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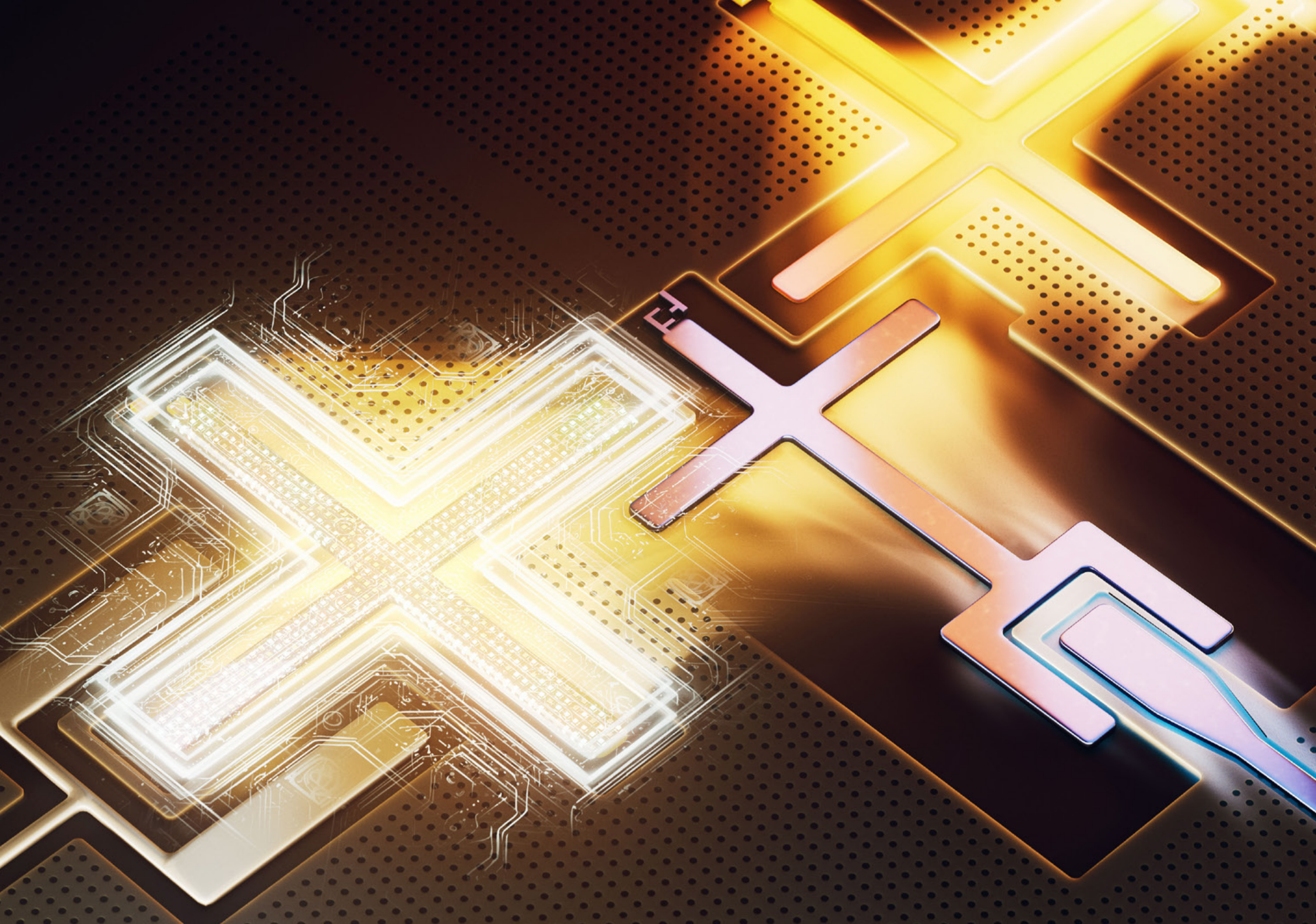

QUANTUM INNOVATORS

INSIGHTS INTO THE R&D INITIATIVES ENABLING TOMORROW'S QUANTUM APPLICATIONS

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ENDEAVOR BUSINESS MEDIA

Spring 2025

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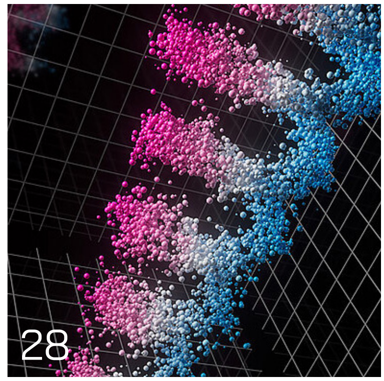

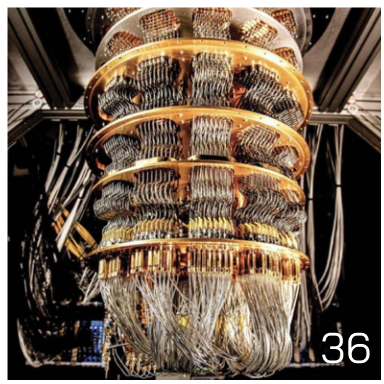

MARKET LEADER, DIGITAL INFRASTRUCTURE Peter Fretty
pfretty@endeavorb2b.com

EDITOR IN CHIEF Sally Cole Johnson
sallyj@laserfocusworld.com

MANAGING EDITOR Lee Dubay
ldubay@endeavorb2b.com

MULTIMEDIA DIRECTOR, DIGITAL INFRASTRUCTURE Justine Murphy
jmurphy@endeavorb2b.com

ART DIRECTOR Kelli Mylchreest

PRODUCTION MANAGER Sheila Ward

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CUSTOMER MARKETING MANAGER Kevin Bennett

EDITORIAL OFFICES
Laser Focus World
61 Spit Brook Road, Suite 401
Nashua, NH 03060
(603) 891-0123
www.laserfocusworld.com

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CEO Chris Ferrell
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Laser Focus World®, USPS Permit 922380, ISSN 1043-8092 print, ISSN 2688-3589 online, is published 9 times a year by Endeavor Business Media, LLC. 201 N Main St 5th Floor, Fort Atkinson, WI 53538. Periodicals postage paid at Fort Atkinson, WI, and additional mailing offices.

Quantum innovation is everywhere

We're busy celebrating the International Year of Quantum Science and Technology in 2025, and there's certainly no shortage of amazing quantum innovation going on during the first quarter.

One thing that may have flown under the radar for you but I want to highlight quickly is the U.S. Defense Advanced Research Projects Agency's (DARPA) Quantum Benchmarking Initiative (QBI), which selected 15 companies to characterize their concepts for a useful, fault-tolerant quantum computer within the next 10 years.

QBI's goal is to verify and validate whether any quantum computing approach can achieve utility-scale operation—computational value exceeds its cost—by 2033.

During Stage A, the companies have six months to provide technical details of their plans. Those who move on to the year-long Stage B will have their R&D approach examined by DARPA and if all goes well will move on to Stage C, where the QBI Independent verification team will put the companies' computer hardware to the test.

Congrats and good luck to Alice & Bob, Atlantic Quantum, Atom Computing, Diraq, Hewlett Packard Enterprise, IBM, IonQ, Nord Quantique, Oxford Ionics, Photonic Inc., Quantinuum, Quantum Motion, Rigetti Computing, Silicon Quantum Computing Pty. Inc., and Xanadu.

In this issue of *Quantum Innovators*, I'm thrilled to welcome our new editorial advisory board members: Andrew Forbes, Tara Fortier, Jean-Michel Ménard, and Birgit Stiller. And thank you to Andrew for writing a fantastic topology piece for us.

We've got a bunch of cool new quantum work for you. Chalmers University of Technology researchers Aamir Ali and Simon Gasparinetti share their breakthrough work with Nicole Yunger Halpern at NIST/University of Maryland to develop a quantum refrigerator that autonomously cools superconducting qubits to record-low temperatures. The cover image is an artistic impression of the working principle of a quantum refrigerator.

Thank you to everyone who contributed or shared their amazing quantum work with us!

Sally Cole Johnson
EDITOR IN CHIEF
sallyj@laserfocusworld.com

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A 'PESTEL' analysis of the global quantum technology ecosystem

Photonics goes beyond merely enabling quantum advances and becomes one of its core industries.

MICHAEL BACZYK

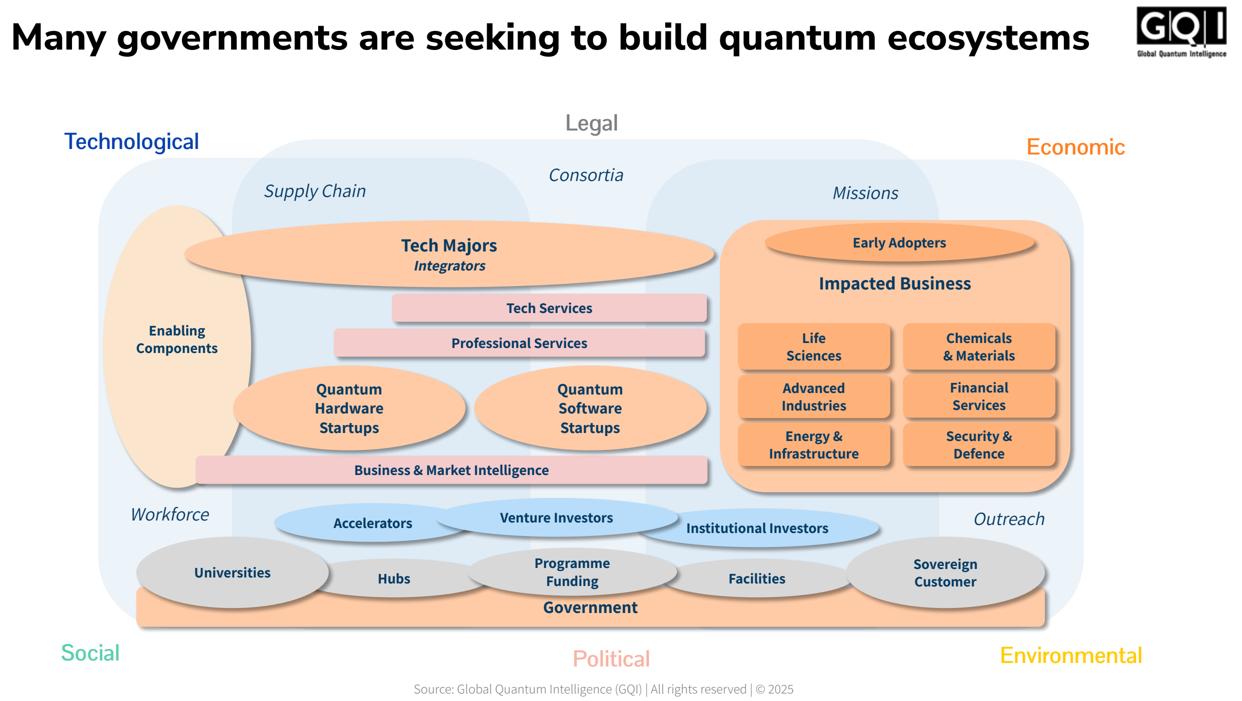
For professionals within the optics and photonics realm, quantum developments create both challenges and opportunities. As critical enablers of quantum systems, optical technologies are at the heart of quantum computing, quantum communication, and quantum sensing. Let's explore the global quantum landscape based on Global Quantum Intelligence's PESTEL framework analysis to provide insights into the ways political, economic, social, technological, environmental, and legal factors shape the industry—and what it means for optics and photonics professionals.

Political: Geopolitics and national strategies

Quantum technology has become a strategic priority for leading nations. The U.S., China, and Europe have all launched multi-billion-dollar national quantum programs.

In the U.S., the National Quantum Initiative Act (2018) structured quantum R&D across multiple agencies, allocating $1.275B for five years. The CHIPS and Science Act of 2022 further expanded funding, and bipartisan support has remained strong with new initiatives like the Defense Quantum Acceleration Act of 2024.

The European Union coordinates efforts through programs such as the EuroQCI initiative, integrating quantum elements into broader



GQI uses a rigorous, data-driven approach to map the quantum ecosystem—systematically tracking over 1,800 quantum technology entities to elucidate the complex network of interrelationships driving field advancements.

technology strategies. China has incorporated quantum into its five-year economic planning, directing both public and private resources into key projects like the Micius quantum satellite.

The U.K., Canada, Japan, Australia, and others are also committing significant resources to building national quantum capabilities.

These programs emphasize technological sovereignty, with governments investing in quantum R&D to ensure national security and economic competitiveness. The U.S. and China are engaged in a race for leadership, particularly in quantum computing and communications, while Europe seeks technological independence through strong public-private collaborations. Geopolitical tensions are leading to restrictions on quantum technology exports, particularly concerning China, as Western nations attempt to secure their supply chains. This environment presents risks for companies operating globally, but also creates funding and partnership opportunities within national quantum ecosystems.

Economic: Investment and commercialization trends

Public and private funding for quantum technology is growing steadily, with venture capital and government grants fueling startups and large tech firms alike. The U.S. leads in private investment, and major players like IBM, Google, and Microsoft are heavily involved in quantum computing. Europe relies more on government-funded academic-industrial collaborations, while China uses a state-driven approach to integrate quantum research into its broader industrial strategy.

Commercialization is accelerating and quantum computing companies are securing partnerships across industries from pharmaceuticals to finance. Quantum sensing applications, such as medical imaging and geophysics, are entering early markets, while quantum communication is advancing through satellite-based networks and secure cryptographic protocols. This expanding market creates supply chain opportunities, particularly for companies that provide enabling technologies like lasers, cryogenics, and photonics components.

In Canada, the National Quantum Strategy (2023) set a long-term vision with projected economic impacts of $142.4B ($99.6M) by 2040. Australia's National Reconstruction Fund allocated $1B AUD ($627M) to quantum and other critical technologies to position the country as a key player in quantum sensing and computing. Across the board, quantum hubs are emerging—such as Waterloo's Quantum Valley in Canada, Munich Quantum Valley in Germany, U.K. Quantum Hubs, and Japan's national quantum centers—and helping to drive commercialization.

Social: Talent and workforce challenges

One of the biggest barriers to quantum progress is a skills gap. The demand for quantum talent outpaces supply, and companies struggle to find experts in quantum hardware, algorithms, and engineering. Governments are addressing this challenge through education initiatives such as the U.S. National Q-12 Education Partnership, the U.K.'s £1.1 billion ($1.3B) training package, and Germany's dedicated quantum master's programs.

For photonics professionals, this presents both challenges and advantages. Those with expertise in optics, lasers, and quantum mechanics will be in high demand as companies scale up their quantum efforts. The integration of quantum principles into engineering programs will also create new career pathways and make quantum knowledge an increasingly valuable skill set.

Technological: Enabling technologies and industry integration

Many quantum computing platforms—such as trapped-ion, neutral-atom quantum processors—depend on high-performance lasers for qubit control and readout. Quantum communication networks require precise single-photon sources and detectors, while quantum sensors leverage ultrasensitive optical and atomic measurement techniques.

Beyond fundamental research, commercialization depends on scalable manufacturing. Companies making photonic integrated circuits (PICs), high-stability laser sources, and quantum-compatible detectors will be essential to the industry's growth. Photonics isn't just enabling quantum technologies—it's becoming one of its core industries.

Environmental: Sustainability and energy considerations

Quantum technology has both environmental costs and benefits. Many quantum computers require cryogenic cooling, which consumes significant energy. But quantum breakthroughs also promise solutions for sustainability and climate tech. Quantum simulations could help develop better materials for batteries. And quantum sensors can enhance environmental monitoring by detecting changes in water levels, pollution, and seismic activity with unprecedented precision.

Beyond fundamental research, commercialization depends on scalable manufacturing.

Legal: IP and regulatory considerations

The rapid progress of quantum technology is creating legal challenges—particularly in intellectual property (IP) and international trade regulations. The race to patent quantum innovations is intensifying, and China is leading in quantum communication patents, while the U.S. and Europe compete in quantum computing IP.

Export controls are also tightening. The U.S. and EU have imposed restrictions on the sale of high-performance quantum computing and cryptographic technologies to certain countries. Companies developing quantum-enabling technologies must be aware of these regulations, because they can impact international business opportunities and supply chain logistics.

Seizing opportunities in quantum: What's in it for the optics and photonics industry?

Quantum technology is no longer merely a research topic—it's becoming a global industry, and optics and photonics professionals are central to its progress. Lasers and optical components are indispensable to quantum computing, communications, and sensing. Companies that embrace quantum-driven opportunities, invest in talent development, and position themselves within the growing quantum supply chain will be well-placed to lead this next technological revolution.

With the transition from research labs to industrial-scale manufacturing, companies supplying high-quality, cost-effective quantum-grade optical components will gain a competitive edge. Governments worldwide are providing funding and regulatory support, which makes it crucial for photonics businesses to stay informed and align their strategies accordingly.

Michael Baczyk is the director of investment advisory for Global Quantum Intelligence (GQI), a business intelligence firm for quantum technology (New York, NY and London, U.K.); e-mail: michael@global-qi.com; https://global-qi.com.

QUANTUM: Problem and solution for the next decade of data security?

Quantum technology is poised to become a revolutionary new threat to data security but at the same time offers a way to better protect it.

NOAH EL ALAMI

In recent years, cybercrime has become a lucrative criminal enterprise and a tool of digital warfare, enabled by cyberattacks that cost companies and governments millions in damages. It compromises trade secrets, personal information, health records, and more. In 2024, half of businesses and around a third of charities within the U.K. reported having experienced some form of cybersecurity breach or attack.

Scary stuff, but how does it relate to the quantum industry? Quantum technology is poised to become a revolutionary new threat to data security, but ironically also a solution to better protect it. Quantum computers can solve certain problems exponentially faster than conventional computers, one of which is the factorization of large prime numbers that underpins one of the most commonly used encryption schemes used today.

But quantum technology also brings us new tools to defend against this threat. These "quantum-ready" data security solutions are being created to secure our data before the threat of encryption cracking by large-scale quantum computers becomes reality.

A post-quantum world

The day quantum computers can break current encryption methods is informally known as "Q-Day" or "Y2Q." Opinions vary about when Q-Day will arrive—ranging from a few years to several decades. Some headlines even suggest it may have already occurred, and national

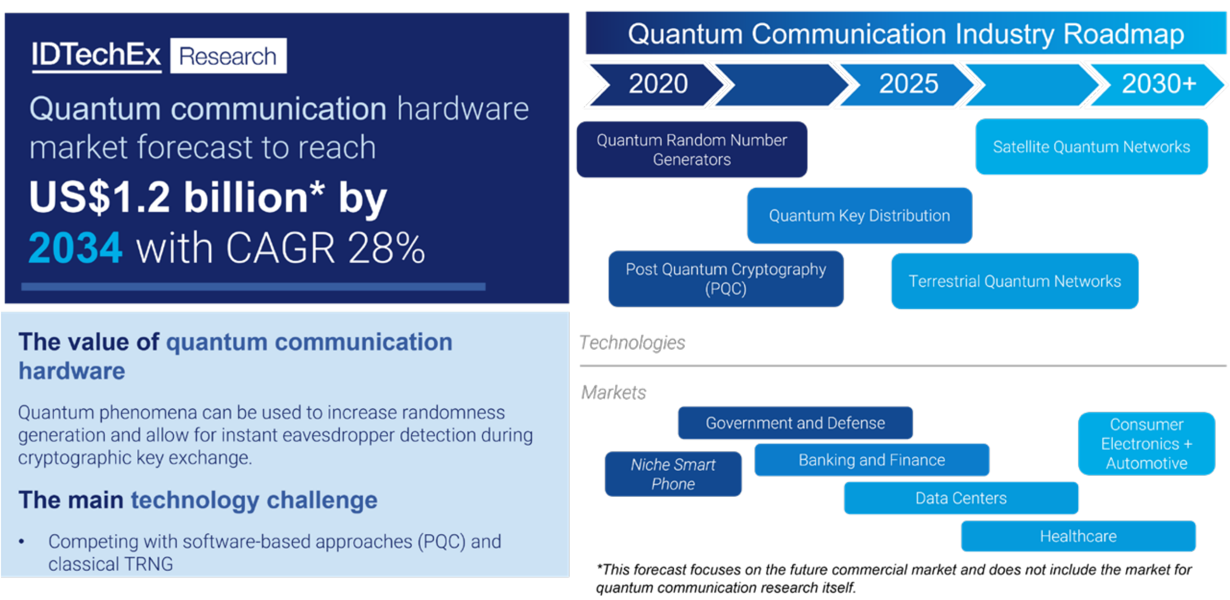


FIGURE 1. Overview of the quantum communications market, which is expected to reach $1.2 billion within the next decade for hardware alone. Credit: IDTechEx

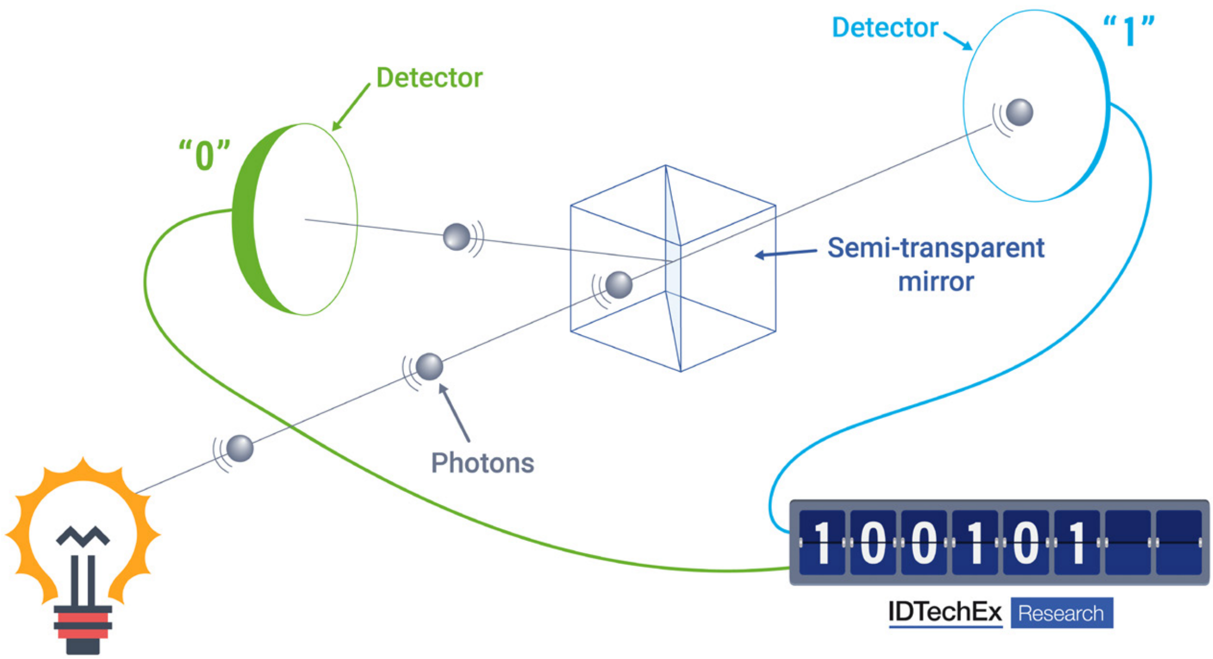


FIGURE 2. Schematic of a quantum random number generator (QRNG). Detecting the path of photons incident on a beam splitter creates a string of ones and zeroes with fundamental quantum randomness. Credit: IDTechEx

security concerns may also lead countries to conceal their actual progress.

Ignoring the quantum threat entirely is increasingly seen as a significant risk. This has spurred investment and interest in "quantum-ready" cybersecurity solutions for both hardware and software. Beyond the threat from quantum computing, these "quantum-ready" solutions are also being aimed at users with long-standing data security vulnerabilities.

The first wave of disruption has already begun as we enter an era of "post-quantum cryptography" (PQC) algorithm adoption. This software-based approach to increasing security essentially changes the method of encryption to a problem that quantum computers should have just as much difficulty cracking as a classical computer. PQC solution providers and governments are raising awareness about the need for crypto-agility, and the market for dedicated quantum-ready platforms is already growing.

Upgrading to PQC is an important first step in defending against the quantum threat. However, long-term safety is expected to depend on quantum hardware, including quantum random number generators (QRNG; see Fig. 1) and quantum key distribution (QKD).

Playing dice with the universe

Exchanging virtual secrets relies on the production and exchange of keys. Once two parties share a key, it can be used to encode messages that only they can decrypt. In the modern era, random number generators (RNGs) create these keys for private and public use. The challenge is that if a key is generated predictably, a malicious third party can deduce the next key and imitate the trusted party. During the past few years, high-profile security breaches have occurred because of poor entropy (randomness) in the numbers used for encryption or, in some cases, even intentional backdoors.

Classical RNGs depend on deterministic processes. While a dice roll may seem to offer statistical randomness, the more you know about the dice, throw, and environment, the more predictable the outcome. Quantum physics, however, is full of nondeterministic and truly random phenomena, such as the number or time of photons emitted, detected, or deflected by a beamsplitter (see Fig. 2). Quantum random number generators (QRNGs) can harness this property to improve the quality of keys generated for cybersecurity.

Chipscale QRNG devices have already been commercialized by the consumer market, with ID Quantique partnering with SK Telecom to integrate their hardware into a line of Samsung smartphones, although these are currently only available in Korea. The newest model, the Galaxy Quantum 5, was released in September 2024. But competition for market share is increasing, and multiple startups are now entering the QRNG industry. These players are finding success within the security industry and areas like gambling and gaming. In the coming years, these players expect cryptography market demands to rise as industry standards become clearer.

Looking ahead, innovation to improve entropy, generation rates, and power consumption will continue. These differentiators already prompted significant stakeholder partnerships in 2024, such as Quantum Dice and BT. But QRNG alone does not offer complete protection from data hackers, and a more complex solution for key distribution may be required.

Quantum keys

Quantum key distribution (QKD) replaces the classical signal pulse with a quantum state of light. Quantum states cannot be cloned or read without disturbing the state, which allows the receiver of the message to detect tampering at a fundamental level. QKD-encoded messages can be sent over existing optical fiber networks, but they require specialized hardware to decode the message.

Quantum networks using QKD are being rolled out within multiple regions and cities, with companies such as ID Quantique and Toshiba deploying their products in pilot projects.

This technology still faces several hurdles. The current limitations on network scalability mean that its primary users are governments and certain financial institutions. The high cost of installing transmitter-receiver pairs, which can exceed a million dollars, remains a significant barrier. Nevertheless, as global efforts to enhance scalability continue, including the development of chipscale QKD, the potential market could grow, especially with trends like V2X and automotive autonomy.

In the near term, there are concerns about the limitations of QKD compared to PQC, particularly for immediate protection needs. Transitioning between cryptographic schemes is a lengthy process, and most experts agree that relying solely on QKD at this stage could be risky.

Furthermore, outside the quantum industry, there is an ongoing ethical debate about encryption, such as how data access rights should differ between law enforcement, government, and social media companies.

Single-photon detector hardware rivalry

Finally, another element of the quantum communications industry is the development of highly sensitive and ultralow-noise single-photon detector hardware to enable QKD systems. QKD systems today are split between semiconductor-based detectors such as single-photon avalanche diodes (SPADs), and superconducting detectors like superconducting nanowire single-photon detectors (SNSPDs).

ID Quantique currently offers both SPAD and SNSPD detectors for applications, including QKD. Meanwhile, the £1.5 million ($1.86M) Innovate UK MARCONI project aims to develop a novel SPAD and SNSPD solution to develop a scalable national QKD network for information security purposes. The SPAD solution will be a cheaper detector for short-range QKD, while the SNSPD will perform better for long-range communications.

It remains to be seen if SPADs and SNSPDs can truly complement each other in developing quantum communications networks in the long term or if players are simply hedging their bets.

> Quantum networks using QKD are being rolled out within multiple regions and cities.

Market outlook

Even ignoring the threat from quantum computers to encryption, existing cryptography technology is increasingly essential and outdated. Almost every industry would benefit from scrutinizing its crypto-agility, including post-quantum approaches.

But the hardware opportunity may be more limited. The adoption of QRNGs is growing, but the competition from incumbent hardware RNG in terms of size, cost, and ease of implantation is very high within the consumer electronics and automotive market. The greater hardware opportunity for both QRNG and QKD is likely limited to data centers in the medium term—a sector with big growth potential, but perhaps more limited than some would suggest from the perspective of quantum communications supply chain players.

Noah El Alami is a technology analyst for IDTechEx, an independent market intelligence company that provides clarity on a range of emerging technologies and how these fit into the bigger picture for data centers, consumer electronics, the automotive industry, and more; e-mail: n.elalami@idtechex.com; www.idtechex.com.

Can commercial quantum computing come to fruition during the next decade?

Billions are currently being invested into quantum computing—and China's outspending everyone else with an estimated funding of £13.3B ($17.6B), while Europe invested £7.2B ($9.5B), the U.S. £2.1B ($2.7B), Japan £1.8B ($2.3B), and the U.K. £1.3B ($1.7B) in 2022.

WILL ASHFORD-BROWN

Traditionally, when scientists and engineers encounter difficulties, they turn to supercomputers to solve them. The computer crunches the numbers and out pops the answer, right? Well, this isn't always the case. Supercomputers aren't so super and struggle to solve certain kinds of problems. So what happens next? We turn to quantum computing. Researchers have long predicted that quantum computers could tackle certain types of problems, especially ones that involve a daunting number of variables and potential outcomes—think simulations or optimization questions—much faster than any classical computer.

While classical computers rely on 0s and 1s, or "bits," to process and relay information, quantum computers rely on quantum mechanics and use qubits (quantum bits) to process and relay information. Qubits can be 0, 1, 1 or 0, 0 or 1, 1 and 1, 0 and 0, all at the same time. This occurs because at the microscopic level, atomic particles such as protons or electrons or ions probabilistically take on states simultaneously. This phenomenon is called superposition. Superposition often takes the form of waves—akin to two musical notes playing at once. Another aspect of the quantum state is entanglement, which refers to the extremely strong correlation that exists between quantum particles even if they are very far away from each other, which Einstein referred to as "spooky action at a distance." In theory, entangled particles will respond together simultaneously regardless of physical separation.

Thanks to superposition and entanglement, quantum computers can do simultaneous computations that classical computers can't. Their ability to rapidly analyze petabyte datasets will be a huge help in medical research, financial services, machine learning, as well as having many applications we haven't even thought of yet. Worryingly, experts believe the power of quantum computers may render conventional passwords and encryption vulnerable to cracking. It would take a traditional computer approximately 300 million years to crack the widely used RSA encryption algorithm, but some estimate the quantum computers of the future may achieve this within 10 seconds.

> Quantum computers can do simultaneous computations that classical computers can't.

What do investors think?

Currently, billions of dollars, pounds, euros, and yen are being poured into the development and productization of quantum computing, with China hosting estimated funding of £13.3B ($17.6B), Europe at £7.2B ($9.5B), the U.S. at £2.1B ($2.7B), Japan at £1.8B ($2.3B), and the U.K. at £1.3B ($1.7B) in 2022.

With a significant proportion of this overall funding being pumped into the U.K., in 2022 quantum computing startup Universal Quantum was awarded at the time the largest government contract for quantum computing. Worth £67M ($88.8M), the award is to create quantum chips for scalable quantum computers for the German Aerospace Centre in Hamburg. This was only recently surpassed by a £496M ($658M) contract awarded by the Australian Government to PsiQuantum toward the end of 2024.

£1.2B ($1.5B) was invested in quantum technology in 2024, with a further £30.25B ($40.12B) committed by governments during the next decade to support developments. Leading into 2025, some of Europe's top quantum startups have seen increased investment, including Quantinuum with £617M ($818M), Alice & Bob with £150M ($198M), Pascal with £140M ($185M), and Riverlane with £131M ($173M).

Is the future quantum?

The market for quantum computing is predicted to grow from £412M ($546M) in 2020 to £8.6B ($11.4B) in 2027, but this feels instinctively like an underestimation. Today's limited offerings will soon be replaced by a new generation of quantum computing platforms and trigger a surge in customer demand.

The market was mostly limited to national research laboratories and supercomputing labs, but commercial adoption is underway, beginning with the tech giants. Microsoft, Amazon, Google, and IBM are all partnering with quantum computing startups to provide quantum-based cloud services or are developing their own machines. By the end of 2025, IBM, for example, aims to build its own quantum computer with 1,000 qubits—which is the point at which quantum computers are expected to challenge the performance of classical counterparts. Google plans to have one by 2029.

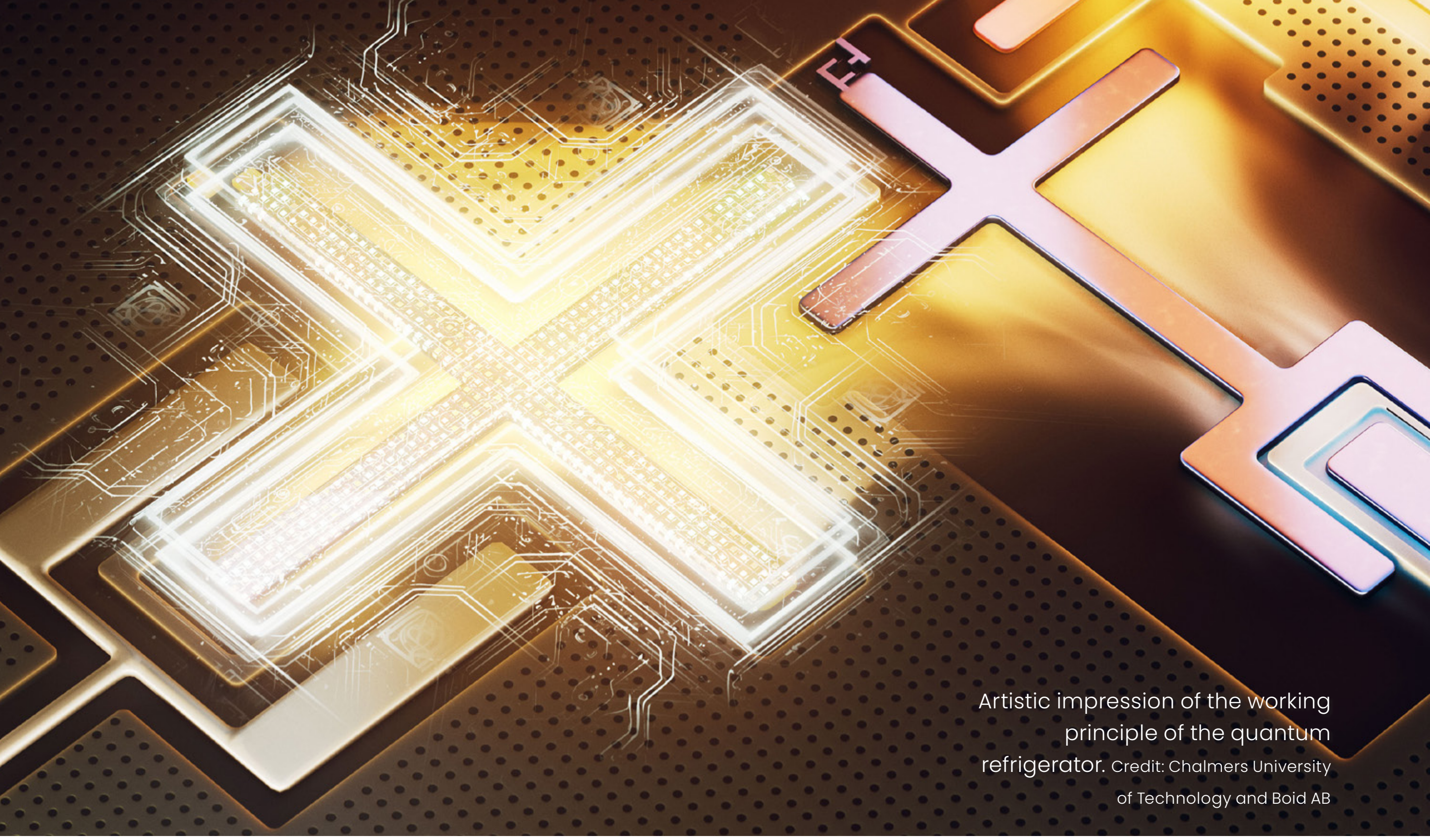
The standing joke within the quantum community for the last 40 years has been that a quantum computer is five to 10 years away—always just teetering on the horizon of possible. Today, we are much closer to achieving commercial quantum usage for real applications and many would argue we've already arrived. Size, cooling, price, speed, and impact are all part of the long tail of improvements being made, but it would seem we're at the point where commercial application, investment, and opportunity are knocking at the door.

Will Ashford-Brown is the director of strategic insights for Heligan Group, an investment bank in Birmingham, U.K.; https://heligangroup.com.

Cooling down the QUANTUM REALM

An autonomous quantum refrigerator marks a milestone bridging the gap between theoretical concepts in quantum thermodynamics and practical applications for quantum technology.

AAMIR ALI AND SIMONE GASPARINETTI



Artistic impression of the working principle of the quantum refrigerator. Credit: Chalmers University of Technology and Boid AB

Quantum computers hold promise for tackling complex problems beyond the reach of today's most powerful supercomputers—from designing new drugs and materials to breaking sophisticated encryption. But these machines operate on the principles of quantum mechanics, which makes them hypersensitive to environmental disturbances and various sources of errors. To perform calculations accurately, the fundamental building block quantum bits (a.k.a. qubits) are often cooled to temperatures near absolute zero and initialized to a well-defined ground state.

A team of researchers led by Professor Simone Gasparinetti at Chalmers University of Technology in Sweden and Professor Nicole Yunger Halpern at the U.S. National Institute of Standards and Technology and the University of Maryland made a significant breakthrough by developing a novel quantum refrigerator that can autonomously cool superconducting qubits to record-low temperatures. This invention, reported in *Nature Physics*,[1] demonstrates the first practical application of a quantum thermal machine that may pave the way for more-reliable and less error-prone quantum computations.

The new quantum refrigerator, visible as the square chip at the center of the copper enclosure, is built of superconducting qudits to cool a target superconducting qubit. Credit: Chalmers University of Technology

The need for a clean quantum slate

Qubits, unlike classical bits that are either in logical state 0 or 1, can exist in a superposition of both states simultaneously. This allows quantum computers to explore a vast number of possibilities concurrently, which can be exploited in quantum algorithms and grant them a computational advantage. But before any computation, qubits need to be initialized in a fiduciary state, often associated with the lowest-energy state, corresponding to the logical state “0”. Any uncertainty in its initial state is an error that can compound to even more errors down the line and derail the calculation. The closer qubits are to their ground state, the more accurate and reliable the subsequent computations will be. One way to set the qubits to their ground states is to cool them extremely well to drain them of any energy needed to be in the excited (logical) state “1”.

Superconducting qubits offer one of the most promising platforms for building a quantum computer. They are cooled to extremely low temperatures using dilution refrigerators, reaching a base temperature below 10 mK. But the qubits themselves are significantly hotter, typically around 50 mK, and cooling them down further becomes exceedingly difficult. This temperature leaves a small but non-negligible likelihood that qubits remain in an excited state, a source of significant error for quantum computing. The quantum refrigerator demonstrated by Gasparinetti, Yunger-Halpern, and coworkers offers a way to reset the qubits to the ground state more effectively by cooling them down to 22 mK, preparing a cleaner slate for computations.

Harnessing heat to create cold

A remarkable feature of the quantum refrigerator is its mechanism: it uses a heat flow within the system to achieve cooling, operating autonomously, without the need for continuous external control. This kind of refrigerator is known as a quantum absorption refrigerator. It consists of three superconducting "qudits"—generalizations of qubits with more than two energy levels. These qudits are engineered to interact with one another and their respective thermal environments.

One qudit is coupled to a warmer environment, acting as a hot thermal bath, to provide the energy to drive the refrigeration process. This hot bath excites this "hot" qudit. The second qudit is coupled to a colder environment, serving as a cold thermal bath, where heat can be expelled. The third qudit is the target qubit that needs to be cooled and reset to the ground state.

This work may inspire further exploration into the potential of autonomous quantum machines.

A precisely engineered three-body interaction between the qudits drives the refrigeration process: a quantum of energy from the hot qudit and a quantum of energy from the target qubit are concurrently transferred to the cold qudit, which then dissipates this energy into the cold thermal bath. This process continues until the target qubit reaches a record-low effective temperature of 22 mK. This temperature corresponds to a high probability (99.97%) of the target qubit being in its ground state—improving on current state-of-the-art qubit reset protocols that "only" achieve 99.8 to 99.9% success probability. While this improvement may seem modest, such gains are significant in the battle against errors in quantum computing.

The experiment was initially designed as a proof of concept, but the research team realized that the machine outperforms all existing qubit-reset protocols and cools the qubit to record-low temperatures.

The significance of autonomous quantum machines

The fact that this useful quantum refrigerator operates autonomously is a significant novelty. Most cooling systems require external energy input like the electricity powering a conventional refrigerator. An autonomous machine, however, draws its power directly from the temperature difference between thermal baths. This not only simplifies the operation, but also potentially reduces the energy and control resources needed to maintain the delicate quantum state of the qubits. This demonstration, the research team points out, marks the first autonomous quantum thermal machine performing a practically useful task. The team also envisions the different-temperature layers of the dilution refrigerator could be used as resourceful thermal baths during computations.

Quantum analogy with typical cooling

The concept of an absorption refrigerator might sound familiar from the macroscopic world. A traditional absorption refrigerator, often used in recreational vehicles or off-grid applications, also uses a main heat source (like propane combustion or solar energy) to drive a cooling cycle, typically involving a refrigerant and an absorbent. The quantum absorption refrigerator operates on a similar principle, using a "hot" quantum system to extract heat from another "cold" quantum system, albeit through fundamentally quantum mechanical interactions rather than classical thermodynamics of fluids.

Just as real-world absorption refrigerators can provide cooling in situations where electricity is scarce, perhaps future iterations of quantum absorption refrigerators could offer practical and localized cooling solutions within complex quantum processors. This could be relevant in other kinds of quantum devices that require sophisticated thermal management strategies.

A cooler quantum future

This is the first demonstration of how quantum thermodynamics, the study of energy and heat at the quantum level, can be harnessed to solve practical challenges in quantum computing. Classical thermodynamics emerged in the 18th century and facilitated the industrial revolution, but so far quantum thermodynamics hasn't been very practical.

This autonomous quantum refrigerator represents a milestone in bridging the gap between theoretical concepts in quantum thermodynamics and practical applications in quantum technology. This work may inspire further exploration into the potential of autonomous quantum machines for tackling other challenges in quantum computing and beyond.

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M. A. Aamir et al., *Nat. Phys.*, 21, 318–323 (2025); https://doi.org/10.1038/s41567-024-02708-5.

Aamir Ali is a research specialist and **Simone Gasparinetti** is an associate professor in the Department of Microtechnology and Nanoscience at Chalmers University of Technology, Gothenburg, Sweden; e-mails: aamir.ali@chalmers.se and simoneg@chalmers.se; www.chalmers.se/en.

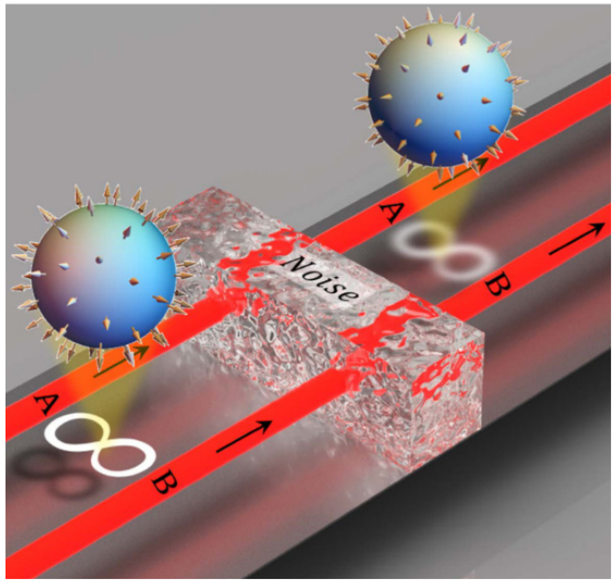
Topology preserves quantum information

Advances in topology work reveal its promise as a tool to embed information into quantum light as well as read it out—forming the basis for a topological alphabet.

ANDREW FORBES

Entanglement, the virtual link by which information can be exchanged across vast distances, is the cornerstone of modern quantum technologies essential for communication and computing. Unfortunately, quantum entangled states are notoriously fragile and decay when they experience a perturbation. This can be as mundane as background and stray light, noisy detectors, lost photons, or defects within materials, common effects in real-world quantum systems, which render the link useless.

How can we overcome the issue of the entanglement decaying so that information flows? The traditional approach is to try to preserve the entanglement, but so far with very limited success. Quantum computers are notoriously noisy, which is a major barrier to their scalability. Recent trends suggest topology—a branch of mathematics—might hold the answer.



Two entangled photons, A and B, are engineered to be topological. After passing through a noisy real-world system, the entanglement decays but the topology remains intact. Credit: Pedro Ornelas

Quantum topological materials

One approach is to engineer materials to be topological to support topological modes. By engineering these modes as quantum states, the entanglement itself can be preserved. This has proven useful in making entanglement sources and waveguides for transport that, even with defects, do not adversely affect the entanglement of the quantum state.

A controversial recent example[1,2] is the announcement by Microsoft of topological qubits using Majorana states, which claim to move fault-tolerant computing tangibly closer. By careful engineering of selected materials, they can form topological superconducting nanowires that support topological modes at their ends—collective states of the electrons within a material that are resistant to noise—and it promises preservation of quantum information. The team claims to be able to read the information out, a key ingredient to using a topological alphabet, although they are careful to say that the evidence itself is not proof that the states were topological.[3]

Photonic topologies

Another strategy recently mooted is to engineer the quantum state to be imbued with topology, without requiring any special materials. It has been demonstrated with photons,[4] and the idea is to give the light a property that is immune to distortion so long as some entanglement exists—even a very small amount. The entangle is allowed to be fragile, but the quantum information encoded into the topology should remain intact. This holds exciting promise for information resilience in real-world systems such as global quantum networks and noisy quantum computers.

To explain how this works, think of two entangled photons, where photon A "lives" in space, while photon B "lives" in polarization. When we measure photon A, it influences the measurement outcome of the polarization of photon B by collapsing its state to some value. This is the entanglement connection between the two—colloquially explained as changing one photon affects the joint outcome with the other—even at a distance. Now, if we measure all of space for photon A, we create a complete map to all the possible polarizations of photon B, wrapping around its sphere one or more times. This wrapping is what we call topology—it's a way of mapping one space onto another. The number of times we wrap the space is the "topological invariant."

Recently, researchers have shown how such photonic topologies can be used to protect information against real-world sources of noise.[5] The team showed that while traditional entanglement observables all decayed as the noise increased, the topological observables remained completely intact until the entanglement itself vanished. This can be seen as a form of "digitization of quantum information" made possible by the discrete nature of the topological observables, which only take on integer values. Discrete signals are always more robust against the effects of noise, which is why our classical systems today are all digital. Just as digital technology has enabled successful classical computation and communication, so too will digital quantum signals allow successful quantum computation and communication under realistic conditions without the need for compensating strategies.

This newfound understanding promises to open a path to constructing a topological toolkit: Tools for putting information into quantum light based on topology, and tools for reading the topological information out. Together they form the basis for a new topological alphabet with the promise of immutability to noise, which is essential for computation and communication by entanglement.

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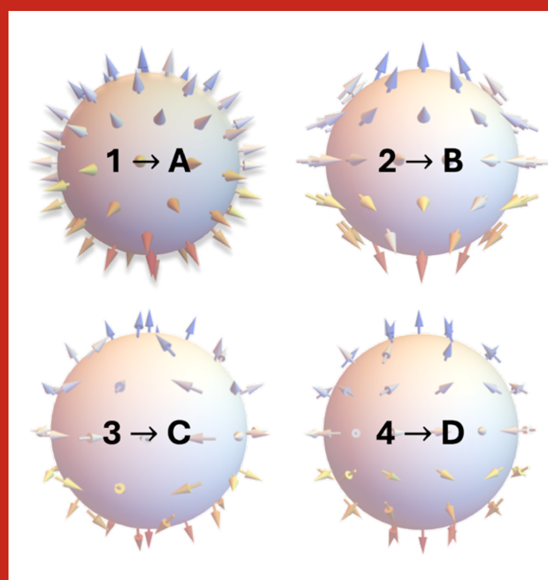
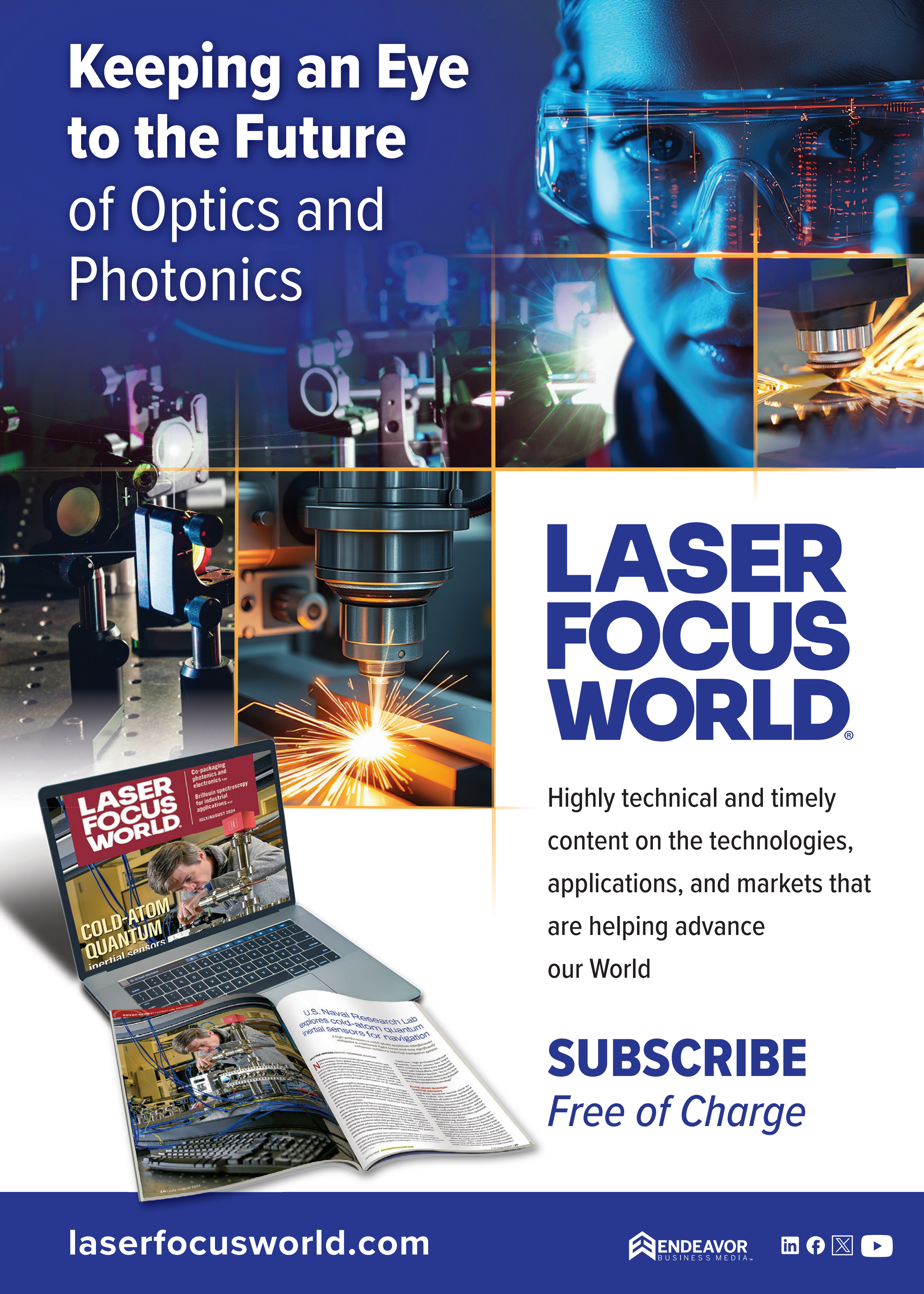
Andrew Forbes is head of the Structured Light Laboratory and a Distinguished Professor in the School of Physics at University of the Witwatersrand, Johannesburg, South Africa; e-mail: andrew.forbes@wits.ac.za; www.wits.ac.za/witsq/research/imaging.

What is topology?

Topology is a global, underlying property of "something," and two "somethings" with the same topology are mathematically equivalent. A popular example is the topological equivalence of donuts and coffee mugs. At face value they look completely different, but they have the same number of holes and can be smoothly deformed from one to the other (think of stretching and squashing the donut into a coffee mug)—because they are the same in a topological sense. This is the mooted benefit of topology: An underlying feature of the system, in this example the number of holes, remains unchanged after undergoing such a deformation. Can this immutability be exploited with quantum light, too? Recent advances paved the way toward a topological alphabet, as shown below.



Quantum topologies, shown as the stereographic projection of vectors on the spheres, could be used as an encoding alphabet. For instance, 1 wrapping of the sphere for the letter A, 2 wrapping for the letter B, and so on. The number of wrappings plays a similar roles to the number of holes in the coffee mug and donut example, for a new form of digitization of quantum information. The challenge is creating the toolkit to read the information out.
Credit: Pedro Ornelas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Aziza Almanakly working on the dilution refrigerator; the quantum interconnect experiment took place inside this dilution refrigerator.

‘Photon-shuttling’ quantum interconnects enable remote entanglement

In this Q&A with Aziza Almanakly, an electrical engineering and computer science graduate student within the Engineering Quantum Systems group of the Research Laboratory of Electronics at MIT (about to become faculty at NYU), she shares her team’s work on a scalable quantum interconnect to enable an all-to-all communication network of superconducting quantum processors.

Quantum Innovators: **What inspired your work with photon-shuttling interconnects?**

Aziza Almanakly: A traditional computer has a motherboard, memory chip, a central processing unit (CPU)—and all of these different components of the computer need to work together to carry out operations. A quantum computer will also require communication between multiple processors. Classically, you shuttle around information with currents in wires. But for quantum computers, transferring quantum information is a whole science of its own because quantum information is very fragile—we’re talking about maintaining a single photon’s coherence (ability to hold quantum information for a specific amount of time). Styles of point-to-point quantum interconnects exist—they connect a chip to another chip—but there hasn’t been a scalable all-to-all interconnect option.

So we designed a new style of quantum interconnect by leveraging waveguide quantum electrodynamics. We can have several chips coupled to a waveguide, which is similar to a wire that can extend as long as we need, so that we can connect all of these chips together in an all-to-all fashion. By emitting and absorbing photons in a particular direction, we can network many chips together on-demand.

***Quantum Innovators:* Can you describe the basic concepts and design work involved?**

Almanakly: A qubit is a quantum mechanical system composed of two energy levels (or states). The simplest example we get from nature is an atom, which can have many energy states, but we can select two to be the ground and excited states. Qubits obey the laws of quantum mechanics. The first principle I will describe is superposition. An atom in a superposition state behaves this way—half of the time we'll measure it in the ground state and the other half in the excited state.

There are many ways to form these two-level systems—I work with a superconducting qubit, which we engineer; it doesn't come from nature. It's a circuit and, once we get to low enough temperatures, we can actually identify these ground and excited energy levels—it's why we call them artificial atoms. We can design them with energies and properties we need.

When an atom is excited and decays, it emits a photon. The same sort of physics is happening here. We couple a qubit to a waveguide and if we excite this qubit, it emits a photon at a frequency that's determined by the difference between the energy levels. The ground state and excited state are 5 GHz apart in our setups, and in our communication modules we have not just one atom but several atoms with connections (couplings) between them. You can think of our module as a molecule—instead of an artificial atom, it's an artificial molecule. By getting these atoms to interact with each other in the way we want, we can get them to emit a photon into the waveguide in the direction we choose. This was the first experiment we did a couple of years ago.

Then we put two of these artificial molecules on the same waveguide and sent photons back and forth between them and used the photons to generate entanglement. Entanglement is a correlation between two qubits that aren't necessarily right next to each other. If you have two qubits in an entangled state and you measure one, you know the state of the other; it's a statistical property and by using photons, you can create entanglement between two qubits that are far apart. Entangled qubits "share" one photon, so either you measure a photon of energy at one qubit or at the other. Entanglement is a key resource for quantum computing in general, and generating remote entanglement enables the implementation of operations between two qubits that aren't local to each other—for the purpose of distributing computation over different modules.

We're using single photons at microwave frequencies. People tend to think of photons as coming from visible lasers—but microwaves are also an electromagnetic field at a different frequency, and if you go to low enough temperatures you can measure single microwave photons. But there is a catch: there is more thermal noise at microwave frequencies, which is why we need to go down to such low temperatures (about 10 mK).

***Quantum Innovators:* How do you create the interconnects?**

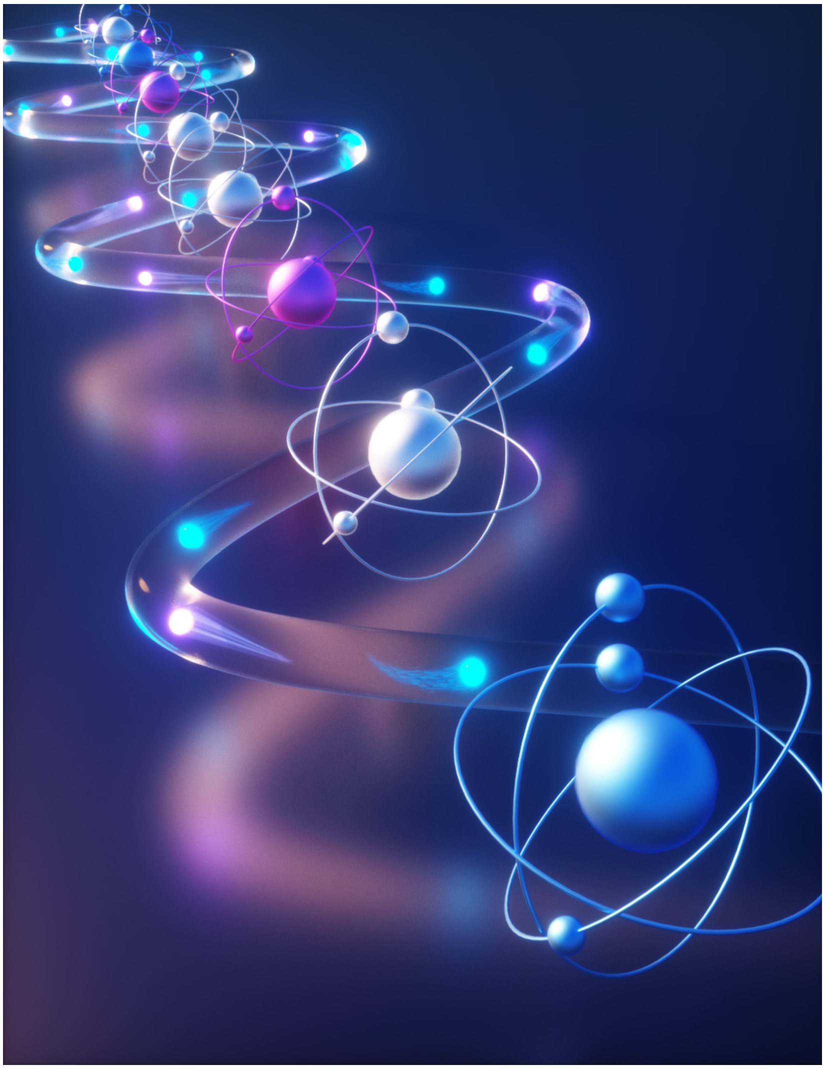
Almanakly: We're using superconducting qubits that operate at microwave frequencies, so the system involves microwave cables and electronics inside a dilution refrigerator. A superconductor is a material through which current flows without resistance. Superconductivity is a property of certain materials at very low temperatures. We use superconducting aluminum to create our qubits.

> Each qubit has a personality of its own and throws temper tantrums, and we need to control all of them with precise pulses.

We take advantage of the consequences of superconductivity to engineer "designer" atoms. In our superconducting quantum interconnect, we have one module of superconducting qubits in one microwave package, and another module in another microwave package, and we connect them with a microwave cable through which we send photons. Using directional photons, we generated entanglement over a distance of about 10 centimeters.

***Quantum Innovators:* What does your interconnect mean in the grand quantum scheme of things?**

Almanakly: Our field is moving from the control of single qubits now to the engineering of larger quantum



Abstract artwork demonstrating the concept of an all-to-all quantum network enabled by this work.

systems, which is another quantum problem in and of itself. A new field called quantum engineering is emerging and it's where our research is going. We get to define this field. How do we control many qubits at the same time and perform high-fidelity operations for computation? This experiment works toward building large quantum systems for distributed computation. Other interconnects exist, but ours is a new variety that has different limitations—it's not perfect. It's another tool in the toolbox. I think a quantum computer architect in the future will find it useful for the computer processor they're designing.

Quantum Innovators: **Any a-ha! moments or surprises along the way?**

Almanakly: Once we optimized the protocol for emitting/absorbing the photon, the entanglement generation was straightforward. We simply stopped the process for emitting the photon halfway through—this meant half of the time we would measure the photon in the waveguide (the photon was emitted) and the other half of the time we would measure the photon of energy in the qubits (the photon was not emitted). The theory I had done before for entanglement generation made me think it was going to be more complicated and I didn't think it would work in this setup and within the time I had. But my advisor, Professor Will Oliver, said to just try it the simplest possible way, and it actually worked—sometimes the easiest way is the best way.

It was very difficult to tune up all of these qubits—this experiment has 16 qubits in total, and while you'd think it's redundant it's really not. Each qubit has a personality of its own and throws temper tantrums, and we need to control all of them with precise pulses. To do this, we turned to machine learning and used a reinforcement learning algorithm to optimize all of the control pulses that we send to our qubits to run the experiment. It was pretty fun to see how much better the algorithm could do than me in tuning up the experiment reliably and repeatedly.

Quantum Innovators: **Any other challenges?**

Almanakly: Even running the fridge itself was a challenge. The experimental apparatus is like a living, breathing system. While I was setting everything up, even getting to the point where I had two chips that met all the requirements and all the control lines were working took between six months to a year because the fridge was acting up.

We use a dilution refrigerator, which mixes helium-3 and helium-4 isotopes that allow us to seemingly magically cool down to temperatures around 10 mK. We call it a circulation—there's a closed loop of these gases circulating through these pumps that cools down the system. The beating heart of the system is the dilution unit/mixing chamber where the two isotopes mix. And while I was doing this experiment, we had to do open-heart surgery on the fridge to replace the inside of the unit.

Our fridge had just been installed when I started, and I helped build it up with all the cabling and equipment that goes inside it—it looks like a chandelier. We'd already spent so much time building it up, and three years later it broke. So we had to take it apart and put it back together again.

The fridge itself is a feat of thermodynamics that needs specialized pumps and compressors. The rest of the lab resembles a standard microwave engineering lab—we operate at around 5 GHz. The lab looks like a server room with the tall shelves and electronic equipment and lots of cables to the fridge. And lots of computers—we need them to control a quantum computer. We're not getting rid of those anytime soon.

***Quantum Innovators:* Coolest part of quantum engineering?**

Almanakly: I really like the research. In quantum engineering we use both fundamental physics and technological advancements, which go hand in hand. We can use fundamental physics as resources for technology, but it also works in reverse. If we have new technology and better engineering, it can enable the discovery of new types of physics. It's what I like about my project—it flows in both directions. The implementation of new physics can create new technology, but state-of-the-art quantum technology allowed us to demonstrate this new physics in the first place. I really like being at this interface—working within the lab and seeing the concepts I've learned come to life, and I like interacting with a living, breathing physical system.

***Quantum Innovators:* Timeline to use?**

Almanakly: We are probably 10 to 15 years out from a large-scale, fault-tolerant quantum computer that can actually have useful applications. It's a really difficult problem and a lot of people from different fields are coming together to work on it.

There was an exciting proof of concept a few months ago that reinvigorated our energy: quantum error correction. Because qubits are very fragile—they're susceptible to lots of noise caused by decay to their environment and introduced by operations—to have reliable computation, you need to be able to correct these errors. In classical, digital bits encoded by transistors, there are very few errors; it isn't really a problem with classical computation. The idea is instead of having just one qubit encode your information, you use multiple qubits to create redundant information so you can catch an error and fix it. The proof-of-principle demonstration of quantum error correction was accomplished by Google Quantum AI last year. When they increased the number of qubits, the logical error rate of the system decreased. They made a system of noisy parts bigger, with more noisy parts, and the system behaved with less error than when it was a smaller system. Pretty amazing, and it shows a path forward for quantum technology.

FURTHER READING

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Photon-counting cameras for the life sciences

With advancing camera technology, wide-field photodetectors with photon-level sensitivity can provide super-resolution, single-molecule tracking, computational imaging, and quantum approaches such as ghost or sub-shot noise imaging.

ZANE PETERKOVIC

Since Robert Hooke and Jan van Leeuwenhoek made their first studies of microorganisms with early microscopes, optical imaging has been at the forefront of advancing knowledge of life and organic materials. A key challenge within the life sciences is imaging photosensitive samples that can easily experience photobleaching, where the strength of the signal dims due to overexposure, and photo damage, where the sample itself is harmed. These effects are prevalent in fluorescence microscopy, which typically use high-intensity laser sources for illumination to gain sufficient signal.

To minimize deleterious effects on photosensitive samples, life scientists illuminate them with low levels of optical power. But this leads to extremely faint fluorescence signals that are very difficult to detect without being swamped by the camera's inherent noise, as well as being limited by the bounds of classical imaging such as shot noise.

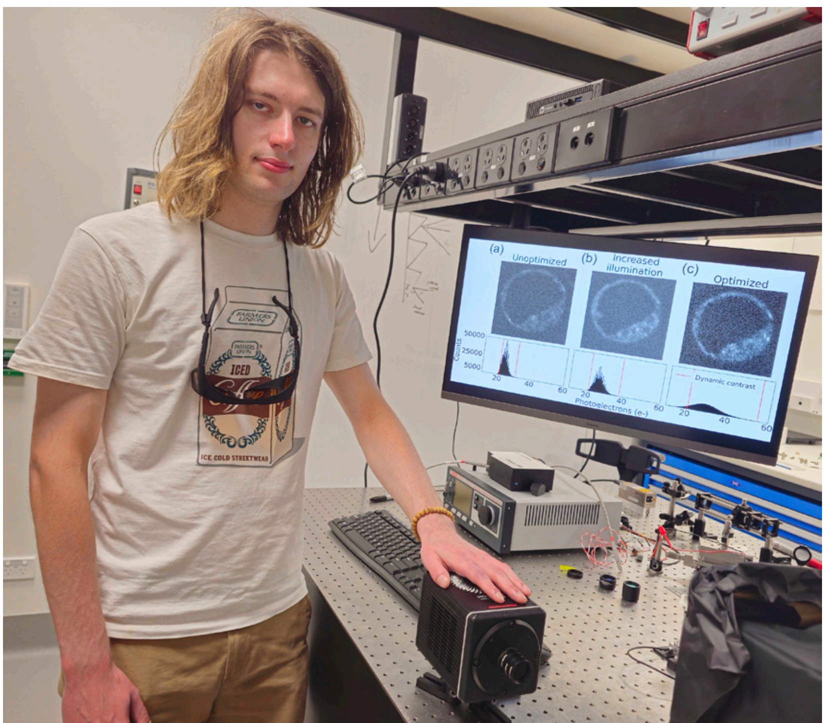
This is where photon-counting cameras come in—they provide sufficiently low noise so that single-photon events can be registered on each individual pixel of the array. It makes them ideal for imaging dim samples with a tight "photon budget."

Bridging the gap between novel camera technology and application to life sciences is not necessarily straightforward—there are different camera architectures available, with numerous user-controlled parameters to be considered and optimized.

The Centre of Light for Life (based in Adelaide, Australia) is well positioned to perform an analysis of cutting-edge camera technologies by combining expertise with sensitive biological samples and extremely "gentle" low-photodose microscopy techniques such as light sheet microscopy. The research was conducted between the groups of Kishan Dholakia and Kylie Dunning and published as a tutorial in *APL Photonics*.[1]

Photon-counting cameras

Digital photography originated in the 1970s with the invention of the charge-coupled device (CCD) array. Advancements such as the development of complementary metal-oxide semiconductor (CMOS) arrays led to



Ph.D. student Zane Peterkovic with a photon-counting camera; the screen behind displays the improvement in quality possible with camera optimization.

such refinement that the ability to snap a picture is now available on every smartphone. Scientists have benefited from the advancement of this technology, and these sensors can detect and register events right down at the single-photon level.

Detection of single photons is only possible due to the exceedingly low electronic noise of modern cameras. Quantum theory gives us only statistical predictions, and therefore it's extremely difficult to distinguish between a photon and a bit of noise, so it must be kept to a minimum.

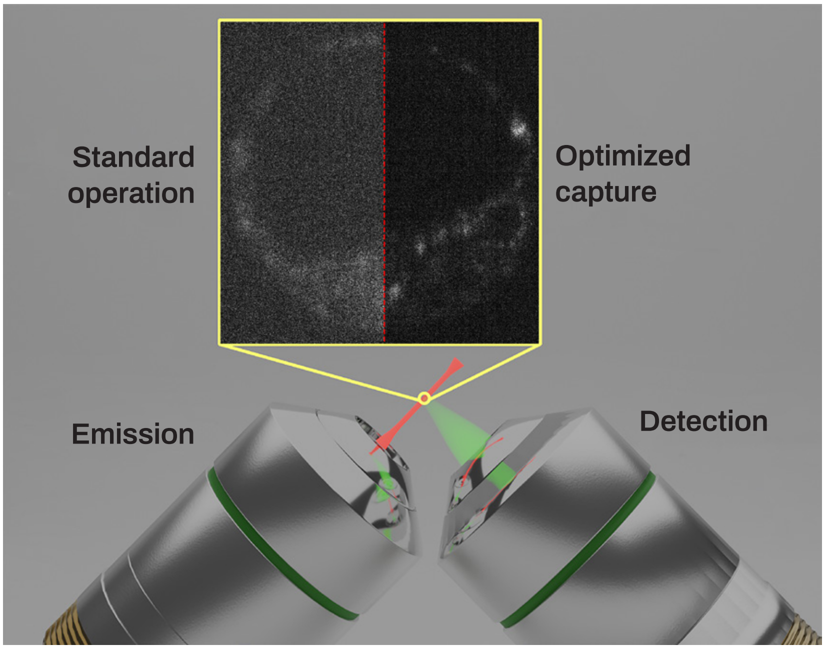
Combating electronic noise, much of which is thermal in nature, makes it necessary to cool camera sensors well below the freezing point of water. Further, instruments such as the electron-multiplying CCD (EMCCD) use what is effectively an internal photomultiplier to reduce electronic noise further—at the expense of introducing "excess noise" from the multiplication process.

Within the past few years the CMOS camera architectures have advanced to being worthy of scientific use. Scientific CMOS (sCMOS) cameras are steadily growing in popularity and sophistication, and the recently released "quantitative CMOS" (qCMOS) architecture of digital camera claims to offer similar photon-detecting capability to EMCCD cameras without the burden of excess noise.

Comparing CCD and sCMOS architectures, there are numerous minor tradeoffs regarding detection efficiency, pixel size, frame-capture rate, and unique sources of noise. While much of this is well understood and familiar to instrumentalists in the case of, say, astronomy, this is not true for the life sciences, which carry a whole host of different challenges (especially in regard to the range of sensible exposure times). Close analysis is necessary to get the most out of these cutting-edge technologies.

A boon for life sciences

Cameras are enormously powerful pieces of technology—images contain vast amounts of information and allow unprecedented insights into the natural world. Cameras are so common they can easily be taken for granted, and it's tempting to adopt a "point and shoot" mindset when snapping pictures. But to be fully rigorous it's necessary to think about every step of the imaging process—from the sample, through the optical system, onto the camera sensor, and into a computer hard drive.



The setup of a light sheet microscope imaging a blastocyst embryo; a system of this type was used for analysis in the tutorial, and the optimization depicts the effects of confocal line scan mode.

Every step in this process can introduce artefacts that distort physical reality, and it's important to be mindful of this in the age of artificial intelligence (AI), where algorithms that only know what we give them are becoming increasingly dominant.

For instance, a major impetus behind our tutorial was to determine whether EMCCD or qCMOS cameras are better suited for quantitative imaging. To make this comparison fair, it was necessary to develop a procedure to determine signal-to-noise and contrast-to-noise ratios for fluorescent images in a way that was independent of pixel size or camera imaging settings. With this in hand, we discovered that the excess noise from the electron-multiplication process in EMCCDs inflated the effect of a fluorescence background, a persistent fact of fluorescence microscopy due to the incoherent nature of the emission.

Certain modern sCMOS/qCMOS cameras include a "confocal linescan mode" which helps to reduce this fluorescent background even further. For quantitative imaging, which may require an accurate biological measurement of relative intensity level, such as is the case for the study of certain metabolic factors, the qCMOS is the better choice. But the presence of row- and column-based fixed-pattern noise in the images can degrade certain datasets, especially those for training AI models. EMCCD cameras remain the most sensitive cameras available, and are still a good option when qualitative image analysis is of interest, such as imaging an extremely weakly fluorescent signal to confirm its presence.

What's next?

The increasing advance of camera technology has a role to play in the "second quantum revolution." For the life sciences, the ability to detect single photons allows another layer of physical understanding to be applied to images captured by microscopes. This could have powerful implications for advanced modalities such as super-resolution, single-molecule tracking, computational imaging, and quantum approaches such as ghost or sub-shot noise imaging. It means researchers must be extremely familiar with the cameras they use to get the most out of them and effectively apply them to the most challenging biological questions of our day, while illuminating the sample as gently as possible—imaging with a light touch.

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Zane Peterkovic is a Ph.D. student at the Centre of Light for Life, Institute for Photonics and Advanced Sensing, University of Adelaide (Australia); e-mail: zane.peterkovic@adelaide.edu.au; www.adelaide.edu.au/centre-of-light-for-life and www.adelaide.edu.au/ipas.

Quantum confinement achieved inside 2D TMD materials

Saiphaneendra Bachu, a Penn State alumni, shares the work he carried out while he was a Ph.D. student at the university in collaboration with scientists at Universite Paris-Saclay exploring how light emitted from 2-dimensional (2D) materials can be modulated by embedding a nanodot inside them.

Quantum Innovators: **What inspired your quantum nanodot work?**
Saiphaneendra Bachu: Quantum confinement is the phenomenon where we confine electrons to a small space and they start to behave in a unique way. In such a scenario, they can be used as qubits that are fundamental building blocks of quantum computers. Also, their energy levels become quantized, which means they become a discrete characteristic enabling single-photon emission—useful for quantum communication applications.

Traditionally, quantum confinement is achieved by shrinking materials down to form nanoparticles and quantum dots, which are known as zero-dimensional materials. We wanted to explore whether we could achieve similar confinement inside 2D materials. Our quest to answer this question kickstarted this work.

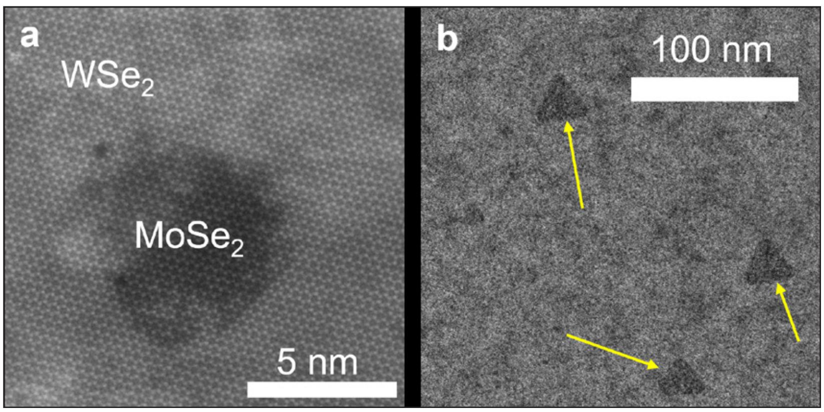

FIGURE 1. Atomically resolved TEM image of a $MoSe_2$ nanodot embedded in WSe_2 matrix (a); low magnification TEM image shows $MoSe_2$ nanodots (yellow arrows) dispersed in WSe_2 matrix (b).

Quantum Innovators: **Can you describe the basic concepts and design work involved? Why 2D materials?**
Bachu: 2D materials are ultrathin sheet-like materials, typically one atom thick, so they are already spatially confined along their thickness direction. A class of 2D materials known as "2D transition metal dichalcogenides (TMDs)" convert from indirect bandgap semiconductors to direct bandgap semiconductors when their thickness is reduced to one atomic layer—and it makes them attractive for light-emitting applications such as light-emitting diodes (LEDs), lasers, etc.

Moreover, light emission efficiency and other electronic and optical properties vary among the family of TMD materials—like molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), molybdenum diselenide ($MoSe_2$) and tungsten diselenide (WSe_2)—because they each have different bandgap energies. By mixing various TMDs (like combining $MoSe_2$ and WSe_2 in specific ratios), we can fine-tune the bandgap to emit light at a specific color/energy. This flexibility in band structures makes 2D TMDs an excellent platform for studying and creating light sources, particularly toward quantum applications.

In our work, we formed nanometer-sized islands of 2D $MoSe_2$, nanodots, and embedded them inside a matrix of WSe_2 (see Fig. 1). The resulting material is a lateral/in-plane heterostructure and it comprises a nearly continuous WSe_2 monolayer interspersed with $MoSe_2$ nanodots of varying sizes under 100 nm. Because of the

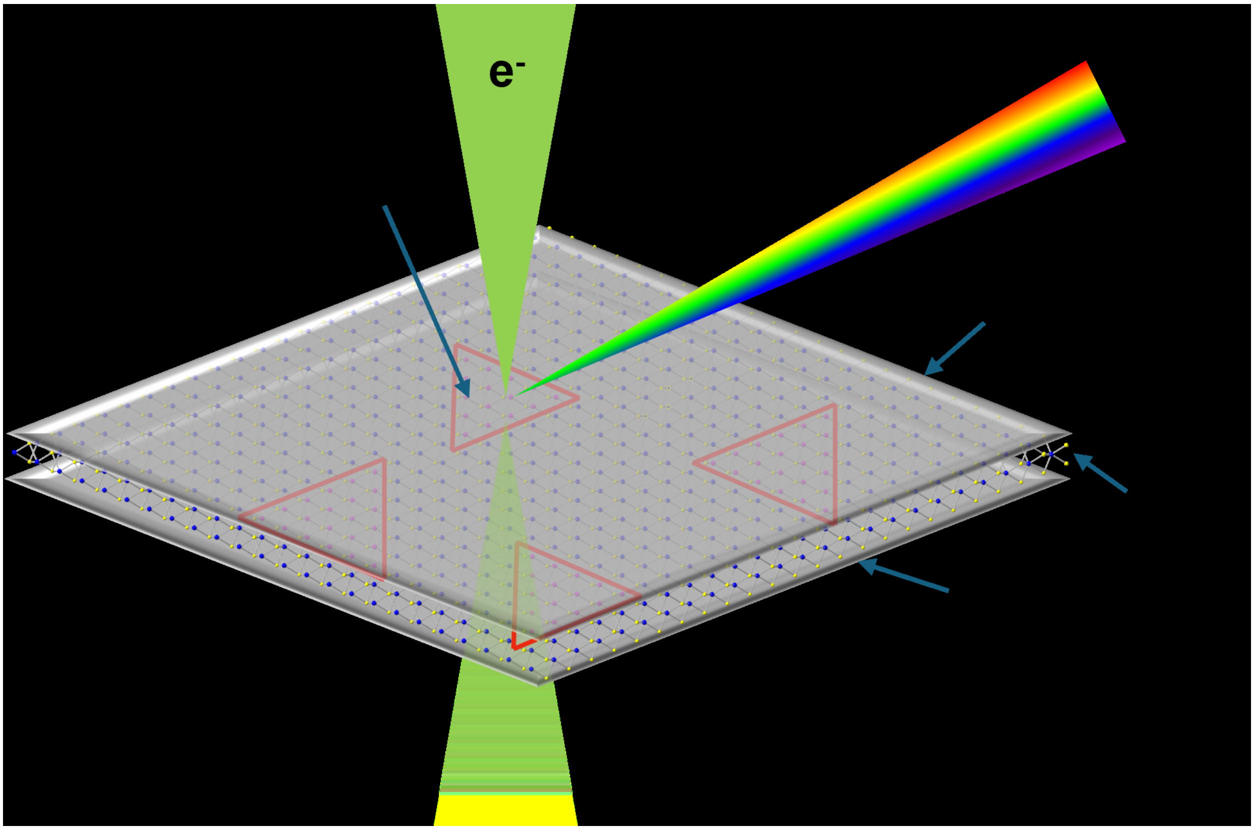

FIGURE 2. An illustration of our experimental setup: $MoSe_2$ nanodots, represented by red triangles, are embedded in WSe_2 matrix and encapsulated by hexagonal boron nitride (hBN) on top and bottom. An electron beam, shown in green, in a TEM is aimed at the heterostructure. The emitted light is collected by a detector.

way the bandgaps of $MoSe_2$ and WSe_2 align at the $MoSe_2/WSe_2$ interface, all the electrons are localized inside $MoSe_2$, and all the holes are localized in WSe_2. The aim of forming this heterostructure is to see if localizing electrons in $MoSe_2$ nanodots can lead to quantum confinement. To detect quantum confinement inside a material, we capture the light emitted by that material and record its energy/wavelength. If the emitted light exhibits higher energy or lower wavelength than normal, it's a reliable indicator of quantum confinement inside the material.

Quantum Innovators: **How does your method work?**

Bachu: To make 2D semiconductor TMD materials emit light, we first need to excite the material using input radiation such as optical lasers or electrons. Upon excitation, these materials form a type of fundamental quasiparticles known as excitons. Excitons are made of an electron and a hole bound together and when they annihilate post-excitation, they emit light. Laser-based optical microscopes are capable of exciting TMD materials toward light emission, but they lack the required spatial resolution to resolve the light emitted from individual $MoSe_2$ nanodots of nanometer size, as is the case in our study.

So we used a transmission electron microscope (TEM) equipped with a light detection system to investigate the light emission and potential quantum confinement from $MoSe_2$ nanodots embedded inside WSe_2. Briefly, we aim a beam of electrons accelerated at a high voltage inside a TEM to excite the heterostructure and detect the emitted light using a detector. This technique is known as cathodoluminescence (see Fig. 2). Electrons accelerated at high voltages have much smaller wavelengths compared to optical lasers, so the resolution of the instrument is incredibly high, enabling us to resolve light emitted by one nanodot from another nearby dot.

Quantum Innovators: **Most surprising/coolest aspects of your work?**

Bachu: One of the initial challenges we faced was that the light emitted from the $MoSe_2$ nanodots was too weak to detect. We brainstormed a few ideas based on previous experience and knowledge from existing scientific literature and increased

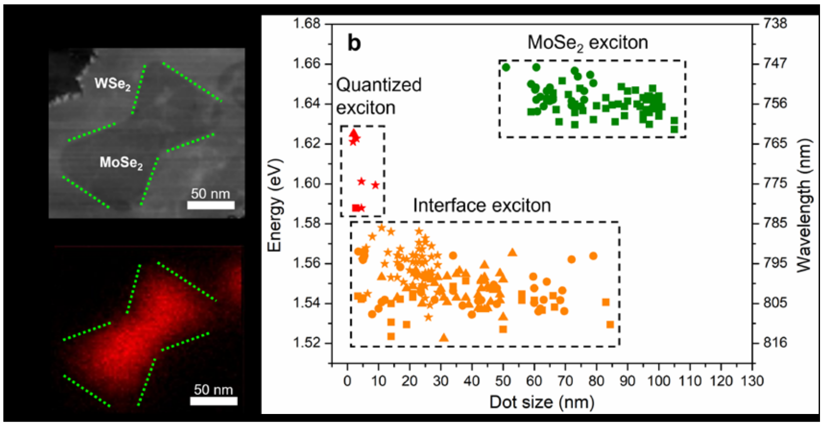

FIGURE 3. A TEM image of a $MoSe_2$ nanodot embedded inside WSe_2 (top left), where the contour of the nanodot is marked by dotted green lines; an artificially colored light emission intensity map of the same region shows the localized light emission from the nanodot (bottom left). A plot of energy of emitted light vs. the $MoSe_2$ nanodot size highlights the evidence of quantum confinement in nanodots under 10 nm in size (right).

light they emit more effectively. This could lead to faster and more secure quantum systems, as well as other customizable, energy-saving devices like higher resolution screen displays.

Quantum Innovators: **Any challenges to overcome?**
Bachu: To fully realize the potential of quantum light sources based on 2D nanodots, future work must focus on precise control of size, spatial position, and area density of nanodots. Once we optimize these aspects during the preparation of the nanodot heterostructures, then we need to comprehensively understand how the nanodots interact with each other in terms of light emission so we can produce quantum nanodot displays reliably and consistently.

the intensity of the emitted light by sandwiching the heterostructure between two sheets of hexagonal boron nitride (hBN), which is a wide bandgap insulator that helps provide more electrons and holes to the heterostructure when exposed to electron beam and also improves the efficiency of light emission.

The first time we detected the light emitted by the $MoSe_2$ nanodots and saw that the light is completely localized inside the nanodots, it was a significant breakthrough for our project (see Fig. 3a). We further observed that the light emission from the $MoSe_2$ nanodots strongly depends on the nanodot size wherein the emission is dominated by $MoSe_2$ excitons in dots larger than 85 nm, and by $MoSe_2$/WSe_2 interface excitons below 50 nm. Interestingly, at extremely small dot sizes (<10 nm), we observe the energy of the emitted light from interface excitons increases, which is clear evidence of quantum confinement (see Fig. 3b). These results validated our hypothesis that we can localize electrons in spatially confined 2D material nanodots and achieve quantum confinement in 2D nanodots under a threshold size.

Quantum Innovators: **What does this mean for quantum computing?**
Bachu: We demonstrated we can confine electrons within the tiniest $MoSe_2$ nanodots and achieve quantum confinement. Also, our results demonstrate that the light emitted by the dots is controlled by the size of the dots. And it should be possible to apply electrostatic gating on the heterostructure to further control the light emission from the nanodots. So our work represents a significant step toward controllably making 2D quantum light sources.

> Quantum confinement 'confines' electrons to a small space, where they start behaving in a unique way.

Quantum Innovators: **Other applications?**
Bachu: By precisely controlling the excitons in materials, like we did in our study, we can manipulate the

Quantum Innovators: **What's next?**
Bachu: This study is just the tip of the iceberg. Next, we plan to work on optimizing our synthesis process to achieve precise control over nanodot sizes and expand the study to other family members of TMDs. We also plan to investigate the interaction between nearby nanodots. Overall, by exploring the role of atomic structure, chemistry, and other factors in controlling light emission while expanding on lessons learned in this study, we can move this research to the next level and develop practical applications.

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Quantum 'tornadoes' experimentally shown within momentum space

Scientists experimentally show electrons form vortices, tornado-like structures, within momentum space—and it's a milestone for quantum materials research.

SALLY COLE JOHNSON, EDITOR IN CHIEF

A quantum "tornado" is a simplified term for an orbital vortex line, and work led by Maximilian Ünzelmann, a Complexity and Topology in Quantum Matter (ct.qmat) postdoctoral researcher at the Universities of Würzburg and Dresden in Germany, experimentally demonstrated electrons form these vortices within the momentum space of quantum semimetal tantalum arsenide (TaAs).

Momentum space describes electron motion in terms of energy and direction—not a precise physical position. Position space is the realm where phenomena like water vortices or hurricanes occur and, until Ünzelmann and colleagues' most recent work, quantum vortices within materials had only been observed within position space.

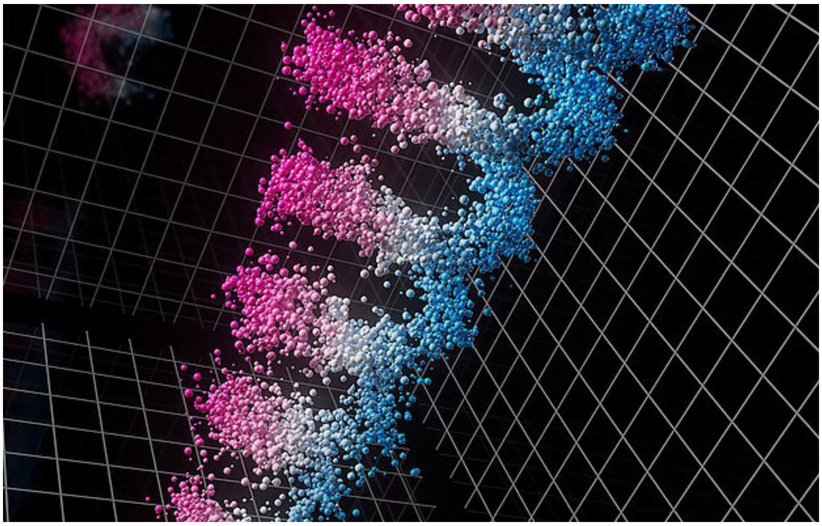
Quantum materials' electronic structure is described within momentum space, in which each discrete point represents an electron wave spread over the entire crystal within position space. And for quantum materials, topological momentum space textures can occur with different shapes—such as charges/monopoles (hedgehogs) or whirls/vortices.

Topology is the basic quantum concept underlying the team's work. Originally a mathematical concept, topology has evolved as a central concept for condensed matter physics—with a focus on quantum materials—during the past few decades.

"It describes nature in terms of geometrical shapes associated with integer quantum numbers—in terms of mathematics, like the number of holes within an object," says Ünzelmann. "In our case, the 'quantum tornado' or the orbital momentum space vortex is a topological object with a well-defined quantum number, which winds around the vortex core."

In 2021, Ünzelmann discovered orbital monopoles (charges) within the same topological quantum materials (TaAs). "These are zero-dimensional point-like structures," he says. "And it inspired us to search for topological line features such as vortices/tornadoes."

Several years prior to this, ct.qmat Cofounder Roderich Moessner theorized that a quantum tornado could



Quantum tornado within momentum space: Quantum material tantalum arsenide's electrons form vortices within momentum space—a physics concept used to analyze how electrons behave within solids. Work by researchers from the Cluster of Excellence ct.qmat at Würzberg and Dresden recently provided the first experimental evidence of these quantum tornadoes.

Credit: think-design/Jochen Thamm

form within momentum space—akin to a smoke ring (which is made of vortices). The problem? No one knew how to measure them.

The team's experiments showed the quantum vortex is created by orbital momentum—electrons' circular motion around atomic nuclei—and as soon as they saw signs that the predicted quantum vortices actually exist and could be measured, they reached out to Moessner and launched a joint project.

ARPES meets dicroism

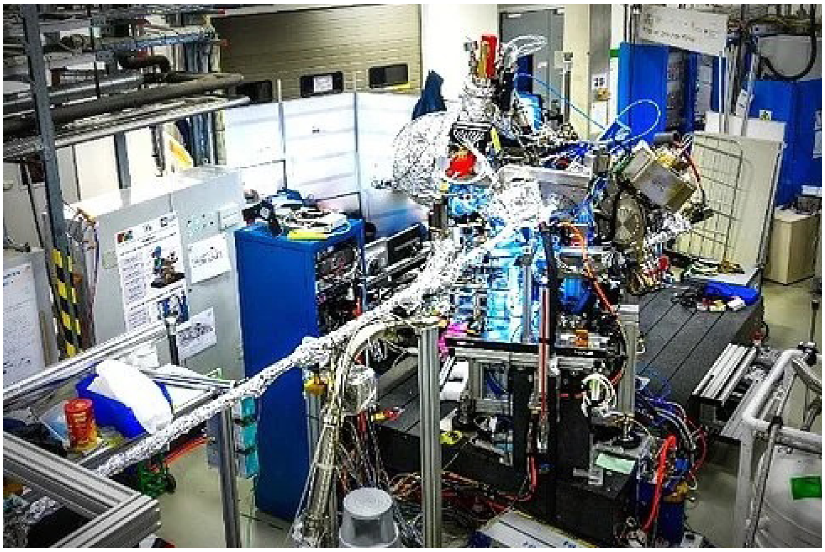
How does the team's topology-based method work? They combine angle-resolved photoemission spectroscopy (ARPES) with linear and circular dichroism to create dichroism ARPES—and image the winding atomic orbital angular momentum.

"Our method relies on the photoelectric effect—described by Albert Einstein," explains Ünzelmann. "Electrons are emitted from sample surfaces upon light irradiation. And we detect the excited electrons as a function of energy and exit angle, so we can analyze the characteristic momentum-dependent intensities (when varying the light polarization)."

When carried out at soft x-ray photon energies, "dichroism ARPES allows us to reconstruct topological textures such as 'orbital monopoles' or, in our case, orbital vortices," Ünzelmann says.

One of the challenges of using this method was to image a vortex-like object that occurs within three-dimensional (3D) momentum space and requires 3D imaging. "Soft x-ray dichroism ARPES lets us take measurements at different photon energies," says Ünzelmann. "In general, this is a standard way to sweep through 3D momentum space. We've now shown that it does indeed allow us to address the 3D dichroism signal and, with it, the vortex."

After the team analyzed the sample layer by layer, they stitched together individual images (akin to medical tomography) to reconstruct the 3D structure of the orbital angular momentum and confirm that electrons form vortices within momentum space.



A shot of the team's lab setup.

Isn't physics/science cool?

Not surprisingly, the coolest aspect of this work for Ünzelmann was actually observing the vortices within momentum space. "The fact that electronic wave functions form such textures within momentum space—and we can measure them—is really surprising and cool," he says. "Who knows what other types of structures exist that we don't know about? For the experimental core team of Hendrik Bentmann, Tim Figgemeier, and me, this observation of vortices was: 'Wow—isn't physics/science cool?!'"

As far as what this means for quantum materials, "these methodological developments may allow us to find novel—so far completely unexplored—phases within quantum materials," Ünzelmann says.

Orbitronics ahead

The team's work is also intriguing for a more application-related research field: Orbitronics. "It aims to make use of the measured quantum degree of freedom in information technologies," Ünzelmann says. "I leave the question of the 'timeline to use' to the specialists within this particular field because it's all basic research at this point."

Ünzelmann and colleagues are now exploring whether this class of materials and textures can indeed "show 'orbitronic' phenomena," he adds. "Another goal is to apply our method to other classes of quantum materials, which are currently of interest within the scientific community, such as chiral materials and altermagnets."

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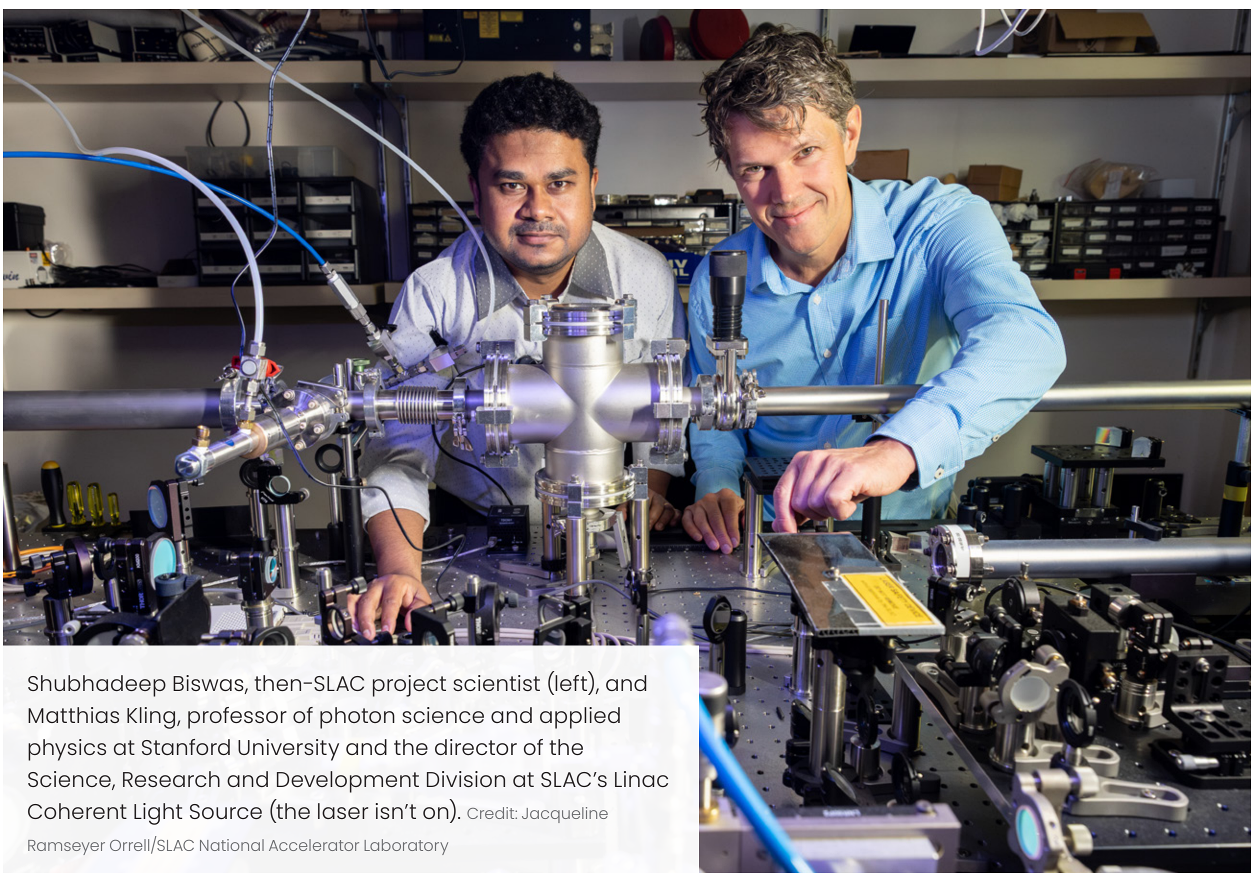
Attosecond XUV laser triggers smallest, shortest dance of electrons ever recorded

First attosecond measurement of electrons excited by ultrafast light pulses dancing around a particle—< 1 nm in diameter—demonstrates insights into nanoplasmonics.

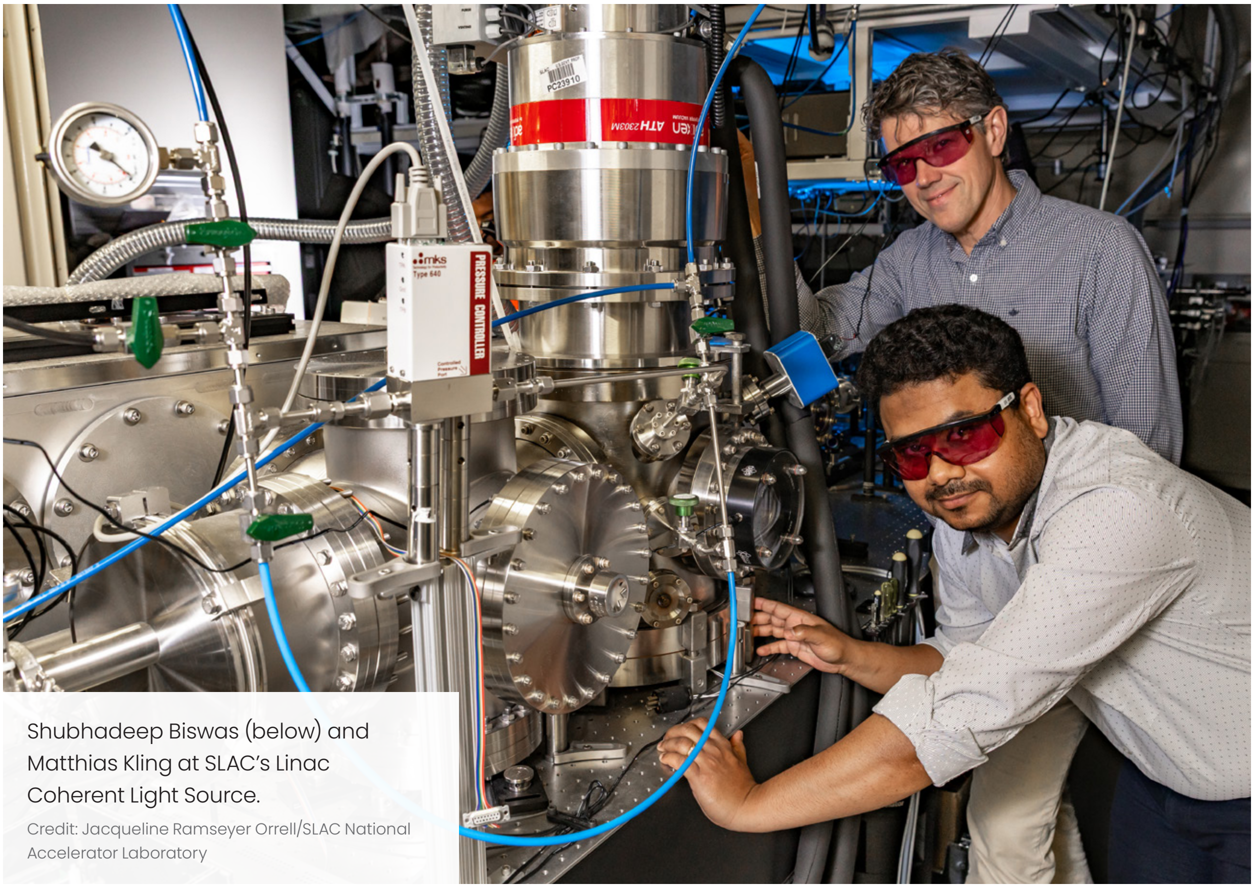
SHUBHADEEP BISWAS AND **MATTHIAS KLING**

The ability to manipulate light at the nanoscale has long been a dream for the field of photonics—and its implications range from more efficient solar cells to high-speed computing. But as researchers delved deeper into nanoplasmonics—the study of the way light interacts with free electrons in tiny metallic structures—they encountered a fundamental limitation: Existing theories and experimental techniques were largely confined to structures at least 10 nm in size. The behavior of plasmonic resonances at even smaller scales, especially below 1 nm, remained elusive.

This motivated a team of researchers to explore the way electrons move collectively at these unprecedented scales. It is well known that plasmons—coherent oscillations of electrons—enable extreme light confinement, but the tools to observe these effects in real time and at the subnanometer level were lacking.



Shubhadeep Biswas, then-SLAC project scientist (left), and Matthias Kling, professor of photon science and applied physics at Stanford University and the director of the Science, Research and Development Division at SLAC's Linac Coherent Light Source (the laser isn't on). Credit: Jacqueline Ramseyer Orrell/SLAC National Accelerator Laboratory



Shubhadeep Biswas (below) and Matthias Kling at SLAC's Linac Coherent Light Source.

Credit: Jacqueline Ramseyer Orrell/SLAC National Accelerator Laboratory

Attosecond laser advances meet nanoplasmonics

Advances in attosecond laser technology now allow capturing events occurring within mere billionths of a billionth of a second, which was the breakthrough necessary to push the boundaries of this field. The result was the first measurement of how electrons, excited by ultrafast light pulses, danced in unison around a particle <1 nm in diameter—demonstrating that attosecond measurements can provide valuable insights for this area.

A recent paper published in *Science Advances* highlights collaborative work between researchers from SLAC National Accelerator Laboratory, Stanford University, Ludwig-Maximilians-Universität Munich, University of Hamburg, DESY, Northwest Missouri State University, Politecnico di Milano, and the Max Planck Institutes of Quantum Optics and the Structure and Dynamics of Matter.[1] Our team focused on exploring the giant plasmon resonance (GPR) within C_{60} fullerene, a molecule composed of 60 carbon atoms arranged in a soccer-ball-like shape.

These fullerenes provide an extreme test case for nanoplasmonics, because they exhibit strong plasmonic resonances—despite their subnanometer size. Unlike larger plasmonic systems, where classical electromagnetic models can be used to describe the behavior of collective electron oscillations, fullerenes require a quantum mechanical treatment to fully capture the role of electron correlations in shaping the plasmonic response. Further, by demonstrating that subnanometer plasmons are governed by many-body electron correlations rather than single-particle excitations, this research challenges conventional wisdom in nanoplasmonics and opens new frontiers for ultrafast science.

Attosecond extreme ultraviolet (XUV) pulses trigger plasmonic excitations

Our experimental methodology used to study these effects involved attosecond extreme ultraviolet (XUV) pulses to trigger plasmonic excitations in C_{60} and measure the time delay between the excitation event and the emission of electrons. This measurement, which ranged from 50 to 300 attoseconds, provided unprecedented insights into the way electron interactions contribute to the plasmonic response at subnanometer scales. Our experimental findings demonstrated that large-scale electron correlations significantly influence the observed plasmon linewidth and emission timing. Unlike the larger nanoparticles, whose plasmonic behavior is adequately described by classical models, our new findings require full-scale quantum descriptions involving electron correlations.

One of the central findings of this study is the role of many-body interactions in shaping the GPR in C_{60}. It revealed that when the collective plasmon is excited, due to large-scale electron-electron correlations, a transient attractive potential is formed in the system. The outgoing electron, which carries the energy for deexcitation, gets trapped in that transient potential and momentarily causes a photoemission delay. This insight challenges previous assumptions that plasmonic effects at nanoscales could be effectively described using classical electromagnetic theories and highlights the necessity of quantum mechanical approaches.

Our experiments used attosecond streaking spectroscopy, a sophisticated technique that allows us to track electron dynamics with attosecond precision. Using the technique, we isolated the effects of plasmonic resonance from other concurrent ionization processes. This enabled a clear interpretation of the correlation-induced photoemission delays observed in C_{60}, and theoretical simulations based on time-dependent density functional theory (TDDFT) provided further validation of the experimental results.

Broad range of future applications

Beyond its fundamental significance, this research has profound implications for future technological applications. The ability to manipulate and control plasmons at the subnanometer scale opens new possibilities for next-generation quantum computing, ultrafast data transmission, solar energy harvesting, advanced catalysis, and highly sensitive molecular detection. Our findings suggest that attosecond plasmonics could be harnessed to create novel light-based computing architectures capable of operating at petahertz (PHz) frequencies—several orders of magnitude faster than current semiconductor technologies. Moreover, the extreme light confinement enabled by these quantum plasmonic effects could enhance the sensitivity of molecular sensors and allow for real-time detection of chemical and biological interactions at the atomic scale.

While the streaking metrology approach used in this study represents a state-of-the-art technique, further improvements in laser pulse shaping and phase stabilization could push the time resolution down to single-digit attoseconds, providing even deeper insights into ultrafast electron dynamics. And the recent advancements of free-electron-lasers (FELs) such as the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory,[2] might be the game-changer. These sources provide high x-ray photon flux for a wide spectral range and ultrashort pulse duration suitable for high temporal resolution studies. Integrating these experimental techniques with emerging quantum technologies could also open new avenues to explore light-matter interactions in hybrid quantum systems, where plasmonic excitations are coupled with solid-state qubits or superconducting circuits.

Another promising research direction is the study of hybrid plasmonic-quantum systems, where plasmonic excitations are coupled to quantum emitters such as quantum dots, excitons, or single-photon sources. These hybrid platforms could serve as building blocks for quantum networks, where information is encoded in entangled light-matter states and transmitted via nanoscale plasmonic waveguides. The ability to control plasmonic coherence on attosecond timescales could lead to significant advances in quantum optics and secure quantum communication technologies.

The implications extend across multiple disciplines—from fundamental physics and computational modeling to applied nanotechnology and biomedical engineering. As researchers continue to refine both experimental and theoretical techniques, the coming decade is likely to witness remarkable progress in our ability to manipulate and control plasmons at the quantum level, which will bring us closer to a future where light-based computing, ultrafast sensors, and quantum plasmonic devices become a practical reality. By pushing the limits of temporal and spatial resolution in electron dynamics, this study lays the foundation for a new era of scientific exploration, where the quantum nature of plasmonic excitations can be fully harnessed for transformative technological applications.

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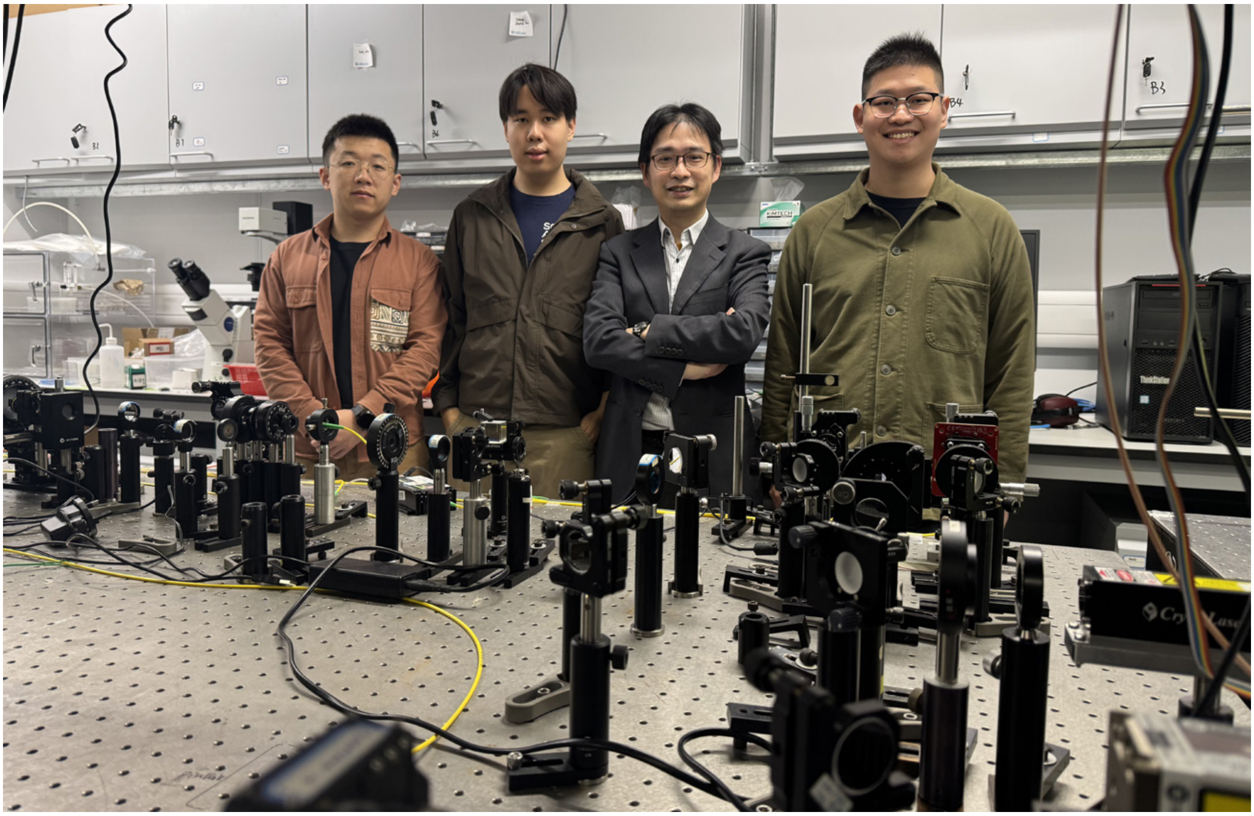
2. See www6.slac.stanford.edu.

Shubhadeep Biswas is an assistant physics professor at the Indian Institute of Science, Bengaluru in India; he was a project scientist at SLAC at the time of this research's publication. **Matthias Kling** is the director of the Science and R&D Division at Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory and professor of photon science at Stanford University.



Quantum holograms via metasurfaces?

Quantum optics and advanced nanophotonics combo enables precise control of entangled holographic information

SALLY COLE JOHNSON, EDITOR IN CHIEF

A new twist on metasurfaces by researchers from the University of Exeter in the U.K. and the Hong Kong University of Science and Technology generates quantum holograms in which polarization and holographic information are entangled.

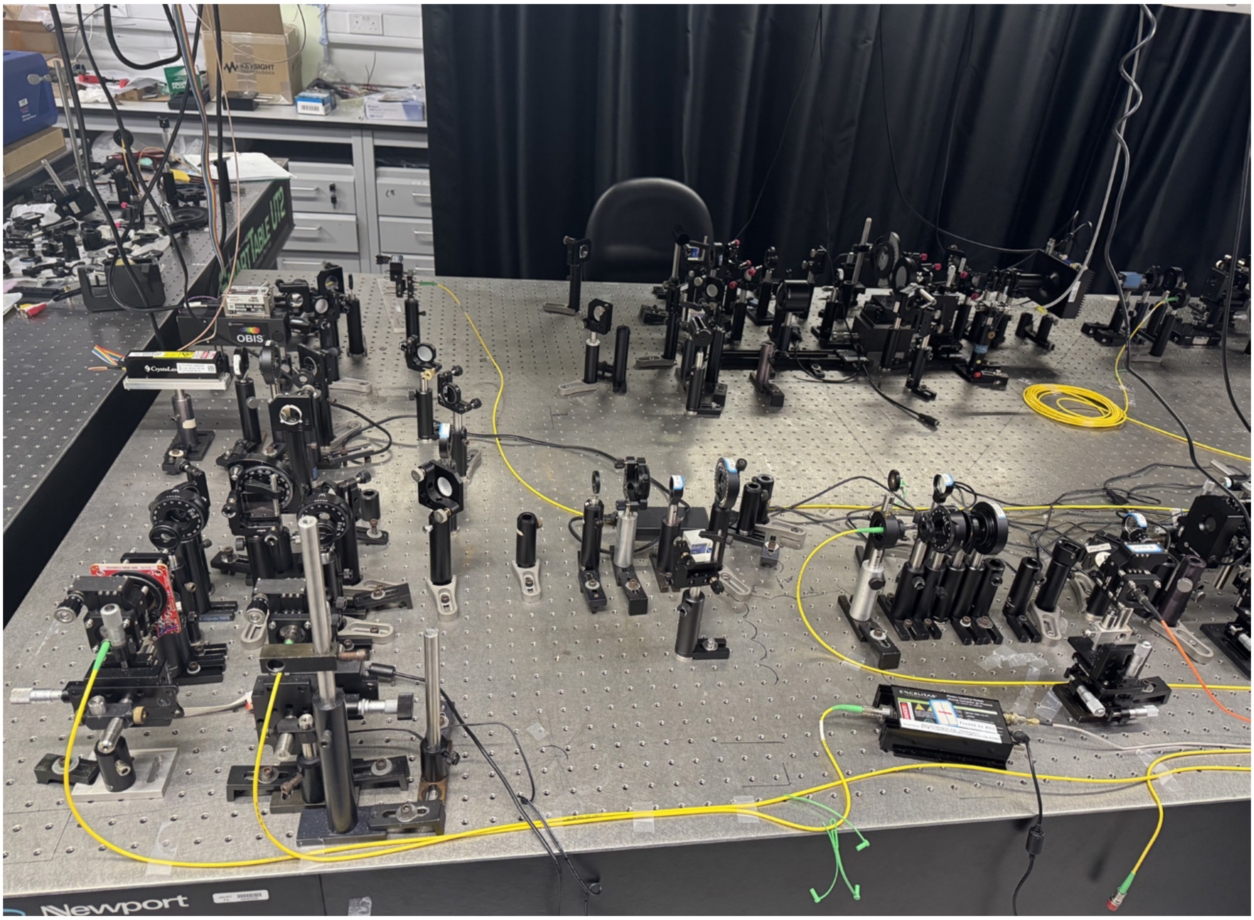
The team's quantum holograms are essentially light patterns with a quantum mechanical property—entanglement—that Einstein famously viewed as "spooky action at a distance."

"We entangle holograms displaying four letters—H, V, D, A—with the polarization of a separate light beam," explains Jensen Tsan Hang Li, a professor of computational engineering and metamaterials at the University of Exeter.

It's intriguing because the correlation is caused by entanglement. "When we measure a photon in one beam to have a certain polarization (horizontal, for example), we see a corresponding destructive interference pattern in the matching letter 'H' within the hologram," says Li. "This demonstrates how quantum information can be encoded and manipulated within spatial light patterns."

Li and his colleagues' work builds on previous research with metasurfaces that manipulate quantum properties of light. "Our work was driven by a desire to extend these quantum optical concepts into the spatial domain," he says. "We became fascinated by the potential connections between

The team—left to right: Qinmiao Chen, Randy Stefan Tanuwijaya, Jensen Li, and Tailin An—with their optical setup.



The team's optical setup for constructing and characterizing metasurface quantum holograms.

traditional holography and quantum entanglement."

Quantum optics meets advanced nanophotonics

The team's work combines quantum optics principles with advanced nanophotonics. Metasurfaces, which are specialized surfaces crafted of subwavelength structures that can manipulate light properties with much greater versatility than conventional optics, are at the heart of their approach.

They designed metasurfaces to respond differently to left-handed vs. right-handed polarized light, which create distinct hologram patterns depending on the polarization state.

"Our design required modifying standard computer-generated holography algorithms," says Li. "The algorithm needs to generate the appropriate phase patterns for our metasurface to produce the desired polarization-dependent holograms."

How do you generate quantum holograms?

How does the team's method to generate quantum holograms work? It begins by generating polarization-entangled photon pairs using a nonlinear crystal of beta-barium borate (BBO). When these photon pairs are created, their polarization is perfectly correlated. If one has left-handed polarization its partner will also have left-handed polarization, and the same for right-handed polarization.

"We direct one of these entangled photons toward our metasurface, which then transforms the photon into a specific hologram pattern that directly depends on its polarization state," says Li.

If the photon has left-handed polarization, a certain hologram pattern appears. With right-handed polarization you'll see a completely different pattern.

"It's fascinating that this process creates an entanglement between the polarization of one photon and the hologram pattern of its partner, the quantum hologram, which stores multiple holograms in an entanglement state," Li says.

Phase relation and timing are everything

A few technical challenges had to be

overcome during the team's experiment. The biggest one was designing the precise phase relation between the two holograms in the entangled state. This phase difference ultimately determines the interference pattern, so the researchers had to carefully control it to successfully erase or maintain the letter pattern.

"We overcame this design problem by using a modified Gerchberg-Saxton algorithm developed by my current postdoc Philip Wai Chun Wong," says Li. "We were surprised by how well this approach worked, and the resulting letter patterns were remarkably clear and well defined."

Another challenge was to get their timing system just right. "In our setup, we use a single-photon detector to capture the photon with polarization information, which is in the shorter path," Li adds. "When this detector registers a photon, it sends a detection signal to our single-photon camera in the other arm to take a picture."

The trickiest part? Tuning an electronic delay in this signal. They had to match it to the path length difference between the two arms of the detector. If the delay is too short, they'd shoot pictures before the partner photon arrived at the camera. Too long and they'd miss it entirely. Getting this timing calibration right is crucial for observing the quantum effects they were exploring.

"The coolest aspect of our work is that we can use this platform to study very fundamental quantum problems," says Li. "We visualized the quantum eraser effect, in which inserting a quantum eraser restores quantum interference, and it actually shows up visually as erasing specific holographic content that we designed."

When they realized this experiment parallels the quantum eraser concept, "it was a genuine 'a-ha!' moment," Li adds. "Our work deepened our understanding of the quantum eraser phenomenon and provided a new way to see these abstract quantum concepts in a more visual form."

Quantum metasurfaces replace bulky optical components

For quantum optics, the team's work shows many traditionally bulky optical operations like generating complex holograms can be performed by an ultrathin metasurface instead of conventional optical components. And miniaturization is crucial for practical quantum technologies.

> The team's work combines quantum optics principles with advanced nanophotonics.

Quantum metasurfaces offer significant advantages because "they're incredibly compact compared to components in traditional optics, provide remarkable design flexibility to create custom light manipulation, and allow us to integrate multiple optical functions onto a single platform," says Li. "These benefits make metasurfaces ideal for miniaturizing quantum optical devices, which is essential for transitioning quantum technologies from lab demonstrations to practical applications."

Anticounterfeiting technology and secure comms ahead

Imagine a credit card or passport with a quantum security feature. "A metasurface would be extremely difficult to copy for two main reasons," explains Li. "First, manufacturing these metasurfaces requires specialized tools to fabricate the tiny subwavelength structures—it makes physical counterfeiting very challenging. Second, the quantum entanglement created by the metasurface adds another layer of security that's difficult to replicate without knowledge of quantum optics."

As for the timeline to practical use, "we're still very much within the research phase," he adds. "It will depend on manufacturing processes advances and integration with existing security systems. My best estimate is it'll be five to 10 years before we might see commercial applications, but the fundamental technology demonstrates a promising new approach to anticounterfeiting."

The team is now working on using their quantum holograms to secure communication systems. "Our research shows these structured light patterns could significantly improve quantum key distribution," says Li. "We expect that this approach has a low error rate and can carry more information per measurement than traditional methods. It's like upgrading from a two-lane road to a four-lane highway—for quantum information. Looking ahead, we plan to scale it up further by modifying our metasurfaces to handle even more complex patterns. The beauty of this approach is that as we increase the complexity we also strengthen the security.

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Break the wiring bottleneck in superconducting quantum chips

A new design that decouples control complexity from the number of qubits replaces the traditional model of individual qubit control with global control and enables multiple qubits to be manipulated via shared control lines.

MARCO POLINI

In the race to build scalable quantum computers, one critical issue has remained unsolved: wiring. As the qubit count increases in superconducting quantum processors, the demand for individual control lines per qubit becomes an insurmountable obstacle—introducing excessive wiring complexity that results in greater errors, higher costs, and packaging and thermal challenges within cryogenic systems.

This inefficient design could require millions of wires in future architectures (see Fig. 1). A new superconducting quantum architecture engineered with a novel control mechanism has demonstrated potential for a dramatic reduction in the wiring demands required to operate large arrays of qubits.

This breakthrough design developed by Planckian replaces the traditional model of individual qubit control with a global control approach to enable multiple qubits to be manipulated via shared control lines. By decoupling control complexity from the number of qubits, this efficient and cost-effective solution keeps wiring at manageable levels as the system grows, which reduces thermal demands and operating costs.

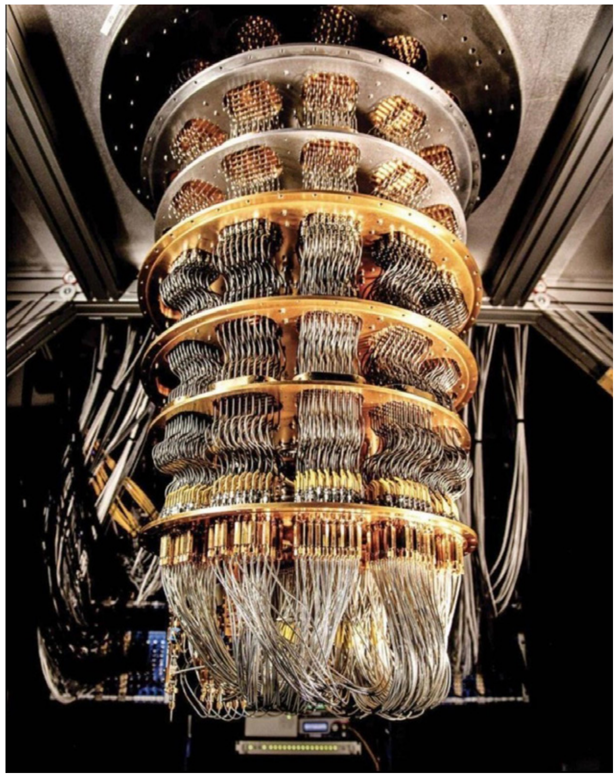

FIGURE 1. The tyranny of wires.

Counterintuitive control

Sending the same control pulse to many qubits at once using global control makes it challenging to get only one qubit to respond while the others remain untouched. How is it possible to perform a logic operation on one qubit if all qubits are being driven with the same signal?

Planckian's solution counterintuitively uses a type of qubit interaction typically held to a minimum. ZZ coupling (see Fig. 2) is a type of interaction between qubits in which the energy levels and resonance frequency of a qubit shift slightly, depending on the state of its neighboring qubit (0 or 1). While these state-dependent qubit interactions are necessary to control and excite a qubit as well as to create entanglement and conduct gate operations, this approach can also lead to crosstalk and errors.

As a result, most superconducting platforms minimize these interactions, instead opting for tunable couplers for dynamic control. But these alternatives often increase circuit complexity and create additional noise sources.

Rather than avoiding ZZ coupling, Planckian's platform exploits it by using the state of a neighboring qubit to block a target qubit from being excited or manipulated. Applying a specific sequence of pulses across qubits driven by the same control lines can use ZZ coupling to create a "blockade effect" that prevents the simultaneous excitation of two nearby qubits.

When two qubits are coupled via ZZ interaction, it's possible to design pulses so only one of them can be excited at a time. If qubit A is already in the excited state, then qubit B becomes off-resonant with the global pulse. It can't absorb energy and stays in place.

This global control approach uses this blockade effect for selective control so that operations are performed only where and when needed. This isolates individual qubits within a globally addressed network and enables them to perform logical operations.

Operations behind the blockade

The system's unique arrangement of superconducting qubits—with fixed always-on ZZ interactions—configures qubits in such a way that only one location at a time has the right local neighborhood configuration to respond to the global pulse.

When a sequence of pulses is sent across the processor, only the target qubit flips or rotates, while others remain untouched due to the blockade. With the blockade effect on the front lines to protect against unwanted excitations, the approach forms the basis for a globally controlled quantum processing unit (QPU) where logical operations are performed by broadcasting carefully timed microwave pulses along shared lines.

This design is natively universal and can implement all necessary gate operations for quantum computation. In its latest iteration, where qubits are connected within a closed-loop geometry, the system supports single-qubit gates and a direct one-shot implementation of the three-qubit Toffoli gate, a fundamental component for many quantum algorithms and error correction protocols.

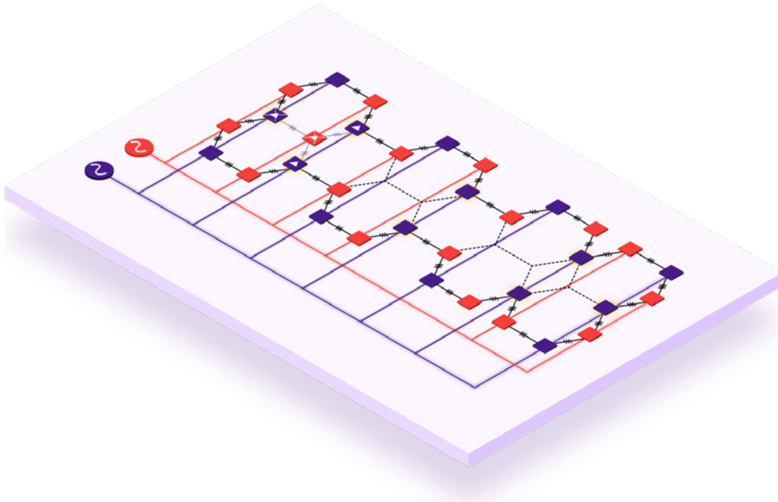

FIGURE 2. This schematic shows the proposed architecture addressing the wiring problem. Black and gray springs represent ZZ coupling between superconducting qubits. Purple and red squares represent two types of qubits, while purple and red lines represent the classical sources separately driving the qubits..

Tackling the scalability crisis

Major quantum players have made headlines with superconducting quantum processors surpassing hundreds of qubits, but these platforms typically require two coaxial cables per qubit to deliver and read out control signals. This means a million-qubit processor could demand as many as 2 million individual wires—and it creates unscalable constraints on cryostat design, thermal management, and signal integrity.

Even at smaller scales, a cryostat for a 150-qubit processor with coaxial wiring costs approximately $5M, with as much as 80% of the cost allocated for wiring.

Planckian's global control approach significantly reduces wiring density to minimize crosstalk, noise, and operational costs while simplifying packaging and cryogenic integration.

As the broader quantum industry marches toward the million-qubit era, this approach demonstrates that innovation in control architectures—not just qubit counts—is crucial to unlocking the power of practical, scalable quantum computers.

Future experiments

While global control schemes have long intrigued quantum theorists, practical implementation was hindered by issues like fidelity, overhead, and selectivity. The new architecture, however, serves as a promising rebuttal—proving it's possible to build a scalable QPU with high fidelities and universal quantum logic.

The next step is further experimental validation, which will include gathering relevant data on key performance metrics to inform its future scale-up, as well as derisking the technology.

Marco Polini is the chief scientific officer of Planckian and a full professor of condensed matter physics at the University of Pisa (Italy); www.planckian.co.

Quantum-resilient edge computing: A blueprint for a decentralized, sustainable future

Balancing quantum resilience with eco-consciousness, Vogon Cloud is designed for a future where technology and sustainability go hand in hand.

SEAN MICHAEL BREHM

Data is the new oil in our modern, data-driven world, needed to power everything from the global financial markets to the latest trending meme on social media. This reality is driving unprecedented demand for data infrastructure and pushing traditional systems to their limits.

A 2024 report from Meticulous Research projects the global market for cloud computing will grow to more than $1 trillion by 2030, with a compound annual growth rate (CAGR) exceeding 15%, which further fuels the urgent need for sustainable, scalable, and secure cloud infrastructure.

Vogon Cloud, a solution from Spectral Capital, is rising to the challenge, delivering quantum-resilient edge computing that combines decentralized processing with distributed quantum ledger database (DQLDB) technology. It addresses common challenges associated with latency, scalability, and environmental sustainability that traditional cloud systems face.

Core value proposition: Edge computing reimagined

At the heart of Vogon Cloud's value proposition are its meticulously designed modular data centers that offer a unique solution to address latency and network congestion typically faced by traditional edge computing infrastructure.

These data centers are constructed from graphene-enhanced concrete and consist of five specialized 40-foot containers: one for battery storage, one for network operations, and three housing an array of 1,504 servers each. The platform optimizes resource allocation and environmental impact by positioning these modular centers within urban environments, underutilized spaces, or regions with natural cooling advantages.

This infrastructure is not only agile and sustainable but also highly adaptable and capable of supporting applications with varying demands, from the low latency requirements of Internet of Things (IoT) systems to resource-intensive computation powering AI and real-time analytics. Its DQLDB-driven architecture ensures robust, cross-regional data connectivity and quantum-level security to empower organizations to scale digital operations without compromising performance or sustainability.

Diverse industry applications

Vogon Cloud's infrastructure addresses the unique challenges and requirements of industries ranging from finance to healthcare, as well as the wide-ranging applications of technologies such as IoT. Financial institutions must adhere to stringent security and compliance requirements. Its encrypted, decentralized ledger system reduces vulnerability to fraud and cyberattacks while ensuring tamper-proof data handling. Healthcare is similar in its highly regulated nature and requires sensitive medical information be safeguarded through robust encryption and handled in compliance with regulations like HIPAA.

Its infrastructure not only offers this high level of security, but its decentralized architecture also ensures rapid access to patient data and medical research to enable quality care and effective collaboration. IoT technologies have the potential to transform a range of sectors, but fragmented infrastructure has limited its scalability and success to date. These applications can benefit significantly from an edge-first architecture.

By supporting real-time processing, robust security, and sustainable energy use, the platform redefines IoT's potential by transforming it from a concept with unrealized potential into a practical solution ready for a truly connected world. By leveraging deterministic concurrency, consensus validation, and state-of-the-art encryption, it meets the stringent operational standards across these sectors, while its decentralized nature enhances data privacy and security to provide truly scalable infrastructure for an interconnected economy.

Environmental commitment and sustainable infrastructure

Spectral Capital's commitment to sustainability is reflected in Vogon Cloud's business model. Each data center is designed to use renewable energy sources like wind and solar, significantly reducing the carbon footprint and energy costs of data processing while concurrently transforming the operation into an eco-friendly, revenue-generating entity. Each modular unit is designed to support up to 15,000 small- and medium-sized enterprises (SMEs) or up to 150 large enterprises, making it possible for organizations to reduce their environmental footprint without sacrificing performance.

These units can be deployed in underused urban spaces or water-cooled locations, which creates new opportunities to partner with landowners, investors, and businesses. Spectral Capital takes great pride in Vogon Cloud's industry leadership, supporting a digital ecosystem that drives innovation and aligns with global climate objectives.

Quantum-resilient security architecture

As quantum computing advances, traditional encryption methods become increasingly vulnerable to sophisticated quantum attacks. Recognizing this, Vogon Cloud integrates SPHINCS+ post-quantum cryptography within its distributed quantum ledger database (DQLDB) to fortify data security and protect against these emerging threats. Each transaction within Vogon's DQLDB retains immutable time-stamped and detailed provenance records to ensure data integrity and support governance, compliance, and auditability. Vogon Cloud's quantum-resilient framework provides robust cross-regional data sharing and coalition-based, real-time support. This architecture enables organizations to confidently address both current and emerging cybersecurity challenges.

2.0- to 5.5-MWh sodium-ion battery energy storage solution (BESS)

At the core of the platform's energy infrastructure lies a powerful 5.5-MWh sodium-ion battery energy storage system (BESS) engineered for long-term sustainability. With a lifespan of over 25 years and an energy efficiency rate of more than 90%, the system maintains consistent energy performance regardless of environmental conditions, including the ability to withstand extreme temperatures.

The high-capacity BESS system enables Vogon Cloud to store surplus energy from renewable sources such as solar and wind, which extends its reliability and efficiency even within remote, rugged, or harsh locations. This energy strategy not only provides consistent high-performance energy delivery, but also supports its broader environmental commitment to sustainable operations and ecological preservation goals.

Future of digital infrastructure: Security, scalability, and sustainability

Vogon Cloud represents a paradigm shift in data infrastructure by delivering a new model tailored to the evolving needs of a digital-first economy. Decentralized edge computing minimizes reliance on centralized data hubs to enable localized data processing to meet the needs of latency-sensitive applications—from AI analytics to real-time data streaming.

The platform's DQLDB structure is underpinned by consensus groups and deterministic concurrency to provide a scalable and flexible structure that can efficiently expand across regions. This design ensures a balance between security, scalability, and sustainability, which allows industries to grow their operations responsibly while meeting the demands of the digital age and emerging intelligence age.

These units can be deployed in underused urban spaces.

Driving innovation today and tomorrow

Vogon Cloud offers more than just a data solution—it delivers a strategic, comprehensive blueprint to empower visionaries and tech pioneers to build a secure, sustainable, interconnected digital economy for today and tomorrow. By balancing quantum resilience with eco-consciousness, Vogon Cloud enables companies to grow and innovate without compromising their environmental values. With a platform designed to meet the evolving challenges of modern computing, it promotes a future where technology and sustainability go hand in hand, unlocking human potential and redefining the possibilities of the digital age.

Sean Michael Brehm is the chairman of Spectral Capital Corporation, Seattle, WA; www.spectralcapital.com.