

# Supercomputers aid Gamma Ray Research

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*The proposal envisages a new 100km circumference tunnel that would be bored through the Earth, encircling the city of Geneva and the surrounding countryside. [30]*

*On Wednesday, 25 July, for the very first time, operators injected not just atomic nuclei but lead "atoms" containing a single electron into the LHC. [29]*

*The case for an ambitious new particle accelerator to be built in the United States has just gotten a major boost. [27]*

*Physics textbooks might have to be updated now that an international research team has found evidence of an unexpected transition in the structure of atomic nuclei. [26]*

*The group led by Fabrizio Carbone at EPFL and international colleagues have used ultrafast transmission electron microscopy to take attosecond energy-momentum resolved snapshots (1 attosecond =  $10^{-18}$  or quintillionths of a second) of a free-electron wave function. [25]*

*Now, physicists are working toward getting their first CT scans of the inner workings of the nucleus. [24]*

*The process of the sticking together of quarks, called hadronisation, is still poorly understood. [23]*

*In experimental campaigns using the OMEGA EP laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, Lawrence Livermore National Laboratory (LLNL), University of California San Diego (UCSD) and Massachusetts Institute of Technology (MIT) researchers took radiographs of the shock front, similar to the X-ray radiology in hospitals with protons instead of X-rays. [22]*

*Researchers generate proton beams using a combination of nanoparticles and laser light. [21]*

*Devices based on light, rather than electrons, could revolutionize the speed and security of our future computers. However, one of the major challenges in today's physics is the design of photonic devices, able to transport and switch light through circuits in a stable way. [20]*

*Researchers characterize the rotational jiggling of an optically levitated nanoparticle, showing how this motion could be cooled to its quantum ground state. [19]*

*Researchers have created quantum states of light whose noise level has been “squeezed” to a record low. [18]*

*An elliptical light beam in a nonlinear optical medium pumped by “twisted light” can rotate like an electron around a magnetic field. [17]*

*Physicists from Trinity College Dublin's School of Physics and the CRANN Institute, Trinity College, have discovered a new form of light, which will impact our understanding of the fundamental nature of light. [16]*

*Light from an optical fiber illuminates the metasurface, is scattered in four different directions, and the intensities are measured by the four detectors. From this measurement the state of polarization of light is detected. [15]*

*Converting a single photon from one color, or frequency, to another is an essential tool in quantum communication, which harnesses the subtle correlations between the subatomic properties of photons (particles of light) to securely store and transmit information. Scientists at the National Institute of Standards and Technology (NIST) have now developed a miniaturized version of a frequency converter, using technology similar to that used to make computer chips. [14]*

*Harnessing the power of the sun and creating light-harvesting or light-sensing devices requires a material that both absorbs light efficiently and converts the energy to highly mobile electrical current. Finding the ideal mix of properties in a single material is a challenge, so scientists have been experimenting with ways to combine different materials to create “hybrids” with enhanced features. [13]*

*Condensed-matter physicists often turn to particle-like entities called quasiparticles—such as excitons, plasmons, magnons—to explain complex phenomena. Now Gil Refael from the California Institute of Technology in Pasadena and colleagues report the theoretical concept of the topological polariton, or “topolariton”: a hybrid half-light, half-matter quasiparticle that has special topological properties and might be used in devices to transport light in one direction. [12]*

*Solitons are localized wave disturbances that propagate without changing shape, a result of a nonlinear interaction that compensates for wave packet dispersion. Individual solitons may collide, but a defining feature is that they pass through one another and emerge from the collision unaltered in shape, amplitude, or velocity, but with a new trajectory reflecting a discontinuous jump.*

*Working with colleagues at the Harvard-MIT Center for Ultracold Atoms, a group led by Harvard Professor of Physics Mikhail Lukin and MIT Professor of Physics Vladan Vuletic have managed to coax photons into binding together to form molecules – a state of matter that, until recently, had been purely theoretical. The work is described in a September 25 paper in Nature.*

*New ideas for interactions and particles: This paper examines the possibility to origin the Spontaneously Broken Symmetries from the Planck Distribution Law. This way we get a Unification of the Strong, Electromagnetic, and Weak Interactions from the interference occurrences of oscillators. Understanding that the relativistic mass change is the result of the magnetic induction we arrive to the conclusion that the Gravitational Force is also based on the electromagnetic forces, getting a Unified Relativistic Quantum Theory of all 4 Interactions.*

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Author: George Rajna

## Supercomputers aid in novel simulations of gamma ray generation research

While intense magnetic fields are naturally generated by neutron stars, researchers have been striving to achieve similar results for many years. UC San Diego mechanical and aerospace engineering graduate student Tao Wang recently demonstrated how an extremely strong magnetic field, similar to that on the surface of a neutron star, can be not only generated but also detected using an X-ray laser inside a solid material.

Wang carried out his research with the help of simulations conducted on the Comet supercomputer at the San Diego Supercomputer Center (SDSC) as well as Stampede and Stampede2 at the Texas Advanced Computing Center (TACC). All resources are part of a National Science Foundation program called the Extreme Science and Engineering Discovery Environment (XSEDE).

"Wang's findings were critical to our recently published study's overall goal of developing a fundamental understanding of how multiple laser beams of extreme intensity interact with matter," said Alex Arefiev, a professor of mechanical and aerospace engineering at the UC San Diego Jacobs School of Engineering.

Wang, Arefiev, and their colleagues used multiple large three-dimensional simulations, remote visualization, and data post-processing to complete their study, which showed how an intense laser pulse is able to propagate into the dense material because of its relativistic intensity.

In other words, as the velocity of the electrons approaches the speed of light, their mass becomes so heavy that the target becomes transparent. Because of the transparency, the laser pulse pushes the electrons to form a [strong magnetic field](#). This strength is comparable to that on a neutron star's surface, which is at least 100 million times stronger than the Earth's magnetic field, and about one thousand times stronger than the field of superconducting magnets.

The findings were published in a *Physics of Plasma* journal article titled "Structured Targets for Detection of Megatesla-level Magnetic Fields Through Faraday Rotation of XFEL Beams."

"Now that we have completed this study, we are working on ways to detect this type of magnetic field at a one-of-a-kind facility called the European X-Ray Free Electron Laser (XFEL), which encompasses a 3.4-kilometer-long accelerator that generates extremely intense X-ray flashes to be used by researchers like our team," explained Arefiev.

Located in Schenefeld, Germany, the European XFEL is the working place of Toma Toncian, where he leads the project group construction and commissioning of the Helmholtz International Beamline for Extreme Fields at the High Energy Density instrument. He is also a co-author on the recently published study.

"The very fruitful collaboration between UC San Diego and Helmholtz-Zentrum Dresden-Rossendorf is paving the road to future high impact experiments," said Toncian. "As we pass nowadays from construction to commissioning and first experiments, the theoretical predictions by Tao Wang are timely and show us how to further develop and fully exploit the capabilities of our instrument."

According to Mingsheng Wei, a senior scientist at the University of Rochester's Laboratory for Laser Energetics and co-author on the paper, "the innovative micro-channel target design explored in the simulation work could be demonstrated using the novel low-density polymer foam material that is only a few times heavier than the dry air contained in micro-structured tubes."

"Because the resulting data sets of our experiments using XFEL are very large, our research would not have been possible on a regular desktop—we could not have completed this study without the use of XSEDE supercomputers," said Arefiev. "We are also very grateful to the Air Force Office of Scientific Research for making this project possible."

Arefiev said that their group's supercomputer usage efforts relied upon the guidance of Amit Chourasia, SDSC's senior visualization scientist, who helped set up remote parallel visualization tools for the researchers.

"It is fantastic to work in tandem with research groups and equip them with powerful methods, tools, and an execution plan that in turn propels their research at an accelerated pace with aid of HPC and visualization, it we're grateful to play a role in enabling new discoveries," said Chourasia. [33]

## **Supercomputing enables sound prediction model for controlling noise**

Combining principles from computational fluid dynamics and acoustics, researchers at the TU Berlin have developed an analytical model that could simplify the process of designing Helmholtz resonators, a type of noise cancelling structure used in airplanes, ships, and ventilation systems. The model can predict a potential Helmholtz cavity's sound spectrum as turbulent air flows over it, and could potentially be used to tune Helmholtz resonators to cancel or avoid any frequency of interest.

Noise-cancelling headphones have become a popular accessory for frequent flyers. By analyzing the background frequencies produced by an airplane in flight and generating an "anti-noise" [sound wave](#) that is perfectly out of phase, such headphones eliminate disturbing background sounds. Although the headphones can't do anything about the cramped seating, they can make watching a film or listening to music in flight nearly as enjoyable as at home.

To minimize the disturbing noise caused by loud machines like cars, ships, and airplanes, acoustic engineers use many strategies. One technology, called a Helmholtz cavity, is based on a similar concept to that used in noise-cancelling headphones. Here, engineers build a resonating box that opens to a slit on one side. As air passes over the slit, the box vibrates like a church organ pipe, producing a tone. By adjusting the size and shape of the cavity and its slit, acoustic engineers can tune it to produce a specific tone that—like the headphones—cancels a dominant, irritating sound produced by machinery.

Historically, the process of tuning a Helmholtz resonator was a brute force undertaking involving costly and time-consuming trial and error. Engineers had no other choice but to physically build and test many

different geometries experimentally to find an optimal shape for a specific application, especially in an environment of turbulent flow.

Today, however, [high-performance computing](#) offers the potential to undertake such tests virtually, making the design process faster and easier.

In a paper just published in the journal *Acta Mechanica*, Lewin Stein and Jörn Sesterhenn of the TU Berlin describe a new analytical [model](#) for sound prediction that could make the design of Helmholtz cavities cheaper and more efficient. The development of the model was facilitated by a dataset produced using direct numerical simulation at the High-Performance Computing Center Stuttgart (HLRS). The analytical model can predict, in a way that is more generally applicable than before, a potential Helmholtz cavity's [sound spectrum](#) as turbulent air flows over it. The authors suggest that such a tool could potentially be used to tune Helmholtz cavities to cancel out or to avoid any frequency of interest.

### ***Simulation approaches all the scales of nature***

When moving air passes over the slit of a Helmholtz cavity, its flow becomes disrupted and turbulence is enhanced. Vortices typically arise, detaching from the slit's upstream edge. Together they form a sheet of vortices that covers the slit and can interact with the acoustic vibrations being generated inside the cavity. The result is a frequency-dependent damping or excitation of the acoustic wave as air passes through this vortex sheet.

In the past it was difficult to study such interactions and their effects numerically without making crude approximations. For the first time, Stein's simulation realistically integrates turbulent and acoustic phenomena of a Helmholtz cavity excited by a turbulent flow passing over its slit. At an unprecedented resolution, it makes it possible to track the flow-acoustic interaction and its implications for the cavity's resonance.

This achievement is possible using a method called direct numerical simulation (DNS), which describes a gas or liquid at a fundamental level. "I'm using the most complex form of fluid equations—called the Navier-Stokes equations—to get as close as possible to the actual phenomenon in nature while using as little approximation as necessary," Stein says. "Our DNS enabled us to gain new insights that weren't there before."

Stein's direct numerical simulation divides the system into a mesh of approximately 1 billion grid points and simulates more than 100 thousand time steps, in order to fully resolve the system dynamics for just 30 milliseconds of physical time. Each run of the numerical model on HLRS's Hazel Hen supercomputer required approximately four 24-hour days, using some 40,000 computing cores.

Whereas a physical experiment is spatially limited and can only track a few physically relevant parameters, each individual DNS run provides a 20-terabyte dataset that documents all flow variables at all time steps and spaces within the mesh, delivering a rich resource that can be explored in detail. Stein says that running the simulation over this time period provided a good compromise between being able to set up a reliable database and getting results in a practical amount of time.

### ***Moving toward a general sound prediction model***

Once the details of the acoustic model were developed, the next challenge was to confirm that it could predict acoustic properties of other Helmholtz cavity geometries and airflow conditions. By comparing the

extrapolated model results with experimental data provided by Joachim Golliard at the Centre de Transfert de Technologie du Mans in France, Stein found that the model did so with great accuracy.

The model reported in the paper is optimized for low speed airflows and for low frequencies, such as those found in ventilation systems. It is also designed to be modular so that a cavity that includes complex materials like foam instead of a hard wall can be investigated as well. Stein anticipates that gaining more computing time and access to faster supercomputers would enable him to numerically predict a wider range of potential resonator shapes and flow conditions.

Having recently completed his Ph.D. and now working as a postdoc at the Institute of Fluid Dynamics and Technical Acoustics in the group of Prof. Sesterhenn (TU Berlin), Stein foresees some attractive opportunities to cooperate with industrial partners and possibly to apply his model in real-life situations. "Although I studied theoretical physics," he explains, "it is fulfilling to work on problems that reach beyond pure academic research and can be applied in industry, where people can potentially profit from what you've accomplished. This latest paper is an opportunity to prove the utility and applicability of our work. It's a great moment after years of working on a Ph.D." [32]

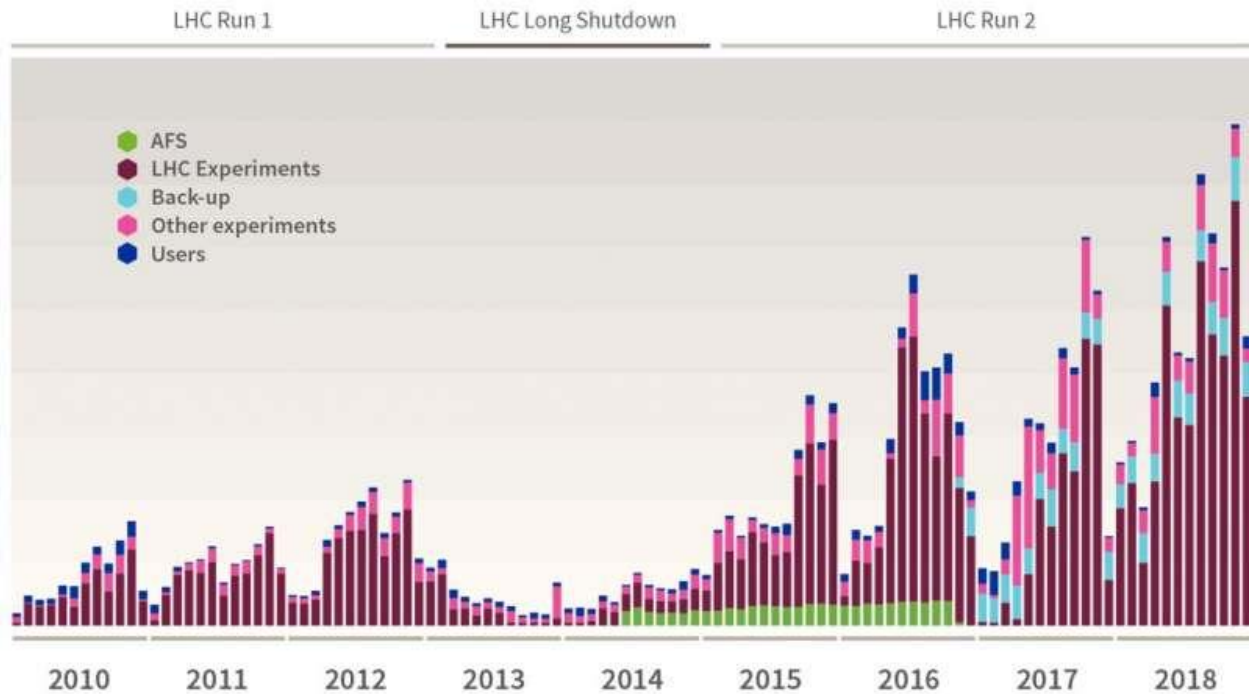
## Large Hadron Collider pushing computing to the limits

At the end of 2018, the [Large Hadron Collider \(LHC\)](#) completed its second multi-year run ("Run 2") that saw the machine reach a proton–proton collision energy of 13 TeV, the highest ever reached by a particle accelerator. During this run, from 2015 to 2018, LHC experiments produced unprecedented volumes of data with the machine's performance exceeding all expectations.

This meant exceptional use of computing, with many records broken in terms of data acquisition, data rates and data volumes. The [CERN Advanced Storage system \(CASTOR\)](#), which relies on a tape-based backend for permanent data archiving, reached 330 PB of data (equivalent to 330 million gigabytes) stored on tape, an equivalent of over 2000 years of 24/7 HD video recording. In November 2018 alone, a record-breaking 15.8 PB of data were recorded on tape, a remarkable achievement given that it corresponds to more than what was recorded during the first year of the LHC's Run 1.

The distributed storage system for the LHC experiments exceeded 200 PB of raw storage with about 600 million files. [This system \(EOS\)](#) is disk-based and open-source, and was developed at CERN for the extreme LHC computing requirements. As well as this, 830 PB of data and 1.1 billion files were transferred all over the world by [file transfer service](#). To face these computing challenges and to better support the CERN experiments during Run 2, the entire computing infrastructure, and notably the [storage systems](#), went through major upgrades and consolidation over the past few years.





Data (in terabytes) recorded on tape at CERN month-by-month. This plot shows the amount of data recorded on tape generated by the LHC experiments, other experiments, various back-ups and users. In 2018, over 115 PB of data in total [...more](#)

New IT research-and-development activities have already begun in preparation for the LHC's Run 3 (foreseen for 2021 to 2023). "Our new software, named CERN Tape Archive (CTA), is the new tape storage system for the custodial copy of the physics data and a replacement for its predecessor, CASTOR. The main goal of CTA is to make more efficient use of the tape drives, to handle the higher data rate anticipated during Run 3 and Run 4 of the LHC," explains German Cancio, who leads the Tape, Archive & Backups storage section in CERN's IT department. CTA will be deployed during the ongoing second long shutdown of the LHC (LS2), replacing CASTOR. Compared to the last year of Run 2, data archival is expected to be two-times higher during Run 3 and five-times higher or more during Run 4 (foreseen for 2026 to 2029).

The LHC's computing will continue to evolve. Most of the data collected in CERN's data centre is highly valuable and needs to be preserved and stored for future generations of physicists. CERN's IT department will therefore be taking advantage of LS2, the current maintenance and upgrade of the accelerator complex, to perform the required consolidation of the computing infrastructure. They will be upgrading the [storage](#) infrastructure and software to face the likely scalability and performance challenges when the LHC restarts in 2021 for Run 3. [31]

## Large Hadron Collider replacement plans unveiled – here's what it could discover

The Large Hadron Collider (LHC) at CERN is the most powerful particle accelerator in the world. During its ten years of operations it has led to remarkable discoveries, including the long sought-after Higgs boson. On January 15, an international team of physicists [unveiled the concept design for a new particle accelerator](#) that would dwarf the LHC.

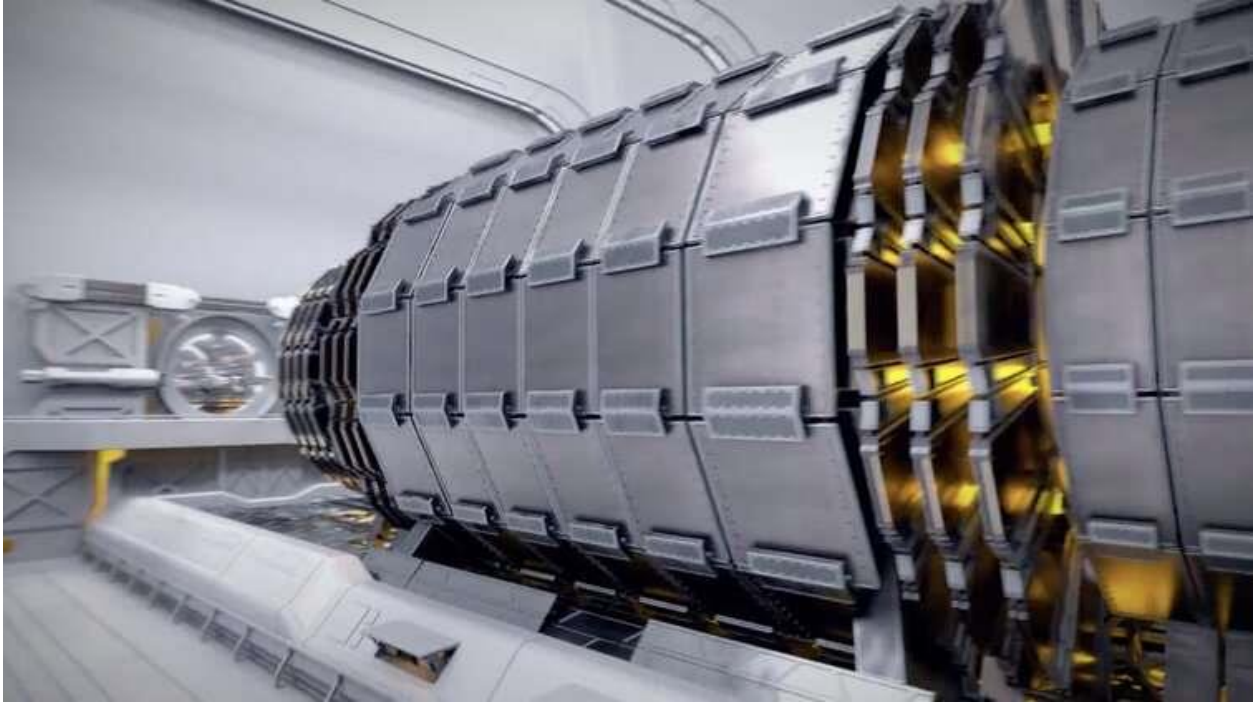
The "[Future Circular Collider](#)" is conceived as a successor to the LHC, and – if given the green light – it would allow physicists to seek answers to some of the greatest mysteries in physics. This includes finding out what the vast majority of the universe is actually made of or discovering entirely new physics.

The proposal envisages a new 100km circumference tunnel that would be bored through the Earth, encircling the city of Geneva and the surrounding countryside. The 27km LHC would feed particles into the new collider – like a motorway slipway. This would ultimately allow it to collide particles with energies around seven times higher than the LHC can manage. This would let this collider create particles that are beyond the reach of the LHC – pushing particle physics deep into an unexplored microscopic realm.

### ***Portal to a dark world***

The Future Circular Collider is really several projects in one. The first phase imagines a machine that collides electrons with their so-called "antimatter versions," positrons. All particles are thought to have an antimatter companion, virtually identical to itself but with opposite charge. When a matter and an antimatter particle meet, they completely annihilate each other, with all their energy converted into new particles.

The collision energy of such a collider could be very precisely controlled. Also, collisions would be very "clean" compared to the LHC, which collides protons (particles that make up the atomic nucleus along with neutrons). Protons are not fundamental particles like electrons, but haphazard bags of smaller particles including quarks and gluons. When protons collide, their innards get sprayed all over the place, making it much harder to spot new particles among the debris.



Detector layout. Credit: CERN

The primary goal of the electron-positron collider would be to study the Higgs boson, the particle implicated in the origin of the masses of the other fundamental particles. The new collider would create millions of Higgs bosons and measure their properties in unprecedented detail.

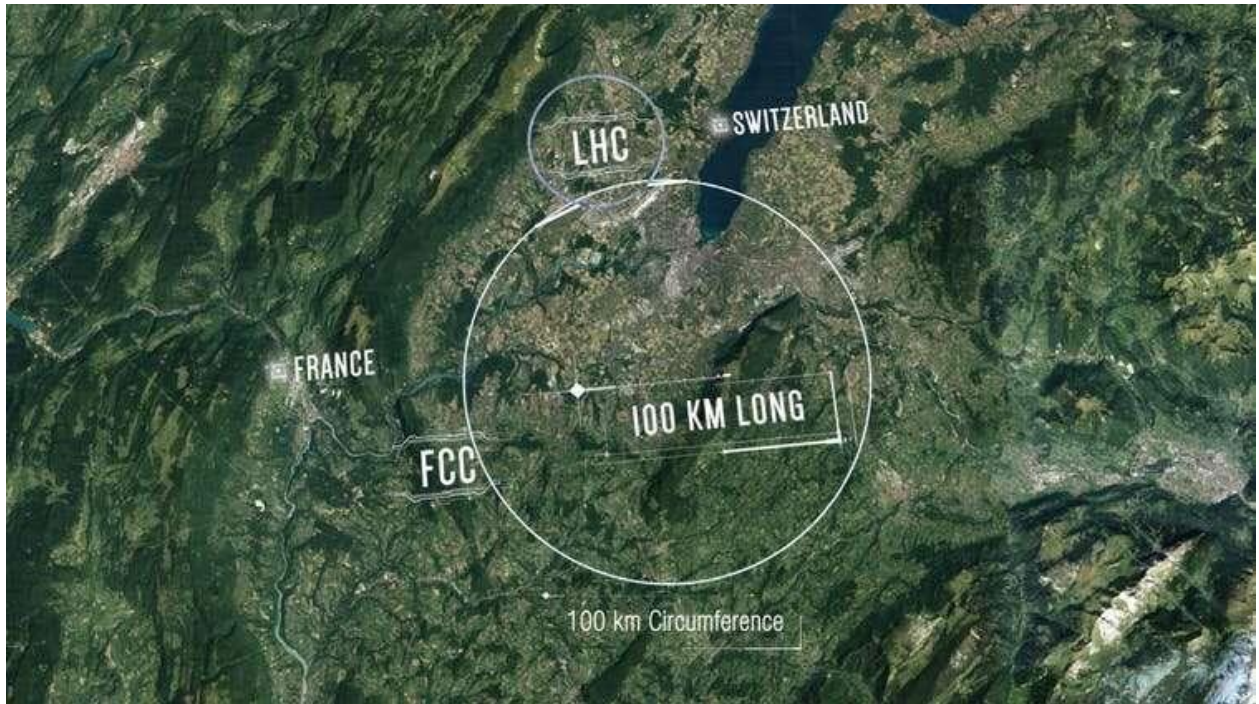
Such precision measurements offer numerous possibilities for new discoveries. One of the most tantalising is that the Higgs could act as portal connecting the world of ordinary atomic matter that we inhabit, with a hidden world of particles that are otherwise undetectable. Some 85% of all the matter in the universe in the universe is "dark," made up of particles we have never been able to see. We only know it exists because of the gravitational pull it has on surrounding matter. Excitingly, an electron-positron collider could reveal the Higgs boson decaying into these hidden particles.

In the second phase, the collider would be replaced by a far more powerful proton-proton collider – reaching collision energies of 100 trillion electron volts. This would be a discovery machine, capable of creating a huge range of new particles that physicists suspect may lie beyond the reach of the LHC.

In particular, it would almost completely explore the energy range where most forms of dark matter are likely to be found. It would also be able to probe the conditions that existed a trillionth of a second after the Big Bang. This moment in the universe's history is crucial as it is when the Higgs field – an all-pervading energy field that the Higgs boson is a little ripple in – collapsed into its current state, which is what generated the masses of the fundamental particles.

Understanding how the Higgs field acquired its current energy is one of the greatest outstanding problems in physics, as it appears to be unbelievably finely tuned to allow atoms – and therefore stars, planets and people – to exist.

As a physicist working on the [LHC beauty experiment](#), I personally hope this new collider could eventually also help us solve the riddle of why the universe is made almost entirely from matter and not antimatter.



#### Map. Hefty price tag

The first phase of the new collider would come online in the 2040s, after the final run of the upgraded LHC. The more powerful proton-proton collider would be installed in the 2050s. Both projects come with a hefty price tag: €9 billion for the electron-positron machine and a further €15 billion for the proton-proton collider. This has raised understandable criticism that the money could be better spent elsewhere, for example in tackling climate change.

[John Womersley](#), a senior physicist involved in the Future Circle Collider, told me that beyond the value of fundamental knowledge in its own right, there will be other significant short-term benefits. He said: "The FCC will push the development of innovative technologies to solve new challenges. The World Wide Web, Wi-Fi and superconducting magnets in MRI machines were all developed to meet the needs of fundamental physics." The project also has huge power to inspire the next generation of physicists.

Ultimately, such an ambitious scheme will only be possible through a large international collaboration, with funding from dozens of countries. The project already includes 1,300 contributors from 150 universities, research institutes and industrial partners around the world. Meanwhile, a [similar collider project](#) is also being considered by China, perhaps the only country capable of mobilising the resources necessary to build such a vast machine on its own.

The advocates of the Future Circular Collider hope that the project will be adopted in the new European strategy for particle physics, to be published in 2020. If accepted, it will begin a long process of research and development, but also of persuading national governments and the general public that the exciting fundamental research that could be performed at the [collider](#) is worth investing in.

The political challenges are undoubtedly enormous, but physicists are determined not to give up the quest for a deeper understanding of our universe. [30]

## LHC accelerates its first 'atoms'

Protons might be the Large Hadron Collider's bread and butter, but that doesn't mean it can't crave more exotic tastes from time to time. On Wednesday, 25 July, for the very first time, operators injected not just atomic nuclei but lead "atoms" containing a single electron into the LHC. This was one of the first proof-of-principle tests for a new idea called the Gamma Factory, part of CERN's Physics Beyond Colliders project.

"We're investigating new ideas of how we could broaden the present CERN research programme and infrastructure," says Michaela Schaumann, an LHC Engineer in Charge. "Finding out what's possible is the first step."

During normal operation, the LHC produces a steady stream of proton–proton collisions, then smashes together [atomic nuclei](#) for about four weeks just before the annual winter shutdown. But for a handful of days a year, accelerator physicists get to try something completely new during periods of machine development. Previously, they accelerated xenon nuclei in the LHC and tested other kinds of partially stripped lead ions in the SPS accelerator.

"This special LHC run was really the last step in a series of tests," says physicist Witold Krasny, who is coordinating a study group of about 50 scientists to develop new ways to produce [high-energy gamma rays](#).

Accelerating lead nuclei with one remaining electron can be challenging because of how delicate these atoms are. "It's really easy to accidentally strip off the electron," explains Schaumann. "When that happens, the nucleus crashes into the wall of the beam pipe because its charge is no longer synchronised with the LHC's magnetic field."

During the first run, operators injected 24 bunches of "atoms" and achieved a low-energy stable beam inside the LHC for about an hour. They then ramped the LHC up to its full power and maintained the beam for about two minutes before it was ejected into the beam dump. "If too many particles go off course, the LHC automatically dumps the beam," states Schaumann. "Our main priority is to protect the LHC and its magnets."

After running the magnets through the restart cycle, Schaumann and her colleagues tried again, this time with only six bunches. They kept the beam circulating for two hours before intentionally dumping it.

"We predicted that the lifetime of this special kind of beam inside the LHC would be at least 15 hours," says Krasny. "We were surprised to learn the lifetime could be as much as about 40 hours. Now the question is whether we can preserve the same beam lifetime at a higher intensity by optimising the collimator settings, which were still set-up for protons during this special run."

Physicists are doing these tests to see if the LHC could one day operate as a gamma-ray factory. In this scenario, scientists would shoot the circulating "atoms" with a laser, causing the electron to jump into a higher energy level. As the electron falls back down, it spits out a particle of light. In normal circumstances, this particle of light would not be very energetic, but because the "atom" is already moving at close to the

speed of light, the energy of the emitted photon is boosted and its wavelength is squeezed (due to the Doppler effect).

These gamma rays would have sufficient energy to produce normal "matter" particles, such as quarks, electrons and even muons. Because matter and energy are two sides of the same coin, these high-energy gamma rays would transform into massive particles and could even morph into new kinds of matter, such as dark matter. They could also be the source for new types of particle beams, such as a muon [beam](#).

Even though this is still a long way off, the tests this week were an important first step in seeing what is possible. [29]

## US targets electron-ion collider to stay top in nuclear physics

The US should begin planning a next generation electron-ion collider (EIC) to study the structure of protons and neutrons in unprecedented detail. That is according to a 15-strong committee of the National Academies of Sciences, Engineering, and Medicine. It's [115-page report](#), commissioned by the US [Department of Energy](#) (DOE), says that an EIC with high energy and luminosity as well as highly-polarized electron and ion beams "would be unique to greatly further our understanding of visible matter".

The science that can be addressed by an EIC is compelling, fundamental, and timely

Gordon Baym

By accelerating and smashing together electrons with protons or ions, an EIC, the report says, would address profound questions about nucleons such as how their mass and spin arise and what is the role of gluons, the carrier of the strong force. The report calls for a machine that can accelerate electrons up to 20 GeV and ions with an energy up to 300 GeV at high luminosity.

"The science that can be addressed by an EIC is compelling, fundamental, and timely," says [Gordon Baym](#) from the University of at Urbana-Champaign, who co-chaired the committee. "The realization of an EIC is absolutely crucial to maintaining the health of the field of US nuclear physics and would open up new areas of scientific investigation."

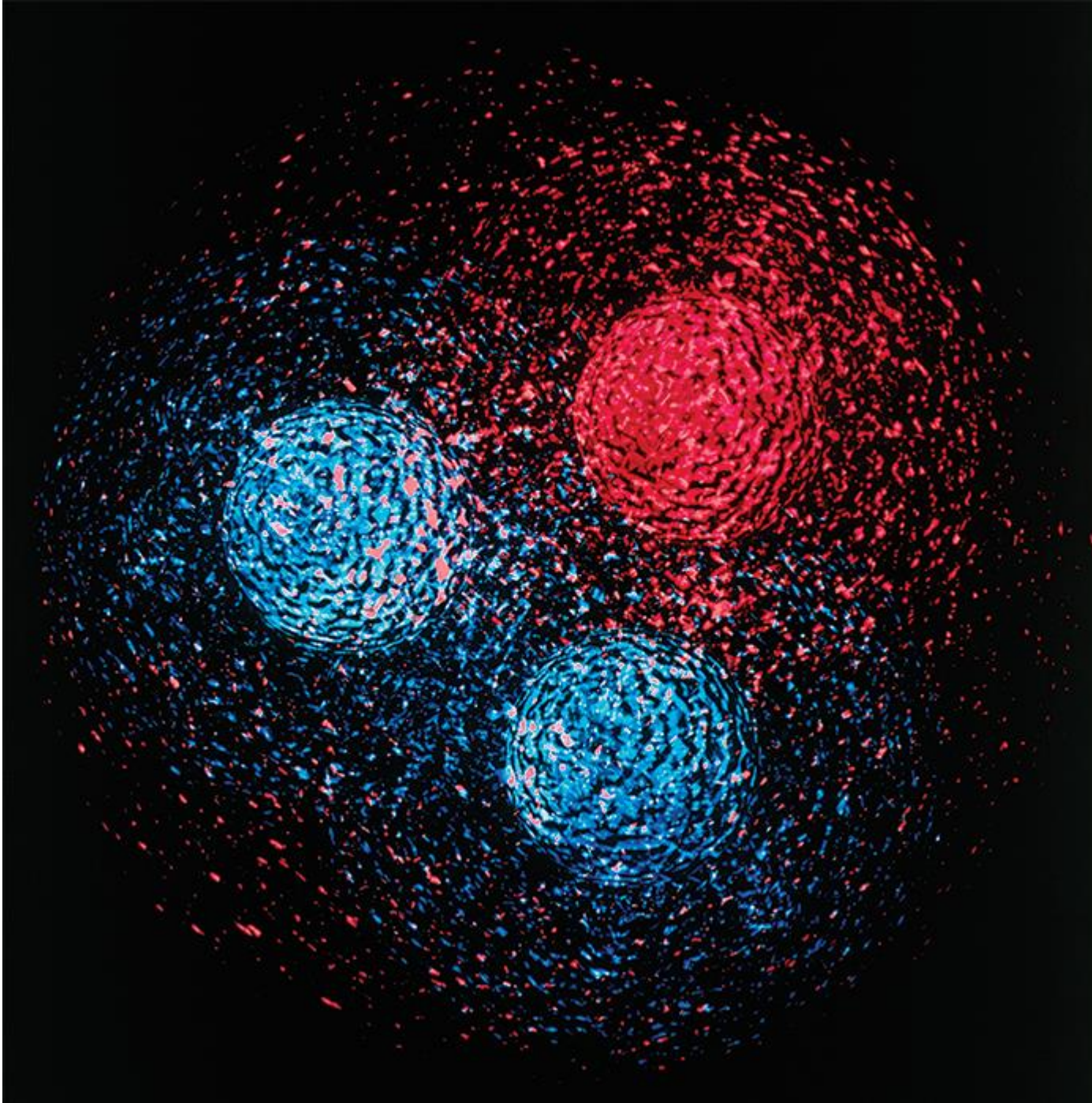
That view is backed up by panel member [Richard Milner](#), a physicist at the Massachusetts Institute of Technology. He told a press briefing that the EIC "would have a substantial impact on US accelerator science, and in the production of breakthroughs in understanding materials and in life science".

### *Compelling questions*

The committee emphasizes that no specific design for the facility is under way and that the committee's remit did not include any estimate of the US EIC's costs or location. However, the long-range plan for nuclear physics — as set out in 2015 by the DOE and the National Science Foundation — identifies construction of a high-luminosity polarized EIC as the highest priority following the completion of Michigan State University's [Facility for Rare Isotope Beams](#) in 2020.

Indeed, the panel asserts that significant and relevant accelerator infrastructure and expertise already exists in the US. The Brookhaven National Laboratory (BNL) operates the [Relativistic Heavy Ion](#)

[Collider](#), which smashes together heavy ions to study quark-gluon plasma, while the Thomas Jefferson National Accelerator Laboratory's recently upgraded [Continuous Beam Accelerator Facility](#) accelerates electrons before firing them into fixed targets.



## The spin of a proton

The report notes that both labs have proposed design concepts for an EIC “that can use existing infrastructure and both laboratories have significant accelerator expertise and experience”. However, it cautions that “neither of the existing designs can fully deliver on the three compelling science questions” that the EIC would need to address.

Stuart Henderson, director of the Jefferson Lab, BNL director Doon Gibbs and Bernd Surrow from Temple University, who is chair of the electron ion collider user group, note in [a joint statement](#) that they are “very pleased” with the report’s conclusions. “Just as studies of fundamental particles and forces have driven scientific, technological, and economic advances for the past century -from the discovery of the electrons that power modern life to the understanding of the structure of the cosmos [so] research conducted with an EIC will spark innovation and enable widespread technological advances,” they note.

China is the only other country that has tentative plans for such a facility, but it would be much lower in energy and intensity than the US machine. “At the moment we are the only one,” panel co-chair [Ani Aprahamian](#) from the University of Notre Dame told *Physics World*. “That would ensure global leadership for this project.” [28]

## Richard Milner discusses new U.S. particle accelerator project

The case for an ambitious new particle accelerator to be built in the United States has just gotten a major boost.

Today, the National Academies of Sciences, Engineering, and Medicine have endorsed the development of the Electron Ion Collider, or EIC. The proposed facility, consisting of two intersecting accelerators, would smash together beams of protons and electrons traveling at nearly the speed of light. In the aftermath of each collision, scientists should see “snapshots” of the particles’ inner structures, much like a CT scan for atoms. From these images, scientists hope to piece together a multidimensional picture, with unprecedented depth and clarity, of the quarks and gluons that bind together protons and all the visible matter in the universe.

The EIC, if built, would significantly advance the field of quantum chromodynamics, which seeks to answer fundamental questions in physics, such as how quarks and gluons produce the strong force—the “glue” that holds all matter together. If constructed, the EIC would be the largest accelerator facility in the U.S. and, worldwide, second only to the Large Hadron Collider at CERN. MIT physicists, including Richard Milner, professor of physics at MIT, have been involved from the beginning in making the case for the EIC.

MIT News checked in with Milner, a member of MIT’s Center for Theoretical Physics and the Laboratory for Nuclear Science, about the need for a new particle collider and its prospects going forward.

**Q: Tell us a bit about the history of this design. What has it taken to make the case for this new particle accelerator?**



A: The development of both the scientific and technical case for the EIC has been in progress for about two decades. With the development of quantum chromodynamics (QCD) in the 1970s by MIT physics Professor Frank Wilczek and others, nuclear physicists have long sought to bridge the gap between QCD and the successful theory of nuclei based on experimentally observable particles, where the fundamental constituents are the undetectable quarks and gluons.

A high-energy collider with the ability to collide electrons with the full range of nuclei at high rates and to have the electrons and nucleons polarized was identified as the essential tool to construct this bridge. High-energy electron scattering from the proton was how quarks were experimentally discovered at SLAC in the late 1960s (by MIT physics faculty Henry Kendall and Jerome Friedman and colleagues), and it is the accepted technique to directly probe the fundamental quark and gluon structure of matter.

Significant initial impetus for the EIC came from nuclear physicists at the university user-facilities at the University of Indiana and MIT as well as from physicists seeking to understand the origin of the proton's spin, at laboratories and universities in the U.S. and Europe. Over the last three long-range planning exercises by U.S. nuclear physicists in 2002, 2007, and 2015, the case for the EIC has matured and strengthened. After the 2007 exercise, the two U.S. flagship nuclear facilities, namely the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and the Continuous Electron Beam Accelerator Facility at Jefferson Laboratory, took a leadership role in coordinating EIC activities across the broad U.S. QCD community. This led to the production in 2012 of a succinct summary of the science case, "Electron-Ion Collider: The Next QCD Frontier (Understanding the glue that binds us all)."

The 2015 planning exercise established the EIC as the highest priority for new facility construction in U.S. nuclear physics after present commitments are fulfilled. This led to the formation of a committee by the U.S. National Academy of Sciences (NAS) to assess the EIC science case. The NAS committee deliberated for about a year and the report has been publicly released this month.

**Q: Give us an idea of how powerful this new collider will be and what kind of new interactions it will produce. What kinds of phenomena will it help to explain?**

A: The EIC will be a powerful and unique new accelerator that will offer an unprecedented window into the fundamental structure of matter. The electron-ion collision rate at the EIC will be high, more than two orders of magnitude greater than was possible at the only previous electron-proton collider, namely HERA, which operated at the DESY laboratory in Hamburg, Germany, from 1992 to 2007. With the EIC, physicists will be able to image the virtual quarks and gluons that make up protons, neutrons, and nuclei, with unprecedented spatial resolution and shutter speed. A goal is to provide images of the fundamental structure of the microcosm that can be appreciated broadly by humanity: to answer questions such as, what does a proton look like? And what does a nucleus look like?

There are three central scientific issues that can be addressed by an [electron-ion collider](#). The first goal is to understand in detail the mechanisms within QCD by which the mass of protons and neutrons, and thus the mass of all the visible matter in the universe, is generated. The problem is that while gluons have no mass, and quarks are nearly massless, the protons and neutrons that contain them are heavy, making up most of the visible mass of the universe. The total mass of a nucleon is some 100 times greater than the mass of the various quarks it contains.

The second issue is to understand the origin of the intrinsic angular momentum, or spin, of nucleons, a fundamental property that underlies many practical applications, including magnetic resonance imaging (MRI). How the angular momentum, both intrinsic as well as orbital, of the internal quarks and gluons gives rise to the known nucleon spin is not understood. And thirdly, the nature of gluons in matter—that is, their arrangements or states—and the details of how they hold matter together, is not well-known. Gluons in matter are a little like dark matter in the universe: unseen but playing a crucial role. An electron-ion collider would potentially reveal new states resulting from the close packing of many gluons within nucleons and nuclei. These issues are fundamental to our understanding of the matter in the universe.

**Q: What role will MIT have in this project going forward?**

A: At present, more than a dozen MIT physics department faculty lead research groups in the Laboratory for Nuclear Science that work directly on understanding the fundamental structure of matter as described by QCD. It is the largest university-based group in the U.S. working on QCD. Theoretical research is focused at the Center for Theoretical Physics, and experimentalists rely heavily on the Bates Research and Engineering Center for technical support.

MIT theorists are carrying out important calculations using the world's most powerful computers to understand fundamental aspects of QCD. MIT experimental physicists are conducting experiments at existing facilities, such as BNL, CERN, and Jefferson Laboratory, to reach new insight and to develop new techniques that will be used at the EIC. Further, R&D into new polarized sources, detectors, and innovative data-acquisition schemes by MIT scientists and engineers is in progress. It is anticipated that these efforts will ramp up as the realization of the EIC approaches.

It is anticipated that the U.S. Department of Energy Office of Science will initiate in the near future the official process for EIC by which the U.S. government approves, funds, and constructs new, large scientific facilities. Critical issues are the selection of the site for EIC and the participation of international users. An EIC user group has formed with the participation of more than 700 Ph.D. scientists from over 160 laboratories and universities around the world. If the realization of EIC follows a schedule comparable to that of past large facilities, it should be doing science by about 2030. MIT has a long history of providing leadership in U.S. nuclear physics and will continue to play a significant role as we proceed along the path to EIC. [27]

## **Evidence for a new nuclear phase transition could rewrite physics textbooks**

Physics textbooks might have to be updated now that an international research team has found evidence of an unexpected transition in the structure of atomic nuclei.

The discovery was published in the journal *Physical Review Letters*. Lead author Bo Cederwall, professor of nuclear physics at KTH Royal Institute of Technology, says that lifetime measurements of neutron-deficient nuclides in a range of short-lived heavy metal isotope chains revealed never-before-observed behavior at the lowest states of energy.

Cederwall says the patterns indicate a phase transition – that is, rapid change in matter from one state to another – that is unexpected for this group of isotopes and unexplained by theory.

"Discoveries of phenomena that go against standard theory are always very exciting and rather uncommon," Cederwall says. The research team from KTH included doctoral students Özge Aktas and Aysegul Ertoprak, Assistant Professor Chong Qi, Professor Emeritus Robert Liotta, postdocs Hongna Liu and Maria Doncel, and visiting researchers Sanya Matta and Pranav Subramaniam.

"Continuing with theory development and with complementary experiments could lead to the need to revise what is said about atomic nuclei in the textbooks," Cederwall says.

The research focused on excited states in nuclei situated closely above the ground state in energy that are extremely short-lived, on the order of millionths of a millionth of a second.

"Not only are the states we are studying very short-lived, the nuclei we have investigated are so unstable, difficult to produce and to identify, that very little information about their structure has been measured before," he says.

For a year, the research group analyzed several terabytes of data. Gamma radiation has been studied from nuclear reactions at the particle accelerator facility at the University of Jyväskylä, Finland. The measuring equipment, which uses high-purity germanium crystals at its core, can identify the rarest nuclear species from a vast background of more stable nuclides produced in the reactions.

In addition to in-depth understanding of how the universe's smallest components are built, the methods and detector systems that the research team has developed can be applied in medicine and technology. Diagnosis and radiation treatment of cancer, technologies for detecting radioactive substances in the environment, and nuclear safety control against nuclear proliferation are some examples. The nuclear physics group at KTH also works with such applications of its basic research.

"It is the extreme sensitivity of the measurement technique that is crucial to our results. Our increasingly refined technology will serve both new applications and next-generation experiments," Cederwall says. [26]

## **Can ultrashort electron flashes help harvest nuclear energy?**

The group led by Fabrizio Carbone at EPFL and international colleagues have used ultrafast transmission electron microscopy to take attosecond energy-momentum resolved snapshots (1 attosecond =  $10^{-18}$  or quintillionths of a second) of a free-electron wave function. Though unprecedented in itself, the scientists also used their experimental success to develop a theory of how to create electron flashes within zeptosecond ( $10^{-21}$  of a second) timeframes, using existing technology. This breakthrough could allow physicists to increase the energy yield of nuclear reactions using coherent control methods, which relies on the manipulation of quantum interference effects with lasers and which has already advanced fields like spectroscopy, quantum information processing, and laser cooling.

In fact, one of the most elusive phenomena in physics is the excitation of an atom's nucleus by absorption of an electron. The process, known as "nuclear excitation by electron capture" (NEEC), was theoretically predicted forty years ago, though it proved difficult to observe experimentally.

But in February 2018, US physicists were finally able to catch a glimpse of NEEC in the lab. The work was hailed as ushering in new nuclear energy-harvesting systems, as well as explaining why certain elements like gold and platinum are so abundant in the universe.

The EPFL researchers suggest a potential method to exploit the several orders of magnitude in energy in the nucleus of an atom via the [coherent control](#) of the NEEC effect. Such method would be enabled by the availability of ultrashort (as to zs) electron flashes. "Ideally, one would like to induce instabilities in an otherwise stable or metastable nucleus to prompt energy-producing decays, or to generate radiation," says Carbone. "However, accessing nuclei is difficult and energetically costly because of the protective shell of electrons surrounding it."

The authors write, "Our coherent control scheme with ultrashort electron pulses would offer a new perspective for the manipulation of [nuclear reactions](#) with potential implications in various fields, from fundamental physics to energy-related applications." [25]

## **The nucleus—coming soon in 3-D**

Physicians have long used CT scans to get 3-D imagery of the inner workings of the human body. Now, physicists are working toward getting their first CT scans of the inner workings of the nucleus. A measurement of quarks in helium nuclei demonstrates that 3-D imaging of the inner structure of the nucleus is now possible.

Nathan Baltzell is a postdoctoral researcher at the Department of Energy's Thomas Jefferson National Accelerator Facility in Newport News, Va. He says this successful measurement is one of the first steps toward imaging nuclei in a new way.

"It's a proof-of-principle measurement that opens up a new field – imaging nuclear structure in three dimensions with GPD tomography," he says.

He explains that GPDs, or generalized parton distributions, provide a framework that, when combined with experimental results, allows nuclear physicists to complete a 3-D rendering of the building blocks of subatomic particles, such as the proton, neutron, and now, even the nucleus.

GPDs are already being applied to 3-D imaging studies of protons and neutrons at Jefferson Lab. These studies are helping researchers understand how quarks and gluons build protons and neutrons. Now, Baltzell and his colleagues want to open a new window into the structure of the nucleus by extending this GPD tomography technique to nuclei.

"We've done these kinds of studies of quarks and gluons inside protons and neutrons for quite a while," he says. "But in a nucleus, where you have multiple neutrons and protons together... We don't quite know how the behaviors of quarks and gluons change and how they move together differently when you put them in a nucleus."

The experiment was conducted in 2009 at Jefferson Lab's Continuous Electron Beam Accelerator Facility, a DOE Office of Science User Facility. In it, electrons were beamed into the nuclei of helium-4 atoms.

"We started with helium-4 as our proof of principle for this study," Baltzell says. "We chose helium-4 because it is a light nucleus, relatively dense, and spinless. These characteristics make it experimentally attractive and the theoretical interpretation much simpler."

The experimenters were interested in the roughly 3,200 events they recorded of the electrons interacting with individual quarks inside the nuclei. For each of these events, the outgoing electron, the helium nucleus and a photon given off by the individual [quark](#) were all recorded.

"To make a precise measurement like this, you want to measure everything that comes out. This is the first time we measured all of the particles in the final state," Baltzell adds.

The result of the experiment was published last fall in *Physical Review Letters*.

Now that the researchers have shown that this technique is feasible, the collaboration is taking the next step to continue these studies with the new capabilities afforded by the upgraded accelerator and experimental equipment at Jefferson Lab. A new experiment has already been planned to begin the long process of actually composing that 3-D image of the internal quark-gluon structure of the helium-4 [nucleus](#). [24]

## How are hadrons born at the huge energies available in the LHC?

Our world consists mainly of particles built up of three quarks bound by gluons. The process of the sticking together of quarks, called hadronisation, is still poorly understood. Physicists from the Institute of Nuclear Physics Polish Academy of Sciences in Cracow, working within the LHCb Collaboration, have obtained new information about it, thanks to the analysis of unique data collected in high-energy collisions of protons in the LHC.

When protons accelerated to the greatest energy collide with each other in the LHC, their component particles - quarks and gluons - create a puzzling intermediate state. The observation that in the collisions of such relatively simple particles as protons this intermediate state exhibits the properties of a liquid, typical for collisions of much more complex structures (heavy ions), was a big surprise. Properties of this type indicate the existence of a new state of matter: a quark-gluon plasma in which quarks and gluons behave almost as free particles. This exotic liquid cools instantly. As a result, the quarks and gluons re-connect with each other in a process called hadronisation. The effect of this is the birth of hadrons, particles that are clumps of two or three quarks. Thanks to the latest analysis of data collected at energies of seven teraelectronvolts, researchers from the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN) in Cracow, working within the LHCb Collaboration, acquired new information on the mechanism of hadronisation in proton-proton collisions.

"The main role in proton collisions is played by strong interaction, described by the quantum chromodynamics. The phenomena occurring during the cooling of the [quark-gluon plasma](#) are, however, so complex in terms of computation that until now it has not been possible fully understand the details of hadronisation. And yet it is a process of key significance! It is thanks to this that in the first moments after the Big Bang, the dominant majority of particles forming our everyday environment was formed from [quarks](#) and gluons," says Assoc. Prof. Marcin Kucharczyk (IFJ PAN).

In the LHC, hadronisation is extremely fast, and occurs in an extremely small area around the point of proton collision: its dimensions reach only femtometres, or millionths of one billionth of a metre. It is no wonder then, that direct observation of this process is currently not possible. To obtain any information about its course, physicists must reach for various indirect methods. A key role is played by the basic tool of quantum mechanics: a wave function whose properties are mapped by the characteristics of particles of a given type (it is worth noting that although it is almost 100 years since the birth of quantum mechanics, there still exists various interpretations of the wave function!).

"The wave functions of identical particles will effectively overlap, i.e. interfere. If they are enhanced as a result of interference, we are talking about Bose-Einstein correlations, if they are suppressed - Fermi-Dirac correlations. In our analyses, we were interested in the enhancements, that is, the Bose-Einstein correlations. We were looking for them between the pi mesons flying out of the area of hadronisation in directions close to the original direction of the colliding beams of protons," explains Ph.D. student Bartosz Malecki (IFJ PAN).

The method used was originally developed for radioastronomy and is called HBT interferometry (from the names of its two creators: Robert Hanbury Brown and Richard Twiss). When used with reference to particles, HBT interferometry makes it possible to determine the size of the area of hadronisation and its evolution over time. It helps to provide information about, for example, whether this area is different for different numbers of emitted particles or for their different types.

The data from the LHCb detector made it possible to study the hadronisation process in the area of so-called small angles, i.e. for hadrons produced in directions close to the direction of the initial proton beams. The analysis performed by the group from the IFJ PAN provided indications that the parameters describing the source of hadronisation in this unique region covered by LHCb experiment at LHC are different from the results obtained for larger angles.

"The analysis that provided these interesting results will be continued in the LHCb experiment for various collision energies and different types of colliding structures. Thanks to this, it will be possible to verify some of the models describing hadronisation and, consequently, to better understand the course of the process itself," sums up Prof. Mariusz Witek (IFJ PAN).

The work of the team from the IFJ PAN was financed in part by the OPUS grant from the Polish National Science Centre.

The Henryk Niewodniczanski Institute of Nuclear Physics (IFJ PAN) is currently the largest research institute of the Polish Academy of Sciences. The broad range of studies and activities of IFJ PAN includes basic and applied research, ranging from particle [physics](#) and astrophysics, through hadron physics, high-, medium-, and low-energy [nuclear physics](#), condensed matter physics (including materials engineering), to various applications of methods of nuclear physics in interdisciplinary research, covering medical physics, dosimetry, radiation and environmental biology, environmental protection, and other related disciplines. The average yearly yield of the IFJ PAN encompasses more than 600 scientific papers in the Journal Citation Reports published by the Thomson Reuters. The part of the Institute is the Cyclotron Centre Bronowice (CCB) which is an infrastructure, unique in Central Europe, to serve as a clinical and research centre in the area of medical and nuclear physics. IFJ PAN is a member of the Marian Smoluchowski Krakow Research Consortium: "Matter-Energy-Future" which possesses the status of a Leading National Research Centre

(KNOW) in physics for the years 2012-2017. The Institute is of A+ Category (leading level in Poland) in the field of sciences and engineering. [23]

### **Shock front probed by protons**

A shock front is usually considered as a simple discontinuity in density or pressure. Yet in strongly shocked gases, the atoms are ionized into electrons and ions. The large difference in the electron pressure across the shock front can generate a strong electric field.

In experimental campaigns using the OMEGA EP laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, Lawrence Livermore National Laboratory (LLNL), University of California San Diego (UCSD) and Massachusetts Institute of Technology (MIT) researchers took radiographs of the shock front, similar to the X-ray radiology in hospitals with protons instead of X-rays.

Protons are charged particles that can be deflected by an electric field. Therefore, detecting the changes in their trajectories will provide information on the electric field. "Our proton probe is broadband," said Rui Hua, a graduate student at UCSD and the first author of the paper published in Applied Physical Letters. "Measuring energy-dependent deflections allows us to quantitatively study the electric potential and the potential width." The team also published a paper in Review of Scientific Instruments earlier this year to describe this platform.

The team observed an electric field of about 800 million volts per meter. "An analytical model agrees very well with our data," said Yuan Ping, LLNL co-author and the campaign lead. "So we don't have to rely on hydrodynamic codes to interpret the data."

The team plans to carry out more shots with higher-pressure shocks, and also in convergent geometry to simulate the conditions in the capsule implosion for ICF. "This is a perfect example of collaboration between the Lab and academia," said Farhat Beg, director of the Center for Energy Research at UCSD.

The team's research is available at Applied Physical Letters. [22]

### **Researchers generate proton beams using a combination of nanoparticles and laser light**

Light, when strongly concentrated, is enormously powerful. Now, a team of physicists led by Professor Jörg Schreiber from the Institute of Experimental Physics – Medical Physics, which is part of the Munich-Centre for Advanced Photonics (MAP), a Cluster of Excellence at LMU Munich, has used this energy source with explosive effect. The researchers focus high-power laser light onto beads of plastic just a few micrometers in size. The concentrated energy blows the nanoparticles apart, releasing radiation made up of positively charged atoms (protons). Such proton beams could be used in future for treating tumors, and in advanced imaging techniques. Their findings appear in the journal Physical Review E.

At Texas Petawatt Lasers in Austin, Texas, the LMU physicists concentrated laser light so strongly on plastic nanobeads that these essentially exploded. In the experiment, approximately one quadrillion billion photons (3 times  $10^{20}$  photons) were focused onto microspheres of about 500 nanometers in diameter. Each bead consists of about 50 billion carbon and hydrogen atoms and is held in suspension by the electromagnetic fields of a so-called "Paul trap", where the laser beam can irradiate them.

The laser radiation rips away some 15 per cent of the electrons bound in these atoms. The remaining, positively charged atomic nuclei are then violently repelled, and the nanospheres explode at speeds of around 10 per cent the speed of light. The radiation from the positively charged particles (protons) then spreads out in all directions.

This mode of production of proton beams with laser light promises to open up new opportunities for nuclear medicine – for example, in the fight against tumors. At present, proton beams are produced in conventional accelerators. In contrast, laser-generated proton beams open the door to the development of novel, perhaps even cheaper and more efficient, methods of treatment. The Munich-based team led by Jörg Schreiber has hitherto produced proton radiation using a diamondlike film, which is targeted by extremely strong laser light. The proton radiation thus emitted could then be directed onto the body of a patient.

The ability to produce radiation by the explosive disintegration of plastic nanobeads might even allow the nanoparticles to be placed inside a tumor, and be vaporized with laser light. Thus proton beams could be put to work in destroying tumors without causing damage to surrounding healthy tissue. [21]

## **Towards stable propagation of light in nano-photonic fibers**

Devices based on light, rather than electrons, could revolutionize the speed and security of our future computers. However, one of the major challenges in today's physics is the design of photonic devices, able to transport and switch light through circuits in a stable way. Sergej Flach, Director of the Center for Theoretical Physics of Complex Systems, within the Institute for Basic Science (IBS) and colleagues from the National Technical University of Athens and the University of Patras (Greece) have studied how to achieve a more stable propagation of light for future optical technologies. Their model was recently published in Scientific Reports.

Optical fibers can carry a large amount of information and are already used in many countries for communications via phone, internet and TV. However, when light travels long distances through these fibers, it suffers from losses and leakages, which could lead to a loss of information. In order to compensate for this problem, amplifiers are positioned at specific intervals to amplify the signal. For example, amplifiers are needed in submarine communications cables that allow the transfer of digital data between all continents (except for Antarctica). Researchers have tried to build fibers where the signal is stable along the pathway and does not need amplifiers, using the so-called "PT symmetry". P stands for parity reversal and T for time reversal.

The PT symmetry can be simplified with an example. Imagine a situation where two cars are traveling at the same speed at some instant in time. However, one car is speeding up and the other one is slowing down. Using parity reversal (P) we exchange one car for the other. Using time



reversal (T) we go back in time. If you are in the car that is accelerating, you can jump to the car that is slowing down (P) and you also go back in time (T). As a result, you will end up with the same speed as the accelerating car. The cars are like light waves inside the optical fibers and the speed is a representation of the intensity of light. The jumping symbolizes of the transfer of light from one fiber to another, which happens when the light waves propagating in each fiber overlap partially with each other, through a phenomenon called tunneling.

The PT symmetry idea is that one can carefully balance the intensity of light inside the fibers and achieve a stable propagation. Researchers expected PT symmetry to be the solution to achieve stable propagation in all-optical devices (diodes, transistors, switches etc.). However, stable propagation is still a challenge because the PT symmetry conditions have to be balanced extremely carefully, and because the material of the fibers reacts and destroys the exact balance. In the example of the cars, in order to achieve perfect PT symmetry, you would need really identical cars and street conditions. Reality is of course much different.

The team led by IBS found that the stability of light propagation can be achieved by breaking the PT symmetry in a controlled way. In the example of the cars, you would have to choose two cars that are actually different (for example, one has a better engine than the other), but you choose the differences deliberately.

"You have the potential to realize a lot of the items of the wish-list of the PT symmetry, by breaking the PT symmetry. But you have to break it in the right way," explains Professor Flach. "Now we know how to tune the characteristics of the fiber couplers to achieve a long-lasting constant light propagation." [20]

## **Synopsis: Twisting in Thin Air**

Levitated nanoparticles can be used in ultrasensitive force measurements and fundamental tests of quantum physics. Unlike prior efforts that have focused on the translational vibrations of these nanoparticles, a new study considers the torsional motion. The researchers used polarized laser light to measure, for the first time, the twisting oscillations of oblong-shaped nanoparticles in a vacuum. The results suggest that this torsional motion can be cooled to zero oscillations (on average), corresponding to the torsional ground state.

For levitation experiments, focused laser beams create a trap that confines the translational motion of nanoparticles to back-and-forth oscillations at a specific frequency. Laser cooling can reduce these oscillations, but current techniques cannot reach the ground state. One solution is higher oscillation frequencies. In this case, the energy left after cooling is less than one quantum of oscillation, so the nanoparticle ends up in its ground state. However, making a higher-frequency optical trap would require higher laser power, which has the negative effect of heating the nanoparticles.

An alternative path is the use of a different oscillation mode. Tongcang Li of Purdue University, Indiana, and collaborators investigated the torsional motions of nanoparticles levitated with a linearly polarized laser. The oblong-shaped nanoparticles within the sample aligned themselves lengthwise along the laser's polarization axis. The researchers showed that these ellipsoids twist back and forth around this axis with a frequency of 1 MHz, a factor of 6 higher than that of the

particles' translational vibrations. The team outlined a possible cooling method that could place nanoparticles in their torsional ground state. They also imagined the system as an ultrasensitive detector that could measure torques on single particles. [19]

## **Researchers have created quantum states of light whose noise level has been “squeezed” to a record low**

Squeezed quantum states of light can have better noise properties than those imposed by classical limits set by shot noise. Such states might help researchers boost the sensitivity of gravitationalwave (GW) detectors or design more practical quantum information schemes. A team of researchers at the Institute for Gravitational Physics at the Leibniz University of Hanover, Germany, has now demonstrated a method for squeezing noise to record low levels. The new approach—compatible with the laser interferometers used in GW detectors—may lead to technologies for upgrading LIGO and similar observatories.

Squeezed light is typically generated in nonlinear crystals, in which one pump photon produces two daughter photons. Because the two photons are generated in the same quantum process, they exhibit correlations that can be exploited to reduce noise in measuring setups. Quantum squeezing can, in principle, reduce noise to arbitrarily low levels. But in practice, photon losses and detector noise limit the maximum achievable squeezing. The previous record was demonstrated by the Hanover team, who used a scheme featuring amplitude fluctuations that were about a factor of 19 lower than those expected from classical noise (12.7 dB of squeezing).

In their new work, the researchers bested themselves by increasing this factor to 32 (15 dB of squeezing), using a light-squeezing scheme with low optical losses and minimal fluctuations in the phase of the readout scheme. The squeezed states are obtained at 1064 nm, the laser wavelength feeding the interferometers of all current GW observatories.

This research is published in Physical Review Letters. [18]

## **Liquid Light with a Whirl**

An elliptical light beam in a nonlinear optical medium pumped by “twisted light” can rotate like an electron around a magnetic field.

Magnetism and rotation have a lot in common. The effect of a magnetic field on a moving charge, the Lorentz force, is formally equivalent to the fictitious force felt by a moving mass in a rotating reference frame, the Coriolis force. For this reason, atomic quantum gases under rotation can be used as quantum simulators of exotic magnetic phenomena for electrons, such as the fractional quantum Hall effect. But there is no direct equivalent of magnetism for photons, which are massless and chargeless. Now, Niclas Westerberg and co-workers at Heriot-Watt University, UK, have shown how to make synthetic magnetic fields for light. They developed a theory that predicts how a light beam in a nonlinear optical medium pumped by “twisted light” will rotate as it propagates, just as an electron will whirl around in a magnetic field. More than that, the light will expand as it goes, demonstrating fluid-like behavior. We can expect synthetic magnetism for light to bring big insights into magnetism in other systems, as well as some beautiful images.

The idea that light can behave like a fluid and, even more interestingly, a superfluid (a fluid with zero viscosity), goes back at least to the 1990s. The analogy comes about because Maxwell's equations for nearly collimated light in a nonlinear medium look like the Schrödinger equation for a superfluid of matter, modified to include particle interactions. Fluids of light, or photon fluids, propagating in bulk nonlinear media show a range of fluid and superfluid behavior, such as free expansion and shock waves. In microcavities, fluids of light can be strongly coupled to matter, such as semiconductor electron-hole pairs, to make hybrid entities known as polariton condensates. These condensates can exhibit quantized vortices, which are characteristic of superfluidity. Despite these impressive advances, it has proven difficult to induce the strong bulk rotation required for phenomena such as the quantum Hall effect to show up in photon fluids, hence the need for synthetic magnetism.

The concept of synthetic magnetism is borrowed from ultracold atoms. With atoms, it is experimentally unfeasible to reach a regime of rapid rotation corresponding to a large magnetic field, not least because the traps that confine the atoms are unable to provide the centripetal force to stop them from flying out. Instead, it is possible to take advantage of the fact that atoms have multiple internal states. These can be used to generate geometric phases, as opposed to dynamic phases (which can be imposed by any forces, whatever the structure of the internal states may be). A geometric phase, otherwise known as a Berry phase, arises when a system's internal states (for example, its spin) smoothly follow the variations of an external field, so that its phase depends on which path it takes between two external states (for example, two positions of the system), even if the paths have the same energy. In atomic systems, the variations of the external field in position are achieved with phase or amplitude structures of the electromagnetic field of laser light. These variations can be engineered to produce the rotational equivalent of the vector potential for a magnetic field on a charged particle, inducing strong bulk rotation that shows up as many vortices in a superfluid Bose-Einstein condensate.

To produce a geometric phase in a fluid of light, Westerberg and colleagues considered light with two coupled internal states—a spinor photon fluid. They studied two types of nonlinear media, with second- and third-order optical nonlinearities, respectively. The second-order nonlinearity comes in the form of mixing of three fields in a birefringent crystal, in which one field, the pump light field, splits into two further fields with orthogonal polarizations, these being the two required internal states of the spinor fluid. Slow spatial variations of the strong pump field generate a synthetic vector potential that is equivalent to a magnetic field for electric charges or rotation for atoms.

The third-order optical nonlinearity occurs in a medium with a refractive index that depends on the intensity of light. The spinor photon fluid in this case consists of weak fluctuations around a strong light field that carries orbital angular momentum (colloquially known as twisted light). The two internal states of the fluid are distinguished by their differing orbital angular momentum. The resulting vector potential produces synthetic magnetism, much as with the second-order nonlinearity.

Coincidentally, for the medium with a second-order nonlinearity, Westerberg and co-workers also propose using twisted light.

The authors present numerical simulations for both types of nonlinearity. For the second-order nonlinear medium, they show that an elliptical light beam in a synthetic magnetic field rotates about its propagation axis and expands as it propagates (Fig 1). The expansion shows that the light is behaving as a fluid in rotation. For the third-order nonlinear medium there is a trapped vortex that causes the beam to rotate, which is akin to cyclotron motion of a charge in a magnetic field. Short of spinning the medium extremely rapidly [9], it is not obvious how one could otherwise make a beam continuously rotate as it propagates.

Westerberg and colleagues' work makes important connections between several disparate topics: nonlinear optics, atomic physics, geometric phases, and light with orbital angular momentum. Spinor photon fluids in themselves are a new development. The complete state of a photon fluid—its amplitude, phase, and polarization—can be mapped out; this is not possible for atoms or electrons. Some of the authors of the present study have recently experimentally driven photon fluids past obstacles in ways that are hard to achieve for atoms, and obtained evidence for superfluidity through the phase of the photon fluid [10]—evidence that cannot be obtained for electronic magnetism. Furthermore, they have also made photon fluids that have nonlocal interactions, via thermal effects. Generalizing synthetic magnetism to nonlocal fluids of light will enlighten us about magnetism and rotation in solid-state and atomic superfluids. Experimental implementation will surely follow hot on the heels of this proposal. [17]

## Physicists discover a new form of light

Physicists from Trinity College Dublin's School of Physics and the CRANN Institute, Trinity College, have discovered a new form of light, which will impact our understanding of the fundamental nature of light.

One of the measurable characteristics of a beam of light is known as angular momentum. Until now, it was thought that in all forms of light the angular momentum would be a multiple of Planck's constant (the physical constant that sets the scale of quantum effects).

Now, recent PhD graduate Kyle Ballantine and Professor Paul Eastham, both from Trinity College Dublin's School of Physics, along with Professor John Donegan from CRANN, have demonstrated a new form of light where the angular momentum of each photon (a particle of visible light) takes only half of this value. This difference, though small, is profound. These results were recently published in the online journal *Science Advances*.

Commenting on their work, Assistant Professor Paul Eastham said: "We're interested in finding out how we can change the way light behaves, and how that could be useful. What I think is so exciting about this result is that even this fundamental property of light, that physicists have always thought was fixed, can be changed."

Professor John Donegan said: "My research focuses on nanophotonics, which is the study of the behaviour of light on the nanometer scale. A beam of light is characterised by its colour or wavelength and a less familiar quantity known as angular momentum. Angular momentum measures how much something is rotating. For a beam of light, although travelling in a straight line it can also be rotating around its own axis. So when light from the mirror hits your eye in the morning, every photon twists your eye a little, one way or another."

"Our discovery will have real impacts for the study of light waves in areas such as secure optical communications."

Professor Stefano Sanvito, Director of CRANN, said: "The topic of light has always been one of interest to physicists, while also being documented as one of the areas of physics that is best understood. This discovery is a breakthrough for the world of physics and science alike. I am delighted to once again see CRANN and Physics in Trinity producing fundamental scientific research that challenges our understanding of light."

To make this discovery, the team involved used an effect discovered in the same institution almost 200 years before. In the 1830s, mathematician William Rowan Hamilton and physicist Humphrey Lloyd found that, upon passing through certain crystals, a ray of light became a hollow cylinder. The team used this phenomenon to generate beams of light with a screw-like structure.

Analyzing these beams within the theory of quantum mechanics they predicted that the angular momentum of the photon would be half-integer, and devised an experiment to test their prediction. Using a specially constructed device they were able to measure the flow of angular momentum in a beam of light. They were also able, for the first time, to measure the variations in this flow caused by quantum effects. The experiments revealed a tiny shift, one-half of Planck's constant, in the angular momentum of each photon.

Theoretical physicists since the 1980s have speculated how quantum mechanics works for particles that are free to move in only two of the three dimensions of space. They discovered that this would enable strange new possibilities, including particles whose quantum numbers were fractions of those expected. This work shows, for the first time, that these speculations can be realised with light. [16]

## **Novel metasurface revolutionizes ubiquitous scientific tool**

Light from an optical fiber illuminates the metasurface, is scattered in four different directions, and the intensities are measured by the four detectors. From this measurement the state of polarization of light is detected.

What do astrophysics, telecommunications and pharmacology have in common? Each of these fields relies on polarimeters—instruments that detect the direction of the oscillation of electromagnetic waves, otherwise known as the polarization of light.

Even though the human eye isn't particularly sensitive to polarization, it is a fundamental property of light. When light is reflected or scattered off an object, its polarization changes and measuring that change reveals a lot of information. Astrophysicists, for example, use polarization measurements to analyze the surface of distant, or to map the giant magnetic fields spanning our galaxy. Drug manufacturers use the polarization of scattered light to determine the chirality and concentration of drug molecules. In telecommunications, polarization is used to carry information through the vast network of fiber optic cables. From medical diagnostics to high-tech manufacturing to the food industry, measuring polarization reveals critical data.

Scientists rely on polarimeters to make these measurements. While ubiquitous, many polarimeters currently in use are slow, bulky and expensive.

Now, researchers at the Harvard John A. Paulson School of Engineering and Applied Sciences and Innovation Center Iceland have built a polarimeter on a microchip, revolutionizing the design of this widely used scientific tool.

"We have taken an instrument that is can reach the size of a lab bench and shrunk it down to the size of a chip," said Federico Capasso, the Robert L. Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering, who led the research. "Having a microchip polarimeter will make polarization measurements available for the first time to a much broader range of applications, including in energy-efficient, portable devices."

"Taking advantage of integrated circuit technology and nanophotonics, the new device promises high-performance polarization measurements at a fraction of the cost and size," said J. P. Balthasar Mueller, a graduate student in the Capasso lab and first author of the paper.

The device is described in the journal *Optica*. Harvard's Office of Technology Development has filed a patent application and is actively exploring commercial opportunities for the technology.

Capasso's team was able to drastically reduce the complexity and size of polarimeters by building a two-dimensional metasurface—a nanoscale structure that interacts with light. The metasurface is covered with a thin array of metallic antennas, smaller than a wavelength of light, embedded in a polymer film. As light propagates down an optical fiber and illuminates the array, a small amount scatters in four directions. Four detectors measure the intensity of the scattered light and combine to give the state of polarization in real time.

"One advantage of this technique is that the polarization measurement leaves the signal mostly intact," said Mueller. "This is crucial for many uses of polarimeters, especially in optical telecommunications, where measurements must be made without disturbing the data stream."

In telecommunications, optical signals propagating through fibers will change their polarization in random ways. New integrated photonic chips in fiber optic cables are extremely sensitive to polarization, and if light reaches a chip with the wrong polarization, it can cause a loss of signal.

"The design of the antenna array make it robust and insensitive to the inaccuracies in the fabrication process, which is ideal for large scale manufacturing," said Kristjan Leosson, senior researcher and division manager at the Innovation Center and coauthor of the paper.

Leosson's team in Iceland is currently working on incorporating the metasurface design from the Capasso group into a prototype polarimeter instrument.

Chip-based polarimeters could for the first time provide comprehensive and real-time polarization monitoring, which could boost network performance and security and help providers keep up with the exploding demand for bandwidth.

"This device performs as well as any state-of-the-art polarimeter on the market but is considerably smaller," said Capasso. "A portable, compact polarimeter could become an important tool for not

only the telecommunications industry but also in drug manufacturing, medical imaging, chemistry, astronomy, you name it. The applications are endless." [15]

## **New nanodevice shifts light's color at single-photon level**

Converting a single photon from one color, or frequency, to another is an essential tool in quantum communication, which harnesses the subtle correlations between the subatomic properties of photons (particles of light) to securely store and transmit information. Scientists at the National Institute of Standards and Technology (NIST) have now developed a miniaturized version of a frequency converter, using technology similar to that used to make computer chips.

The tiny device, which promises to help improve the security and increase the distance over which next-generation quantum communication systems operate, can be tailored for a wide variety of uses, enables easy integration with other information-processing elements and can be mass produced.

The new nanoscale optical frequency converter efficiently converts photons from one frequency to the other while consuming only a small amount of power and adding a very low level of noise, namely background light not associated with the incoming signal.

Frequency converters are essential for addressing two problems. The frequencies at which quantum systems optimally generate and store information are typically much higher than the frequencies required to transmit that information over kilometer-scale distances in optical fibers. Converting the photons between these frequencies requires a shift of hundreds of terahertz (one terahertz is a trillion wave cycles per second).

A much smaller, but still critical, frequency mismatch arises when two quantum systems that are intended to be identical have small variations in shape and composition. These variations cause the systems to generate photons that differ slightly in frequency instead of being exact replicas, which the quantum communication network may require.

The new photon frequency converter, an example of nanophotonic engineering, addresses both issues, Qing Li, Marcelo Davanço and Kartik Srinivasan write in *Nature Photonics*. The key component of the chip-integrated device is a tiny ring-shaped resonator, about 80 micrometers in diameter (slightly less than the width of a human hair) and a few tenths of a micrometer in thickness. The shape and dimensions of the ring, which is made of silicon nitride, are chosen to enhance the inherent properties of the material in converting light from one frequency to another. The ring resonator is driven by two pump lasers, each operating at a separate frequency. In a scheme known as four-wave-mixing Bragg scattering, a photon entering the ring is shifted in frequency by an amount equal to the difference in frequencies of the two pump lasers.

Like cycling around a racetrack, incoming light circulates around the resonator hundreds of times before exiting, greatly enhancing the device's ability to shift the photon's frequency at low power and with low background noise. Rather than using a few watts of power, as typical in previous experiments, the system consumes only about a hundredth of that amount. Importantly, the added amount of noise is low enough for future experiments using single-photon sources.

While other technologies have been applied to frequency conversion, "nanophotonics has the benefit of potentially enabling the devices to be much smaller, easier to customize, lower power,

and compatible with batch fabrication technology," said Srinivasan. "Our work is a first demonstration of a nanophotonic technology suitable for this demanding task of quantum frequency conversion." [14]

## Quantum dots enhance light-to-current conversion in layered semiconductors

Harnessing the power of the sun and creating light-harvesting or light-sensing devices requires a material that both absorbs light efficiently and converts the energy to highly mobile electrical current. Finding the ideal mix of properties in a single material is a challenge, so scientists have been experimenting with ways to combine different materials to create "hybrids" with enhanced features.

In two just-published papers, scientists from the U.S. Department of Energy's Brookhaven National Laboratory, Stony Brook University, and the University of Nebraska describe one such approach that combines the excellent light-harvesting properties of quantum dots with the tunable electrical conductivity of a layered tin disulfide semiconductor. The hybrid material exhibited enhanced light-harvesting properties through the absorption of light by the quantum dots and their energy transfer to tin disulfide, both in laboratory tests and when incorporated into electronic devices. The research paves the way for using these materials in optoelectronic applications such as energy-harvesting photovoltaics, light sensors, and light emitting diodes (LEDs).

According to Mircea Cotlet, the physical chemist who led this work at Brookhaven Lab's Center for Functional Nanomaterials (CFN), a DOE Office of Science User Facility, "Two-dimensional metal dichalcogenides like tin disulfide have some promising properties for solar energy conversion and photodetector applications, including a high surface-to-volume aspect ratio. But no semiconducting material has it all. These materials are very thin and they are poor light absorbers. So we were trying to mix them with other nanomaterials like light-absorbing quantum dots to improve their performance through energy transfer."

One paper, just published in the journal *ACS Nano*, describes a fundamental study of the hybrid quantum dot/tin disulfide material by itself. The work analyzes how light excites the quantum dots (made of a cadmium selenide core surrounded by a zinc sulfide shell), which then transfer the absorbed energy to layers of nearby tin disulfide.

"We have come up with an interesting approach to discriminate energy transfer from charge transfer, two common types of interactions promoted by light in such hybrids," said Prahlad Routh, a graduate student from Stony Brook University working with Cotlet and co-first author of the *ACS Nano* paper. "We do this using single nanocrystal spectroscopy to look at how individual quantum dots blink when interacting with sheet-like tin disulfide. This straightforward method can assess whether components in such semiconducting hybrids interact either by energy or by charge transfer."

The researchers found that the rate for non-radiative energy transfer from individual quantum dots to tin disulfide increases with an increasing number of tin disulfide layers. But performance in laboratory tests isn't enough to prove the merits of potential new materials. So the scientists



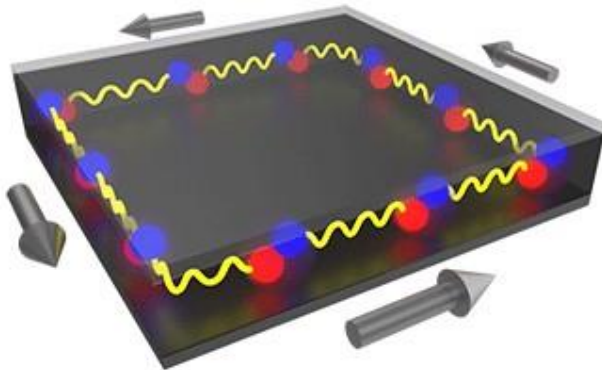
incorporated the hybrid material into an electronic device, a photo-field-effect-transistor, a type of photon detector commonly used for light sensing applications.

As described in a paper published online March 24 in Applied Physics Letters, the hybrid material dramatically enhanced the performance of the photo-field-effect transistors—resulting in a photocurrent response (conversion of light to electric current) that was 500 percent better than transistors made with the tin disulfide material alone.

"This kind of energy transfer is a key process that enables photosynthesis in nature," said ChangYong Nam, a materials scientist at Center for Functional Nanomaterials and co-corresponding author of the APL paper. "Researchers have been trying to emulate this principle in light-harvesting electrical devices, but it has been difficult particularly for new material systems such as the tin disulfide we studied. Our device demonstrates the performance benefits realized by using both energy transfer processes and new low-dimensional materials."

Cotlet concludes, "The idea of 'doping' two-dimensional layered materials with quantum dots to enhance their light absorbing properties shows promise for designing better solar cells and photodetectors." [13]

## Quasiparticles dubbed topological polaritons make their debut in the theoretical world



Condensed-matter physicists often turn to particle-like entities called quasiparticles—such as excitons, plasmons, magnons—to explain complex phenomena. Now Gil Refael from the California Institute of Technology in Pasadena and colleagues report the theoretical concept of the topological polariton, or “topolariton”: a hybrid half-light, half-matter quasiparticle that has special topological properties and might be used in devices to transport light in one direction.

The proposed topolaritons arise from the strong coupling of a photon and an exciton, a bound state of an electron and a hole. Their topology can be thought of as knots in their gapped energy-band structure. At the edge of the systems in which topolaritons emerge, these knots unwind and allow the topolaritons to propagate in a single direction without back-reflection. In other words, the topolaritons cannot make U-turns. Back-reflection is a known source of detrimental feedback and loss in photonic devices. The topolaritons’ immunity to it may thus be exploited to build devices with increased performance.

The researchers describe a scheme to generate topolaritons that may be feasible to implement in common systems—such as semiconductor structures or atomically thin layers of compounds known as transition-metal dichalcogenides—embedded in photonic waveguides or microcavities. Previous approaches to make similar one-way photonic channels have mostly hinged on effects that are only applicable at microwave frequencies. Refael and co-workers' proposal offers an avenue to make such "one-way photonic roads" in the optical regime, which despite progress has remained a challenging pursuit. [12]

## **'Matter waves' move through one another but never share space**

Physicist Randy Hulet and colleagues observed a strange disappearing act during collisions between forms of Bose Einstein condensates called solitons. In some cases, the colliding clumps of matter appear to keep their distance even as they pass through each other. How can two clumps of matter pass through each other without sharing space? Physicists have documented a strange disappearing act by colliding Bose Einstein condensates that appear to keep their distance even as they pass through one another.

BECs are clumps of a few hundred thousand lithium atoms that are cooled to within one-millionth of a degree above absolute zero, a temperature so cold that the atoms march in lockstep and act as a single "matter wave." Solitons are waves that do not diminish, flatten out or change shape as they move through space. To form solitons, Hulet's team coaxed the BECs into a configuration where the attractive forces between lithium atoms perfectly balance the quantum pressure that tends to spread them out.

The researchers expected to observe the property that a pair of colliding solitons would pass through one another without slowing down or changing shape. However, they found that in certain collisions, the solitons approached one another, maintained a minimum gap between themselves, and then appeared to bounce away from the collision.

Hulet's team specializes in experiments on BECs and other ultracold matter. They use lasers to both trap and cool clouds of lithium gas to temperatures that are so cold that the matter's behavior is dictated by fundamental forces of nature that aren't observable at higher temperatures.

To create solitons, Hulet and postdoctoral research associate Jason Nguyen, the study's lead author, balanced the forces of attraction and repulsion in the BECs.

Cameras captured images of the tiny BECs throughout the process. In the images, two solitons oscillate back and forth like pendulums swinging in opposite directions. Hulet's team, which also included graduate student De Luo and former postdoctoral researcher Paul Dyke, documented thousands of head-on collisions between soliton pairs and noticed a strange gap in some, but not all, of the experiments.

Many of the events that Hulet's team measures occur in one-thousandth of a second or less. To confirm that the "disappearing act" wasn't causing a miniscule interaction between the soliton pairs -- an interaction that might cause them to slowly dissipate over time -- Hulet's team tracked one of the experiments for almost a full second.

The data showed the solitons oscillating back and fourth, winking in and out of view each time they crossed, without any measurable effect.

"This is great example of a case where experiments on ultracold matter can yield a fundamental new insight," Hulet said. "The phase-dependent effects had been seen in optical experiments, but there has been a misunderstanding about the interpretation of those observations." [11]

## Photonic molecules

Working with colleagues at the Harvard-MIT Center for Ultracold Atoms, a group led by Harvard Professor of Physics Mikhail Lukin and MIT Professor of Physics Vladan Vuletic have managed to coax photons into binding together to form molecules – a state of matter that, until recently, had been purely theoretical. The work is described in a September 25 paper in Nature.

The discovery, Lukin said, runs contrary to decades of accepted wisdom about the nature of light. Photons have long been described as massless particles which don't interact with each other – shine two laser beams at each other, he said, and they simply pass through one another.

"Photonic molecules," however, behave less like traditional lasers and more like something you might find in science fiction – the light saber.

"Most of the properties of light we know about originate from the fact that photons are massless, and that they do not interact with each other," Lukin said. "What we have done is create a special type of medium in which photons interact with each other so strongly that they begin to act as though they have mass, and they bind together to form molecules. This type of photonic bound state has been discussed theoretically for quite a while, but until now it hadn't been observed. [9]

## The Electromagnetic Interaction

This paper explains the magnetic effect of the electric current from the observed effects of the accelerating electrons, causing naturally the experienced changes of the electric field potential along the electric wire. The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories. [2]

## Asymmetry in the interference occurrences of oscillators

The asymmetrical configurations are stable objects of the real physical world, because they cannot annihilate. One of the most obvious asymmetry is the proton – electron mass rate  $M_p = 1840 M_e$  while they have equal charge. We explain this fact by the strong interaction of the proton, but how remember it his strong interaction ability for example in the H – atom where are only electromagnetic interactions among proton and electron.

This gives us the idea to origin the mass of proton from the electromagnetic interactions by the way interference occurrences of oscillators. The uncertainty relation of Heisenberg makes sure that the particles are oscillating.

The resultant intensity due to  $n$  equally spaced oscillators, all of equal amplitude but different from one another in phase, either because they are driven differently in phase or because we are looking at them an angle such that there is a difference in time delay:

$$(1) \quad I = I_0 \frac{\sin^2 n \varphi/2}{\sin^2 \varphi/2}$$

If  $\varphi$  is infinitesimal so that  $\sin \varphi = \varphi$  then

$$(2) \quad I = n^2 I_0$$

This gives us the idea of

$$(3) \quad M_p = n^2 M_e$$

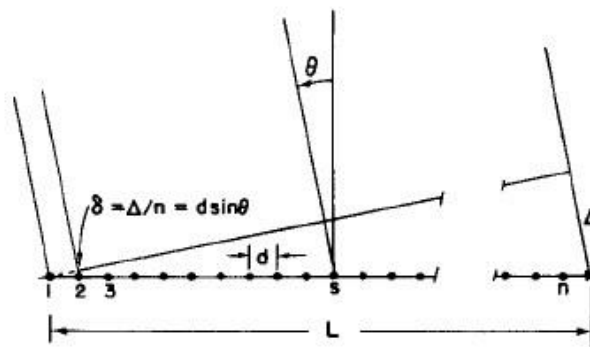


Fig. 30-3. A linear array of  $n$  equal oscillators, driven with phases  $\alpha_s = s\alpha$ .

Figure 1.) A linear array of  $n$  equal oscillators

There is an important feature about formula (1) which is that if the angle  $\varphi$  is increased by the multiple of  $2\pi$  it makes no difference to the formula.

So

$$(4) \quad d \sin \theta = m \lambda \text{ and we get } m\text{-order beam if } \lambda \text{ less than } d. [6]$$

If  $d$  less than  $\lambda$  we get only zero-order one centered at  $\theta = 0$ . Of course, there is also a beam in the opposite direction. The right choices of  $d$  and  $\lambda$  we can ensure the conservation of charge.

For example

$$(5) \quad 2(m+1) = n$$

Where  $2(m+1) = N_p$  number of protons and  $n = N_e$  number of electrons.

In this way we can see the H<sub>2</sub> molecules so that 2n electrons of n radiate to 4(m+1) protons, because  $d_e > \lambda_e$  for electrons, while the two protons of one H<sub>2</sub> molecule radiate to two electrons of them, because of  $d_e < \lambda_e$  for this two protons.

To support this idea we can turn to the Planck distribution law, that is equal with the Bose – Einstein statistics.

### **Spontaneously broken symmetry in the Planck distribution law**

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

Max Planck found for the black body radiation

As a function of wavelength ( $\lambda$ ), Planck's law is written as:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$

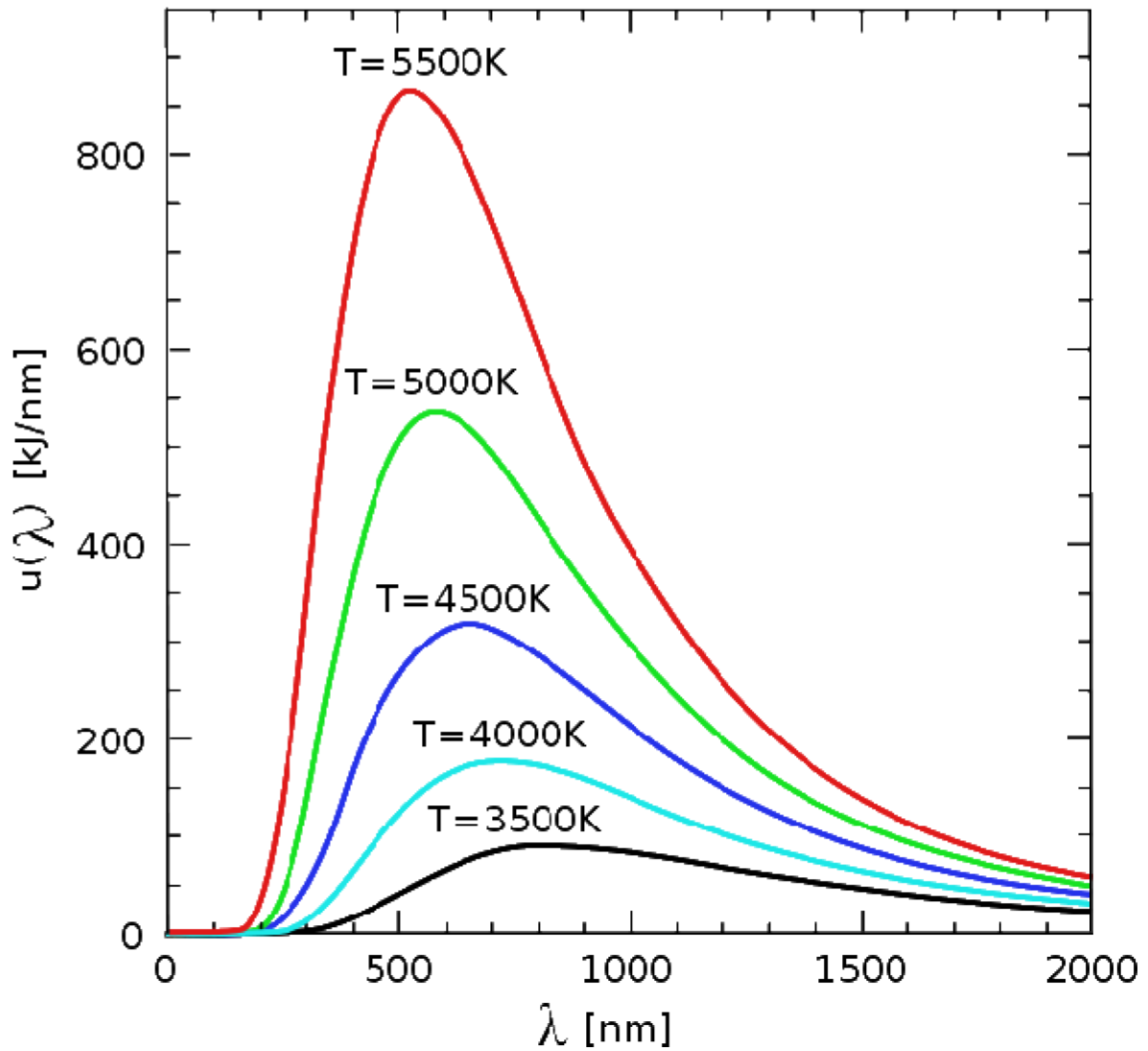


Figure 2. The distribution law for different T temperatures

We see there are two different  $\lambda_1$  and  $\lambda_2$  for each T and intensity, so we can find between them a d so that  $\lambda_1 < d < \lambda_2$ .

We have many possibilities for such asymmetrical reflections, so we have many stable oscillator configurations for any T temperature with equal exchange of intensity by radiation. All of these configurations can exist together. At the  $\lambda_{\max}$  is the annihilation point where the configurations are symmetrical. The  $\lambda_{\max}$  is changing by the Wien's displacement law in many textbooks.

$$(7) \quad \lambda_{\max} = \frac{b}{T}$$

where  $\lambda_{\max}$  is the peak wavelength, T is the absolute temperature of the black body, and b is a constant of proportionality called *Wien's displacement constant*, equal to  $2.8977685(51) \times 10^{-3} \text{ m} \cdot \text{K}$  (2002 CODATA recommended value).

By the changing of T the asymmetrical configurations are changing too.

## The structure of the proton

We must move to the higher T temperature if we want look into the nucleus or nucleon arrive to  $d < 10^{-13}$  cm. If an electron with  $\lambda_e < d$  move across the proton then by (5)  $2(m+1) = n$  with  $m = 0$  we get  $n = 2$  so we need two particles with negative and two particles with positive charges. If the proton can fraction to three parts, two with positive and one with negative charges, then the reflection of oscillators are right. Because this very strange reflection where one part of the proton with the electron together on the same side of the reflection, the all parts of the proton must be quasi lepton so  $d > \lambda_q$ . One way dividing the proton to three parts is, dividing his oscillation by the three direction of the space. We can order  $1/3$  e charge to each coordinates and  $2/3$  e charge to one plane oscillation, because the charge is scalar. In this way the proton has two  $+2/3$  e plane oscillation and one linear oscillation with  $-1/3$  e charge. The colors of quarks are coming from the three directions of coordinates and the proton is colorless. The flavors of quarks are the possible oscillations differently by energy and if they are plane or linear oscillations. We know there is no possible reflecting two oscillations to each other which are completely orthogonal, so the quarks never can be free, however there is an asymptotic freedom while their energy are increasing to turn them to the orthogonally. If they will be completely orthogonal then they lose this reflection and take new partners from the vacuum. Keeping the symmetry of the vacuum the new oscillations are keeping all the conservation laws, like charge, number of baryons and leptons. The all features of gluons are coming from this model. The mathematics of reflecting oscillators show Fermi statistics.

Important to mention that in the Deuteron there are 3 quarks of  $+2/3$  and  $-1/3$  charge, that is three u and d quarks making the complete symmetry and because this its high stability.

The Pauli Exclusion Principle says that the diffraction points are exclusive!

## The Strong Interaction

### ***Confinement and Asymptotic Freedom***

For any theory to provide a successful description of strong interactions it should simultaneously exhibit the phenomena of confinement at large distances and asymptotic freedom at short distances. Lattice calculations support the hypothesis that for non-abelian gauge theories the two domains are analytically connected, and confinement and asymptotic freedom coexist. Similarly, one way to show that QCD is the correct theory of strong interactions is that the coupling extracted at various scales (using experimental data or lattice simulations) is unique in the sense that its variation with scale is given by the renormalization group. [4]

Lattice QCD gives the same results as the diffraction theory of the electromagnetic oscillators, which is the explanation of the strong force and the quark confinement. [1]

## 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.

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  $\frac{1}{2}$  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. [5]

## Fermions and Bosons

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

The Higgs boson or Higgs particle is a proposed elementary particle in the Standard Model of particle physics. The Higgs boson's existence would have profound importance in particle physics because it would prove the existence of the hypothetical Higgs field - the simplest of several

proposed explanations for the origin of the symmetry-breaking mechanism by which elementary particles gain mass. [3]

## The fermions' spin

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

The Heisenberg uncertainty relation says that the minimum uncertainty is the value of the spin:  $1/2 \hbar = \Delta x \Delta p$  or  $1/2 \hbar = \Delta t \Delta E$ , that is the value of the basic energy status.

What are the consequences of this in the weak interaction and how possible that the neutrinos' velocity greater than the speed of light?

The neutrino is the one and only particle doesn't participate in the electromagnetic interactions so we cannot expect that the velocity of the electromagnetic wave will give it any kind of limit.

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 source of the Maxwell equations

The electrons are accelerating also in a static electric current because of the electric force, caused by the potential difference. The magnetic field is the result of this acceleration, as you can see in [2].

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

Also an interesting question, how the changing magnetic field creates a negative electric field? The answer also the accelerating electrons will give. When the magnetic field is increasing in time by increasing the electric current, then the acceleration of the electrons will increase, decreasing the charge density and creating a negative electric force. Decreasing the magnetic field by decreasing the electric current will decrease the acceleration of the electrons in the electric current and increases the charge density, creating an electric force also working against the change. In this way

we have explanation to all interactions between the electric and magnetic forces described in the Maxwell equations.

The second mystery of the matter is the mass. We have seen that the acceleration change of the electrons in the flowing current causing a negative electrostatic force. This is the cause of the relativistic effect - built-in in the Maxwell equations - that is the mass of the electron growing with its acceleration and its velocity never can reach the velocity of light, because of this growing negative electrostatic force. The velocity of light is depending only on 2 parameters: the magnetic permeability and the electric permittivity.

There is a possibility of the polarization effect created by electromagnetic forces creates the negative and positive charges. In case of equal mass as in the electron-positron pair it is simply, but on higher energies can be asymmetric as the electron-proton pair of neutron decay by weak interaction and can be understood by the Feynman graphs.

Anyway the mass can be electromagnetic energy exceptionally and since the inertial and gravitational mass are equals, the gravitational force is electromagnetic force and since only the magnetic force is attractive between the same charges, is very important for understanding the gravitational force.

The Uncertainty Relations of Heisenberg gives the answer, since only this way can be sure that the particles are oscillating in some way by the electromagnetic field with constant energies in the atom indefinitely. Also not by chance that the uncertainty measure is equal to the fermions spin, which is one of the most important feature of the particles. There are no singularities, because 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 greatest proton mass.

## **The Special Relativity**

The mysterious property of the matter that the electric potential difference is self maintained by the accelerating electrons in the electric current gives a clear explanation to the basic sentence of the relativity that is the velocity of the light is the maximum velocity of the matter. If the charge could move faster than the electromagnetic field than this self maintaining electromagnetic property of the electric current would be failed. [8]

## **The Heisenberg Uncertainty Principle**

Moving faster needs stronger acceleration reducing the  $\Delta x$  and raising the  $\Delta p$ . It means also mass increasing since the negative effect of the magnetic induction, also a relativistic effect!

The Uncertainty Principle also explains the proton – electron mass ratio since the  $\Delta x$  is much less requiring bigger  $\Delta p$  in the case of the proton, which is partly the result of a bigger mass  $m_p$  because of the higher electromagnetic induction of the bigger frequency (impulse).

## The Gravitational force

The changing magnetic field of the changing current causes electromagnetic mass change by the negative electric field caused by the changing acceleration of the electric charge.

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 ratio  $M_p = 1840 M_e$ . 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. [1]

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

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

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

## The 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]

## 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 Casimir effect

The Casimir effect is related to the Zero-point energy, which is fundamentally related to the Heisenberg uncertainty relation. The Heisenberg uncertainty relation says that the minimum uncertainty is the value of the spin:  $1/2 h = dx dp$  or  $1/2 h = dt dE$ , that is the value of the basic energy status.

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

charge distribution.

Electric charge and electromagnetic waves are two sides of the same thing; the electric charge is the diffraction center of the electromagnetic waves, quantified by the Planck constant  $h$ .

## The Fine structure constant

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

$$E = h\nu .$$

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

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

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

The expression of the fine-structure constant becomes the abbreviated

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

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

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

## Path integral formulation of Quantum Mechanics

The path integral formulation of quantum mechanics is a description of quantum theory which generalizes the action principle of classical mechanics. It replaces the classical notion of a single, unique trajectory for a system with a sum, or functional integral, over an infinity of possible trajectories to compute a quantum amplitude. [7]

It shows that the particles are diffraction patterns of the electromagnetic waves.

## Conclusions

The proposed topolaritons arise from the strong coupling of a photon and an exciton, a bound state of an electron and a hole. Their topology can be thought of as knots in their gapped energy-band structure. At the edge of the systems in which topolaritons emerge, these knots unwind and allow the topolaritons to propagate in a single direction without back-reflection. In other words, the topolaritons cannot make U-turns. Back-reflection is a known source of detrimental feedback and loss in photonic devices. The topolaritons' immunity to it may thus be exploited to build devices with increased performance. [12]

Solitons are localized wave disturbances that propagate without changing shape, a result of a nonlinear interaction that compensates for wave packet dispersion. Individual solitons may collide, but a defining feature is that they pass through one another and emerge from the collision unaltered in shape, amplitude, or velocity, but with a new trajectory reflecting a discontinuous jump. This remarkable property is mathematically a consequence of the underlying integrability of the onedimensional (1D) equations, such as the nonlinear Schrödinger equation, that describe solitons in a variety of wave contexts, including matter waves<sup>1, 2</sup>. Here we explore the nature of soliton collisions using Bose–Einstein condensates of atoms with attractive interactions confined to a quasi-1D waveguide. Using real-time imaging, we show that a collision between solitons is a complex event

that differs markedly depending on the relative phase between the solitons. By controlling the strength of the nonlinearity we shed light on these fundamental features of soliton collisional dynamics, and explore the implications of collisions in the proximity of the crossover between one and three dimensions where the loss of integrability may precipitate catastrophic collapse. [10]

"It's a photonic interaction that's mediated by the atomic interaction," Lukin said. "That makes these two photons behave like a molecule, and when they exit the medium they're much more likely to do so together than as single photons." To build a quantum computer, he explained, researchers need to build a system that can preserve quantum information, and process it using quantum logic operations. The challenge, however, is that quantum logic requires interactions between individual quanta so that quantum systems can be switched to perform information processing. [9]

The magnetic induction creates a negative electric field, causing an electromagnetic inertia responsible for the relativistic mass change; it is the mysterious Higgs Field giving mass to the particles. The Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass ratio by the diffraction patterns. The accelerating charges 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 Relativistic Quantum Theories. The self-maintained electric potential of the accelerating charges equivalent with the General Relativity space-time curvature, and since it is true on the quantum level also, gives the base of the Quantum Gravity. The electric currents causing self-maintaining electric potential is the source of the special and general relativistic effects. The Higgs Field is the result of the electromagnetic induction. The Graviton is two photons together.

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