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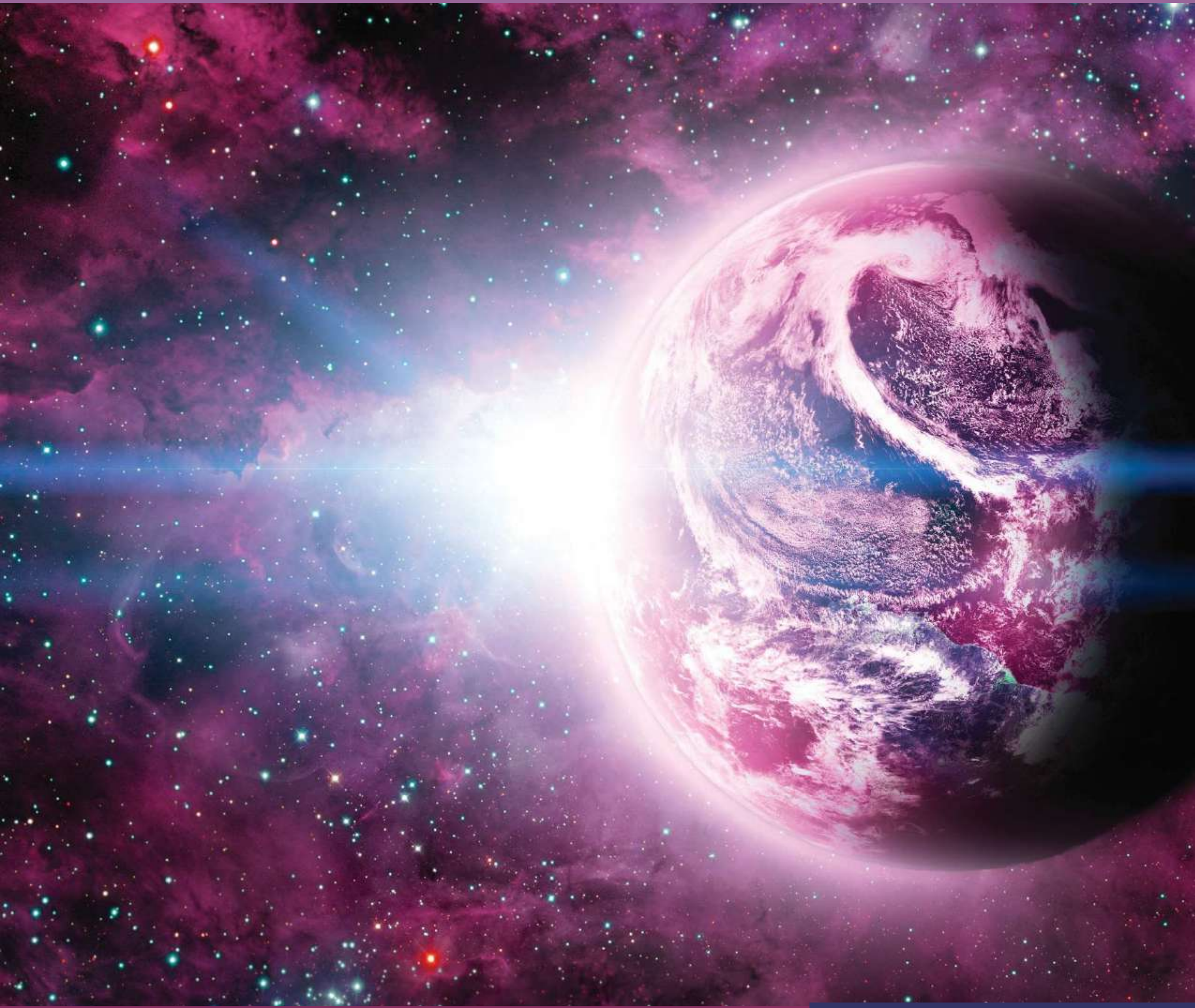

QUANTUM PHYSICS NEWS LETTER 15-AUG-2024

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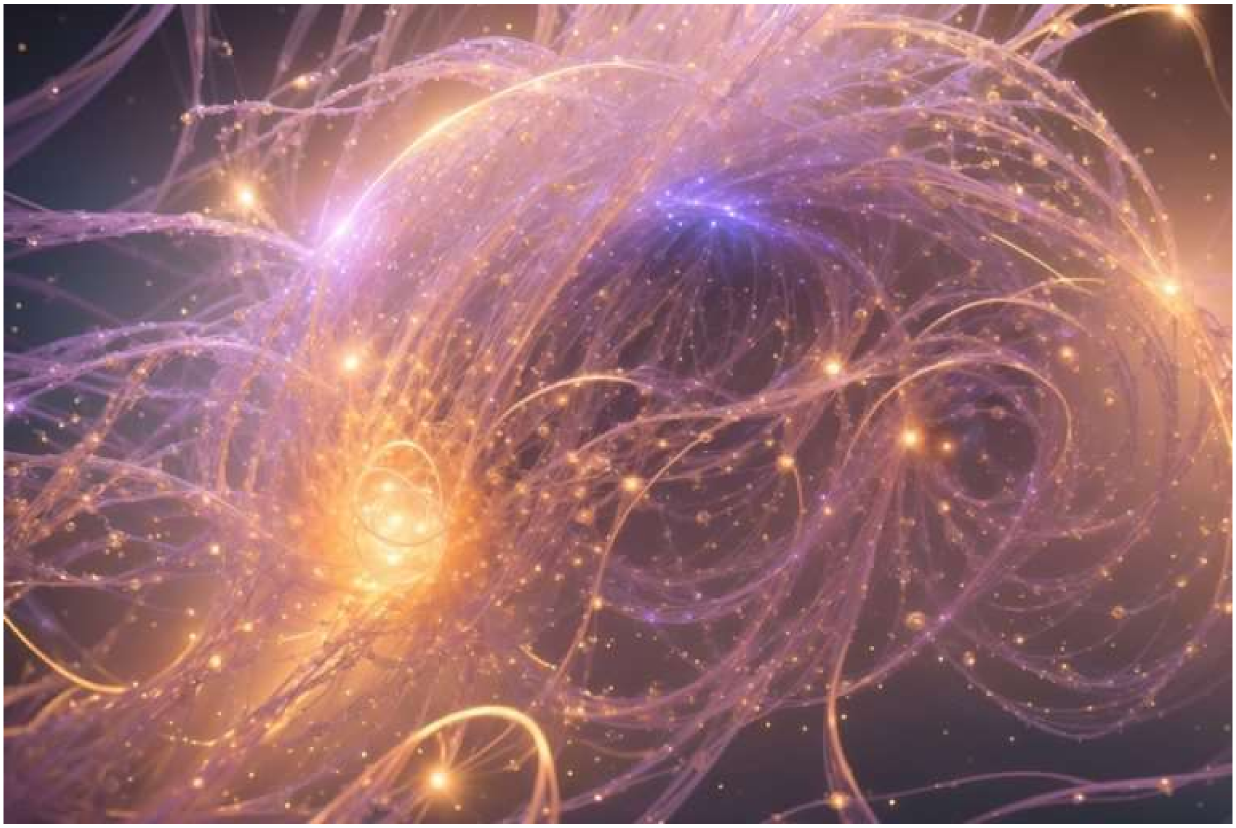
New Shapes Of Photons Open Doors To Advanced Optical Technologies

In their recent paper, researchers from the University of Twente in the Netherlands have gained important insights into the elementary particles that make up light.

These particles, photons, ‘behave’ in an amazingly greater variety than electrons surrounding atoms, while also being much easier to control. These new insights have broad applications from smart LED lighting to new photonic bits of information controlled with quantum circuits, to sensitive nano-sensors.



Particles – illustrative photo. Image credit: Pixabay (Free Pixabay license)

In atoms, minuscule elementary particles called electrons occupy regions around the nucleus in shapes called orbitals. These orbitals give the probability of finding an electron in a particular region of space. Quantum mechanics determines the shape and energy of these orbitals.

Similarly to electrons, researchers describe the region of space where a photon is most likely found with orbitals too.

‘Whatever wild shape you design’

Researchers at the University of Twente studied these photonic orbitals and discovered with careful design of specific materials, they can create and control these orbitals with a great variety of shapes and symmetries. These results have potential applications in advanced optical technologies and quantum computing.

First author Kozon explains: “In textbook chemistry, the electrons always orbit around the tiny atomic core at the centre of the orbital. So an electron orbital’s shape cannot deviate much from a perfect sphere. With photons, the orbitals can have whatever wild shape you design by combining different optical materials in designed spatial arrangements”.

Easier to design

The researchers conducted a computational study to understand how photons behave when they are confined in a specific 3D nanostructure consisting of tiny pores (a photonic crystal). These cavities are intentionally designed to have defects, creating a superstructure that isolates the photonic states from the surrounding environment. Physicists Vos and Lagendijk enthuse: “Given the rich toolbox in nanotechnology, it is much easier to design nifty nanostructures with novel photonic orbitals than it is to modify atoms to realize novel electronic orbitals and chemistry.”

Advanced optical technologies

Photonic orbitals are important for developing advanced optical technologies, such as efficient lighting, quantum computing, and sensitive photonic sensors. The researchers also studied how these nanostructures enhance the local density of optical states, which is important for applications in cavity quantum electrodynamics. They found that structures with smaller defects reveal greater enhancement than those with larger defects. This makes them more suitable for integrating quantum dots and creating networks of single photons.

More information

The research was done by Marek Kozoň, Ad Lagendijk, Matthias Schlottbom, Jaap van der Vegt and Willem Vos from the University of Twente. Marek is a theoretical physicist who recently graduated from the COPS and MACS chairs (now with Pixel Photonics GmbH, a single photon detector company in Germany), Matthias and Jaap are professors of MACS, and Ad and Willem are professors of COPS.

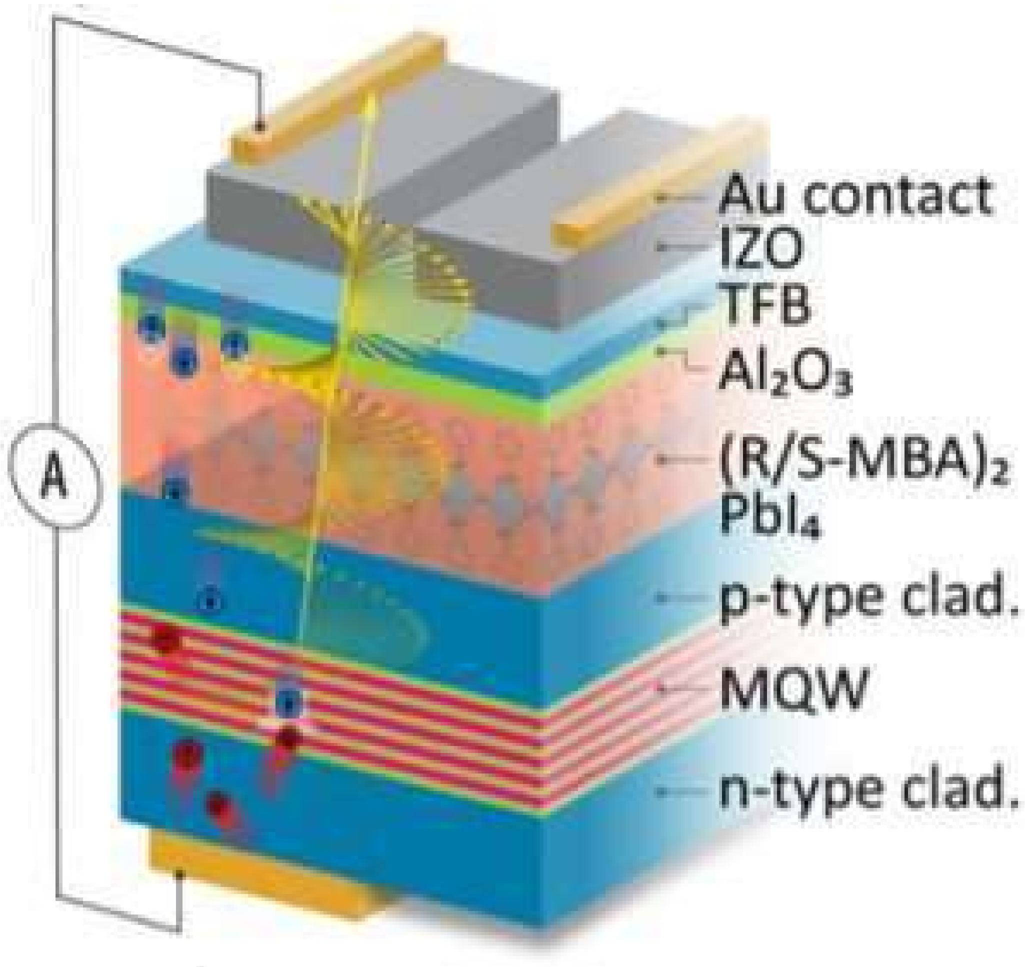
The work is supported by the NWO-CSER program, project “Understanding the absorption of interfering light for improved solar cell efficiency” under the Project No. 680.93.14CSER035; the NWO-JCER program, project “Accurate and Efficient Computation of the Optical Properties of Nanostructures for Improved Photovoltaics” under the Project No. 680-91-084; the NWO-GROOT program, project “Self-Assembled Icosahedral Photonic Quasicrystals with a Band Gap for Visible Light” under the Project No. OCENW.GROOT.2019.071; the NWO-TTW Perspectief program P15-36 “Free-Form Scattering Optics” (FFSO); and the MESA+ Institute for Nanotechnology, section Applied Nanophotonics (ANP).

The paper entitled “Symmetries and wave functions of photons confined in three-dimensional photonic band gap superlattices” is open access and appears online in the Physical Review B (by the American Physical Society (APS)).

DOI: 10.1103/PhysRevB.109.235141

‘Miracle’ Filter Turns Store-Bought LEDs Into Spintronic Devices

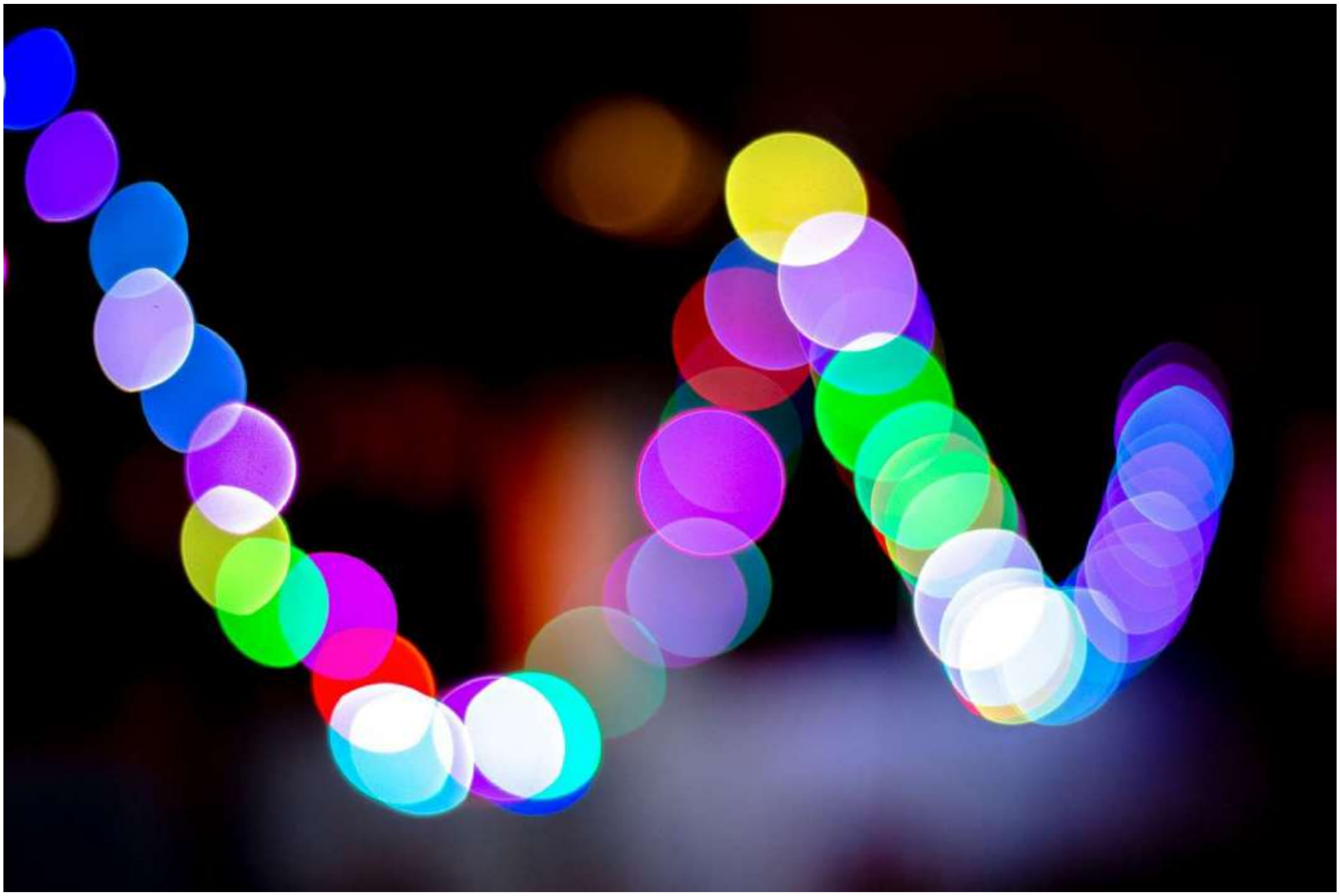
Traditional electronics use semiconductors to transmit data through bursts of charged carriers (electrons or holes) conveying messages in “1s” and “0s.” Spintronic devices can process an order of magnitude more information by assigning binary code to the orientation of electrons’ magnetic poles, a property known as spin—an “up” spin is a 1, a “down” spin is a 0.



Stack of the spin-LED emitting circularly polarized electroluminescence. The (R-MBA2PbI) acts as a spin filter, allowing only polarized carriers (blue circles) to flow through the LED and recombine in the multiple quantum wells (MQW)s emitting circularly polarized light (yellow helix). Image credit: Hautzinge, M. ET AL. Nature (2024)

A major barrier to commercial spintronics is setting and maintaining the electron spin orientation. Most devices tune spin-orientation using ferromagnets and magnetic fields, a burdensome and unreliable process. Decades of research has shown that carriers lose their spin orientation moving from materials with high-conductivity to low-conductivity—for example, from metallic ferromagnets to undoped silicon and conjugated polymer materials that make up most modern semiconductors.

For the first time, scientists transformed existing optoelectronic devices into ones that can control electron spin at room temperature, without a ferromagnet or magnetic field.



Blurred LED lights – illustrative photo. Image credit: kirklai via Unsplash, free license

Most optoelectronic devices, such as LEDs, only control charge and light but not the spin of the electrons. In the new study led by the University of Utah physicists and researchers at the National Renewable Energy Laboratory (NREL), replaced the electrodes of store-bought LEDs with a patented spin filter, made from hybrid organic-inorganic halide perovskite material. The LEDs produced circularly polarized light, a tell-tale sign that the filter had injected spin-aligned electrons into LED’s existing semiconductor infrastructure, a massive step forward for spintronics technology.

“It’s a miracle. For decades, we’ve been unable to efficiently inject spin-aligned electrons into semiconductors because of the mismatch of metallic ferromagnets and non-magnetic semiconductors,” said Valy Vardeny, Distinguished Professor in the Department of Physics & Astronomy at the U and co-author of the paper. “All kinds of devices that use spin and optoelectronics, like spin-LEDs or magnetic memory, will be thrilled by this discovery.”

The study was published in the journal Nature.

Spin filters

In 2021, the same collaborators developed the technology that acts as an active spin filter made of two successive layers of material, called chiral hybrid organic-inorganic halide perovskites. Chirality describes molecule’s symmetry, where its mirror image cannot be superimposed on itself. Human hands are the classic example; hold yours out, palms facing away. The right and left hands are arranged as mirrors of one another—you can flip your right hand 180° to match the silhouette, but now the right palm is facing you while the left palm faces away. They’re not the same.

Some molecules, such as DNA, sugar and layers of chiral hybrid organic-halide perovskites, have their atoms arranged in chiral symmetry. The filter works by using a “left-handed” oriented chiral layer to allow electrons with “up” spins to pass, but block electrons with “down” spins, and vice versa. At the time, the scientists claimed the discovery could be used to transform conventional optoelectronics into spintronic devices simply by incorporating the chiral spin filter. The new study did just that.

“We took an LED from the shelf. We removed one electrode and put the spin filter material and another regular electrode. And voila! The light was highly circularly polarized,” said Vardeny.

Chemists from the NERL fabricated the spin LEDs by stacking several layers, each with specific physical properties.The first layer is a common transparent metallic electrode; the second layer’s material blocks electrons having spin in the wrong direction, a layer that the authors call a chirality-induced spin filter. The spin-aligned electrons then recombine in the third layer, a standard semiconductor used as an active layer in regular LEDs. The injected spin aligned electrons cause this layer to produce photons that move in unison along a spiral path, rather than a conventional wave pattern, to produce the LED’s signature circular polarized electroluminescence,

“This work demonstrates the unique and powerful ability for these emerging ‘hybrid’ semiconductors to combine and take advantage of the interplay of the distinct properties of organic and inorganic systems,” said Matthew Beard, coauthor of the study of NREL. “Here the chirality is borrowed from the organic molecules and provides control over spin while the inorganic component both orients the organic component and provides conductivity or control over charge.”

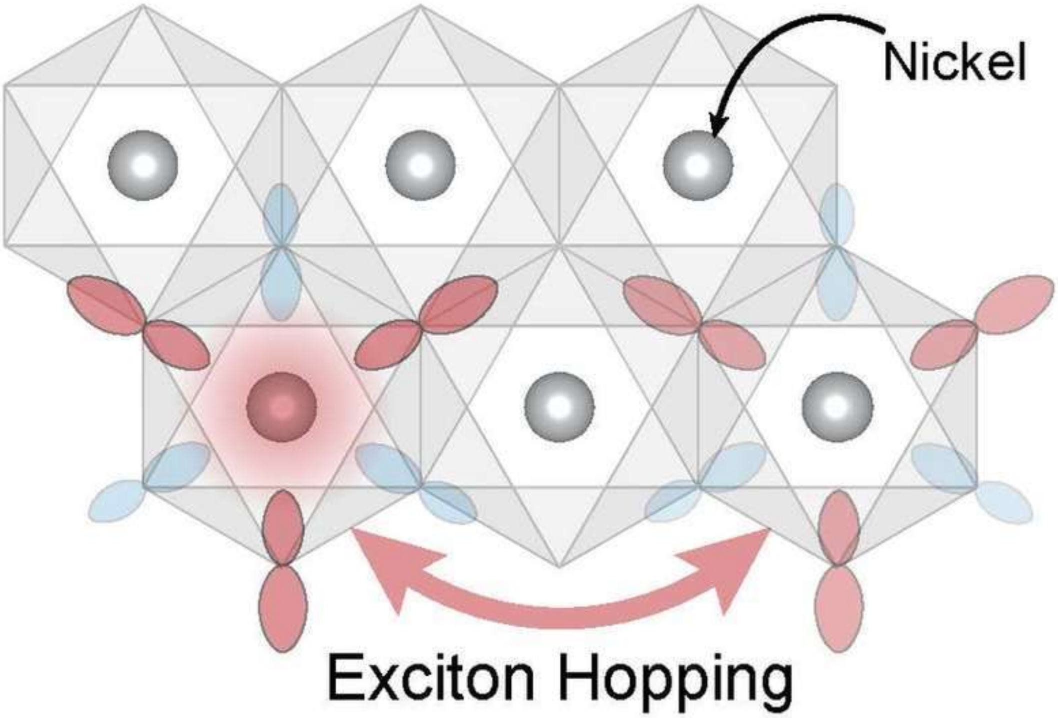
Once they installed the filter into a standard LED, Xin Pan, research assistant in the Department of Physics & Astronomy at the U, confirmed that the device worked as intended, namely by spin-aligned electrons. However, more research is needed to explain the exact mechanisms at work to create the polarized spins.

“That’s the $64,000 question for a theorist to answer,” said Vardeny. “It’s really a miracle. And the miracle is without knowing the exact underlying mechanism. So that’s the beauty of being experimentalist. You just try it.”

New Insights Into Exotic Particles Key To Magnetism

The work, originating from ultrathin materials, could impact future electronics and establishes a new way to study these particles through a powerful instrument at the Brookhaven National Laboratory.

MIT physicists and colleagues report new insights into exotic particles key to a form of magnetism that has attracted growing interest because it originates from ultrathin materials only a few atomic layers thick. The work, which could impact future electronics and more, also establishes a new way to study these particles through a powerful instrument at the National Synchrotron Light Source II at Brookhaven National Laboratory.



Schematic showing how exotic particles known as excitons can "hop" between nickel atoms (grey dots) in nickel dihalide materials. The excitons are represented by the red and light-blue orbitals. Image courtesy of the Comin Laboratory.

Among their discoveries, the team has identified the microscopic origin of these particles, known as excitons. They showed how they can be controlled by chemically "tuning" the material, which is primarily composed of nickel. Further, they found that the excitons propagate throughout the bulk material instead of being bound to the nickel atoms.

Finally, they proved that the mechanism behind these discoveries is ubiquitous to similar nickel-based materials, opening the door for identifying — and controlling — new materials with special electronic and magnetic properties.

The open-access results are reported in the issue of *Physical Review X*.

“We’ve essentially developed a new research direction into the study of these magnetic two-dimensional materials that very much relies on an advanced spectroscopic method, resonant inelastic X-ray scattering (RIXS), which is available at Brookhaven National Lab,” says Riccardo Comin, MIT’s Class of 1947 Career Development Associate Professor of Physics and leader of the work. Comin is also affiliated with the Materials Research Laboratory and the Research Laboratory of Electronics.

Comin’s colleagues on the work include Connor A. Occhialini, an MIT graduate student in physics, and Yi Tseng, a recent MIT postdoc now at Deutsches Elektronen-Synchrotron (DESY). The two are co-first authors of the *Physical Review X* paper.

Additional authors are Hebatalla Elnaggar of the Sorbonne; Qian Song, a graduate student in MIT’s Department of Physics; Mark Blei and Seth Ariel Tongay of Arizona State University; Frank M. F. de Groot of Utrecht University; and Valentina Bisogni and Jonathan Pelliciari of Brookhaven National Laboratory.

Ultrathin layers

The magnetic materials at the heart of the current work are known as nickel dihalides. They are composed of layers of nickel atoms sandwiched between layers of halogen atoms (halogens are one family of elements), which can be isolated to atomically thin layers. In this case, the physicists studied the electronic properties of three different materials composed of nickel and the halogens chlorine, bromine, or iodine. Despite their deceptively simple structure, these materials host a rich variety of magnetic phenomena.

The team was interested in how these materials’ magnetic properties respond when exposed to light. They were specifically interested in particular particles — the excitons — and how they are related to the underlying magnetism. How exactly do they form? Can they be controlled?

Enter excitons

A solid material is composed of different types of elementary particles, such as protons and electrons. Also ubiquitous in such materials are “quasiparticles” that the public is less familiar with. These include excitons, which are composed of an electron and a “hole,” or the space left behind when light is shone on a material and energy from a photon causes an electron to jump out of its usual position.

Through the mysteries of quantum mechanics, however, the electron and hole are still connected and can “communicate” with each other through electrostatic interactions. This interaction leads to a new composite particle formed by the electron and the hole — an exciton.

Excitons, unlike electrons, have no charge but possess spin. The spin can be thought of as an elementary magnet, in which the electrons are like little needles orienting in a certain way. In a common refrigerator magnet, the spins all point in the same direction. Generally speaking, the spins can organize in other patterns leading to different kinds of magnets. The unique magnetism associated with the nickel dihalides is one of these less-conventional forms, making it appealing for fundamental and applied research.

The MIT team explored how excitons form in the nickel dihalides. More specifically, they identified the exact energies, or wavelengths, of light necessary for creating them in the three materials they studied.

“We were able to measure and identify the energy necessary to form the excitons in three different nickel halides by chemically ‘tuning,’ or changing, the halide atom from chlorine to bromine to iodine,” says Occhialini. “This is one essential step towards understanding how photons — light — could one day be used to interact with or monitor the magnetic state of these materials.” Ultimate applications include quantum computing and novel sensors.

The work could also help predict new materials involving excitons that might have other interesting properties. Further, while the studied excitons originate on the nickel atoms, the team found that they do not remain localized to these atomic sites. Instead, “we showed that they can effectively hop between sites throughout the crystal,” Occhialini says. “This observation of hopping is the first for these types of excitons, and provides a window into understanding their interplay with the material’s magnetic properties.”

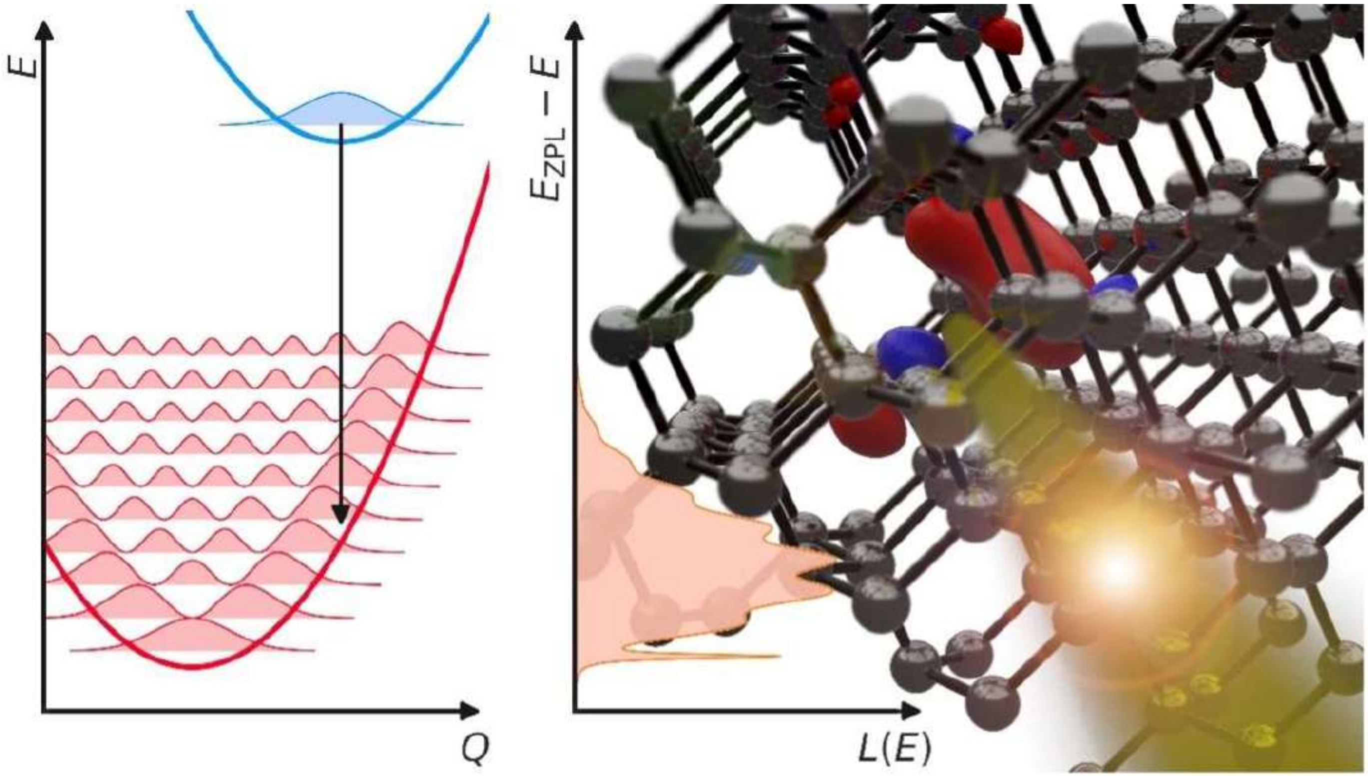
A special instrument

Key to this work — in particular for observing the exciton hopping — is resonant inelastic X-ray scattering (RIXS), an experimental technique that co-authors Pelliciari and Bisogni helped pioneer. Only a few facilities in the world have advanced high energy resolution RIXS instruments. One is at Brookhaven. Pelliciari and Bisogni are part of the team running the RIXS facility at Brookhaven. Occhialini will be joining the team there as a postdoc after receiving his MIT PhD.

RIXS, with its specific sensitivity to the excitons from the nickel atoms, allowed the team to “set the basis for a general framework for nickel dihalide systems,” says Pelliciari. “it allowed us to directly measure the propagation of excitons.”

Bright Prospects For Engineering Quantum Light

Computers greatly benefit from being connected to the Internet, so we might ask: What good is a quantum computer without a quantum internet?



Concept illustration depicting a quantum defect emitting a single photon. Image credit: Mark Turianksy, UCSB

The secret to our modern internet is the ability for data to remain intact while traveling over long distances, and the best way to achieve that is by using photons. Photons are single units ("quanta") of light. Unlike other quantum particles, photons interact very weakly with their environment. That stability also makes them extremely appealing for carrying quantum information over long distances, a process that requires maintaining a delicate state of entanglement for an extended period of time. Such photons can be generated in a variety of ways. One possible method involves using atomic-scale imperfections (quantum defects) in crystals to generate single photons in a well-defined quantum state.

Decades of optimization have resulted in fiber-optic cables that can transmit photons with extremely low loss. However, this low-loss transmission works only for light in a narrow range of wavelengths, known as the “telecom wavelength band.” Identifying quantum defects that produce photons at these wavelengths has proven difficult, but funding from the U.S. Department of Energy and the National Science Foundation (NSF) has enabled researchers in the UC Santa Barbara College of Engineering to understand why that is. They describe their findings in “Rational Design of Efficient Defect-Based Quantum Emitters,” published in the journal APL Photonics.

“Atoms are constantly vibrating, and those vibrations can drain energy from a light emitter,” says UCSB materials professor Chris Van de Walle. “As a result, rather than emitting a photon, a defect might instead cause the atoms to vibrate, reducing the light-emission efficiency.” Van de Walle’s group developed theoretical models to capture the role of atomic vibrations in the photon-emission process and studied the role of various defect properties in determining the degree of efficiency.

Their work explains why the efficiency of single-photon emission drastically decreases when the emission wavelength increases beyond the wavelengths of visible light (violet to red) to the infrared wavelengths in the telecom band. The model also allows the researchers to identify techniques for engineering emitters that are brighter and more efficient.

“Choosing the host material carefully, and conducting atomic-level engineering of the vibrational properties are two promising ways to overcome low efficiency,” said Mark Turiansky, a postdoctoral researcher in the Van de Walle lab, a fellow at the NSF UC Santa Barbara Quantum Foundry, and the lead researcher on the project.

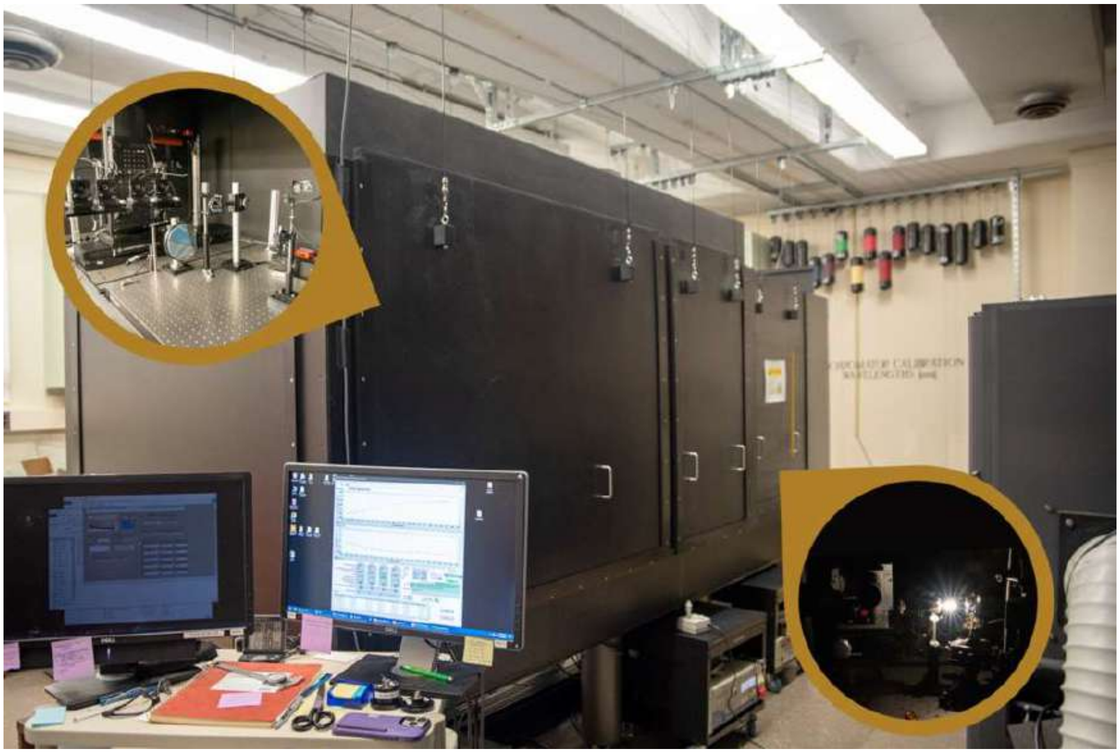
Another solution involves coupling to a photonic cavity, an approach that benefited from the expertise of two other Quantum Foundry affiliates: computer engineering professor Galan Moody and Kamyar Parto, a graduate student in the Moody lab.

The team hopes that their model and the insights it provides will prove useful in designing novel quantum emitters that will power the quantum networks of the future.

From Pandemics To Pedicures: NIST Rebuilds World-Class UV Calibration System

Ultraviolet (UV) light may seem like an invisible hero, quietly disinfecting our hospitals, curing our nail polish, and killing pathogens in our water. But how can we be sure it's being used in ways that are safe and effective?

To help ensure that every UV beam serves its purpose with accuracy and precision, the National Institute of Standards and Technology (NIST) has rebuilt its specialized calibration laboratory, called the Ultraviolet Spectral Comparator Facility (UVSCF), where industry customers send their UV detection equipment to be precisely measured and calibrated.



This automobile-sized black box is the heart of NIST's Ultraviolet Spectral Comparator Facility, which holds the instruments used to calibrate UV detectors. Credit: B. Hayes/NIST

UV light serves a wide variety of applications. The germicidal properties of UV light make it a valuable tool for sanitization and disinfection, especially in health-care settings. It also is an effective way to combat microbial contamination in water and is used for drinking water, wastewater and surface water disinfection. Homeowners use UV-cured epoxy to put new kitchen countertops in place. In the nail salon industry, UV light boxes cure gel nail products. And, in recent years, a proliferation of new consumer products, such as UV-protective clothing, prevent unwanted exposure to UV light. Carefully calibrated UV light sources are needed to ensure that these products work as intended.

Understanding the UV Spectrum

Ultraviolet light is invisible, having shorter wavelengths than the light we can see with our eyes. There are three different categories of UV light based on the wavelength: UVA, UVB and UVC. Wavelength refers to the distance between the peaks of a light wave and, when visible, different colors of light. While NIST’s new calibration system caters to all three, its unique forte lies in accurately measuring UVC light, which falls into the 200-300 nanometer range.

UVC light has shorter, higher-energy wavelengths compared with UVA and UVB. This makes UVC very effective at killing germs and viruses.

“Approximately 100,000 people a year die from health care-associated infections in the U.S. They go into a hospital to be treated for one thing, but then end up with an infection from inadequate sanitization,” said NIST research chemist Cameron Miller. “Using UV light to disinfect rooms and equipment offers a potential solution.”

However, UVC light can also harm human skin and eyes, so it needs to be used carefully.

Organizations that use UV light, from the military and research institutions to universities and industrial manufacturers, can check that UV light sources are emitting the right amount and intensity of light with a compact, hand-held device called a UV detector. Like any other measurement instrument, these detectors need to be calibrated, so users periodically pack them up and send them to NIST’s Ultraviolet Spectral Comparator Facility.

Just as one might calibrate a scale by putting an object of known weight on it, NIST experts calibrate the detectors by exposing them to specific UV wavelengths and comparing their readings to a precisely calibrated standard detector. They then assign the calibration values for each detector.

“We are able to measure UV light at very short wavelengths with extremely high accuracy and precision,” said NIST physicist Jeanne Houston. “The UVC range of the

UV spectrum is the most challenging part to measure, so achieving this level of precision is something we don’t typically see in this field.”

NIST then returns the detector to the customer, who can have confidence in using it to ensure the safety and effectiveness of their UV systems and products.

Serving the Needs of Emerging Technologies

NIST has maintained a UV calibration facility since the late 1980s. However, by the mid-2010s, the facility could no longer meet the needs of emerging technologies such as UV disinfection because it was not optimized for the critical wavelength range needed for disinfection. The COVID-19 pandemic brought a new interest in improving and rebuilding the system.

“Once COVID struck, UV disinfection was hitting the big time and we were able to totally rebuild the system,” said Houston. “We have implemented massive improvements, and it is my opinion that our new facility is the best in the world.”

END OF NEWS LETTER

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