, Los Angeles come in.

"We think the situation can be improved if detailed quantitative information on the nanocrystal assembly process could be identified and if the crystallization process were better controlled," said Orme, an LLNL material scientist and corresponding author of a paper appearing in the journal *Nature Communications*.

Nanocrystals inside devices form ensembles, whose collective physical properties, such as charge carrier mobility, depend on both the properties of individual nanocrystals and the way they are arranged. In principle, ordered nanocrystal ensembles, or superlattices, allow for more control in charge transport by facilitating the formation of minibands. However, in practice, few devices built from ordered nanocrystal superlattices are on the market.

Most previous studies use solution evaporation methods to generate nanocrystal superlattices and probe the assembly process as the solvent is being gradually removed. It is difficult to obtain quantitative information on the assembly process, however, because the volume and shape of the nanocrystal solution is continually changing in an uncontrollable manner and the capillary forces can drive nanocrystal motion during drying.

Electric field-driven growth offers a solution to this problem. "We have recently demonstrated that an electric field can be used to drive the assembly of well-ordered, 3-D nanocrystal superlattices," Orme said.

Because the electric field increases the local concentration without changing the volume, shape or composition of nanocrystal solution, the crystallizing system can be probed quantitatively without complications associated with capillary forces or scattering from drying interfaces.

As anticipated, the team found that the electric field drives nanocrystals toward the surface, creating a concentration gradient that leads to nucleation and growth of superlattices. Surprisingly, the field also sorts the particles according to size. In essence, the electric field both concentrates and purifies the nanocrystal solution during growth.

"Because of this size sorting effect, the [superlattice](#) crystals are better ordered and the size of the [nanocrystals](#) in the lattice can be tuned during growth," Orme said. "This might be a useful tool for optoelectronic devices. We're working on infrared detectors now and think it might be an interesting strategy for improving color in monitors." [28]

## Nanoparticles form supercrystals under pressure

Self-assembly and crystallisation of nanoparticles (NPs) is generally a complex process, based on the evaporation or precipitation of NP-building blocks. Obtaining high-quality supercrystals is slow, dependent on forming and maintaining homogenous crystallisation conditions. Recent studies have used applied pressure as a homogenous method to induce various structural transformations and phase transitions in pre-ordered nanoparticle assemblies. Now, in work recently published in the *Journal of Physical Chemistry Letters*, a team of German researchers studying solutions of gold nanoparticles coated with poly(ethylene glycol)- (PEG-) based ligands has discovered that supercrystals can be induced to form rapidly within the whole suspension.

Over the last few decades, there has been considerable interest in the formation of nanoparticle (NP) supercrystals, which can exhibit tunable and collective properties that are different from that of their component parts, and which have potential applications in areas such as optics, electronics, and sensor platforms. Whilst the formation of high-quality supercrystals is normally a slow and complex process, recent research has shown that applying [pressure](#) can induce gold nanoparticles to form supercrystals. Building on this and the established effect of salts on the solubility of gold nanoparticles (AuNP) coated with PEG-based ligands, Dr. Martin Schroer and his team carried out a series of experiments investigating the effect of varying pressure on [gold nanoparticles](#) in aqueous solutions. They made an unexpected observation – when a salt is added to the solution, the [nanoparticles](#) crystallise at a certain pressure. The phase diagram is very sensitive, and the crystallisation can be tuned by varying the type of salt added, and its concentration.

The team used small angle x-ray scattering (SAXS) on beamline I22 to study the crystallisation in situ with different chloride salts (NaCl, KCl, RbCl, CsCl). As Dr. Schroer explains,

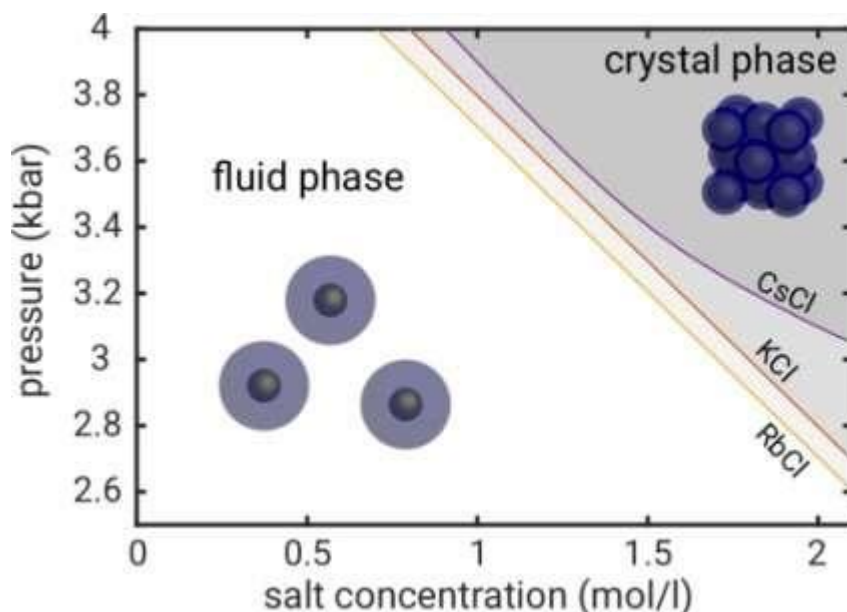


Fig. 2: Pressure – salt concentration phase diagram of AuNP@PEG. For low pressures, the particles are in the liquid state, beyond a critical pressure, face-centred cubic (fcc) superlattices are formed within solution. The crystallisation ...[more](#)

I22 is one of the few beamlines to offer a high-pressure environment, and it is unusual because the experimental setup is easily managed by the users themselves. The beamline staff are excellent, and we are particularly grateful for their expertise in data processing, which was invaluable."

The resulting pressure-salt concentration phase diagram shows that the crystallisation is a result of the combined effect of salt and pressure on the PEG coatings. Supercrystal formation occurs only at high salt concentrations, and is reversible. Increasing the salt concentration leads to a continuous decrease of the crystallisation pressure, whereas the lattice structure and degree of crystallinity is independent of the salt type and concentration.

When reaching the crystallisation pressure, supercrystals form within the whole suspension; compressing the liquid further results in changes of the lattice constant, but no further crystallisation or structural transitions. This technique should be applicable to a variety of nanomaterials, and future studies may reveal insights into supercrystal formation that will help to understand crystallisation processes and enable the development of new and quicker methods for the synthesis of NP supercrystals.

The NP crystallisation appears to be instantaneous, but in this set of experiments there was a delay of around 30 seconds between applying the pressure and taking the SAXS measurements. Dr. Schroer and his team are returning to Diamond later this year to carry out time-resolved studies to further investigate this phenomenon. [27]

## Researchers develop nanoparticle films for high-density data storage

As we generate more and more data, the need for high-density data storage that remains stable over time is becoming critical. New nanoparticle-based films that are more than 80 times thinner than a human hair may help to fill this need by providing materials that can holographically archive more than 1000 times more data than a DVD in a 10-by-10-centimeter piece of film. The new technology could one day enable tiny wearable devices that capture and store 3-D images of objects or people.

"In the future, these new films could be incorporated into a tiny [storage](#) chip that records 3-D color information that could later be viewed as a 3-D hologram with realistic detail," said Shencheng Fu, who led researchers from Northeast Normal University in China who developed the new films.

"Because the storage medium is environmentally stable, the device could be used outside or even brought into the harsh radiation conditions of outer space."

In the journal *Optical Materials Express*, the researchers detail their fabrication of the new films and demonstrate the technology's ability to be used for an environmentally-stable holographic storage system. The films not only hold large amounts of data, but that data can also be retrieved at speeds up to 1 GB per second, which is about twenty times the reading speed of today's flash memory.

### Storing more data in less space

The new films are designed for holographic data storage, a technique that uses lasers to create and read a 3-D holographic recreation of data in a material. Because it can record and read millions of bits at once, holographic data storage is much faster than optical and magnetic approaches typically used for data storage today, which record and read individual bits one at a time. Holographic approaches are also inherently high-density because they record information throughout the 3-D volume of the material, not just on the surface, and can record multiple images in the same area using light at different angles or consisting of different colors.

Recently, researchers have been experimenting with using metal-semiconductor nanocomposites as a medium for storing nanoscale holograms with high spatial resolution. Porous films made of the semiconductor titania and silver nanoparticles are promising for this application because they change color when exposed to various wavelengths, or colors, of laser light and because a set of 3-D images can be recorded at the focus area of laser beam using a single step. Although the films could be used for multiwavelength holographic data storage, exposure to UV light has been shown to erase the data, making the films unstable for long-term information storage.



Shuangyan Liu is holding the new UV-resistant holographic storage film. The new technology could one day be used to make tiny wearable devices that capture and store 3-D images of objects or people. Credit: Northeast Normal University

Recording a holographic image into titania-silver films involves using a laser to convert the silver particles into silver cations, which have a positive charge due to extra electrons. "We noticed that UV light could erase the data because it caused electrons to transfer from the semiconductor film to the metal nanoparticles, inducing the same photo transformation as the laser," said Fu. "Introducing electron-accepting molecules into the system causes some of the electrons to flow from the semiconductor to these molecules, weakening the ability of UV light to erase the data and creating an environmentally stable high-density data storage medium."

### **Changing the electron flow**

For the new films, the researchers used electron-accepting molecules that measured only 1 to 2 nanometers to disrupt the electron flow from the semiconductor to the metal nanoparticles. They fabricated semiconductor films with a honeycomb nanopore structure that allowed the nanoparticles, electron-accepting molecules and the semiconductor to all interface with each other. The ultrasmall size of the electron-accepting molecules allowed them to attach inside the pores without affecting the pore structure. The final films were just 620 nanometers thick.

The researchers tested their new films and found that holograms can be written into them efficiently and with high stability even in the presence of UV light. The researchers also demonstrated that using the electron-acceptors to change the electron flow formed multiple electron transferring paths, making the material respond faster to the laser light and greatly accelerating the speed of data writing.

"Particles made from noble metals such as silver are typically viewed as a slow-response media for optical storage," said Fu. "We show that using a new electron transport flow improves the optical response speed of the particles while still maintaining the particle's other advantages for information storage."

The researchers plan to test the environmental stability of the new films by performing outdoor tests. They also point out that real-life application of the films would require the development of high efficiency 3-D image reconstruction techniques and methods for color presentation for displaying or reading the stored data. [26]

## Researchers developing materials for quantum computing

Creation of innovative materials is one of the most important areas of modern science. Active development of Industry 4.0 requires new properties from composite elements of electronics. Researches of scientists from South Ural State University are implemented within this area. SUSU's Crystal Growth Laboratory performs modification of properties and structure of ferrites, which are oxides of iron with other metals' oxides. This task is performed by introducing other chemical elements into the structure of barium hexaferrite in order to obtain new working characteristics of the material.

One of the latest research articles dedicated to this topic was published at the end of 2017 in *Ceramics International*.

"The specificity of ferrite crystal structure is in the fact that it has five different positions of iron in the crystal lattice. This is exactly what allows modifying the structure and properties of the material in a sufficiently wide range. Structure of the initial material changes its properties after introduction of other elements, which expands the possibilities for its use. Therefore, by changing material's chemical composition, we can modify its working characteristics. We researched distribution of indium on positions of the substitute element," says Denis Vinnik, Head of the Crystal Growth Laboratory.

The scientists have a special interest in determining which of iron's positions in the lattice of barium hexaferrite is the most preferential for the new element: properties of the modified material depend on its structure. At the present time, the crystallographic positions that indium will place have been determined. Research is being carried out in the area of studying super-high frequency characteristics and the nature of other various properties of ferrites.



Viktoria Matveychuk. Credit: A. Trukhanov

"Our interest to barium ferrites is conditioned by their high functional properties," explains Aleksey Valentinovich. "Chemical stability and corrosion resistance makes these materials environmentally safe and usable for practically unlimited time. Hexaferrites possess excellent magnetic parameters. Low specific electrical conductivity allows applying hexaferrite magnets at the presence of high-frequency magnet fields, which is prospective for microelectronics. Nowadays this material has a great potential in absorbing electromagnetic interference (EMI) in the microwave range. Therefore, hexaferrites are applicable for microwave technologies and for data transmission and protection from wave exposure at high frequencies."

"We are working with a 'palette' of various chemical elements, including wolframium, aluminum, titanium, manganese and silicon. We would like to find out how such substitutions affect the material's properties," says Svetlana Aleksandrovna. "Now, we are working with lead germanate. Additionally, we are studying physical characteristics of barium hexaferrite with placeable lead and its behavior at high temperatures. At some point of heating till a specific temperature, the sample starts shrinking; this is a quite extraordinary phenomenon. Within this experiment, we calculated the linear expansion coefficient and obtained interesting dependences. There are materials with negative or zero expansion coefficient; they don't change their size during heating. This is



important at extreme temperatures, because some electronic details get overheated even under normal conditions."

Barium hexaferrite with placeable lead is one of study fields of the Crystal Growth Laboratory. The scientists have now grown monocrystals with low defect density that can be applied as working elements of electronic devices. Potentially, the material can be used for creation of a quantum computer which would have the highest performance capacity among the existing computational devices.

Development of new magnetic materials in the 21st century will allow creating memory elements with high-speed response, significant volume, and reliability. This class of materials has many applications. [25]

## Terahertz computer chip now within reach

Following three years of extensive research, Hebrew University of Jerusalem (HU) physicist Dr. Uriel Levy and his team have created technology that will enable computers and all optic communication devices to run 100 times faster through terahertz microchips.

Until now, two major challenges stood in the way of creating the terahertz [microchip](#): overheating and scalability.

However, in a paper published this week in *Laser & Photonics Reviews*, Dr. Levy, head of HU's Nano-Opto Group and HU emeritus professor Joseph Shappir have shown proof of concept for an optic [technology](#) that integrates the speed of optic (light) communications with the reliability—and manufacturing scalability—of electronics.

Optic communications encompass all technologies that use light and transmit through [fiber optic cables](#), such as the internet, email, text messages, phone calls, the cloud and data centers, among others. Optic communications are super fast but in microchips they become unreliable and difficult to replicate in large quantities.

Now, by using a Metal-Oxide-Nitride-Oxide-Silicon (MONOS) structure, Levy and his team have come up with a new integrated circuit that uses flash memory technology—the kind used in flash drives and discs-on-key—in microchips. If successful, this technology will enable standard 8-16 gigahertz computers to run 100 times faster and will bring all optic devices closer to the holy grail of communications: the terahertz chip.

As Dr. Uriel Levy shared, "this discovery could help fill the 'THz gap' and create new and more powerful wireless devices that could transmit data at significantly higher speeds than currently possible. In the world of hi-tech advances, this is game-changing technology,"

Meir Grajower, the leading HU Ph.D. student on the project, added, "It will now be possible to manufacture any optical [device](#) with the precision and cost-effectiveness of flash technology." [24]

## Revolutionizing computer memory—with magnets

When the energy efficiency of electronics poses a challenge, magnetic materials may have a solution.

Energy efficiency will make or break the future. As the demand for energy from electronics continues growing, the Semiconductor Research Corporation warns that within two decades, the global computational demand for energy will be greater than the total amount produced. Vincent Sokalski, an assistant professor of [materials](#) science and engineering at Carnegie Mellon University, is working on a solution to this problem—using [magnetic materials](#) for energy-efficient memory and computing.

Sokalski recently received a \$1.8 million grant from the Defense Advanced Research Projects Agency (DARPA) for his project, "Domain wall skyrmions: Topological excitations confined to 1-D channels." Along with CMU Professors Marc De Graef (MSE) and Di Xiao (Physics), Sokalski will explore new ways to efficiently process and store information with magnetic materials.

Although magnetic materials are already used in today's hard disk drives for long-term storage, semiconductors are currently used for short-term memory and processing, which is where most of the energy is consumed. However, as semiconductors shrink to meet consumer expectations for speed and density, there comes a limit to how small they can be made without risking the loss of information. DARPA recognizes this challenge, and [research projects](#) funded by DARPA's "Topological Excitations in Electronics" program center on finding ways to use "topological protection" to improve magnetic materials that can be used for computer memory storage or processors.

Imagine a bowl with a small ball rolling inside. As you shake it, the ball moves up and down the walls of the bowl, staying inside. However, if you did this with a smaller bowl, the ball might eventually fall out. Similarly, when a semiconductor is exposed to heat, it is at risk of losing information. The smaller you manufacture semiconductors, the more risk there is of data loss.

Credit: Carnegie Mellon University College of Engineering

"The fundamental physics behind that isn't something we can readily change," explains Sokalski, "but we can look at entirely different material systems and mechanisms where we're moving around magnetic features, and using those magnetic features to change the resistance of a computing device. But in order to do that, we really need to explore and discover new materials that can serve that purpose."

Enter magnetic materials. By improving magnetic materials, Sokalski hopes to one day find [new materials](#) that could augment, or even replace, semiconductors in computing.

Sokalski's project begins with magnetic skyrmions, or 2-D magnetic bubbles. If used in computer memory, each bubble would store a single bit of data.

"Skyrmions are a rebirth of the idea of bubble memory" that was widely studied in the 1970s and 80s, says Sokalski. "Except now the bubbles are much smaller, more stable, and have topological

protection, so we can move them around with greater energy efficiency than we ever could have moved them around 40 or 50 years ago."

In magnetic materials, think of each electron as a tiny bar magnet with a north and south pole that are all pointing in the same direction. These are called spins. Sokalski is interested in how to create topological defects in lines of these spins.

To understand the importance of topological protection, you first have to understand topological defects. Imagine stacking a cheese tray with a friend. One of you starts on the right side of the tray, stacking up each piece of cheese on top of the next, and the other starts on the left side. Eventually, you'll meet in the middle, and your slices of cheese will collide, rather than aligning at the same angle. That point where they collide is the essence of a topological defect.

To erase a topological defect, you'd have to flip every "slice of cheese" on one side of the defect. In magnetism, if half of your spins in a chain point inward to the left, and all the others point the opposite direction, you'd get a defect in the middle. In order to make the defect disappear, you'd have to reverse every spin on one side, moving it away to the edge of the chain.

In magnetism, these topological defects are very valuable. If you have a topological defect, that means your data are topologically protected, because if just one spin spontaneously flips to point in the opposite direction, the defect just shifts, rather than goes away.

Why is this topic suddenly emerging in magnetic materials research? All magnetism is based on something called the Heisenberg Exchange, a quantum mechanical effect that causes electron spins to align in a parallel orientation. However, the discovery of a new phenomenon called the Dzyaloshinskii-Moriya Interaction (DMI) leads to a perpendicular alignment of neighboring spins. The combination of Heisenberg Exchange and DMI, which is what Sokalski studies, gives rise to a new kind of magnetism that causes electron spins to have a continuously spiraling configuration.

"It turns out that features in magnetic materials that are stabilized by this new interaction can actually be manipulated with better efficiency than in cases where it's only the Heisenberg Exchange," says Sokalski.

Having greater control over skyrmions and topological defects would mean more reliable data storage and energy efficiency in computing.

"DARPA is looking to circumvent the pending challenge of energy-efficient electronics," says Sokalski, "and that scales from the most fundamental physical concepts of spin to the design of computers that have an entirely different circuit architecture. Our research will lead to energy-efficient computing that meets the needs of artificial intelligence and small-scale computers, while mitigating their global energy footprint."

MSE Ph.D. students Maxwell Li and Derek Lau and Physics postdoctoral researcher Ran Cheng are collaborators on this project, in addition to Co-PIs Tim Mewes and Claudia Mewes at the University of Alabama. [23]

## The quantum states on the surface of conducting materials can strongly interact with light

An exotic state of matter that is dazzling scientists with its electrical properties, can also exhibit unusual optical properties, as shown in a theoretical study by researchers at A\*STAR.

Atomically thin materials, such as graphene, derive some of their properties from the fact that electrons are confined to traveling in just two-dimensions. Similar phenomena are also seen in some three-dimensional materials, in which electrons confined to the [surface](#) behave very differently from those within the bulk—for example, [topological insulators](#), whose surface electrons conduct electricity even though their bulk electrons do not. Recently, another exciting class of materials has been identified: the topological semimetal.

The difference in insulator and conductor [electrical properties](#) is down to the bandgap: a gap between the ranges, or bands, of energy that an electron traveling through the material can assume. In an insulator, the lower band is full of electrons and the bandgap is too large to enable a current to flow. In a semimetal, the lower band is also full but the lower and upper bands touch at some points, enabling the flow of a small current.

This lack of a full bandgap means that topological semimetals should theoretically exhibit very different properties from those of the more conventional topological insulators.

To prove this, Li-kun Shi and Justin Song from the A\*STAR Institute of High Performance Computing used an 'effective Hamiltonian' approximation to show that the two-dimensional surface states in semimetals, known as Fermi arcs, possess a light–matter interaction much stronger than that found in other gapless two-dimensional systems, such as graphene.

"Typically, the bulk dominates material absorption," explains Song. "But we show that Dirac semimetals are unusual in that they possess a very optically active surface due to these peculiar Fermi arc states."

Shi and Song analyzed a proto-typical semimetal with a symmetric band structure where the electronic bands touch at two places, known as Dirac points, and predicted the strength with which incident radiation induces electron transitions from the lower band to the upper one. They found that surface absorption depends heavily on the polarization of light, being 100 to 1,000 times stronger when light is polarized perpendicular—rather than parallel—to the crystal's rotational axis. This strong anisotropy offers a way of optically investigating and probing the topological surface states of Dirac semimetals.

"Our goal is to identify more unconventional optics that arise due to Fermi arcs," says Song.

"Topological semimetals could host unusual opto-electronic behavior that goes beyond conventional materials." [22]

## Breakthrough in circuit design makes electronics more resistant to damage and defects

People are growing increasingly dependent on their mobile phones, tablets and other portable devices that help them navigate daily life. But these gadgets are prone to failure, often caused by small defects in their complex electronics, which can result from regular use. Now, a paper in today's *Nature Electronics* details an innovation from researchers at the Advanced Science Research Center (ASRC) at The Graduate Center of The City University of New York that provides robust protection against circuitry damage that affects signal transmission.

The breakthrough was made in the lab of Andrea Alù, director of the ASRC's Photonics Initiative. Alù and his colleagues from The City College of New York, University of Texas at Austin and Tel Aviv University were inspired by the seminal work of three British researchers who won the 2016 Noble Prize in Physics for their work, which teased out that particular properties of matter (such as electrical conductivity) can be preserved in certain materials despite continuous changes in the matter's form or shape. This concept is associated with topology—a branch of mathematics that studies the properties of space that are preserved under continuous deformations.

"In the past few years there has been a strong interest in translating this concept of matter topology from material science to light propagation," said Alù. "We achieved two goals with this project: First, we showed that we can use the science of topology to facilitate robust electromagnetic-wave propagation in electronics and circuit components. Second, we showed that the inherent robustness associated with these topological phenomena can be self-induced by the signal traveling in the circuit, and that we can achieve this robustness using suitably tailored nonlinearities in circuit arrays."

To achieve their goals, the team used nonlinear resonators to mold a band-diagram of the circuit array. The array was designed so that a change in signal intensity could induce a change in the band diagram's topology. For low signal intensities, the electronic circuit was designed to support a trivial topology, and therefore provide no protection from defects. In this case, as defects were introduced into the array, the signal transmission and the functionality of the circuit were negatively affected.

As the voltage was increased beyond a specific threshold, however, the band-diagram's topology was automatically modified, and the signal transmission was not impeded by arbitrary defects introduced across the circuit array. This provided direct evidence of a topological transition in the circuitry that translated into a self-induced robustness against defects and disorder.

"As soon as we applied the higher-voltage signal, the system reconfigured itself, inducing a topology that propagated across the entire chain of resonators allowing the signal to transmit without any problem," said A. Khanikaev, professor at The City College of New York and co-author in the study. "Because the system is nonlinear, it's able to undergo an unusual transition that makes signal transmission robust even when there are defects or damage to the circuitry."

"These ideas open up exciting opportunities for inherently robust electronics and show how complex concepts in mathematics, like the one of topology, can have real-life impact on common electronic devices," said Yakir Hadad, lead author and former postdoc in Alù's group, currently a professor at Tel-Aviv University, Israel. "Similar ideas can be applied to nonlinear optical [circuits](#) and extended to two and three-dimensional nonlinear metamaterials." [21]

## Researchers develop heat switch for electronics

Researchers at the University of Illinois at Urbana-Champaign have developed a new technology for switching heat flows 'on' or 'off'. The findings were published in the article "Millimeter-scale liquid metal droplet thermal switch," which appeared in *Applied Physics Letters*.

Switches are used to control many technical products and engineered systems. Mechanical switches are used to lock or unlock doors, or to select gears in a car's transmission system. Electrical switches are used to turn on and off the lights in a room. At a smaller scale, [electrical switches](#) in the form of transistors are used to turn electronic devices on and off, or to route logic signals within a circuit.

Engineers have long desired a switch for heat flows, especially in electronics systems where controlling heat flows can significantly improve system performance and reliability. There are however significant challenges in creating such a heat switch.

"Heat [flow](#) occurs whenever you have a region of higher temperature near a region of lower temperature," said William King, the Andersen Chair Professor in the Department of Mechanical Science and Engineering and the project co-leader. "In order to control the [heat flow](#), we engineered a specific heat flow path between the hot region and cold region, and then created a way to break the heat flow path when desired."

"The technology is based on the motion of a liquid metal droplet," said Nenad Miljkovic, Assistant Professor in the Department of Mechanical Science and Engineering and the project co-leader. "The metal droplet can be positioned to connect a heat flow path, or moved away from the heat flow path in order to limit the heat flow."

The researchers demonstrated the technology in a system modeled after modern electronics systems. On one side of the switch there was a heat source representing the power electronics component, and on the other side of the switch, there was liquid cooling for heat removal. When the switch was on, they were able to extract heat at more than 10 W/cm<sup>2</sup>. When the switch was off, the [heatflow](#) dropped by nearly 100X.

Besides King and Miljkovic, other authors of the paper include Paul Braun, Racheff Professor of Materials Science and Engineering and the Director of Materials Research Laboratory; and graduate students Tianyu Yang, Beomjin Kwon and Patricia B. Weisensee (now an assistant professor at Washington University in St. Louis) from mechanical science and engineering and Jin Gu Kang and Xuejiao Li from materials science and engineering.

King says that the next step for the research is to integrate the [switch](#) with power electronics on a circuit board. The researchers will have a working prototype later this year. [20]

## Converting heat into electricity with pencil and paper

Thermoelectric materials can use thermal differences to generate electricity. Now there is an inexpensive and environmentally friendly way of producing them with the simplest tools: a pencil, photocopy paper, and conductive paint. These are sufficient to convert a temperature difference into electricity via the thermoelectric effect, which has now been demonstrated by a team at the Helmholtz-Zentrum Berlin.

The [thermoelectric effect](#) was discovered almost 200 years ago by Thomas J. Seebeck. If two metals of different temperatures are brought together, they can develop an electrical voltage. This effect allows residual heat to be converted partially into electrical energy. Residual heat is a by-product of almost all technological and natural processes, such as in power plants and household appliances, not to mention the human body. It is also one of the most under-utilised energy sources in the world.

### Tiny effect

However, as useful an effect as it is, it is extremely small in ordinary metals. This is because metals not only have high electrical conductivity, but [high thermal conductivity](#) as well, so that differences in temperature disappear immediately. Thermoelectric [materials](#) need to have [low thermal conductivity](#) despite their [high electrical conductivity](#). Thermoelectric devices made of inorganic semiconductor materials such as bismuth telluride are already being used today in certain technological applications. However, such material systems are expensive and their use only pays off in certain situations. Researchers are exploring whether flexible, nontoxic organic materials based on carbon nanostructures, for example, might also be used in the human body.

The team led by Prof. Norbert Nickel at the HZB has now shown that the effect can be obtained much more simply—using a normal HB-grade [pencil](#), they covered a small area with pencil on ordinary photocopy paper. As a second material, they applied a transparent, conductive co-polymer paint (PEDOT: PSS) to the surface.

The pencil traces on the paper delivered a voltage comparable to other far more expensive nanocomposites that are currently used for flexible thermoelectric elements. And this voltage could be increased tenfold by adding indium selenide to the graphite from the pencil.

The researchers investigated graphite and co-polymer coating films using a scanning electron microscope and Raman scattering at HZB. "The results were very surprising for us as well," says Nickel. "But we have now found an explanation of why this works so well—the pencil deposit left on the paper forms a surface characterised by unordered graphite flakes, some graphene, and clay. While this only slightly reduces the electrical conductivity, heat is transported much less effectively."

These simple constituents might be usable in the future to print extremely inexpensive, environmentally friendly, and non-toxic thermoelectric components onto paper. Such tiny and flexible components could also be used directly on the body and could use body heat to operate small devices or sensors. [19]

## **A new efficient and portable electrocaloric cooling device**

A team of researchers with the University of California and SRI International has developed a new type of cooling device that is both portable and efficient. In their paper published in the journal *Science*, the team describes their new device and possible applications for its use. Q.M. Zhang and Tian Zhang with the Pennsylvania State University offer some background on electrocaloric theory and outline the work done by the team in California in a Perspectives piece in the same journal issue.

As most everyone knows, conventional air conditioners are bulky, heavy, use a lot of electricity and often leak greenhouse gases into the atmosphere. Thus, conditions are ripe for something new. Some new devices have been developed such as thermoelectric coolers, which make use of ceramics, but they are not efficient enough to play a major role in cooling. A more recent development is the use of devices exploiting the electrocaloric effect, which is where heat moves through certain materials when an electric current is applied. In this new effort, the researchers used a polymer as the material.

The new cooling device was made by layering a polymer between a heat sink and a heat source. Applying electric current to the polymer when it was touching the heat sink caused its molecules to line up, which reduced entropy, forcing heat into the sink. The polymer was then moved into contact with the heat source while the current was turned off. The molecules relaxed, which caused the temperature to drop. Repeating this process resulted in cooling.

The researchers report that the device is extremely efficient, portable and configurable. They suggest the same technology could be used to create coolers for a chair or hat, for example, or perhaps to chill smartphone batteries. They proved this last claim by actually building such a device and using it to cool down a battery heated by ordinary use—after only five seconds, the temperature of the battery had lessened by 8° C. Comparatively, air cooling the battery reduced its temperature just 3° C in 50 seconds. [18]

## **Fast heat flows in warm, dense aluminum**

Thermal conductivity is one of the most crucial physical properties of matter when it comes to understanding heat transport, hydrodynamic evolution and energy balance in systems ranging from astrophysical objects to fusion plasmas.

In the warm dense matter (WDM) regime, experimental data are very rare, so many theoretical models remain untested.

But LLNL researchers have tested theory by developing a platform called "differential heating" to conduct thermal conductivity measurements. Just as land and water on Earth heat up differently in sunlight, a temperature gradient can be induced between two different materials. The subsequent heat flow from the hotter material to the cooler material is detected by time-resolved diagnostics to determine thermal conductivity.



In an experiment using the Titan laser at the Lab's Jupiter Laser Facility, LLNL researchers and collaborators achieved the first measurements of thermal conductivity of warm dense aluminum—a prototype material commonly used in model development—by heating a dual-layer target of gold and aluminum with laser-generated protons.

"Two simultaneous time-resolved diagnostics provided excellent data for gold, the hotter material, and aluminum, the colder material," said Andrew Mckelvey, a graduate student from the University of Michigan and the first author of a paper appearing in Scientific Reports. "The systematic data sets can constrain both the release equation of state (EOS) and thermal conductivity."

By comparing the data with simulations using five existing thermal conductivity models, the team found that only two agree with the data. The most commonly used model in WDM, called the LeeMore model, did not agree with data. "I am glad to see that Purgatorio, an LLNL-based model, agrees with the data," said Phil Sterne, LLNL co-author and the group leader of EOS development and application group in the Physics Division. "This is the first time these thermal conductivity models of aluminum have been tested in the WDM regime."

"Discrepancy still exists at early time up to 15 picoseconds," said Elijah Kemp, who is responsible for the simulation efforts. "This is likely due to non-equilibrium conditions, another active research area in WDM."

The team is led by Yuan Ping through her early career project funded by the Department of Energy Office of Fusion Energy Science Early Career Program. "This platform can be applied to many pairs of materials and by various heating methods including particle and X-ray heating," Ping said. [17]

## **Controlling heat and particle currents in nanodevices by quantum observation**

Researchers from the Theory Department of the MPSD have realized the control of thermal and electrical currents in nanoscale devices by means of quantum local observations.

Measurement plays a fundamental role in quantum mechanics. The best-known illustration of the principles of superposition and entanglement is Schrödinger's cat. Invisible from the outside, the cat resides in a coherent superposition of two states, alive and dead at the same time.

By means of a measurement, this superposition collapses to a concrete state. The cat is now either dead or alive. In this famous thought experiment, a measurement of the "quantum cat" can be seen as an interaction with a macroscopic object collapsing the superposition onto a concrete state by destroying its coherence.

In their new article published in npj Quantum Materials, researchers from the Max Planck Institute for the Structure and Dynamics of Matter and collaborators from the University of the Basque Country (UPV/EHU) and the Bremen Center for Computational Materials Science discovered how a microscopic quantum observer is able to control thermal and electrical currents in nanoscale devices. Local quantum observation of a system can induce continuous and dynamic changes in its

quantum coherence, which allows better control of particle and energy currents in nanoscale systems.

Classical non-equilibrium thermodynamics was developed to understand the flow of particles and energy between multiple heat and particle reservoirs. The best-known example is Clausius' formulation of the second law of thermodynamics, stating that when two objects with different temperatures are brought in contact, heat will exclusively flow from the hotter to the colder one.

In macroscopic objects, the observation of this process does not influence the flow of energy and particles between them. However, in quantum devices, thermodynamical concepts need to be revisited. When a classical observer measures a quantum system, this interaction destroys most of the coherence inside the system and alters its dynamical response.

Instead, if a quantum observer acts only locally, the system quantum coherence changes continuously and dynamically, thus providing another level of control of its properties. Depending on how strong and where these local quantum observations are performed, novel and surprising quantum transport phenomena arise.

The group of Prof. Dr. Angel Rubio at the Theory Department of the MPSD, along with their colleagues, have demonstrated how the concept of quantum measurements can offer novel possibilities for a thermodynamical control of quantum transport (heat and particle). This concept offers possibilities far beyond those obtained using standard classical thermal reservoirs.

The scientists studied this idea in a theoretical quantum ratchet. Within this system, the left and right side are connected to hot and cold thermal baths, respectively. This configuration forces the energy to flow from hot to cold and the particles to flow clockwise inside the ratchet. The introduction of a quantum observer, however, inverts the particle ring-current against the natural direction of the ratchet—a phenomenon caused by the localized electronic state and the disruption of the system's symmetry.

Furthermore, the quantum observation is also able to invert the direction of the heat flow, contradicting the second law of thermodynamics. "Such heat and particle current control might open the door for different strategies to design quantum transport devices with directionality control of the injection of currents. There could be applications in thermoelectricity, spintronics, photonics, and sensing, among others. These results have been an important contribution to my PhD thesis," says Robert Biele, first author of the paper.

From a more fundamental point of view, this work highlights the role of a quantum observer. In contrast to Schrödinger's cat, where the coherent state is destroyed via the interaction with a macroscopic "observer," here, by introducing a local quantum observer, the coherence is changed locally and dynamically, allowing researchers to tune between the coherent states of the system. "This shows how thermodynamics is very different in the quantum regime. Schrödinger's cat paradox leads to new thermodynamic forces never seen before," says César A. Rodríguez Rosario.

In the near future, the researchers will apply this concept to control spins for applications in spin injection and novel magnetic memories. Angel Rubio suggests that "The quantum observer—besides controlling the particle and energy transfer at the nanoscale—could also observe spins,

select individual components, and give rise to spin-polarized currents without spin-orbit coupling. Observation could be used to write a magnetic memory." [16]

## **Maxwell's demon extracts work from quantum measurement**

Physicists have proposed a new type of Maxwell's demon—the hypothetical agent that extracts work from a system by decreasing the system's entropy—in which the demon can extract work just by making a measurement, by taking advantage of quantum fluctuations and quantum superposition.

The team of Alexia Auffèves at CNRS and Université Grenoble Alpes have published a paper on the new Maxwell's demon in a recent issue of Physical Review Letters.

"In the classical world, thermodynamics teaches us how to extract energy from thermal fluctuations induced on a large system (such as a gas or water) by coupling it to a hot source," Auffèves told Phys.org. "In the quantum world, the systems are small, and they can fluctuate—even if they are not hot, but simply because they are measured. In our paper, we show that it is possible to extract energy from these genuinely quantum fluctuations, induced by quantum measurement."

In the years since James Clerk Maxwell proposed the first demon around 1870, many other versions have been theoretically and experimentally investigated. Most recently, physicists have begun investigating Maxwell's demons that operate in the quantum regime, which could one day have implications for quantum information technologies.

Most quantum versions of the demon have a couple things in common: They are thermally driven by a heat bath, and the demon makes measurements to extract information only. The measurements do not actually extract any work, but rather the information gained by the measurements allows the demon to act on the system so that energy is always extracted from the cycle.

The new Maxwell's demon differs from previous versions in that there is no heat bath—the demon is not thermally driven, but measurement-driven. Also, the measurements have multiple purposes: They not only extract information about the state of the system, but they are also the "fuel" for extracting work from the system. This is because, when the demon performs a measurement on a qubit in the proposed system, the measurement projects the qubit from one state into a superposition of states, which provides energy to the qubit simply due to the measurement process. In their paper, the physicists proposed an experiment in which projective quantum non-demolition measurements can be performed with light pulses repeated every 70 nanoseconds or so.

Since recent experiments have already demonstrated the possibility of performing measurements at such high frequencies, the physicists expect that the new Maxwell's demon could be readily implemented using existing technology. In the future, they also plan to investigate potential applications for quantum computing.

"This engine is a perfect proof of concept evidencing that quantum measurement has some energetic footprint," Auffèves said. "Now I would like to reverse the game and use this effect to

estimate the energetic cost of quantum tasks, if they are performed in the presence of some measuring entity. This is the case in a quantum computer, which is continuously 'measured' by its surroundings. This effect is called decoherence and is the biggest enemy of quantum computation. Our work provides tools to estimate the energy needed to counteract it." [15]

## Physicists read Maxwell's Demon's mind

Pioneering research offers a fascinating view into the inner workings of the mind of 'Maxwell's Demon', a famous thought experiment in physics.

An international research team, including Dr Janet Anders from the University of Exeter, have used superconducting circuits to bring the 'demon' to life.

The demon, first proposed by James Clerk Maxwell in 1867, is a hypothetical being that can gain more useful energy from a thermodynamic system than one of the most fundamental laws of physics—the second law of thermodynamics—should allow.

Crucially, the team not only directly observed the gained energy for the first time, they also tracked how information gets stored in the demon's memory.

The research is published in the leading scientific journal Proceedings of the National Academy of Sciences (PNAS).

The original thought experiment was first proposed by mathematical physicist James Clerk Maxwell—one of the most influential scientists in history—150 years ago.

He hypothesised that gas particles in two adjacent boxes could be filtered by a 'demon' operating a tiny door, that allowed only fast energy particles to pass in one direction and low energy particles the opposite way.

As a result, one box gains a higher average energy than the other, which creates a pressure difference. This non-equilibrium situation can be used to gain energy, not unlike the energy obtained when water stored behind a dam is released.

So although the gas was initially in equilibrium, the demon can create a non-equilibrium situation and extract energy, bypassing the second law of thermodynamics.

Dr Anders, a leading theoretical physicist from the University of Exeter's physics department adds: "In the 1980s it was discovered that this is not the full story. The information about the particles' properties remains stored in the memory of the demon. This information leads to an energetic cost which then reduces the demon's energy gain to null, resolving the paradox."

In this research, the team created a quantum Maxwell demon, manifested as a microwave cavity, that draws energy from a superconducting qubit. The team was able to fully map out the memory of the demon after its intervention, unveiling the stored information about the qubit state.

Dr Anders adds: "The fact that the system behaves quantum mechanically means that the particle can have a high and low energy at the same time, not only either of these choices as considered by Maxwell."

This ground-breaking experiment gives a fascinating peek into the interplay between quantum information and thermodynamics, and is an important step in the current development of a theory for nanoscale thermodynamic processes.

'Observing a Quantum Maxwell demon at Work' is published in PNAS. [14]

## Researchers posit way to locally circumvent Second Law of Thermodynamics

For more than a century and a half of physics, the Second Law of Thermodynamics, which states that entropy always increases, has been as close to inviolable as any law we know. In this universe, chaos reigns supreme.

But researchers with the U.S. Department of Energy's (DOE's) Argonne National Laboratory announced recently that they may have discovered a little loophole in this famous maxim.

Their research, published in *Scientific Reports*, lays out a possible avenue to a situation where the Second Law is violated on the microscopic level.

The Second Law is underpinned by what is called the H-theorem, which says that if you open a door between two rooms, one hot and one cold, they will eventually settle into lukewarm equilibrium; the hot room will never end up hotter.

But even in the twentieth century, as our knowledge of quantum mechanics advanced, we didn't fully understand the fundamental physical origins of the H-theorem.

Recent advancements in a field called quantum information theory offered a mathematical construction in which entropy increases.

"What we did was formulate how these beautiful abstract mathematical theories could be connected to our crude reality," said Valerii Vinokur, an Argonne Distinguished Fellow and corresponding author on the study.

The scientists took quantum information theory, which is based on abstract mathematical systems, and applied it to condensed matter physics, a well-explored field with many known laws and experiments.

"This allowed us to formulate the quantum H-theorem as it related to things that could be physically observed," said Ivan Sadovskyy, a joint appointee with Argonne's Materials Science Division and the Computation Institute and another author on the paper. "It establishes a connection between well-documented quantum physics processes and the theoretical quantum channels that make up quantum information theory."

The work predicts certain conditions under which the H-theorem might be violated and entropy—in the short term—might actually decrease.

As far back as 1867, physicist James Clerk Maxwell described a hypothetical way to violate the Second Law: if a small theoretical being sat at the door between the hot and cold rooms and only let through particles traveling at a certain speed. This theoretical imp is called "Maxwell's demon."

"Although the violation is only on the local scale, the implications are far-reaching," Vinokur said. "This provides us a platform for the practical realization of a quantum Maxwell's demon, which could make possible a local quantum perpetual motion machine."

For example, he said, the principle could be designed into a "refrigerator" which could be cooled remotely—that is, the energy expended to cool it could take place anywhere.

The authors are planning to work closely with a team of experimentalists to design a proof-of-concept system, they said.

The study, "H-theorem in quantum physics," was published September 12 in Nature Scientific Reports. [13]

## What is quantum in quantum thermodynamics?

A lot of attention has been given to the differences between the quantum and classical worlds. For example, quantum entanglement, superposition, and teleportation are purely quantum phenomena with no classical counterparts. However, when it comes to certain areas of thermodynamics—specifically, thermal engines and refrigerators—quantum and classical systems so far appear to be nearly identical. It seems that the same thermodynamic laws that govern the engines in our vehicles may also accurately describe the tiniest quantum engines consisting of just a single particle.

In a new study, physicists Raam Uzdin, Amikam Levy, and Ronnie Kosloff at the Hebrew University of Jerusalem have investigated whether there is anything distinctly quantum about thermodynamics at the quantum level, or if "quantum" thermodynamics is really the same as classical thermodynamics.

For the first time, they have shown a difference in the thermodynamics of heat machines on the quantum scale: in part of the quantum regime, the three main engine types (two-stroke, four-stroke, and continuous) are thermodynamically equivalent. This means that, despite operating in different ways, all three types of engines exhibit all of the same thermodynamic properties, including generating the same amounts of power and heat, and doing so at the same efficiency. This new "thermodynamical equivalence principle" is purely quantum, as it depends on quantum effects, and does not occur at the classical level.

The scientists also showed that, in this quantum regime where all engines are thermodynamically equivalent, it's possible to extract a quantum-thermodynamic signature that further confirms the presence of quantum effects. They did this by calculating an upper limit on the work output of a classical engine, so that any engine that surpasses this bound must be using a quantum effect—namely, quantum coherence—to generate the additional work. In this study, quantum coherence, which accounts for the wave-like properties of quantum particles, is shown to be critical for power generation at very fast engine cycles.

"To the best of my knowledge, this is the first time [that a difference between quantum and classical thermodynamics has been shown] in heat machines," Uzdin told Phys.org. "What has been surprising [in the past] is that the classical description has still held at the quantum level, as many authors have shown. The reasons are now understood, and in the face of this classicality, people

have started to stray to other types of research, as it was believed that nothing quantum can pop up.

Thus, it was very difficult to isolate a generic effect, not just a numerical simulation of a specific case, with a complementing theory that manages to avoid the classicality and demonstrate quantum effects in thermodynamic quantities, such as work and heat."

One important implication of the new results is that quantum effects may significantly increase the performance of engines at the quantum level. While the current work deals with single-particle engines, the researchers expect that quantum effects may also emerge in multi-particle engines, where quantum entanglement between particles may play a role similar to that of coherence. [12]

## **Physicists confirm thermodynamic irreversibility in a quantum system**

The physicists, Tiago Batalhão at the Federal University of ABC, Brazil, and coauthors, have published their paper on the experimental demonstration of quantum thermodynamic irreversibility in a recent issue of Physical Review Letters.

Irreversibility at the quantum level may seem obvious to most people because it matches our observations of the everyday, macroscopic world. However, it is not as straightforward to physicists because the microscopic laws of physics, such as the Schrödinger equation, are "time-symmetric," or reversible. In theory, forward and backward microscopic processes are indistinguishable.

In reality, however, we only observe forward processes, not reversible ones like broken egg shells being put back together. It's clear that, at the macroscopic level, the laws run counter to what we observe. Now the new study shows that the laws don't match what happens at the quantum level, either.

Observing thermodynamic processes in a quantum system is very difficult and has not been done until now. In their experiment, the scientists measured the entropy change that occurs when applying an oscillating magnetic field to carbon-13 atoms in liquid chloroform. They first applied a magnetic field pulse that causes the atoms' nuclear spins to flip, and then applied the pulse in reverse to make the spins undergo the reversed dynamics.

If the procedure were reversible, the spins would have returned to their starting points—but they didn't. Basically, the forward and reverse magnetic pulses were applied so rapidly that the spins' flipping couldn't always keep up, so the spins were driven out of equilibrium. The measurements of the spins indicated that entropy was increasing in the isolated system, showing that the quantum thermodynamic process was irreversible.

By demonstrating that thermodynamic irreversibility occurs even at the quantum level, the results reveal that thermodynamic irreversibility emerges at a genuine microscopic scale. This finding makes the question of why the microscopic laws of physics don't match our observations even more pressing. If the laws really are reversible, then what are the physical origins of the time-asymmetric entropy production that we observe?

The physicists explain that the answer to this question lies in the choice of the initial conditions. The microscopic laws allow reversible processes only because they begin with "a genuine equilibrium process for which the entropy production vanishes at all times," the scientists write in their paper. Preparing such an ideal initial state in a physical system is extremely complex, and the initial states of all observed processes aren't at "genuine equilibrium," which is why they lead to irreversible processes.

"Our experiment shows the irreversible nature of quantum dynamics, but does not pinpoint, experimentally, what causes it at the microscopic level, what determines the onset of the arrow of time," coauthor Mauro Paternostro at Queen's University in Belfast, UK, told Phys.org. "Addressing it would clarify the ultimate reason for its emergence."

The researchers hope to apply the new understanding of thermodynamics at the quantum level to high-performance quantum technologies in the future.

"Any progress towards the management of finite-time thermodynamic processes at the quantum level is a step forward towards the realization of a fully fledged thermo-machine that can exploit the laws of quantum mechanics to overcome the performance limitations of classical devices," Paternostro said. "This work shows the implications for reversibility (or lack thereof) of nonequilibrium quantum dynamics. Once we characterize it, we can harness it at the technological level." [11]

### Physicists put the arrow of time under a quantum microscope

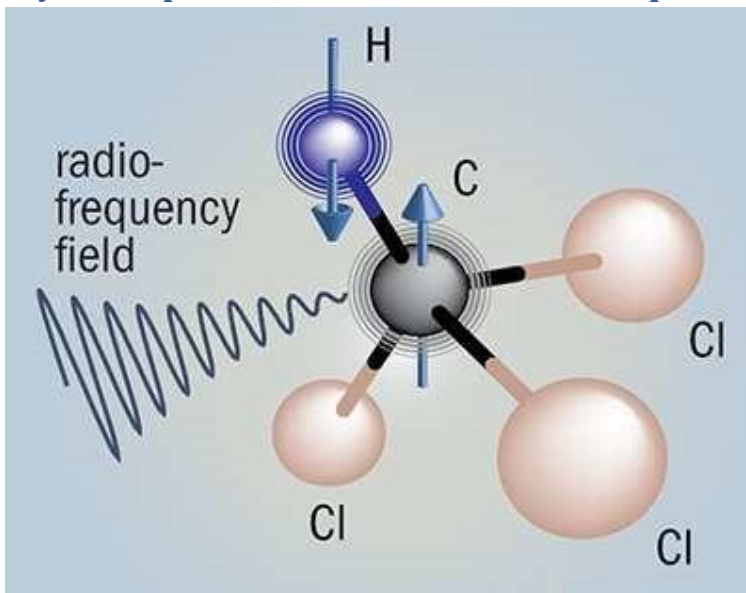


Diagram showing the spin of a carbon atom in a chloroform molecule

Disorder, or entropy, in a microscopic quantum system has been measured by an international group of physicists. The team hopes that the feat will shed light on the "arrow of time": the observation that time always marches towards the future. The experiment involved continually flipping the spin of carbon atoms with an oscillating magnetic field and links the emergence of the arrow of time to quantum fluctuations between one atomic spin state and another.



"That is why we remember yesterday and not tomorrow," explains group member Roberto Serra, a physicist specializing in quantum information at the Federal University of ABC in Santo André, Brazil. At the fundamental level, he says, quantum fluctuations are involved in the asymmetry of time.

### Egging on

The arrow of time is often taken for granted in the everyday world. We see an egg breaking, for example, yet we never see the yolk, white and shell fragments come back together again to recreate the egg. It seems obvious that the laws of nature should not be reversible, yet there is nothing in the underlying physics to say so.

The dynamical equations of an egg breaking run just as well forwards as they do backwards.

Entropy, however, provides a window onto the arrow of time. Most eggs look alike, but a broken egg can take on any number of forms: it could be neatly cracked open, scrambled, splattered all over a pavement, and so on. A broken egg is a disordered state – that is, a state of greater entropy – and because there are many more disordered than ordered states, it is more likely for a system to progress towards disorder than order.

This probabilistic reasoning is encapsulated in the second law of thermodynamics, which states that the entropy of a closed system always increases over time.

According to the second law, time cannot suddenly go backwards because this would require entropy to decrease. It is a convincing argument for a complex system made up of a great many interacting particles, like an egg, but what about a system composed of just one particle?

### Murky territory

Serra and colleagues have delved into this murky territory with measurements of entropy in an ensemble of carbon-13 atoms contained in a sample of liquid chloroform. Although the sample contained roughly a trillion chloroform molecules, the non-interacting quantum nature of the molecules meant that the experiment was equivalent to performing the same measurement on a single carbon atom, one trillion times.

Serra and colleagues applied an oscillating external magnetic field to the sample, which continually flipped the spin state of a carbon atom between up and down.

They ramped up the intensity of the field oscillations to increase the frequency of the spin-flipping, and then brought the intensity back down again.

Had the system been reversible, the overall distribution of carbon spin states would have been the same at the end as at the start of the process. Using nuclear magnetic resonance and quantum-state tomography, however, Serra and colleagues measured an increase in disorder among the final spins. Because of the quantum nature of the system, this was equivalent to an increase in entropy in a single carbon atom.

According to the researchers, entropy rises for a single atom because of the speed with which it is forced to flip its spin. Unable to keep up with the field-oscillation intensity, the atom begins to

fluctuate randomly, like an inexperienced dancer failing to keep pace with up-tempo music. "It's easier to dance to a slow rhythm than a fast one," says Serra.

### **Many questions remain**

The group has managed to observe the existence of the arrow of time in a quantum system, says experimentalist Mark Raizen of the University of Texas at Austin in the US, who has also studied irreversibility in quantum systems. But Raizen stresses that the group has not observed the "onset" of the arrow of time. "This [study] does not close the book on our understanding of the arrow of time, and many questions remain," he adds.

One of those questions is whether the arrow of time is linked to quantum entanglement – the phenomenon whereby two particles exhibit instantaneous correlations with each other, even when separated by vast distances. This idea is nearly 30 years old and has enjoyed a recent resurgence in popularity. However, this link is less to do with growing entropy and more to do with an unstoppable dispersion of quantum information.

Indeed, Serra believes that by harnessing quantum entanglement, it may even be possible to reverse the arrow of time in a microscopic system. "We're working on it," he says. "In the next generation of our experiments on quantum thermodynamics we will explore such aspects." [10]

### **Small entropy changes allow quantum measurements to be nearly reversed**

In 1975, Swedish physicist Göran Lindblad developed a theorem that describes the change in entropy that occurs during a quantum measurement. Today, this theorem is a foundational component of quantum information theory, underlying such important concepts as the uncertainty principle, the second law of thermodynamics, and data transmission in quantum communication systems.

Now, 40 years later, physicist Mark M. Wilde, Assistant Professor at Louisiana State University, has improved this theorem in a way that allows for understanding how quantum measurements can be approximately reversed under certain circumstances. The new results allow for understanding how quantum information that has been lost during a measurement can be nearly recovered, which has potential implications for a variety of quantum technologies.

### **Quantum relative entropy never increases**

Most people are familiar with entropy as a measure of disorder and the law that "entropy never decreases"—it either increases or stays the same during a thermodynamic process, according to the second law of thermodynamics. However, here the focus is on "quantum relative entropy," which in some sense is the negative of entropy, so the reverse is true: quantum relative entropy never increases, but instead only decreases or stays the same.

In fact, this was the entropy inequality theorem that Lindblad proved in 1975: that the quantum relative entropy cannot increase after a measurement. In this context, quantum relative entropy is interpreted as a measure of how well one can distinguish between two quantum states, so it's this distinguishability that can never increase. (Wilde describes a proof of Lindblad's result in greater detail in his textbook *Quantum Information Theory*, published by Cambridge University Press.)

One thing that Lindblad's proof doesn't address, however, is whether it makes any difference if the quantum relative entropy decreases by a little or by a lot after a measurement.

In the new paper, Wilde has shown that, if the quantum relative entropy decreases by only a little, then the quantum measurement (or any other type of so-called "quantum physical evolution") can be approximately reversed.

"When looking at Lindblad's entropy inequality, a natural question is to wonder what we could say if the quantum relative entropy goes down only by a little when the quantum physical evolution is applied," Wilde told Phys.org. "It is quite reasonable to suspect that we might be able to approximately reverse the evolution. This was arguably open since the work of Lindblad in 1975, addressed in an important way by Denes Petz in the late 1980s (for the case in which the quantum relative entropy stays the same under the action of the evolution), and finally formulated as a conjecture around 2008 by Andreas Winter. What my work did was to prove this result as a theorem: if the quantum relative entropy goes down only by a little under a quantum physical evolution, then we can approximately reverse its action."

## Wide implications

Wilde's improvements to Lindblad's theorem have a variety of implications, but the main one that Wilde discusses in his paper is how the new results allow for recovering quantum information.

"If the decrease in quantum relative entropy between two quantum states after a quantum physical evolution is relatively small," he said, "then it is possible to perform a recovery operation, such that one can perfectly recover one state while approximately recovering the other. This can be interpreted as quantifying how well one can reverse a quantum physical evolution." So the smaller the relative entropy decrease, the better the reversal process.

The ability to recover quantum information could prove useful for quantum error correction, which aims to protect quantum information from damaging external effects. Wilde plans to address this application more in the future with his colleagues.

As Wilde explained, Lindblad's original theorem can also be used to prove the uncertainty principle of quantum mechanics in terms of entropies, as well as the second law of thermodynamics for quantum systems, so the new results have implications in these areas, as well.

"Lindblad's entropy inequality underlies many limiting statements, in some cases said to be physical laws or principles," Wilde said. "Examples are the uncertainty principle and the second law of thermodynamics. Another example is that this entropy inequality is the core step in determining

limitations on how much data we can communicate over quantum communication channels. We could go as far as to say that the above entropy inequality constitutes a fundamental law of quantum information theory, which is a direct mathematical consequence of the postulates of quantum mechanics."

Regarding the uncertainty principle, Wilde and two coauthors, Mario Berta and Stephanie Wehner, discuss this angle in a forthcoming paper. They explain that the uncertainty principle involves quantum measurements, which are a type of quantum physical evolution and therefore subject to Lindblad's theorem. In one formulation of the uncertainty principle, two experiments are performed on different copies of the same quantum state, with both experimental outcomes having some uncertainty.

"The uncertainty principle is the statement that you cannot generally make the uncertainties of both experiments arbitrarily small, i.e., there is generally a limitation," Wilde said. "It is now known that a statement of the uncertainty principle in terms of entropies can be proved by using the 'decrease of quantum relative entropy inequality.' So what the new theorem allows for doing is relating the uncertainties of the measurement outcomes to how well we could try to reverse the action of one of the measurements. That is, there is now a single mathematical inequality which captures all of these notions."

In terms of the second law of thermodynamics, Wilde explains how the new results have implications for reversing thermodynamic processes in both classical and quantum systems.

"The new theorem allows for quantifying how well we can approximately reverse a thermodynamic transition from one state to another without using any energy at all," he said.

He explained that this is possible due to the connection between entropy, energy, and work. According to the second law of thermodynamics, a thermodynamic transition from one quantum state to another is allowed only if the free energy decreases from the original state to the final state. During this process, one can gain work and store energy. This law can be rewritten as a statement involving relative entropies and can be proved as a consequence of the decrease of quantum relative entropy.

"What my new work with Stephanie Wehner and Mischa Woods allows for is a refinement of this statement," Wilde said. "We can say that if the free energy does not go down by very much under a thermodynamic transition (i.e., if there is not too much work gained in the process), then it is possible to go back approximately to the original state from the final state, without investing any work at all. The key word here is that you can go back only approximately, so we are not in violation of the second law, only providing a refinement of it."

In addition to these implications, the new theorem can also be applied to other research topics in quantum information theory, including the Holevo bound, quantum discord, and multipartite information measures.

Wilde's work was funded in part by The DARPA Quiness program (ending now), which focused on quantum key distribution, or using quantum mechanics to ensure secret communication between two parties. He describes more about this application, in particular how Alice and Bob might use a

quantum state to share secrets that can be kept private from an eavesdropper Eve (and help them survive being attacked by a bear), in a recent blog post. [9]

## Tricking the uncertainty principle

"If you want to know where something is, you have to scatter something off of it," explains Professor of Applied Physics Keith Schwab, who led the study. "For example, if you shine light at an object, the photons that scatter off provide information about the object. But the photons don't all hit and scatter at the same time, and the random pattern of scattering creates quantum fluctuations"—that is, noise. "If you shine more light, you have increased sensitivity, but you also have more noise. Here we were looking for a way to beat the uncertainty principle—to increase sensitivity but not noise."

Schwab and his colleagues began by developing a way to actually detect the noise produced during the scattering of microwaves—electromagnetic radiation that has a wavelength longer than that of visible light. To do this, they delivered microwaves of a specific frequency to a superconducting electronic circuit, or resonator, that vibrates at 5 gigahertz—or 5 billion times per second. The electronic circuit was then coupled to a mechanical device formed of two metal plates that vibrate at around 4 megahertz—or 4 million times per second. The researchers observed that the quantum noise of the microwave field, due to the impact of individual photons, made the mechanical device shake randomly with an amplitude of 10-15 meters, about the diameter of a proton.

"Our mechanical device is a tiny square of aluminum—only 40 microns long, or about the diameter of a hair. We think of quantum mechanics as a good description for the behaviors of atoms and electrons and protons and all of that, but normally you don't think of these sorts of quantum effects manifesting themselves on somewhat macroscopic objects," Schwab says. "This is a physical manifestation of the uncertainty principle, seen in single photons impacting a somewhat macroscopic thing."

Once the researchers had a reliable mechanism for detecting the forces generated by the quantum fluctuations of microwaves on a macroscopic object, they could modify their electronic resonator, mechanical device, and mathematical approach to exclude the noise of the position and motion of the vibrating metal plates from their measurement.

The experiment shows that a) the noise is present and can be picked up by a detector, and b) it can be pushed to someplace that won't affect the measurement. "It's a way of tricking the uncertainty principle so that you can dial up the sensitivity of a detector without increasing the noise," Schwab says.

Although this experiment is mostly a fundamental exploration of the quantum nature of microwaves in mechanical devices, Schwab says that this line of research could one day lead to the observation of quantum mechanical effects in much larger mechanical structures. And that, he notes, could allow the demonstration of strange quantum mechanical properties like superposition and entanglement in large objects—for example, allowing a macroscopic object to exist in two places at once.

"Subatomic particles act in quantum ways—they have a wave-like nature—and so can atoms, and so can whole molecules since they're collections of atoms,"

Schwab says. "So the question then is: Can you make bigger and bigger objects behave in these weird wave-like ways? Why not? Right now we're just trying to figure out where the boundary of quantum physics is, but you never know." [8]

## Particle Measurement Sidesteps the Uncertainty Principle

Quantum mechanics imposes a limit on what we can know about subatomic particles. If physicists measure a particle's position, they cannot also measure its momentum, so the theory goes. But a new experiment has managed to circumvent this rule—the so-called uncertainty principle—by ascertaining just a little bit about a particle's position, thus retaining the ability to measure its momentum, too.

The uncertainty principle, formulated by Werner Heisenberg in 1927, is a consequence of the fuzziness of the universe at microscopic scales. Quantum mechanics revealed that particles are not just tiny marbles that act like ordinary objects we can see and touch. Instead of being in a particular place at a particular time, particles actually exist in a haze of probability. Their chances of being in any given state are described by an equation called the quantum wavefunction. Any measurement of a particle "collapses" its wavefunction, in effect forcing it to choose a value for the measured characteristic and eliminating the possibility of knowing anything about its related properties.

Recently, physicists decided to see if they could overcome this limitation by using a new engineering technique called compressive sensing. This tool for making efficient measurements has already been applied successfully in digital photographs, MRI scans and many other technologies. Normally, measuring devices would take a detailed reading and afterward compress it for ease of use. For example, cameras take large raw files and then convert them to compressed jpegs. In compressive sensing, however, engineers aim to compress a signal while measuring it, allowing them to take many fewer measurements—the equivalent of capturing images as jpegs rather than raw files.

This same technique of acquiring the minimum amount of information needed for a measurement seemed to offer a way around the uncertainty principle. To test compressive sensing in the quantum world, physicist John C. Howell and his team at the University of Rochester set out to measure the position and momentum of a photon—a particle of light. They shone a laser through a box equipped with an array of mirrors that could either point toward or away from a detector at its end. These mirrors formed a filter, allowing photons through in some places and blocking them in others. If a photon made it to the detector, the physicists knew it had been in one of the locations where the mirrors offered a throughway. The filter provided a way of measuring a particle's position without knowing exactly where it was—without collapsing its wavefunction. "All we know is either the photon can get through that pattern, or it can't," says Gregory A. Howland, first author of a paper reporting the research published June 26 in *Physical Review Letters*. "It turns out that because of that we're still able to figure out the momentum—where it's going. The penalty

that we pay is that our measurement of where it's going gets a little bit of noise on it." A less precise momentum measurement, however, is better than no momentum measurement at all.

The physicists stress that they have not broken any laws of physics. "We do not violate the uncertainty principle," Howland says. "We just use it in a clever way." The technique could prove powerful for developing technologies such as quantum cryptography and quantum computers, which aim to harness the fuzzy quantum properties of particles for technological applications. The more information quantum measurements can acquire, the better such technologies could work. Howland's experiment offers a more efficient quantum measurement than has traditionally been possible, says Aephraim M. Steinberg, a physicist at the University of Toronto who was not involved in the research. "This is one of a number of novel techniques which seem poised to prove indispensable for economically characterizing large systems." In other words, the physicists seem to have found a way to get more data with less measurement—or more bangs for their buck. [7]

## **A new experiment shows that measuring a quantum system does not necessarily introduce uncertainty**

Contrary to what many students are taught, quantum uncertainty may not always be in the eye of the beholder. A new experiment shows that measuring a quantum system does not necessarily introduce uncertainty. The study overthrows a common classroom explanation of why the quantum world appears so fuzzy, but the fundamental limit to what is knowable at the smallest scales remains unchanged.

At the foundation of quantum mechanics is the Heisenberg uncertainty principle. Simply put, the principle states that there is a fundamental limit to what one can know about a quantum system. For example, the more precisely one knows a particle's position, the less one can know about its momentum, and vice versa. The limit is expressed as a simple equation that is straightforward to prove mathematically.

Heisenberg sometimes explained the uncertainty principle as a problem of making measurements. His most well-known thought experiment involved photographing an electron. To take the picture, a scientist might bounce a light particle off the electron's surface. That would reveal its position, but it would also impart energy to the electron, causing it to move. Learning about the electron's position would create uncertainty in its velocity; and the act of measurement would produce the uncertainty needed to satisfy the principle.

Physics students are still taught this measurement-disturbance version of the uncertainty principle in introductory classes, but it turns out that it's not always true. Aephraim Steinberg of the University of Toronto in Canada and his team have performed measurements on photons (particles of light) and showed that the act of measuring can introduce less uncertainty than is required by Heisenberg's principle. The total uncertainty of what can be known about the photon's properties, however, remains above Heisenberg's limit.

## Delicate measurement

Steinberg's group does not measure position and momentum, but rather two different inter-related properties of a photon: its polarization states. In this case, the polarization along one plane is intrinsically tied to the polarization along the other, and by Heisenberg's principle, there is a limit to the certainty with which both states can be known.

The researchers made a 'weak' measurement of the photon's polarization in one plane — not enough to disturb it, but enough to produce a rough sense of its orientation. Next, they measured the polarization in the second plane. Then they made an exact, or 'strong', measurement of the first polarization to see whether it had been disturbed by the second measurement.

When the researchers did the experiment multiple times, they found that measurement of one polarization did not always disturb the other state as much as the uncertainty principle predicted. In the strongest case, the induced fuzziness was as little as half of what would be predicted by the uncertainty principle.

Don't get too excited: the uncertainty principle still stands, says Steinberg: "In the end, there's no way you can know [both quantum states] accurately at the same time." But the experiment shows that the act of measurement isn't always what causes the uncertainty. "If there's already a lot of uncertainty in the system, then there doesn't need to be any noise from the measurement at all," he says.

The latest experiment is the second to make a measurement below the uncertainty noise limit. Earlier this year, Yuji Hasegawa, a physicist at the Vienna University of Technology in Austria, measured groups of neutron spins and derived results well below what would be predicted if measurements were inserting all the uncertainty into the system.

But the latest results are the clearest example yet of why Heisenberg's explanation was incorrect. "This is the most direct experimental test of the Heisenberg measurement-disturbance uncertainty principle," says Howard Wiseman, a theoretical physicist at Griffith University in Brisbane, Australia. "Hopefully it will be useful for educating textbook writers so they know that the naive measurement-disturbance relation is wrong."

Shaking the old measurement-uncertainty explanation may be difficult, however. Even after doing the experiment, Steinberg still included a question about how measurements create uncertainty on a recent homework assignment for his students. "Only as I was grading it did I realize that my homework assignment was wrong," he says. "Now I have to be more careful." [6]

## Quantum entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of



superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

## The Bridge

The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories. [1]

## Accelerating charges

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

## Relativistic effect

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

## Heisenberg Uncertainty Relation

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

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

## Wave – Particle Duality

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

wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

## Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and its kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only that changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

## The Relativistic Bridge

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

## The weak interaction

The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry. The Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

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

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions,

the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

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

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

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

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

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

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

Finally since the weak interaction is an electric dipole change with  $1/2$  spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

### **The General Weak Interaction**

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows

the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. A good example of this is the neutron decay, creating more particles with less known information about them.

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

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater than subatomic matter structures as an electric dipole change. There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.

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

## **Fermions and Bosons**

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

## **Van Der Waals force**

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

## **Electromagnetic inertia and mass**

### **Electromagnetic Induction**

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

### **Relativistic change of mass**

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

## The frequency dependence of mass

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

## Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [2]

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

## Gravity from the point of view of quantum physics

### The Gravitational force

The gravitational attractive force is basically a magnetic force.

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

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

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

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

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force

experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

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## The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have + parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

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

## Higgs mechanism and Quantum Gravity

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

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge

bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

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

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

### What is the Spin?

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

### The Graviton

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

### Conclusions

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

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

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 accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions.

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