

# Protein Structure Biomedical Puzzles

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*Researchers in Dana-Farber's cBio Center have now demonstrated a powerful 'experimental evolution' method to discover details of protein shape and function, and the method may find uses across a very broad spectrum of biomedical research. [37]*

*The discovery, published in Nature Communications, could help uncover treatments for age-related conditions, such as Alzheimer's disease, which are often caused by accumulation of misfolded proteins. [36]*

*Korean researchers have used light to control the binding of two separate and inactive antibody fragments and generate a specific, timely immune response to antigens. [35]*

*A new Empa study recently published in Nature Communications shows how this amazing behavior can be improved—and even used to treat injuries and tissue damage. [34]*

*Scientists at Johns Hopkins Medicine report they have created a tiny, nanosize container that can slip inside cells and deliver protein-based medicines and gene therapies of any size—even hefty ones attached to the gene-editing tool called CRISPR. [33]*

*Protocells—artificial cells—that are active and mimic living cells by moving independently and that are biocompatible and enzymatically active are now possible using an improved method developed by Penn State researchers. [32]*

*Pioneering new research into the way in which cells communicate with each other could hold the key to unlocking new, improved treatment for life-threatening diseases, including cancer. [31]*

*Researchers at the University of Illinois at Chicago have demonstrated that magnetic nanoparticles can be used to ferry chemotherapy drugs into the spinal cord to treat hard-to-reach spinal tumors in an animal model. [30]*

*Small vessel vasculitis—inflammation of the small blood vessels—appears as a stain of tiny, red dots covering the skin that, depending on the severity, can evolve into painful pustules or ulcers. [29]*

*Scientists from the University of Freiburg have developed materials systems that are composed of biological components and polymer materials and are capable of perceiving and processing information. [28]*

*Nanotechnology may provide an effective treatment for Parkinson's disease, a team of researchers suggests. [27]*

*Recent research from Kumamoto University in Japan has revealed that polyoxometalates (POMs), typically used for catalysis, electrochemistry, and photochemistry, may also be used in a technique for analyzing quantum dot (QD) photoluminescence (PL) emission mechanisms. [26]*

*Researchers have designed a new type of laser called a quantum dot ring laser that emits red, orange, and green light. [25]*

*The world of nanosensors may be physically small, but the demand is large and growing, with little sign of slowing. [24]*

*In a joint research project, scientists from the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy (MBI), the Technische Universität Berlin (TU) and the University of Rostock have managed for the first time to image free nanoparticles in a laboratory experiment using a highintensity laser source. [23]*

*For the first time, researchers have built a nanolaser that uses only a single molecular layer, placed on a thin silicon beam, which operates at room temperature. [22]*

*A team of engineers at Caltech has discovered how to use computer-chip manufacturing technologies to create the kind of reflective materials that make safety vests, running shoes, and road signs appear shiny in the dark. [21]*

*In the September 23th issue of the Physical Review Letters, Prof. Julien Laurat and his team at Pierre and Marie Curie University in Paris (Laboratoire Kastler Brossel-LKB) report that they have realized an efficient mirror consisting of only 2000 atoms. [20]*

*Physicists at MIT have now cooled a gas of potassium atoms to several nanokelvins—just a hair above absolute zero—and trapped the atoms within a two-dimensional sheet of an optical lattice created by crisscrossing lasers. Using a high-resolution microscope, the researchers took images of the cooled atoms residing in the lattice. [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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## **New technique to determine protein structures may solve biomedical puzzles**

Researchers in Dana-Farber's cBio Center have now demonstrated a powerful 'experimental evolution' method to discover details of protein shape and function, and the method may find uses across a very broad spectrum of biomedical research.

"Proteins are the workers in the cell, and it's important to know their shape," says Chris Sander, Ph.D., director of Dana-Farber's cBio Center in the Department of Data Sciences. Sander and his colleagues have now demonstrated a powerful "experimental evolution" method to discover details of protein shape and function, and the method may find uses across a very broad spectrum of biomedical research.

"This is a basic discovery in molecular evolutionary biology, with possible applications to cancer," says Sander, professor of cell biology at Harvard Medical School and co-senior-author on a paper describing the work in the journal *Cell Systems*.

Among its potential applications, the "3Dseq" technique may aid in determining the three-dimensional structure of cancer-related proteins that haven't been identified by alternative methods. The new technique also may help in understanding how oncogenes and tumor suppressor genes evolve in cancer, and in pinpointing which mutations in those genes contribute to disease progression.

For decades, molecular biologists have known that a protein's ability to function in a cell relies on its proper shape, which is dictated by the order of its constituent amino acids. Determining protein three-dimensional structure, however, requires complicated experimental techniques.

Back in 2011, working with Harvard associate professor Debora Marks and other colleagues, Sander took a big step forward on the challenge of predicting protein structure using a mathematical approach based on evolution. The "natural evolution" approach begins by analyzing how the genetic sequence of a particular protein changes over millions of years. To do this, the team examined the sequence of the protein across evolutionary time—from ancient species such as bacteria to more recently evolved species such as mice and humans.

The key insight in the earlier study came when the team used computational methods to identify which amino acids in the protein are interacting with each other, by looking at amino acids that change in lockstep across evolution. "We look at things that co-vary, where if one thing changes in the sequence, another thing changes," Sander says. "It's like a nut and a bolt—if you change one part, you have to change the other part so it still fits." He and his colleagues came up with a basic mathematical trick that can find changes in the amino acids that produce a direct effect on protein structure, providing key information that can be fed into existing algorithms from molecular physics to compute the structure.

However, not all proteins can be studied using sequences found in natural evolution. The latest innovation from the Sander group is to bring evolution into lab dishes, where the process can be tightly controlled and take weeks rather than millions of years.

Dana-Farber research scientists Michael Stiffler and Frank Poelwijk are co-lead authors, and Nicholas Gauthier is co-senior author, on the new paper about the project, which is the first-large scale demonstration of an experimental evolution method to determine protein structure.

The scientists started with a gene for an enzyme from E. coli bacteria that renders bacteria resistant to a common antibiotic. First they generated millions of copies of the original gene with mutations sprinkled in various positions, and then put these mutated genes into millions of bacteria. They then put an antibiotic into the lab dishes holding the bacteria, and harvested the bacteria that survive. These surviving bacteria have functional antibiotic resistance genes yet still contained selected mutations. This painstaking procedure was repeated many times to mimic evolutionary processes in analogy to natural evolution. "Out of tens of millions of proteins, we ended up with a few hundred thousand that actually work," Sander says.

Using the computational strategy pioneered in the 2011 study, they produced data that generated 3-D protein structures for two very different antibiotic resistance proteins and got shapes very similar to the ones determined by X-ray crystallography.

3Dseq experimental evolution will join three existing technologies to reveal protein structure: X-ray crystallography, which shoots X-rays at a crystallized protein; nuclear magnetic

resonance (NMR) spectroscopy, based on physics similar to that employed by magnetic resonance imaging (MRI) scanning; and cryo-electron microscopy, which scans frozen specimens with an electron microscope.

Once it is mature, the 3Dseq technology may bring two main advantages to protein structure determination, Sander says. First, the three existing methods do not always work for proteins. Second, 3Dseq provides details on the key interactions in the complicated protein shapes that are required for proteins to function. This capability eventually could prove to be very important for a number of applications in cell biology, ranging from understanding how pathogens evolve to accelerating the development of biotherapeutics, he says.

His group and its collaborators have begun efforts to improve the 3Dseq screening techniques and generalize the technologies for use with other proteins. Their paper was published along with its sequence data and software tools. "We will collaborate with other people to develop the assays to make it more generally applicable to proteins of interest," Sander says. "Whatever we develop, we'll make available publicly."

"This research shows the positive, open-minded scientific culture of Dana-Farber and Harvard Medical School, as an example of basic science that will spawn advances in cancer research," he adds. Lead funding for the work came from Dana-Farber and the National Institute of General Medical Sciences. [37]

### **The secret to a long life? For worms, a cellular recycling protein is key**

Scientists at Sanford Burnham Prebys Medical Discovery Institute have shown that worms live longer lives if they produce excess levels of a protein, p62, which recognizes toxic cell proteins that are tagged for destruction. The discovery, published in *Nature Communications*, could help uncover treatments for age-related conditions, such as Alzheimer's disease, which are often caused by accumulation of misfolded proteins.

"Research, including our own, has shown that lifespan can be extended by enhancing autophagy—the process cells use to degrade and recycle old, broken and damaged cell components," says Malene Hansen, Ph.D., a professor in the Development, Aging and Regeneration Program at Sanford Burnham Prebys and senior author of the study. "Prior to this work, we understood that autophagy as a process was linked to aging, but the impact of p62, a selective autophagy protein, on longevity was unknown."

Scientists used to think that cellular recycling worked the same way for all waste products. In more recent years, researchers are learning that autophagy can be highly selective—meaning the cell uses distinct "recycling trucks," such as the protein p62, to deliver different types of trash to cellular "recycling centers." For example, p62 is known to selectively deliver aggregated proteins and worn-out mitochondria (the powerplants of the cell) to recycling centers.

To better understand p62's role in cellular recycling and longevity, the scientists used short-lived, transparent roundworms called *C. elegans* for their studies. Previously, Hansen's team found that levels of p62 are increased after a short heat shock is administered to the worms. This proved to be beneficial to the animals and required for the longevity that is caused by mild heat stress.

These findings prompted the scientists to genetically engineer *C. elegans* to produce excess levels of the protein p62. Instead of their usual three-week lifespan, these worms lived for a month—equivalent to a 20



to 30% lifespan extension. The researchers were intrigued to find that by increasing the levels of p62, the "recycling truck," the "recycling centers" became more abundant and were able to recycle more "trash," indicating that p62 is a driver of the recycling process.

"Now that we have confirmed that selective autophagy is important for longevity, we can move to our next step: identifying what harmful cellular 'trash' it is removing. With this knowledge, we hope to target specific cell components that are risk factors for longevity," says Caroline Kumsta, Ph.D., a research assistant professor in Hansen's lab and lead author of the study.

Many age-related diseases, including Alzheimer's and Huntington's disease, are caused by accumulation of toxic, misfolded proteins. Hansen and Kumsta previously showed that increased levels of p62 were able to improve lifespan in a *C. elegans* Huntington's disease model. Scientists are hopeful that studying selective autophagy via proteins like p62 could lead to therapies that clear the proteins that are detrimental to living a long, healthy life. Finding possible therapeutic avenues to age-related diseases is increasingly important as the U.S. population ages: In about a decade, about 20 percent of Americans—about 71 million people—will be 65 and older and at higher risk for chronic diseases.

While the scientists see much potential in their findings—and are encouraged that the benefits of increasing p62 levels on longevity seem to be evolutionarily conserved as a [recent study in fruit flies](#) demonstrated—they urge caution for direct translations to humans: High levels of p62 have been shown to be associated with cancer in humans.

"Given the known link between p62 and cancer, it's even more important to map the selective autophagy process from start-to-finish," says Hansen. "Armed with this information, we may be able to enhance beneficial functions for p62 in selective autophagy and find therapeutics that promote healthy aging." [36]

## **Blue light activates antibodies on demand**

Korean researchers have used light to control the binding of two separate and inactive antibody fragments and generate a specific, timely immune response to antigens. The platform that they created could help develop new therapies for cancer or autoimmune diseases ([Nat. Methods. 10.1038/s41592-019-0592-7](#)).

When a pathogen such as a bacteria or virus enters the human body, the immune system reacts by creating antibodies to identify the intruder and kickstart the chemical process that leads to its neutralization. With their Y shape, antibodies bind to a specific antigen and alert nearby phagocytes to the presence of an invader that needs to be eliminated.

Making antibodies more selective and efficient at detecting antigens has been a key research goal for developing new cancer or autoimmune therapies over the last three decades. Such antibodies, which have been engineered to generate a better and immediate immune response against their target antigens, are known as therapeutic antibodies. For example, the CAR T-cell cancer therapy that garnered a lot of

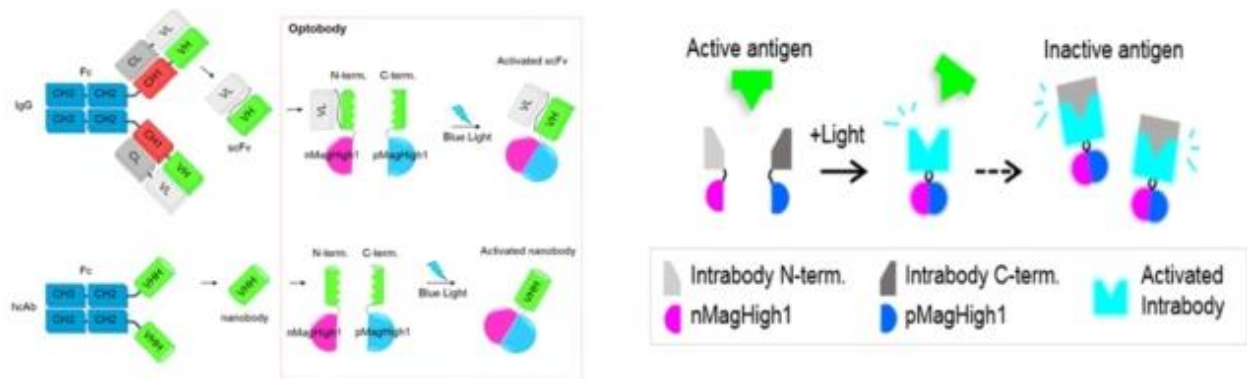


attention following the [2018 Nobel Prize in Medicine](#) associates a tumour-detecting antibody with cancer-killing T cells to create a “living drug” that can fight off tumours.

But for all their advantages, therapeutic antibodies are limited by our ability to control them. Their expression and regulation can be chemically induced, but the ability to precisely fine-tune their activity when and where needed has remained so far elusive, preventing the control of an antibody’s function within a living cell.

### ***A one-in-all platform***

A team led by Won Do Heo and Byung Ouk Park, from the [Institute for Basic Science](#) and [Korean Advanced Institute of Science and Technology](#) in South Korea, has now managed to achieve this control, by using a split–rejoin technique. Briefly, the researchers injected antibodies as two inactive split fragments (two separate branches of the Y shape) and used blue light to stimulate a reaction that led to linking of the branches and consequently, activation of their defensive function. They called the antibodies generated in this way “optogenetically activated intracellular antibody”, or “optobodies”.



[As photoreceptors in GFP \(nMagHigh1 and pMagHigh1\) are triggered by blue light, split GFP nanobody fragments, which were roaming freely in the cell, reassemble. These now whole activated GFP nanobodies move toward their target proteins. \(Courtesy: Institute for Basic Science\)](#)

The researchers first optimized their platform for insertion of binding domains. They tested it on two antibody fragments selected for their high target-specificity and stability: a single-chain variable fragment (scFv) and a single-domain antibody (a so-called nanobody). They first identified in a green fluorescent protein (GFP) nanobody the sites that required optical stimulation to spur the reassembling of the antibodies, and then compared the mitochondrial activities of the optobodies with similar, unmanipulated, antibodies.

While each separated fragment of the antibody did not display much mitochondrial activity, the optobody generated by linking the two branches displayed similar expression patterns to the original antibody. This finding indicates that there is no functional difference between optobodies and the natural antibody they are replicating.

### ***Towards future breakthroughs?***

Finally, the researchers tested whether the platform could generate optobodies targeting specific cells to disrupt pathway signalling. They administered novel nanobody fragments to cells derived from mouse and

human embryos and monitored the ability of the optobodies to inhibit specific target endogenous proteins in these living cells. The team paid close attention to the cell movement and receptor signalling, two characteristics of pathogen expression. All of the optobodies studied bound to their target proteins and induced a reduction in cell movement, along with a significant reduction of signalling transduction.

“Our optobody system is a great tool to study the role of endogenous proteins in living cells and animals, and also shows great clinical promise for therapeutic strategies in the future,” says Heo. This could prove all the more interesting because the trigger source is not limited to blue light – other wavelengths such as near-infrared light could provide similar results with a different pool of antibodies. By offering more precise control of target protein activity, both spatially and temporally, the technique could eventually lead to the design of inducible “living” drugs for conditions where current therapies remain ineffective. [35]

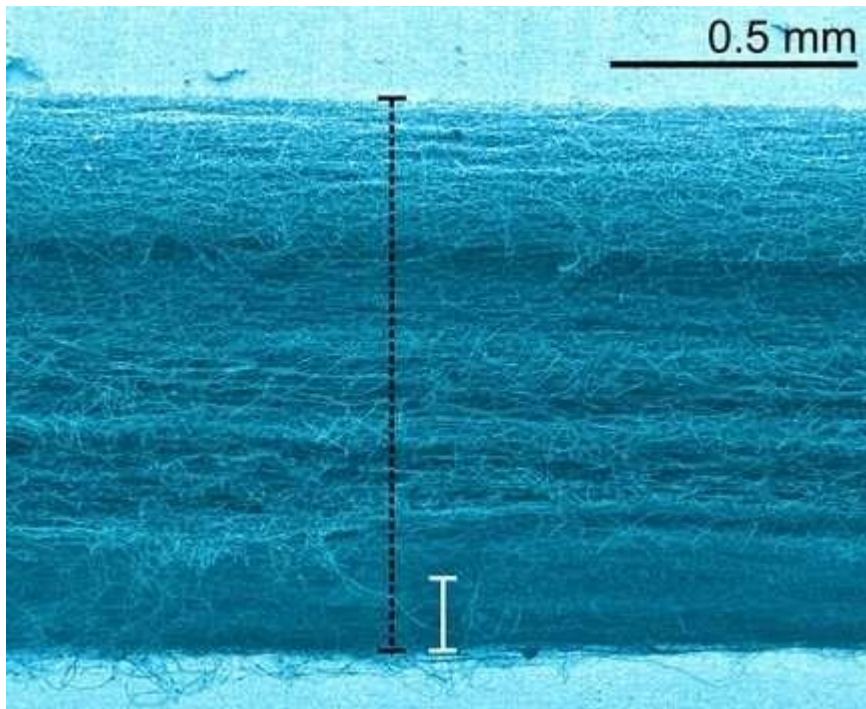
### **Auxetic membranes: Paradoxical replacement tissue for medicine**

A material that thickens when you pull on it seems to contradict the laws of physics. However, the so-called auxetic effect, which also occurs in nature, is interesting for a number of applications. A new Empa study recently published in *Nature Communications* shows how this amazing behavior can be improved—and even used to treat injuries and tissue damage.

Nature shows us how to do it: A calf sucking milk from the udder of a mother cow uses a fascinating physical property of the teat, which consists of an auxetic tissue. Paradoxically, such tissues do not become narrower under tension, such as a rubber band, but wider, transverse to the direction of pull. Therefore, the cow's milk can flow unhindered through the teat. Empa scientists have now demonstrated the astonishing auxetic properties of nanofiber membranes developed specifically for this purpose. The study published in *Nature Communications* points to a wide range of applications for auxetic materials, including the use of auxetic membranes to regenerate human tissue after injuries.

Skin injuries or tissue damage to internal organs heal by, among other things, migrating cells that settle and form a healthy replacement tissue. What is usually done without further ado in the case of, say, a small incision in your fingertip can exceed the possibilities of the human body, for instance, when complex wounds occur, such as burns, or when a more widespread tissue regeneration is required.

However, tissue regeneration can be facilitated: If a suitable scaffold is provided, the desired cells settle down more easily and grow along the predefined structure. Empa researchers at the Biomimetic Membranes and Textiles lab in St. Gallen have now developed novel matrix systems with auxetic properties. By electrospinning, dissolved polymers are spun as wafer-thin filaments in a form similar to the human extracellular matrix. This makes it possible to produce multi-layer membranes from nanofibers that are biocompatible and can be implanted into the human body. "If biopolymers such as polylactic acids are used in the spinning process, the membranes can even be degraded by the body," explains Empa researcher Giuseppino Fortunato. In addition, bioactive substances or drugs can be incorporated into the fibers for controlled and minimized release.



After stretching the auxetic membranes increase about 10-fold by thickness. (colorized image). Credit: Swiss Federal Laboratories for Materials Science and Technology

### ***Attractive pore size***

One of the challenges thus far has been to make the pore size in the spun membrane as attractive as possible for the desired body cells to adhere. In the original membranes, the polymer threads only formed tiny pores of a few micrometers. With its 20 micrometers, however, a tissue cell that is to colonize the scaffold is far too large to fit snugly in the membrane.

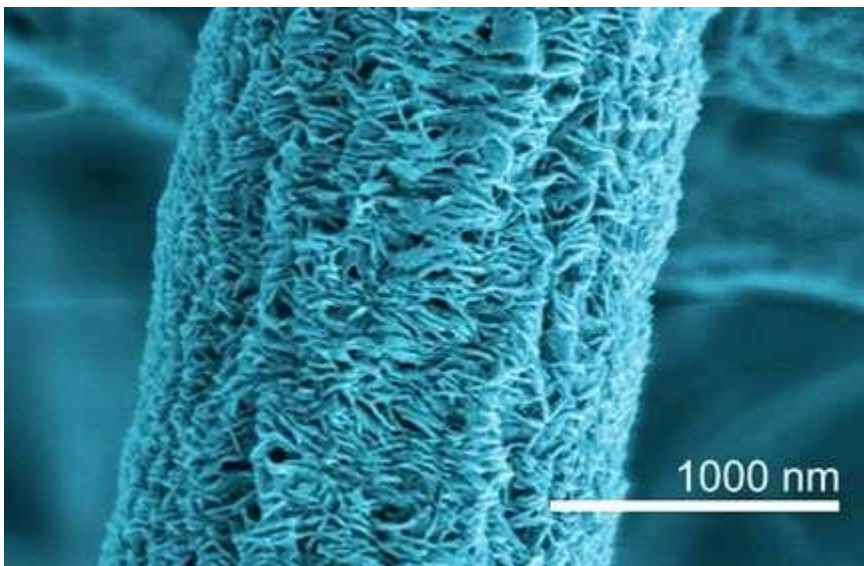
After the researchers had optimized the spinning parameters a polymer network with surprising properties could be produced: When the membrane was exposed to gentle tensile forces, stretching it by about 10 percent, instead of becoming thinner the material increased about 5-fold by volume and even 10-fold by thickness. "An auxetic effect of this magnitude is almost a world record," enthuses Alexander Ehret of Empa's Experimental Continuum Mechanics lab. Ehret and his team had first predicted the extraordinary effect using mechanical modeling and simulated it on the computer before analyzing membrane samples experimentally. "We ran the simulations on the computer several times because the results were so astonishing," says Ehret. The auxetic effect, which can be quantified mathematically by the ratio of transverse to longitudinal strain—the Poisson's ratio —, is characterized by negative values for the Poisson's ratio. "So far, values around -20 have been achieved. Our results were well below -100," says the biomechanics expert.

And sure enough: In the tensile tests, the polymer membranes behaved as simulated on the computer. The effect can be explained by fibers that realign themselves under tension and thereby exert pressure on their transverse colleagues in the network. Depending on their length and thickness, the fibers under pressure are forced to bend up- or downwards and thus lead to an increase in volume.

### ***Expand on demand***

Basically, electro-spun membranes are suitable for the treatment of wounds and tissue damage in locations as diverse as on the skin, in blood vessels and in internal organs or even in bone injuries. An appropriate selection of polymers and optimized spinning parameters allow the polymer membrane to be adapted to the properties of the target tissue. "Thanks to the larger volume caused by the auxetic effect, the matrix structures are now even more attractive for the body's cells and could facilitate the healing process," says Giuseppino Fortunato.

In addition to its use in biomedicine, the concept, which is already patent-pending, can also be applied in numerous other areas. According to the researchers, membranes that can be activated by stress to release enclosed particles, adjustable filters or filling material that only expands to its final volume at the point of use, i.e. quasi "expand on demand," are potential future applications.



In the electron microscope, the fibers appear as shish kebab structures. They influence the mechanical properties of the membranes and the auxetic effect. (colorized image). Credit: Swiss Federal Laboratories for Materials Science and Technology

### ***The structure of nanofibers***

The internal structure of individual nanofibers has a major influence on the properties of the membranes. If nanofibers are treated with certain solvents, the structure of the nanofibers can be elucidated. Empa researcher Alexandre Morel has now discovered that varying the spinning parameters results in different fiber structures, such as fibrillary or shish kebab phases. In the electron microscope shish kebab structures appear as stacked layers resembling a kebab spit. They have a large influence on the membranes' mechanical properties and thus also on the auxetic effect. [34]

### **Nanocontainer ships titan-size gene therapies and drugs into cells**

Scientists at Johns Hopkins Medicine report they have created a tiny, nanosize container that can slip inside cells and deliver protein-based medicines and gene therapies of any size—even hefty ones attached to the

gene-editing tool called CRISPR. If their creation—constructed of a biodegradable polymer—passes more laboratory testing, it could offer a way to efficiently ferry larger medical compounds into specifically selected target cells.

A report on their work appears in the Dec. 6 issue of *Science Advances*.

"Most medicines spread throughout the body in an indiscriminate way and don't target a specific cell," says biomedical engineer Jordan Green, Ph.D., leader of the research team. "Some medicines, such as antibodies, latch on to targets on the cell's surface receptors, but we don't have good systems for delivering biological medicines straight to the inside of a cell, which is where therapies would have the best chance at working properly and with fewer side effects."

Many academic and commercial scientists have long sought better transit systems for therapies, says Green, professor of biomedical engineering, ophthalmology, oncology, neurosurgery, materials science and engineering, and chemical and biomolecular engineering at the Johns Hopkins University School of Medicine, and a member of the Bloomberg~Kimmel Institute for Cancer Immunotherapy at Johns Hopkins.

Some commercially available techniques use stripped down forms of viruses—known for their ability to "infect" cells directly—to deliver therapies, although the noninfectious versions of these delivery systems can unleash an unwanted immune system response. Other therapies aimed at diseased blood cells, for example, are more cumbersome, requiring patients' blood to be removed, then zapped with an electric current that opens pores in the cell membrane to gain entry.

The nanosize container that Green and his team developed at Johns Hopkins borrows an idea from the properties of viruses, many of which are nearly spherical in shape and carry both negative and positive charges. With a more neutral overall charge, viruses can get close to cells. That's not the case with many biological medicines, which consist of highly charged, large proteins and nucleic acids that tend to repel off cells.

To overcome this, graduate student Yuan Rui developed a new biodegradable polymer material. Polymer is the general term for a substance made up of many molecules. To make the polymer, Rui strung together—like the branches of a tree—four component molecules that, over time, break down and dissolve in water. The molecules contain both positive and negative charges.

With a balance of positive and negative charges, the molecules push and pull according to their charge and their hydrogen atoms bond with a biological therapy in the vicinity. The result is a nano-structure containing the biological therapy.

The nanosize container's positive charges interact with the membrane of a cell, and the container is engulfed in a cellular package called an endosome.

Once inside, the nanosize container breaks open the endosome, and the polymers degrade, leaving the medicine to work inside the cell.

To test their invention, Rui made a nanocontainer of a small protein and fed it to mouse kidney cells in culture dishes. She attached a green fluorescent tag to the small protein and saw bright green splashes throughout most of the cells, indicating that the protein was successfully delivered.

Then, Rui packaged a bigger protein: human immunoglobulin, a therapy typically used to strengthen the immune system and a model for antibody therapies. This time, she found that 90% of the kidney cells she treated lit up with the green fluorescent tag attached to the immunoglobulin.

"When nanoparticles enter a cell, they often get sequestered into endosomes, which degrade its contents, but our experiments show the protein packages uniformly spread throughout most of the cells and were not stuck in the endosomes," says Rui.

For an even greater challenge, Rui created a nanopackage containing a CRISPR-based protein and nucleic acid complex that could turn off a green fluorescence signal or cause the cells to glow red when the CRISPR compound cut part of a cell's genome. The researchers saw that the gene editing to disable a gene worked in up to 77% of cells grown in the laboratory and to add or repair a gene in about 4% of cells.

"That's pretty effective considering, with other gene editing systems, you might get the correct gene-cutting result less than 10 percent of the time," said Rui. CRISPR-based therapies have the potential to make medicines far more precise with their ability to precisely target genetic flaws that contribute to disease. Some CRISPR therapies are being tested in clinical trials.

In a final experiment, Rui and her colleagues implanted brain cancer cells into the brains of mice. She injected the nanocontainers with gene editing components directly into the mouse brains and analyzed their cells for a red glow indicating successful gene editing. She found brain cancer cells that glowed red several millimeters away from where she injected them.

"When I first started this project five years ago, scientists didn't think that you could use something other than a virus to deliver these therapies into cells," says Rui. "Developing new technologies can help us understand more about disease, but also more about making new drugs."

Rui and Green are trying to make the nanocontainers more stable so they can be injected into the bloodstream and targeted to cells with certain genetic signatures.

The scientists are filing for patents related to this work. [33]

### **Artificial cells act more like the real thing**

Protocells—artificial cells—that are active and mimic living cells by moving independently and that are biocompatible and enzymatically active are now possible using an improved method developed by Penn State researchers.

Living cells are difficult to grow in the laboratory, so researchers sometimes work with synthetic cells, but these have had research limitations because they lack real cell characteristics.



"One of the challenges of cell research is it's sometimes very hard to run controlled experiments on a cell's motility, especially due to surface enzyme activity," said Darrell Velegol, distinguished professor of chemical engineering. "The research team developed a simple way to make an artificial cell that doesn't do everything a regular cell does, like reproduce, have genetic mutations or anything like that, but it actively moves. That's important because how cells move is poorly understood, especially how enzymes' activity play into cell movement."

The team's protocells are used to investigate how the activity of natural enzymes like ATPase can propel the active movement of the protocells. The biochemical process of ATPase enzyme involves conversion of ATP (adenosine triphosphate) into the product ADP (adenosine diphosphate). ATP is a complex organic chemical that provides energy for living cells and ADP is an organic compound that plays an important role in how cells release and store energy.

"Attempts at similar experiments in the past decade had the enzymes incorporated inside of micron-sized sacks called polymeric vesicles, or tethered onto the surface of hard particles," said Subhadip Ghosh, postdoctoral researcher in chemistry. "But these attempts didn't have significant biological resemblance like our protocells."

In the research team's experiments, the protocells have actual artificial membranes composed of a naturally occurring lipid called phosphatidylcholine. The ATPase enzymes were incorporated directly into the membrane.

"Our results basically give other researchers the first steps toward making artificial cells with enzymatic activity," Ghosh said.

One unexpected result from the study, which was made available online in August 2019 ahead of final publication on September 11, 2019 in an issue of *Nano Letters*, happened during diffusion experiments which were performed at a single molecular regime. As expected, the movement of the protocells was low for low concentrations of ATP.

"Quite surprisingly, the movement of the protocells dropped significantly at high concentration of ATP," said Ayusman Sen, the Verne M. Willaman Professor of Chemistry at Penn State.

According to the researchers, this was as counterintuitive as pressing an automobile's gas pedal and having the vehicle slow down. After performing comprehensive control experiments, the researchers concluded that when ADP concentration is high, it may bind to the ATPase and suppress the substrate ATP activity, causing reduced motility.

Having the ability to fabricate the enzymatically active protocells opens new opportunities. Armed with these mimics of motile living cells, the researchers aim to reveal the fundamental mechanisms governing active membrane dynamics and cellular movement. Given the current limited understanding of how cells move, including how enzyme action plays into cell movement, the research team members believe their work can have significant implications for future medical research.

"A key challenge is to estimate the mechanical forces that drive the protocell movement, and to discover changes in the enzyme structure during that process," said Farzad Mohajerani, research assistant in



chemical engineering. "Knowing that structure-function relationship for the movement of the protocells will enable their design for potential in vivo applications like medical sensing and lab analysis." [32]

## Research into cell-to-cell signaling mechanism may lead to new cancer treatments

Pioneering new research into the way in which cells communicate with each other could hold the key to unlocking new, improved treatment for life-threatening diseases, including cancer.

Various mechanisms exist for cells to communicate with each other, and many are essential for development. A team of international researchers looked at how one important family of signalling molecules—Wnt proteins, which orchestrate and control many cell development processes—are transported between cells.

Accurate transmission of Wnt signals is therefore incredibly important; however, the mechanism for this was previously unknown. It was discovered that cell protrusions called cytonemes, play an essential role in transmitting the signal to control the rate of cell division.

Professor Steffen Scholpp, Principal Investigator at the University of Exeter's Living Systems Institute said: "These are very exciting times for cell biology. We are in the process of changing our understanding of cell communication in a tissue. In the early days researchers believed that signalling molecules are released from cells into the extracellular space, the area between cells, and diffuse randomly.

"This would mean that target cells are surrounded by a mix of various signalling molecules. In contrast, our research shows that there is a flexible grid of tiny protrusions connecting all cells in a multicellular body. This novel concept allows a fast, precise and controlled exchange of information between sender cells and target cells".

As excessive Wnt signalling is known to cause a number of cancers by causing excessive cell division, the scientists believe that this research could lead to the development of new cancer treatments by helping to create drugs to target cytoneme formation, preventing transmission of the signal.

The team, including researchers from the Duke Medical School in Singapore, Karlsruhe Institute of Technology, Germany and Cardiff University, discovered that impeding cytoneme formation prevented transmission from Wnt producing cells.

Wnt was found to move to areas of the cell membrane and interact with a receptor known as Ror2, inducing the formation of a cytoneme. This constitutes the first time a signalling protein has been shown to control its own transport mechanism.

Wnt signalling is also essential to embryo formation, organ development, wound healing and cell regeneration. Further understanding of the mechanism is therefore relevant to other developmental disorders.

Professor Scholpp added: "We have started to understand the characteristics of this [information grid](#) in the matrix of a tissue. Our research provides the first insight how this web of cell protrusions is formed and what kind of consequences it has if we alter these connections.

"A thorough functional and structural characterisation of the information grid and their functions in contact-based signalling is fundamental and calls for further studies at the molecular, cellular and tissue level."

The research is published in leading Biology journal, *eLife*, on Tuesday, July 31 2018. [31]

## **Magnetic nanoparticles deliver chemotherapy to difficult-to-reach spinal tumors**

Researchers at the University of Illinois at Chicago have demonstrated that magnetic nanoparticles can be used to ferry chemotherapy drugs into the spinal cord to treat hard-to-reach spinal tumors in an animal model. The unique delivery system represents a novel way to target chemotherapy drugs to spinal cancer cells, which are hard to reach because the drugs must cross the blood-brain barrier.

Spinal cord tumors are a challenge to treat because they are difficult to surgically remove due to their proximity to healthy spinal tissue and because [chemotherapy](#) drugs must cross the blood-brain barrier in order to reach them. Intramedullary spinal cord tumors account for 8 percent to 10 percent of all spinal cord tumors and are common among children and adolescents. Average survival for patients with these tumors is 15.5 months.

Doxorubicin, a commonly used chemotherapy to treat spinal tumors, is delivered intravenously and affects the whole body with poor penetration to the spine. Radiation therapy is also problematic for these tumors because the radiation often damages healthy nearby spinal tissue and can have devastating effects, including paraplegia.

"Getting [chemotherapy drugs](#) to spinal tumors has always been a problem," said Dr. Ankit Mehta, assistant professor of neurosurgery and director of spinal oncology in the UIC College of Medicine and corresponding author on the paper. "But we can precisely guide chemotherapy to cancer cells into the spinal cord using [magnetic nanoparticles](#)."

The researchers, whose results are published in the journal *Scientific Reports*, used a unique rat model with implanted human intramedullary spinal cord tumors to show that magnetic [nanoparticles](#) could successfully be used to kill [tumor](#) cells.

First, they created nanoparticles made up of tiny, metallic magnets bound to particles of doxorubicin. Next, they implanted a magnet just under the skin covering the spinal vertebrae in the rat models. Then they injected the magnetic nanoparticles into the space around the spinal cord where the tumor was located.

The magnet implanted in close proximity to the tumor guided the nanoparticles to the tumor sites. The researchers were able to show that tumor cells took up the nanoparticles and underwent apoptosis—in

other words, they were effectively destroyed. The impact of the nanoparticles on nearby healthy [cells](#) was very minimal, Mehta said.

"This proof-of-concept study shows that magnetic nanoparticles are an effective way to deliver chemotherapy to an area of the body that has been difficult to reach with available treatments," he said. "We will continue to investigate the potential of this therapy and hope to enter human trials if it continues to show promise." [30]

## Adapting technology to image blood vessels in skin disease

Small vessel vasculitis—inflammation of the small blood vessels—appears as a stain of tiny, red dots covering the skin that, depending on the severity, can evolve into painful pustules or ulcers. In some patients, it may even reflect inflammation in internal organs.

Diagnosis usually requires a [skin biopsy](#), which involves cutting a small piece of skin. This can usually be done as an easy bedside procedure, although certain sites, such as areas around the nails and the tips of fingers and toes, or certain patients may be more prone to poor wound healing and complications from the procedure.

Adela Rambí G. Cardones, MD, HS'06-'09, associate professor of dermatology, wanted to create a device that could capture an image of at least a centimeter of skin area through a quick, non-invasive process. She wanted to detect the speed, color, and amount of blood flowing through the small blood vessels in order to make a fast, painless, accurate diagnosis.

Junjie Yao, Ph.D., assistant professor of biomedical engineering, develops [photoacoustic imaging](#): the conversion of light beamed through tissue into ultrasound waves that are then analyzed to create high-resolution images. Photoacoustic imaging can reveal a tissue's anatomical, functional, and metabolic properties, with specificity at the molecular and neuronal level.

Cardones and Yao teamed up to create a [handheld device](#) that could provide high-resolution imaging of the tiny blood vessels in the skin to diagnose vasculitis. One of the key design inspirations came from, of all places, the supermarket.

"We were inspired by the handheld devices that scan bar codes in grocery stores," says Yao. "The devices use a polygon mirror and a laser diode to quickly 'read' the product information, and we adapted this concept to build a prototype handheld photoacoustic device to 'read' the skin. We printed a 3-D polygon mirror, added a laser and an ultrasound transducer, and then put everything in waterproof frame to detect the emitting ultrasound signals."

The lightweight, handheld prototype is about the size of a flashlight. With their photoacoustic imaging device, Cardones and Yao can provide functional sampling of the skin—a photoacoustic biopsy—that clearly identifies the organization and oxygenation of tiny blood vessels in the tissue.

With functional imaging of up to 13 mm across and 5 mm in depth, there are numerous other potential applications of their device, such as the study of [skin](#) tumors, brain disorders, and eye diseases.

Cardones and Yao hope to win IRB approval and begin clinical testing of their device. Beyond that, they see potential for commercialization and will be working with MEDx and the FDA to navigate the process of safety testing and bringing the device to market. [29]

## Biological signaling processes in intelligent materials

Scientists from the University of Freiburg have developed materials systems that are composed of biological components and polymer materials and are capable of perceiving and processing information. These biohybrid systems were engineered to perform certain functions, such as the counting signal pulses in order to release bioactive molecules or drugs at the correct time, or to detect enzymes and small molecules such as antibiotics in milk. The interdisciplinary team presented their results in some of the leading journals in the field, including *Advanced Materials* and *Materials Today*.

Living systems (such as cells and organisms) and electrical systems (such as computers) respond to different input information, and have diverse output capabilities. However, the fundamental property these complex systems share is the ability to process information. Over the past two decades, scientists have applied the principles of electrical engineering to design and build living cells that perceive and process information and perform desired functions. This field is called synthetic biology, and it has many exciting applications in the medical, biotechnology, energy and environmental sectors.

"Thanks to major progress in our understanding of the components and wiring of biological signalling processes, we are now at a stage where we can transfer biological modules from synthetic biology to materials," explains lead researcher Prof. Wilfried Weber from the Faculty of Biology and the BIOS Centre for Biological Signalling Studies. A critical step in the development of these smart materials systems was to optimally align the activity of the biological building blocks. Similar to computers, incompatibility of individual components might crash the overall system. Key to overcoming this challenge were quantitative mathematical models developed by Prof. Jens Timmer and Dr. Raphael Engesser from the Faculty of Mathematics and Physics.

"A great thing about these synthetic biology-inspired materials systems is their versatility," says Hanna Wagner, the first author of one of the studies and a doctoral candidate in the Spemann Graduate School of Biology and Medicine (SGBM). The modular design concept put forth in these studies provides a blueprint for engineering biohybrid materials systems that can sense and process diverse physical, chemical or biological signals and perform desired functions, such as the amplification of signals, the storage of information, or the controlled release of bioactive molecules. These innovative materials might therefore have broad applications in research, biotechnology and medicine. [28]

## Quantum dots show promise for Parkinson's treatment

Nanotechnology may provide an effective treatment for Parkinson's disease, a team of researchers suggests.

The scientists, led by Donghoon Kim from Johns Hopkins University School of Medicine in the US, report that the deployment of graphene quantum dots (GQDs) into brain tissue severely disrupts the aggregation of a protein called alpha-synuclein, thought to be a primary driver of the loss of neurons and synapses that characterise the disease.

GQDs are made from graphene, which comprises carbon atoms arranged in a hexagonal lattice. They can contain one or many layers, and range in size between 10 and 70 nanometres.

The material is a [hot focus](#) for research, because it is non-toxic in biological systems, stable in environmental systems, and exhibits predictable luminescence, making it attractive in areas as distant as medicine and electronics.

[In a letter](#) published in the journal *Nature Nanotechnology*, Kim and his colleagues report the results of introducing GQDs into the midbrains of test animals with Parkinson's.

This is the region in which alpha-synuclein congregates, clumping into structures called fibrils. The fibrils form into lesions [known as Lewy bodies](#), which are characteristic of Parkinson's and a similar condition known as dementia with Lewy bodies (DLB).

The researchers report that the introduction of GQDs in test subjects inhibited the fibrilisation of the protein, and reduced synaptic loss and neuronal cell death. Moreover, they reduced Lewy body formation.

Because they are so small they could pass through the brain-blood barrier – a major obstacle for many medical molecules – and thus prevent the destruction by already formed alpha-synuclein fibrils of dopamine-producing neurons, potentially mediating one of the most distressing symptoms of the disease.

Although the work reported is preliminary, the results suggest that GQDs might not only slow the progression of Parkinson's, but may actually halt it.

Kim and colleagues measured the number and length of fibril segments in the midbrains of test subjects and found that they grew shorter and more numerous. The process began just six hours after the dots were introduced and peaked at 24. This, they suggest, indicates that larger fibrils were being broken up.

By the third day the number of fibril fragments started to decrease, and were undetectable by day seven.

There is still much work left to be done, but the scientists end their letter on a cautious but distinctly optimistic note.

“It is expected that GQD-based drugs with appropriate modifications might provide a clue to support the development of new therapeutic agents for abnormal protein aggregation-related neurological disorders including Parkinson's disease,” they write. [27]

## **Assessing quantum dot photoemissions**

Recent research from Kumamoto University in Japan has revealed that polyoxometalates (POMs), typically used for catalysis, electrochemistry, and photochemistry, may also be used in a technique for analyzing quantum dot (QD) photoluminescence (PL) emission mechanisms.

Quantum dots (QDs) are small, semiconducting nanocrystals or particles typically between two to ten nanometers in size. Discovered almost 40 years ago, their strong photoluminescent properties are a function of their size and shape making them useful for optical applications ranging from bioimaging to [light emitting diodes](#). Advances in high-quality QD research in the last ten years has produced highly luminescent but somewhat unstable QDs that also, unfortunately, use toxic or rare elements. Efforts to create stable QDs without these toxic or expensive elements has been a driving force in recent research.

To address these issues, researchers have been investigating how to change the size, morphology, and PL of tin dioxide (SnO<sub>2</sub>) to produce cheap, stable, and nontoxic colloidal semiconductor nanocrystals for various applications. Interestingly, the optical properties of SnO<sub>2</sub> have been found to be effected by defects in both the bulk material and the QDs themselves.

Researchers from Professor Kida's Chemical Engineering Laboratory at Kumamoto University synthesized SnO<sub>2</sub> QDs using a liquid phase method to produce QDs of various morphologies. The sizes of the QDs were controlled by changing the temperature during synthesis. All of the QDs produced a blue PL when exposed to UV light (370 nm) and QDs 2 nm in size produced the best intensity. To examine the PL properties and mechanisms related to defects in the synthesized QDs, the researchers used materials (POMs) that quench florescence through excited state reactions.

POMs quenched emissions of the SnO<sub>2</sub> QDs at peak intensities (401, 438, and 464 nm) but, to the surprise of the researchers, a previously unseen peak at 410 nm was revealed.

"We believe that the [emission](#) at 410 nm is caused by a bulk defect, which cannot be covered by POMs, that causes what is known as radiative recombination—the spontaneous emission of a photon with a wavelength related to the released energy," said project leader Professor Tetsuya Kida. "This work has shown that our technique is effective in analyzing PL emission mechanisms for QDs. We believe it will be highly beneficial for future QD research." [26]

## Quantum dot ring lasers emit colored light

Researchers have designed a new type of laser called a quantum dot ring laser that emits red, orange, and green light. The different colors are emitted from different parts of the quantum dot—red from the core, green from the shell, and orange from a combination of both—and can be easily switched by controlling the competition between light emission from the core and the shell.

The researchers, Boris le Feber, Ferry Prins, Eva De Leo, Freddy T. Rabouw, and David J. Norris, at ETH Zurich, Switzerland, have published a paper on the new lasers in a recent issue of *Nano Letters*.

The work demonstrates the interesting effects that are possible with lasers based on quantum dots, which are nanosized crystal spheres made of semiconducting materials. In these lasers, the quantum dots are often coated with shells of a different material. When illuminated, the shells not only emit light of their own, but they also channel photoexcited carriers (excitons) to the cores of the quantum dots, which enhances the [laser's](#) core light [emission](#).

In order to make quantum dot lasers that can switch between emitting light from only the cores or only the shells, the researchers designed a special laser cavity, which is the central part of the laser responsible for confining and reflecting light until it becomes highly coherent. Although quantum dot lasers have been widely researched, the effect of the laser cavity on quantum dot laser performance has been largely unexplored until now.

In the new study, the scientists fabricated high-quality laser cavities made of arrays of highly structured quantum dot rings. The resulting lasers exhibit very high cavity quality factors—almost an order of magnitude higher than those of typical quantum dot lasers, which usually have random cavities.

"We were able to demonstrate a simple fabrication approach that led to high-quality ring cavities that allowed us to explore this 'color switching' behavior in a quantum dot laser," Norris, Professor of Materials Engineering at ETH Zurich, told *Phys.org*. "In poor-quality cavities it is unlikely that we would have been able to observe this effect."

The researchers demonstrated that, at low powers, the new lasers emit red light from their cores, whereas at higher powers, they emit green light from the shells. At intermediate powers, the light comes from both the core and shell, and so appears orange. As the researchers explain, it's possible to completely stifle core emission because the core emission takes place on a picosecond timescale, while shell emission occurs on a subpicosecond timescale and so can greatly outpace core emission, as long as the laser power is sufficiently high.

In the future, the unique properties of the quantum dot ring lasers may lead to applications in laser displays, chemical sensing, and other areas. But before these applications can be realized, the researchers plan to further improve the laser's performance.

"We demonstrate the 'color switching' effect in this work, but the color change occurs at very high powers," Norris said. "Further research is required to see if the same effect can occur at more reasonable powers. This would be useful for applications. Fortunately, quantum dots continue to improve (in terms of their performance for lasers), and we can immediately apply these improvements to our devices." [25]

## **Sensing with a twist: A new kind of optical nanosensor uses torque for signal processing**

The world of nanosensors may be physically small, but the demand is large and growing, with little sign of slowing. As electronic devices get smaller, their ability to provide precise, chip-based sensing of dynamic physical properties such as motion become challenging to develop.

An international group of researchers have put a literal twist on this challenge, demonstrating a new nanoscale optomechanical resonator that can detect torsional motion at near state-of-the-art sensitivity. Their resonator, into which they couple light, also demonstrates torsional frequency mixing, a novel ability to impact optical energies using mechanical motions. They report their work this week in the journal *Applied Physics Letters*.

"With developments of nanotechnology, the ability to measure and control torsional motion at the nanoscale can provide a powerful tool to explore nature," said Jianguo Huang from Xi'an Jiaotong University in China, one of the work's authors. He is also affiliated with the Nanyang Technological



University and with the Institute of Microelectronics, A\*STAR in Singapore. "We present a novel 'beam-in-cavity' design in which a torsional mechanical resonator is embedded into a racetrack optical cavity, to demonstrate nanoscale torsional motion sensing."

Light has already been used in somewhat similar ways to detect the mechanical flexing or "breathing" of nanomaterials, typically requiring complex and sensitive coupling to the light source. This new approach is novel not only in its detection of nanoscale torques, but also in its integrated light-coupling design.

Using a silicon-based nanofabrication method, Huang and his team designed the device to allow light to couple directly via an etched grating to a waveguide configuration, called a racetrack cavity, in which the nanoresonator sits.

"As light is coupled into the racetrack cavity through a grating coupler, mechanical torsional motion in the cavity alters the propagation of light and changes [the] power of output light," said Huang. "By detecting the small variation of output light, the torsional motions can be measured."

Beyond just detecting torques on their micron-length lever arms, the resonators can also affect the resulting optical properties of the incident signal. The torsional frequency of the mechanical system mixes with the modulated optical signals.

"The most surprising part is that when we modulate the input light, we can observe the frequency mixing," Huang said. "It is exciting for frequency mixing since it has only been demonstrated by flexural or breathing modes before. This is the first demonstration of torsional frequency mixing, which may have implications for on-chip RF signal modulation, such as super-heterodyne receivers using optical mechanical resonators."

This is just the start for potential uses of torque-based nanosensors. Theoretically, there are a number of frequency tricks these devices could play for signal processing and sensing applications.

"We will continue to explore unique characters of this torsional optomechanical sensor and try to demonstrate novel phenomena, such as inference of dispersive and dissipative optomechanical coupling hidden behind the sensing," Huang said. "For engineering, magnetic or electrically-sensitive materials can be coated on the surface of torsional beams to sense small variations of physical fields, such as magnetic or electric fields to serve as multifunctional sensors." [24]

## **First imaging of free nanoparticles in laboratory experiment using a high-intensity laser source**

In a joint research project, scientists from the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy (MBI), the Technische Universität Berlin (TU) and the University of Rostock have managed for the first time to image free nanoparticles in a laboratory experiment using a highintensity laser source. Previously, the structural analysis of these extremely small objects via singleshot diffraction was only possible at large-scale research facilities using so-called XUV and x-ray free electron lasers. Their pathbreaking results facilitate the highly-efficient characterisation of the chemical, optical and structural properties of individual nanoparticles and have just been published in Nature Communications. The lead author of the publication is junior researcher Dr

Daniela Rupp who carried out the project at TU Berlin and is now starting a junior research group at MBI.

In their experiment, the researchers expanded helium gas through a nozzle that is cooled to extremely low temperature. The helium gas turns into a superfluid state and forms a beam of freely flying miniscule nanodroplets. "We sent ultra-short XUV pulses onto these tiny droplets and captured snapshots of these objects by recording the scattered laser light on a large-area detector to reconstruct the droplet shape," explains Dr Daniela Rupp.

"Key to the successful experiment were the high-intensity XUV pulses generated in MBI's laser lab that produce detailed scattering patterns with just one single shot," explains Dr Arnaud Rouzée from MBI. "By using the so-called wide-angle mode that provides access to the three-dimensional morphology, we could identify hitherto unobserved shapes of the superfluid droplets," adds Professor Thomas Fennel from MBI and the University of Rostock. The research team's results enable a new class of metrology for analysing the structure and optical properties of small particles. Thanks to state-of-the-art laser light sources, making images of the tiniest pieces of matter is no longer exclusive to the large-scale research facilities. [23]

## **Single molecular layer and thin silicon beam enable nanolaser operation at room temperature**

For the first time, researchers have built a nanolaser that uses only a single molecular layer, placed on a thin silicon beam, which operates at room temperature. The new device, developed by a team of researchers from Arizona State University and Tsinghua University, Beijing, China, could potentially be used to send information between different points on a single computer chip. The lasers also may be useful for other sensing applications in a compact, integrated format.

"This is the first demonstration of room-temperature operation of a nanolaser made of the singlelayer material," said Cun-Zheng Ning, an ASU electrical engineering professor who led the research team. Details of the new laser are published in the July online edition of Nature Nanotechnology.

In addition to Ning, key authors of the article, "Room-temperature Continuous-wave Lasing from Monolayer Molybdenum Ditelluride Integrated with a Silicon Nanobeam Cavity," include Yongzhuo Li, Jianxing Zhang, Dandan Huang from Tsinghua University.

Ning said pivotal to the new development is use of materials that can be laid down in single layers and efficiently amplify light (lasing action). Single layer nanolasers have been developed before, but they all had to be cooled to low temperatures using a cryogen like liquid nitrogen or liquid helium. Being able to operate at room temperatures (~77 F) opens up many possibilities for uses of these new lasers," Ning said.

The joint ASU-Tsinghua research team used a monolayer of molybdenum ditelluride integrated with a silicon nanobeam cavity for their device. By combining molybdenum ditelluride with silicon, which is the bedrock in semiconductor manufacturing and one of the best waveguide materials, the researchers were able to achieve lasing action without cooling, Ning said.

A laser needs two key pieces – a gain medium that produces and amplifies photons, and a cavity that confines or traps photons. While such materials choices are easy for large lasers, they become more difficult at nanometer scales for nanolasers. Nanolasers are smaller than 100th of the thickness of the human hair and are expected to play important roles in future computer chips and a variety of light detection and sensing devices.

The choice of two-dimensional materials and the silicon waveguide enabled the researchers to achieve room temperature operation. Excitons in molybdenum telluride emit in a wavelength that is transparent to silicon, making silicon possible as a waveguide or cavity material. Precise fabrication of the nanobeam cavity with an array of holes etched and the integration of two-dimensional monolayer materials was also key to the project. Excitons in such monolayer materials are 100 times stronger than those in conventional semiconductors, allowing efficient light emission at room temperature.

Because silicon is already used in electronics, especially in computer chips, its use in this application is significant in future applications.

"A laser technology that can also be made on Silicon has been a dream for researchers for decades," said Ning. "This technology will eventually allow people to put both electronics and photonics on the same silicon platform, greatly simplifying manufacture."

Silicon does not emit light efficiently and therefore must be combined with other light emitting materials. Currently, other semiconductors are used, such as Indium phosphide or Indium Gallium Arsenide which are hundreds of times thicker, to bond with silicon for such applications.

The new monolayer materials combined with Silicon eliminate challenges encountered when combining with thicker, dissimilar materials. And, because this non-silicon material is only a single layer thick, it is flexible and less likely to crack under stress, according to Ning.

Looking forward, the team is working on powering their laser with electrical voltage to make the system more compact and easy to use, especially for its intended use on computer chips. [22]

## **Computer chip technology repurposed for making reflective nanostructures**

A team of engineers at Caltech has discovered how to use computer-chip manufacturing technologies to create the kind of reflective materials that make safety vests, running shoes, and road signs appear shiny in the dark.

Those materials owe their shininess to retroreflection, a property that allows them to bounce light directly back to its source from a wide variety of angles. In contrast, a basic flat mirror will not bounce light back to its source if that light is coming from any angle other than straight on.

Retroreflectors' ability to return light to where it came from makes them useful for highlighting objects that need to be seen in dark conditions. For example, if light from a car's headlights shines on the safety vest of a construction worker down the road, the vest's retroreflective strips will bounce that light straight back to the car and into the driver's eyes, making the vest appear to glow.

Retroreflectors have also been used in surveyors' equipment, communications with satellites, and even in experiments to measure the distance of the moon from Earth.

Typically, retroreflectors consist of tiny glass spheres embedded in the surface of reflective paint or in small mirrors shaped like the inner corner of a cube.

The new technology—which was developed by a team led by Caltech's Andrei Faraon, assistant professor of applied physics and materials science in the Division of Engineering and Applied Science—uses surfaces covered by a metamaterial consisting of millions of silicon pillars, each only a few hundred nanometers tall. By adjusting the size of the pillars and the spacing between them, Faraon can manipulate how the surface reflects, refracts, or transmits light. He has already shown that these materials can be tweaked to create flat lenses for focusing light or to create prism-like surfaces that spread the light out into its spectrum. Now, he's discovered that he can build a retroreflector by stacking two layers of the metamaterials atop one another.

In this kind of retroreflector, light first passes through a transparent metamaterial layer (metasurface) and is focused by its tiny pillars onto a single spot on a reflective metamaterial layer. The reflective layer then bounces the light back to the transparent layer, which transmits the light back to its source.

"By placing multiple metasurfaces on top of each other, it is possible to control the flow of light in such a way that was not possible before," Faraon says. "The functionality of a retroreflector cannot be achieved by using a single metasurface."

Since Faraon's metamaterials are created using computer-chip manufacturing technologies, it would be possible to easily integrate them into chips used in optoelectronic devices—electronics that use and control light, he says.

"This could have applications in communicating with remote sensors, drones, satellites, etc.," he adds.

Faraon's research appears in a paper in the June 19, 2017, edition of *Nature Photonics*; the paper is titled "Planar metasurface retroreflector." Other coauthors are Amir Arbabi, assistant professor of computer and electrical engineering at the University of Massachusetts Amherst; and Caltech electrical engineering graduate students Ehsan Arbabi, Yu Horie, and Seyedeh Mahsa Kamali. [21]

## **Physicists create nanoscale mirror with only 2000 atoms**

Mirrors are the simplest means to manipulate light propagation. Usually, a mirror is a macroscopic object composed of a very large number of atoms. In the September 23rd issue of the *Physical Review Letters*, Prof. Julien Laurat and his team at Pierre and Marie Curie University in Paris (Laboratoire Kastler Brossel-LKB) report that they have realized an efficient mirror consisting of only 2000 atoms. This paper is accompanied by a "Focus" item in *APS-Physics*.

By engineering the position of cold atoms trapped around a nanoscale fiber, the researchers fulfill the necessary conditions for Bragg reflection, a well-known physical effect first proposed by William Lawrence Bragg and his father William Henry Bragg in crystalline solids. They earned the Nobel Prize for this work in 1915.

In the current experiment, each trapped atom contributes with a small reflectance, and the engineered position allows the constructive interference of multiple reflections.

"Only 2000 atoms trapped in the vicinity of the fiber were necessary, while previous demonstrations in free space required tens of millions of atoms to get the same reflectance," says Neil Corzo, a Marie-Curie postdoctoral fellow and the lead author of this work. He adds, "This is due to the strong atom-photon coupling and the atom position control that we can now achieve in our system."

The key ingredient is a nanoscale fiber, whose diameter has been reduced to 400 nm. In this case, a large fraction of the light travels outside the fiber in an evanescent field where it is heavily focused over the 1-cm nanofiber length. Using this strong transversal confinement, it is possible to trap cold cesium atoms near the fiber in well-defined chains. The trapping is made with the implementation of an all-fibered dipole trap. With the use of well-chosen pairs of beams, the researchers generate two chains of trapping potentials around the fiber, in which only one atom occupies each site. By selecting the correct colors of the trap beams, they engineered the distance between atoms in the chains to be close to half the resonant wavelength of the cesium atoms, fulfilling the necessary conditions for Bragg reflection.

This setting represents an important step in the emerging field of waveguide quantum electrodynamics, with applications in quantum networks, quantum nonlinear optics, and quantum simulation. The technique would allow for novel quantum network capabilities and many-body effects emerging from long-range interactions between multiple spins, a daunting prospect in free space.

This demonstration follows other works that Laurat's group has done in recent years, including the realization of an all-fibered optical memory. [20]

## **For first time, researchers see individual atoms keep away from each other or bunch up as pairs**

If you bottle up a gas and try to image its atoms using today's most powerful microscopes, you will see little more than a shadowy blur. Atoms zip around at lightning speeds and are difficult to pin down at ambient temperatures.

If, however, these atoms are plunged to ultracold temperatures, they slow to a crawl, and scientists can start to study how they can form exotic states of matter, such as superfluids, superconductors, and quantum magnets.

Physicists at MIT have now cooled a gas of potassium atoms to several nanokelvins—just a hair above absolute zero—and trapped the atoms within a two-dimensional sheet of an optical lattice created by crisscrossing lasers. Using a high-resolution microscope, the researchers took images of the cooled atoms residing in the lattice.

By looking at correlations between the atoms' positions in hundreds of such images, the team observed individual atoms interacting in some rather peculiar ways, based on their position in the lattice. Some atoms exhibited "antisocial" behavior and kept away from each other, while some

bunched together with alternating magnetic orientations. Others appeared to piggyback on each other, creating pairs of atoms next to empty spaces, or holes.

The team believes that these spatial correlations may shed light on the origins of superconducting behavior. Superconductors are remarkable materials in which electrons pair up and travel without friction, meaning that no energy is lost in the journey. If superconductors can be designed to exist at room temperature, they could initiate an entirely new, incredibly efficient era for anything that relies on electrical power.

Martin Zwierlein, professor of physics and principal investigator at MIT's NSF Center for Ultracold Atoms and at its Research Laboratory of Electronics, says his team's results and experimental setup can help scientists identify ideal conditions for inducing superconductivity.

"Learning from this atomic model, we can understand what's really going on in these superconductors, and what one should do to make higher-temperature superconductors, approaching hopefully room temperature," Zwierlein says.

Zwierlein and his colleagues' results appear in the Sept. 16 issue of the journal *Science*. Co-authors include experimentalists from the MIT-Harvard Center for Ultracold Atoms, MIT's Research Laboratory of Electronics, and two theory groups from San Jose State University, Ohio State University, the University of Rio de Janeiro, and Penn State University.

### ***"Atoms as stand-ins for electrons"***

Today, it is impossible to model the behavior of high-temperature superconductors, even using the most powerful computers in the world, as the interactions between electrons are very strong. Zwierlein and his team sought instead to design a "quantum simulator," using atoms in a gas as stand-ins for electrons in a superconducting solid.

The group based its rationale on several historical lines of reasoning: First, in 1925 Austrian physicist Wolfgang Pauli formulated what is now called the Pauli exclusion principle, which states that no two electrons may occupy the same quantum state—such as spin, or position—at the same time. Pauli also postulated that electrons maintain a certain sphere of personal space, known as the "Pauli hole."

His theory turned out to explain the periodic table of elements: Different configurations of electrons give rise to specific elements, making carbon atoms, for instance, distinct from hydrogen atoms.

The Italian physicist Enrico Fermi soon realized that this same principle could be applied not just to electrons, but also to atoms in a gas: The extent to which atoms like to keep to themselves can define the properties, such as compressibility, of a gas.

"He also realized these gases at low temperatures would behave in peculiar ways," Zwierlein says.

British physicist John Hubbard then incorporated Pauli's principle in a theory that is now known as the Fermi-Hubbard model, which is the simplest model of interacting atoms, hopping across a lattice. Today, the model is thought to explain the basis for superconductivity. And while theorists

have been able to use the model to calculate the behavior of superconducting electrons, they have only been able to do so in situations where the electrons interact weakly with each other.

"That's a big reason why we don't understand high-temperature superconductors, where the electrons are very strongly interacting," Zwierlein says. "There's no classical computer in the world that can calculate what will happen at very low temperatures to interacting [electrons]. Their spatial correlations have also never been observed in situ, because no one has a microscope to look at every single electron."

### ***Carving out personal space***

Zwierlein's team sought to design an experiment to realize the Fermi-Hubbard model with atoms, in hopes of seeing behavior of ultracold atoms analogous to that of electrons in high-temperature superconductors.

The group had previously designed an experimental protocol to first cool a gas of atoms to near absolute zero, then trap them in a two-dimensional plane of a laser-generated lattice. At such ultracold temperatures, the atoms slowed down enough for researchers to capture them in images for the first time, as they interacted across the lattice.

At the edges of the lattice, where the gas was more dilute, the researchers observed atoms forming Pauli holes, maintaining a certain amount of personal space within the lattice.

"They carve out a little space for themselves where it's very unlikely to find a second guy inside that space," Zwierlein says.

Where the gas was more compressed, the team observed something unexpected: Atoms were more amenable to having close neighbors, and were in fact very tightly bunched. These atoms exhibited alternating magnetic orientations.

"These are beautiful, antiferromagnetic correlations, with a checkerboard pattern—up, down, up, down," Zwierlein describes.

At the same time, these atoms were found to often hop on top of one another, creating a pair of atoms next to an empty lattice square. This, Zwierlein says, is reminiscent of a mechanism proposed for high-temperature superconductivity, in which electron pairs resonating between adjacent lattice sites can zip through the material without friction if there is just the right amount of empty space to let them through.

Ultimately, he says the team's experiments in gases can help scientists identify ideal conditions for superconductivity to arise in solids.

Zwierlein explains: "For us, these effects occur at nanokelvin because we are working with dilute atomic gases. If you have a dense piece of matter, these same effects may well happen at room temperature."

Currently, the team has been able to achieve ultracold temperatures in gases that are equivalent to hundreds of kelvins in solids. To induce superconductivity, Zwierlein says the group will have to cool their gases by another factor of five or so.



"We haven't played all of our tricks yet, so we think we can get colder," he says. [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 stars, 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.

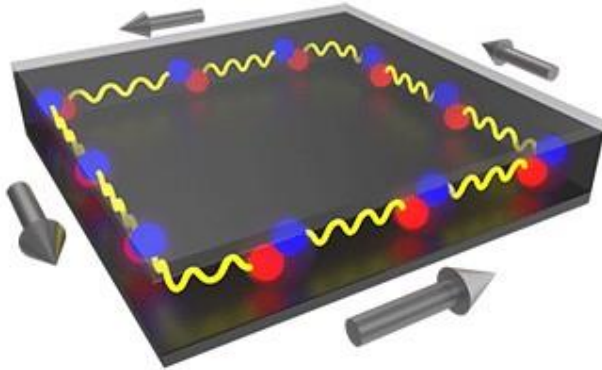


As described in a paper published online March 24 in Applied Physics Letters, the hybrid material dramatically enhanced the performance of the photo-field-effect transistors—resulting in a photocurrent response (conversion of light to electric current) that was 500 percent better than transistors made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

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

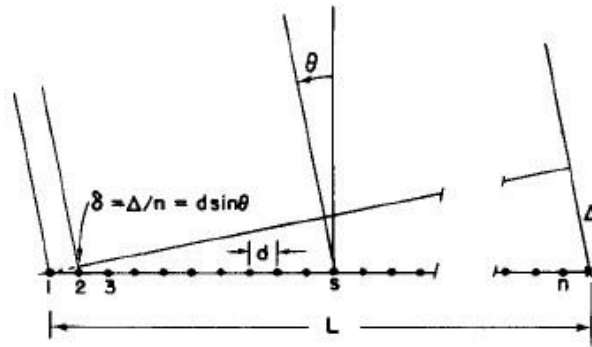


Fig. 30-3. A linear array of  $n$  equal oscillators, driven with phases  $\alpha_s = s\alpha$ .

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 chooses 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:

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

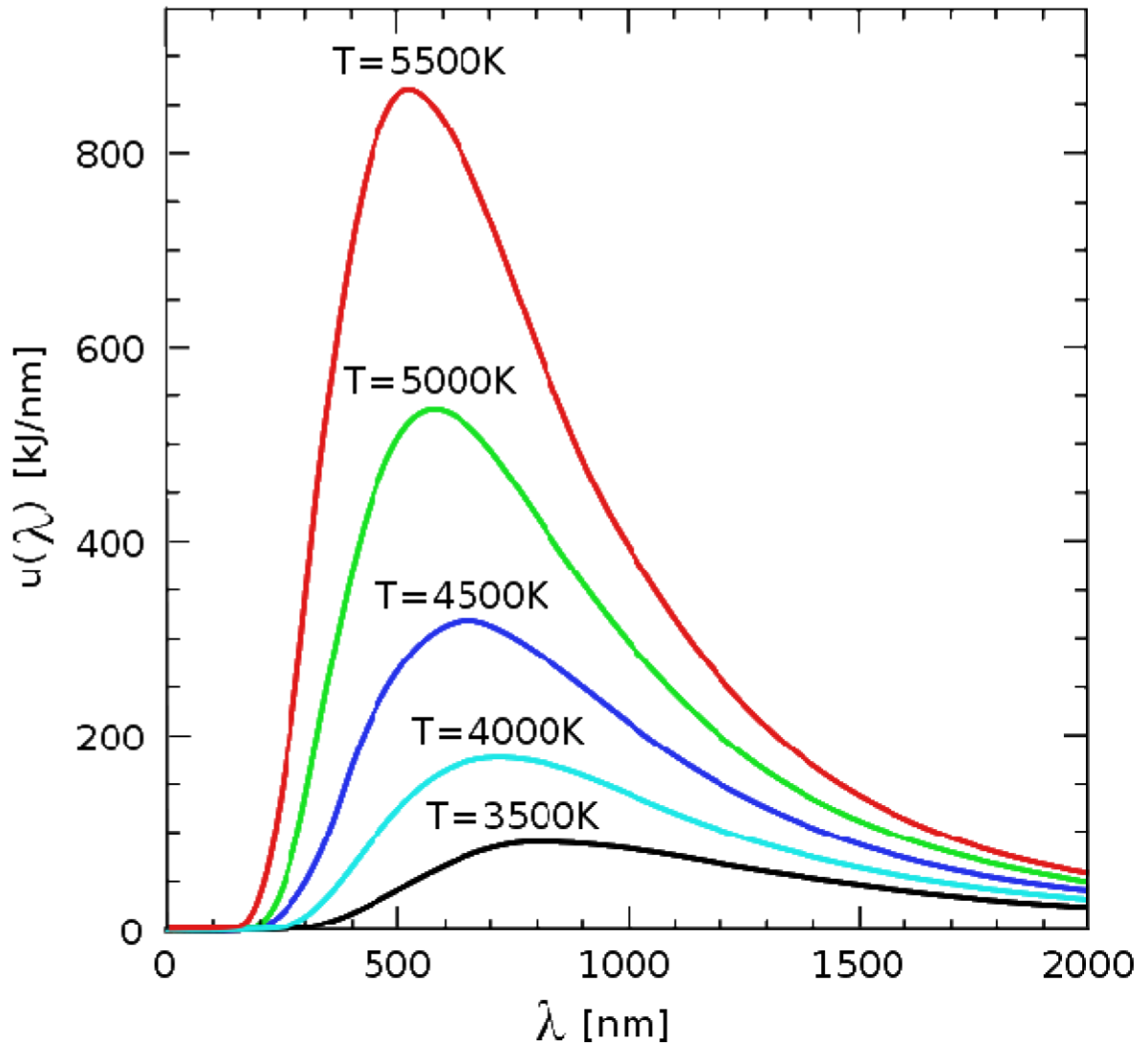


Figure 2. The distribution law for different T temperatures

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 rate 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:  $1/2 h = \Delta x \Delta p$  or  $1/2 h = \Delta t \Delta E$ , 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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