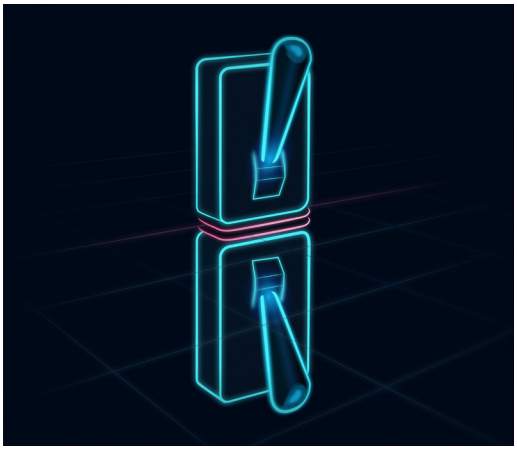
Quantum Hits the Big Time

ORNL is making the quirky world of quantum mechanics work for us

July 28, 2025

Of all areas of science, quantum mechanics — which studies the eccentric behavior of matter at its smallest scales — is perhaps the most perplexing.

In this microscopic world, the term "particle" takes on a new meaning, with electrons, photons and the like behaving sometimes like particles and sometimes like waves. They can exist in a superposition of multiple possible states at the same time until they are measured.

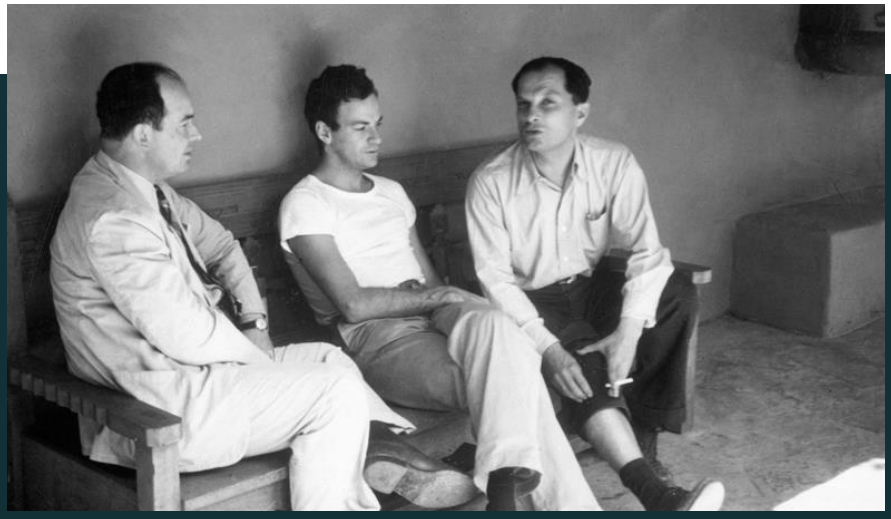


Imagine a quantum switch that can simultaneously be pointing up and down, representing both possibilities at once. This is called quantum superposition.

Particles can also be entangled, meaning that the quantum state of one particle is intrinsically linked to the state of another, even if it is at the other end of the universe. This is known as quantum entanglement.

If you think the quantum world is strange, you're in good company. Even the pioneers of the field thought so.

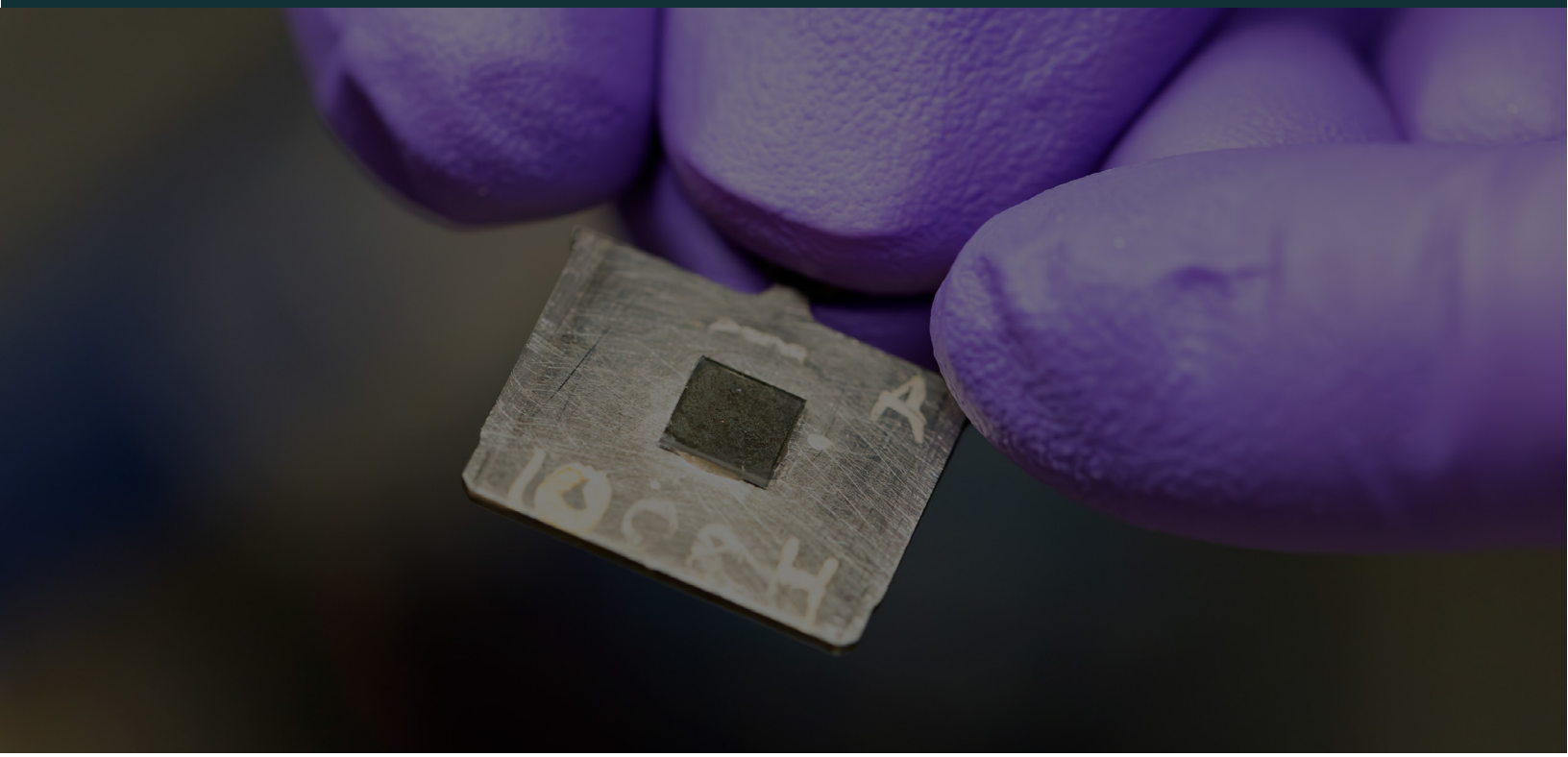
Richard Feynman, Nobel Prize-winning physicist and superstar quantum scientist, made the point during a 1964 talk at Cornell University, **comparing quantum mechanics to Einstein's theory of relativity**.



"There was a time when the newspapers said that only 12 men understood the theory of relativity. I don't believe there ever was such a time. ... On the other hand, I think I can safely say that nobody understands quantum mechanics."

A few years later, Danish physicist Niels Bohr, Nobel winner and quantum pioneer, put it more bluntly in a conversation with Werner Heisenberg, another giant of the field: "Those who are not shocked when they first come across quantum theory cannot possibly have understood it."

Even Einstein himself referred to quantum entanglement as "spooky action at a distance."



Quantum takes off

This year has been designated the International Year of Quantum Science and Technology, marking the 100th anniversary of foundational developments in quantum mechanics. That first quantum revolution fundamentally changed our understanding of the universe at the atomic and subatomic levels, leading to groundbreaking technologies such as semiconductors and lasers.

But we are now in a second quantum revolution. No longer are scientists and engineers just observing quantum phenomena. Rather, they are creating devices that actively control and manipulate individual quantum systems for practical applications such as quantum computers, sensors and communication systems.

Several quantum technologies are emerging with the potential for technological disruption. In just one example, **Google claimed** in December 2024 that its Willow quantum chip performed a calculation in less than five minutes that would take the world's fastest supercomputers roughly 100 trillion times the age of the universe.

"The second quantum revolution is generating so much excitement. It allows us to engineer quantum systems and harness quantum phenomena like superposition and entanglement to address and solve complex problems that are intractable with classical methods," said Gina Tourassi, ORNL's associate laboratory director for computing and computational sciences.

"Quantum sensors can measure physical quantities with unprecedented precision, leading to advancements in areas like medical imaging and navigation; the quantum properties of light can provide for secure communication, potentially revolutionizing data transmission; and quantum computers can solve extraordinarily complex problems that are beyond the reach of classical computers."



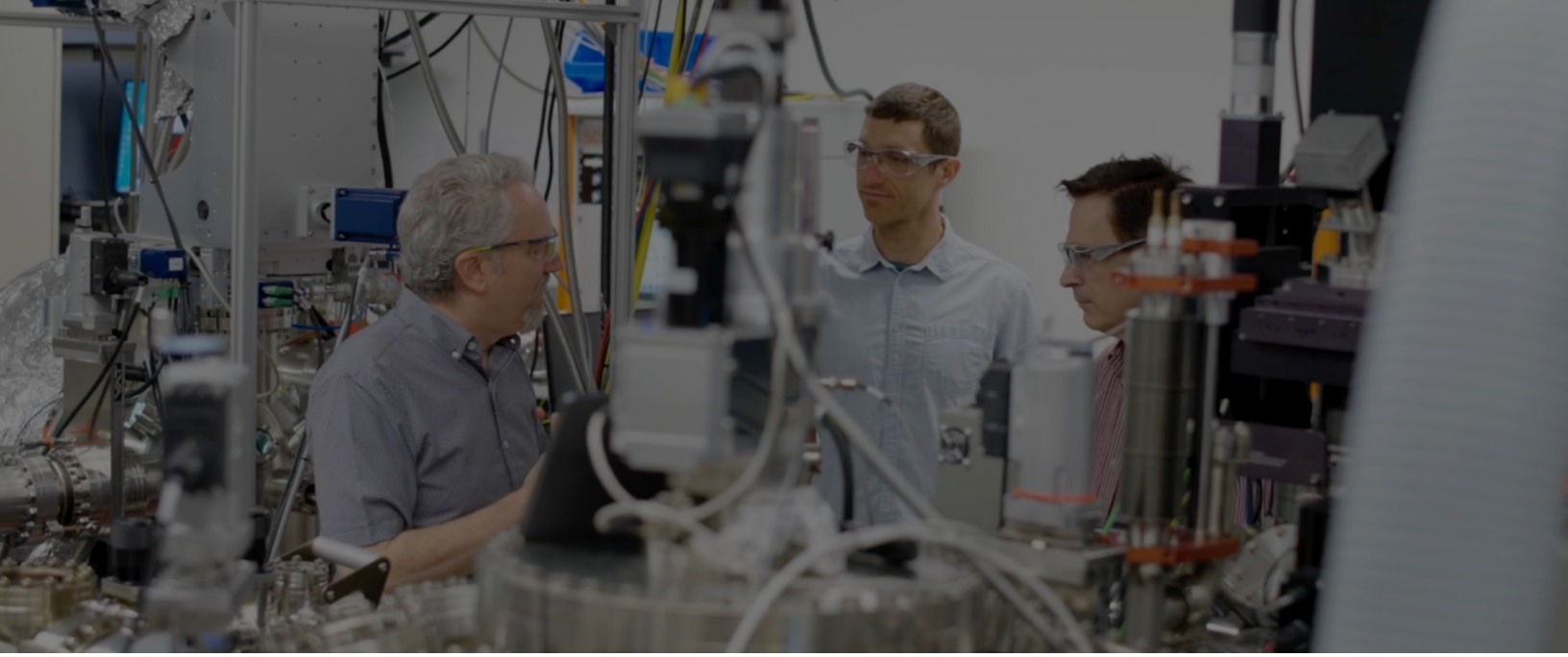
While quantum science has the potential to help people worldwide meet basic needs in food, health and reliable electricity, it's especially valuable in scientific research. Oak Ridge National Laboratory is heavily invested in four interdependent areas of quantum research: computing, materials discovery, sensing and networking.

ORNL is focused on defining and advancing a quantum-enabled future. The lab is a world leader in computing and materials science, both critical for this future. It houses unique user facilities in computing, neutron science and materials research, including the **Oak Ridge Leadership Computing Facility**, the **Spallation Neutron Source**, the **High Flux Isotope Reactor** and the **Center for Nanophase Materials Sciences** — all Department of Energy Office of Science user facilities. And ORNL staff are among the world leaders in each of these fields.

"It's that critical mass of people who understand quantum material properties and how to manipulate them, how to develop new quantum sensors and devices, and how to do computations to understand the phenomena that are being observed. All that plays into why ORNL is a great place for quantum research."

— Cynthia Jenks, ORNL's associate laboratory director for physical sciences (pictured right)





New tools for computer science

Quantum computers work fundamentally differently from your laptop. While traditional computers are built on bits — the familiar ones and zeroes — quantum computers are built on qubits (pronounced CUE-bits).

Qubits are potentially far more powerful than bits because they display quantum effects — particularly superposition and entanglement. In theory, any particle or system that meets these qualifications can act as a qubit. But to be of practical use, a qubit must be able to hold its quantum state, it must have relatively low error rates, and it must be able eventually to scale to larger computers.

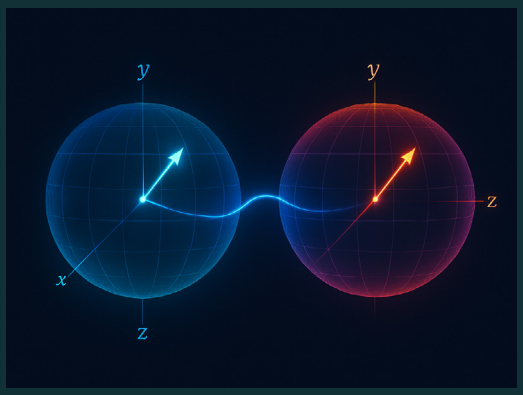
Some qubits are better than others, and researchers are working out which ones they are. ORNL researchers are using computers with several types of qubits, including photons; charged atoms trapped in a magnetic field, called trapped ion qubits; superconducting circuits kept below minus 450 degrees Fahrenheit; and nitrogen atoms placed within synthetic diamonds, known as nitrogen-vacancy qubits.

Building better algorithms

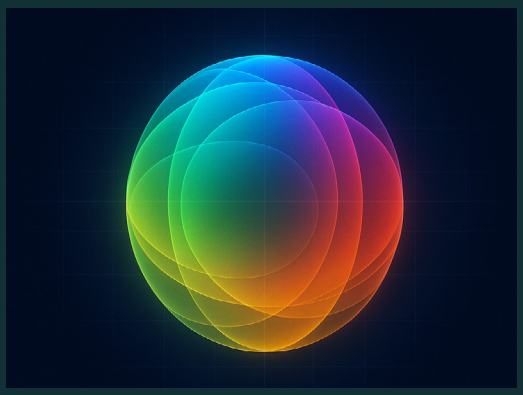
The step-by-step procedure to compute an answer to a problem is called an algorithm. Algorithms for quantum computers are very different from the more familiar ones used for traditional computers.

These differences stem from the nature of quantum mechanics. Because of quantum superposition, a qubit's value can be one, zero or any combination of one and zero. And because of quantum entanglement, qubits can interact with each other in powerful ways.

Another big challenge is that programmers are not allowed to copy — or even know — a qubit's value before a program is completed. The common technique of copying and reusing values multiple times during a computation is not valid in the quantum realm.

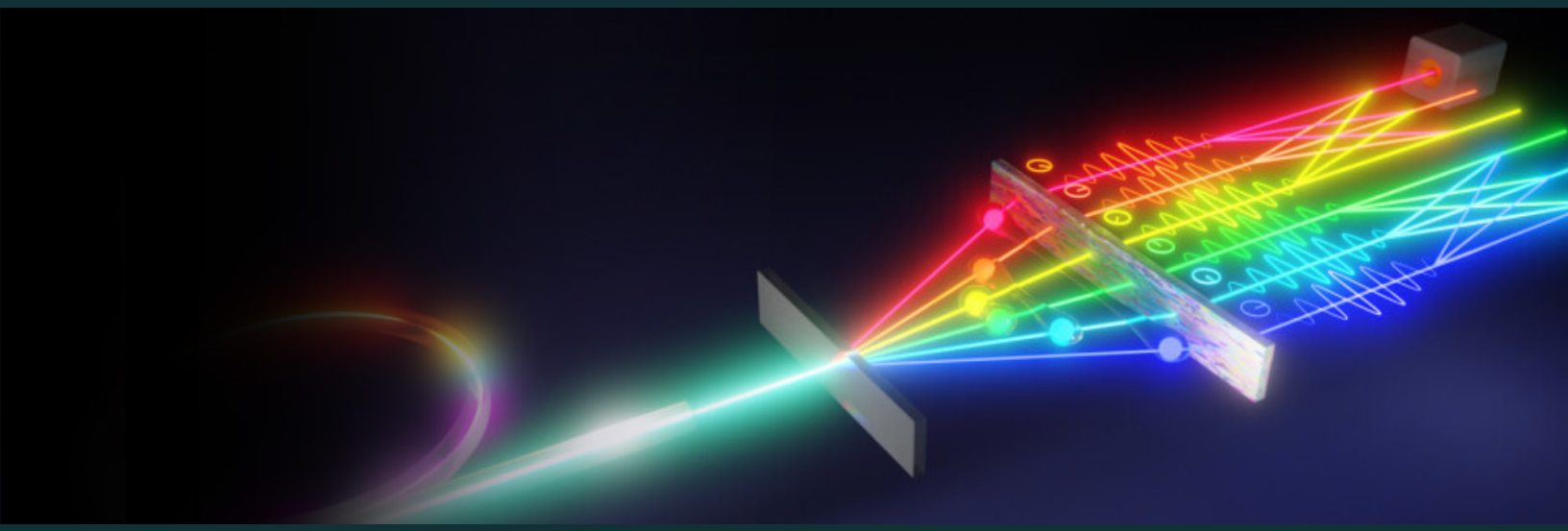


"One of the main differences is that you are not allowed to measure or do anything that reveals the value of your qubits during the computation," said Ryan Bennink, leader of ORNL's Quantum Computational Science Group. "If you do, you destroy the entanglement and the superposition, which are what make it quantum."



Bennink's group works to make the best use of quantum computers.

"We study how quantum computers can be used most effectively, because they're a novel type of computing device. You can't program them and use them like you would traditional computers."



Those differences are a mixed bag. True, there are approaches you can't take with a quantum computer, but there are also powerful new strategies available to these exotic devices, according to Travis Humble, an ORNL Distinguished Scientist and director of the **Quantum Science Center**.

"Imagine you've got a calculator," he said. "The buttons on that calculator are pretty limited. You've got plus, minus, multiply, divide, equal, not much more than that. But with the quantum computer, now we've added more buttons to that calculator, buttons that simply could not have existed otherwise, and people are trying to figure out, 'What's that button do?'"

Two examples of these new buttons are the controlled NOT gate, which changes the state of one qubit based on the value of another, and the **Hadamard gate**, which takes a qubit that has a definite value and changes it to a superposition of two values.

Humble noted that quantum computing is useful in materials research, particularly research on quantum materials. This is an especially difficult area for traditional supercomputers, also known as high-performance computers.

"What is interesting about quantum materials is that predicting their quirky behavior is a hard problem for our high-performance computing methods," Humble said. "And quantum computers look like they'll be a natural solution to solving those systems because they're quantum."

Judging quantum computers

As ORNL and the rest of the research community explore competing designs for quantum computers, they must also, eventually, come to a consensus on how to evaluate these systems. What makes one quantum computer or quantum technology better than another?

Supercomputers have traditionally been ranked according to how fast they can churn through calculations, with the number presented as floating-point operations per second. Because there's a limit to how fast any one computer chip can operate, supercomputers achieve their astonishing speed by dividing a problem to run on many processors concurrently. ORNL's Frontier system, for example, sports more than 9,000 CPUs and more than 37,000 GPUs, which allow it to perform 2 quintillion — or 2,000,000,000,000,000,000 — calculations a second.

Quantum computers, on the other hand, will likely take a different approach. For one thing, Humble noted, quantum computers may be more effective if problems are not split into smaller pieces.

"The number of qubits, even the quality of the qubit alone, isn't a good measure of performance in the end. What you want to find out is, is it giving me a faster time to solution? Is it consuming less energy? Is it more accurate? All these are key questions independent of whether the computer is quantum or not."

— Travis Humble,
Director of the Quantum Science Center at ORNL

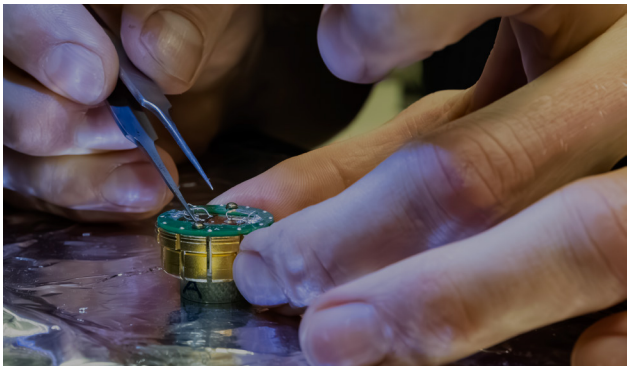




Figuring out hybrid computing

While ORNL researchers use a wide variety of cutting-edge quantum computers, the lab will also be bringing two systems on-site.

The first, a loaner from Australia-based **Quantum Brilliance**, uses nitrogen-vacancy qubits and is coming soon. The second, a system from Finland-based **IQM Quantum Computers**, will contain superconducting qubits.



With these and later systems, the lab will be able to explore how quantum computers can work in tandem with classical computers.

Humble said ORNL supercomputers in the next decade will likely incorporate both classical and quantum systems. Until then, researchers will have to overcome some serious challenges.

Besides the fact that quantum and classical computers approach problems differently, it's no simple task to get them to even talk to each other.

"We are just now learning how to take classical information into the quantum world — here the quantum world is represented by the quantum computer — and then get it back out again," Humble said.

One important question is, how do you get information between quantum and classical systems without getting hacked?

"All new technologies bring along with them new attack surfaces," said Ed Meyer, leader of ORNL's Emerging Technology Analysis Group.

"If you're trying to store your information in a quantum way for some kind of security reasons, or you're processing information that's of a quantum nature, you're going to want to make sure that you understand the ways in which someone might be able to manipulate the processing steps or the storage steps."



This is not a new challenge for computing. For instance, ORNL's Frontier, the world's first exascale supercomputer, is attacked more than 1.5 million times each day. In the case of hybrid systems, adding quantum components simply adds new opportunities for bad actors.

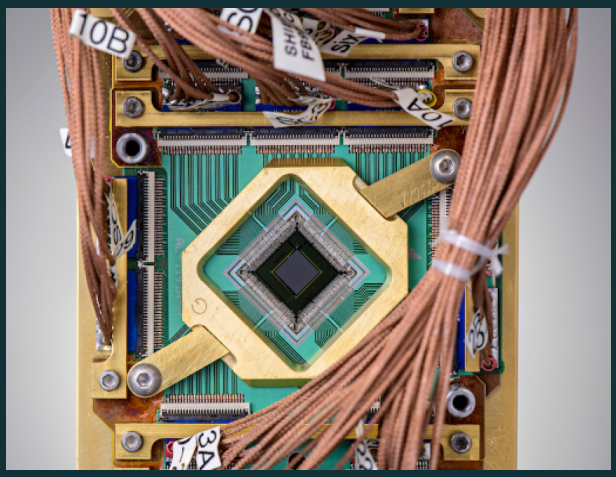
ORNL researchers are working to identify those new lines of attack and close them off before they can be exploited.

"Everywhere those two networks touch each other in order to build up, say, a router or the sharing of information, becomes an additional point at which I have to figure out how to defend against either noise from the environment or attackers," Meyer said.

Exploring quantum materials

All quantum technology depends on **quantum materials**. Without them, quantum computers, for instance, would be dead in the water.

"In the quantum computing space right now, the work is built off a long-standing ORNL legacy of understanding the properties of quantum materials," said Jenks, the lab's associate laboratory director for physical sciences.



"A lot of the foundational research has actually been done at Oak Ridge National Laboratory in understanding the fundamental properties of quantum materials in general. That has led us to this point in time where we can start to develop the qubits needed to develop quantum computers."

But what is a quantum material? On one hand, you can argue that all materials qualify, because they are all made up of quantum particles such as atoms and electrons. On the other hand, the properties of most materials can be adequately described without resorting to quantum explanations.



When they talk about quantum materials, then, researchers are typically referring to things — magnets and superconductors among them — that cannot be described without quantum mechanics.

"We don't need to think too deeply about quantum mechanics to understand why aluminum and steel make good drink cans and skyscrapers," said Michael McGuire, leader of ORNL's Correlated Electron Materials Group. "But when we consider the superconductivity of aluminum at low temperature and the magnetism of iron and steel, the quantum nature of those materials takes center stage."

ORNL's world-class neutron facilities are especially well suited to working with quantum materials, allowing researchers to understand, control and exploit novel quantum functionalities. The upcoming Spallation Neutron Source Proton Power Upgrade and Second Target Station will provide transformative capabilities to probe quantum systems, measuring excitations in thin films and mapping out phase diagrams of entanglement.

"The advancement of quantum technologies and the discovery of new quantum materials rely on the unique ways that neutrons are able to probe quantum states and magnetic order," said ORNL Distinguished Scientist Matthew Stone. "The neutron scattering instruments at the SNS and High Flux Isotope Reactor are indispensable tools in the study and development of quantum materials. New instruments and instrument upgrades at these facilities, as well as the increased neutron flux from the Proton Power Upgrade and future facilities like STS, are all helping to accelerate quantum materials discovery."

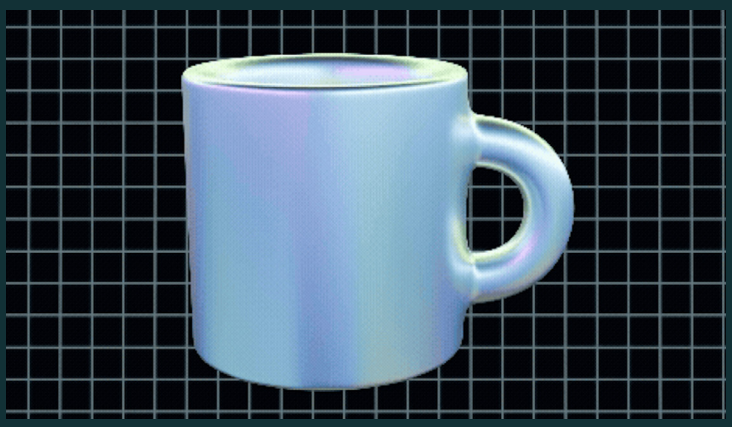
In these materials, the quantum behaviors of tiny particles, particularly electrons, coordinate to make themselves known at larger scales. These collective behaviors are called emergent phenomena, and they are responsible for much of the promise that we see in quantum technology.

Emergent phenomena are also notoriously difficult to understand and to calculate using current tools, providing intriguing problems for quantum computers.



"Magnetism emerges when the interactions between electrons in a metal collectively produce a lower energy state in which all of their magnetic moments — or spins — are aligned in a coordinated way," McGuire said. "Superconductivity emerges when interactions between electrons, caused by their magnetism or the material's atomic lattice, cause them to join together in pairs and form a macroscopic quantum state with many interesting properties, including conducting electricity without resistance."

McGuire pointed to a third phenomenon, known as topological order, that is important to researchers at ORNL and elsewhere as they work to create new qubits and other quantum technology.

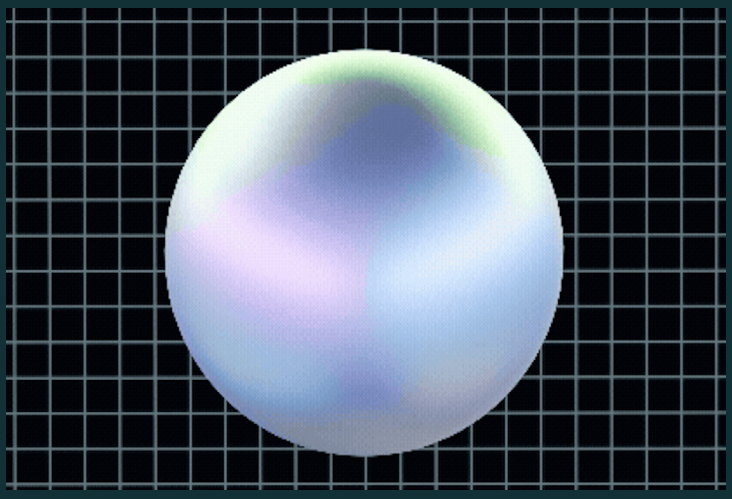


Topological order is usually explained through two examples: a doughnut and a sphere. What makes them distinct is the hole in the doughnut. The presence of the hole in one case and absence in the other means you cannot smoothly deform or stretch one shape into the other — that is, they have different topologies.

You can, for instance, stretch a sphere into a cylinder or a cube, but you cannot give it a hole without tearing it. The doughnut, also known as a torus, can stretch into a coffee mug, for instance, where the hole is found in the handle, but whatever shape you choose, it will always have a hole.

While a simple concept, topological order is very important to the creation of quantum devices.

"Consider the surface of a material that has a topological ordered state within it," McGuire said. "That topological order exists on one side of the surface — the inside — but not the other. So, at the surface something drastic has to happen, like poking a hole to change a sphere into a torus. In this case, what happens is new electronic states emerge right at the surface, unique from those that exist inside the material.



"These states have new and interesting properties. It turns out that superconducting states can also have topological order. This gives us topological superconductors, which also have novel states that appear wherever this topologically ordered state ends and another begins."

McGuire said these three topics — magnetism, superconductivity and topology — play an important role in his and his colleagues' research.

"We do quite a bit of materials discovery at the lab in a lot of areas, but specifically in quantum materials," he said. "In my group, we're often looking for what we would consider new materials, whether that means something no one's ever made before, or something no one's ever studied very closely before.

"So, we're looking for examples of compounds that have some of these properties, magnetism, superconductivity or nontrivial topology. And the really interesting things happen when two or more of these are combined."

Lab researchers are focusing, for instance, on quantum magnets, materials whose magnetism fluctuates because of quantum uncertainty; quantum spin liquids, which have no magnetic order even at very low temperatures; and topological superconductors, whose superconductivity is linked to their topological order.

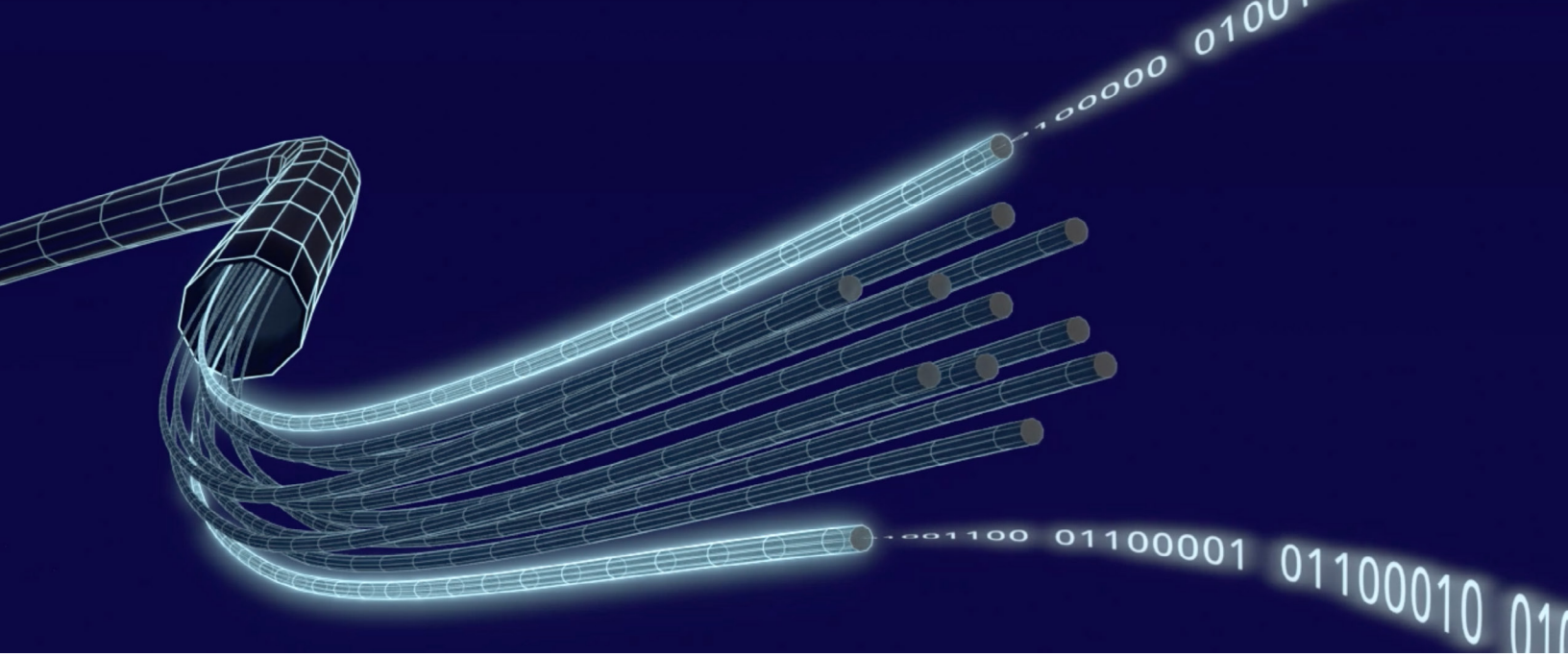


These materials can all host a type of emergent particle, or quasiparticle, called an anyon. Building qubits out of anyons is a promising path toward a new generation of more powerful and robust quantum computers.

McGuire noted that the lab is devoting significant attention to 2D materials, which are only a few atoms thick. These materials are sometimes grown as thin films and sometimes created by exfoliating a 3D crystal.

Much of this atomic-level materials manufacturing is performed at the Center for Nanophase Materials Sciences at ORNL.

"In many cases, the materials of interest are 2D materials," he said. "There are a couple of reasons for this. Quantum effects are generally enhanced in lower dimensions, and some of the exotic quantum states we are after, like anyons, cannot exist in 3D."



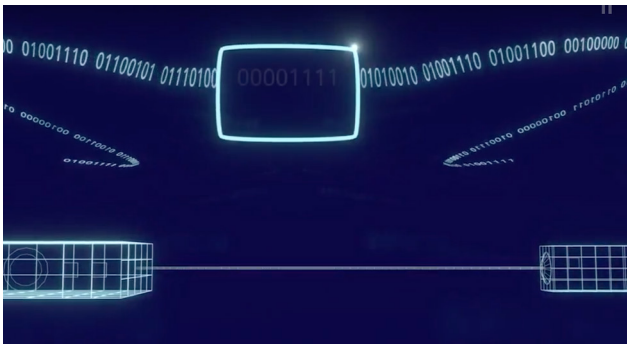
Sharing quantum information

If you want to share quantum information — or if you want to communicate information that can't be eavesdropped on — you'll need a quantum network. Fortunately, quantum information can be shared on the same fiber networks that host your online games and carry your email.

These include unused fiber, known as dark fiber. ORNL researchers are also working to enable quantum communication on existing fiber by limiting the quantum communication to specific frequencies.

"Our group also has been working on this technology called squeezing," said Mariam Kiran, leader of ORNL's Quantum Communications and Networking Group, "which allows you to carry quantum channels on the same fiber as existing classical channels. That means that now the fiber is not dark anymore."

Kiran sees three critical uses for quantum networks.



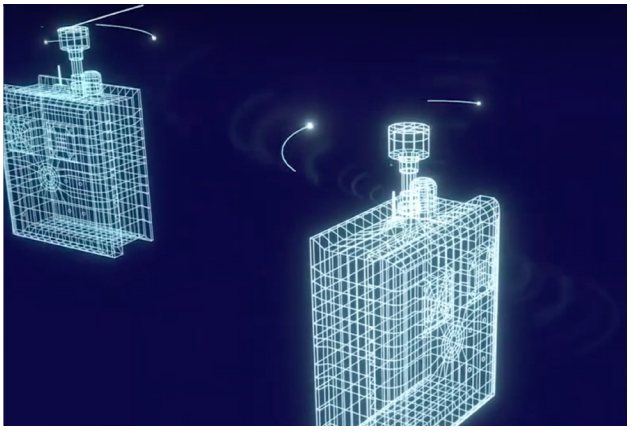
The first is to transmit information securely. With a technology called quantum key distribution, or QKD, two users can share a connection that becomes much more difficult to eavesdrop on.

The process could involve one user entangling two photons and sending one to the other user. The photon cannot be eavesdropped on without being disturbed, thereby interrupting the process.

Once that process is completed, the two users can trade classical information, including encryption keys.

The approach, if done well, creates a security protocol that is not designed with an expiration lifetime, according to Nicholas Peters, head of ORNL's Quantum Information Science Section.

"You can basically have security due to this particular quantum mechanical approach that doesn't depend on the pace of the advance in technology," he said. "You don't have to make assumptions about how big a computer somebody might have if you use this sort of security route."



The second critical use for quantum networking is to connect networks of quantum sensors.

"You can imagine having quantum sensors deployed across the world, and now you can detect dark matter, gravitational waves, etcetera," Kiran said. "People have been using it for temperature detection — because they get very highly accurate temperatures — humidity, gravitational waves, things that cannot be measured by our current classical sensors."

The third use of quantum networks is to scale the scope of quantum computers. If you have two quantum computers with, say, 10 qubits each, effective networking should allow you to turn them into a single quantum computer with 20 qubits, which is potentially much more powerful than having those two computers sitting side by side, unconnected.

ORNL's quantum network test bed

To support its research, ORNL has built a quantum network testbed with more than 300 kilometers — or 186 miles — of dedicated research dark fiber, part of which connects buildings around the lab's campus. It allows researchers and students to conduct experiments and test new hardware, fundamental concepts and protocols.

The lab is also working with the Tennessee Valley Authority to connect the network with the city of Chattanooga, about 100 miles to the southwest of the city of Oak Ridge. ORNL has a long working relationship with Chattanooga's electric power and telecommunications utility, EPB, which launched America's first utility-led, commercially available quantum network in 2023. This ORNL link will further expand collaborations with the University of Tennessee Chattanooga, building on an earlier agreement, and ORNL researchers are also developing the foundations for a quantum satellite connection to the lab's quantum network testbed.

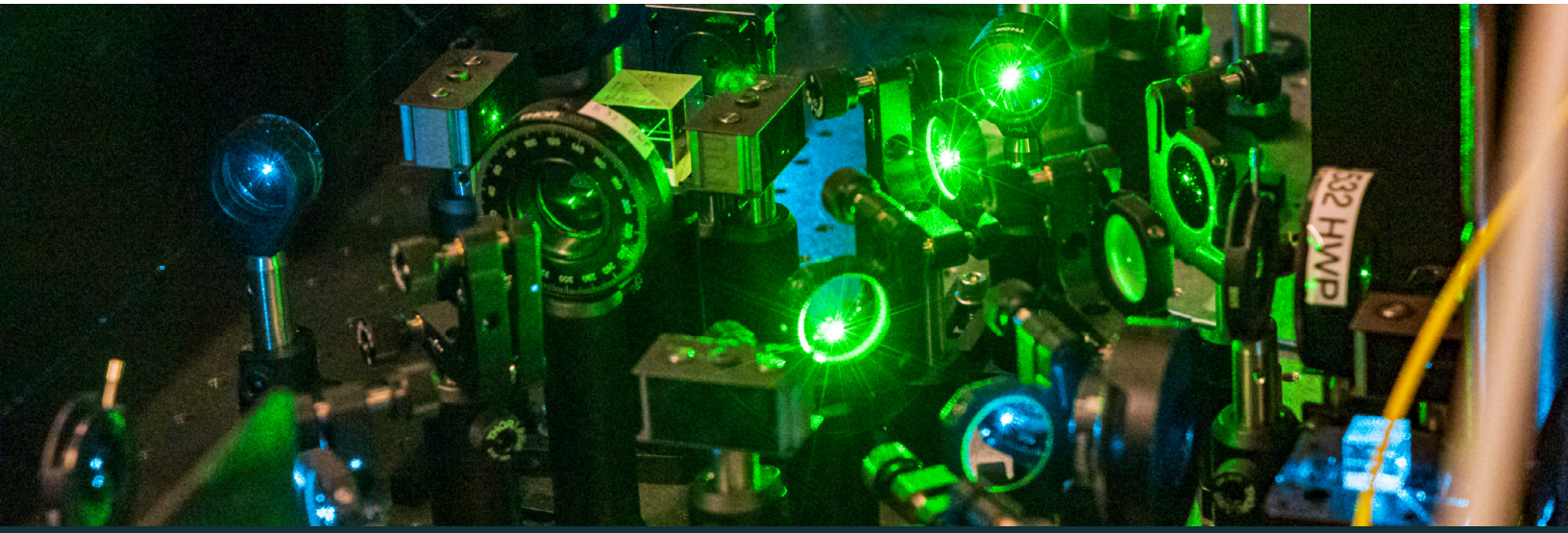
One goal of these projects is to address an ongoing challenge of quantum networking, namely losses that naturally accompany long-distance transmission of information. Quantum information, unlike classical information, cannot be amplified, but researchers are exploring solutions including so-called quantum repeaters to extend the range of a quantum network.

"We are exploring novel ways on solving this," Kiran said, "by either working with materials to help build better transduction for quantum-optical conversions, quantum repeater technologies that help preserve a signal as it travels, or satellite and space communications for long-distance entanglement."

Changes are coming

Even though the challenges are daunting, Kiran thinks quantum networking will be a part of people's lives sooner rather than later, especially in the service of secure communication.

"We could see very soon that our medical data and our citizenship data would be exchanged via QKD networks," she said. "So, hospitals would have their own QKD networks, for example, and some of the companies have already started coming out with products where they say they've put a QKD device in their phone."



Looking for the hard-to-see

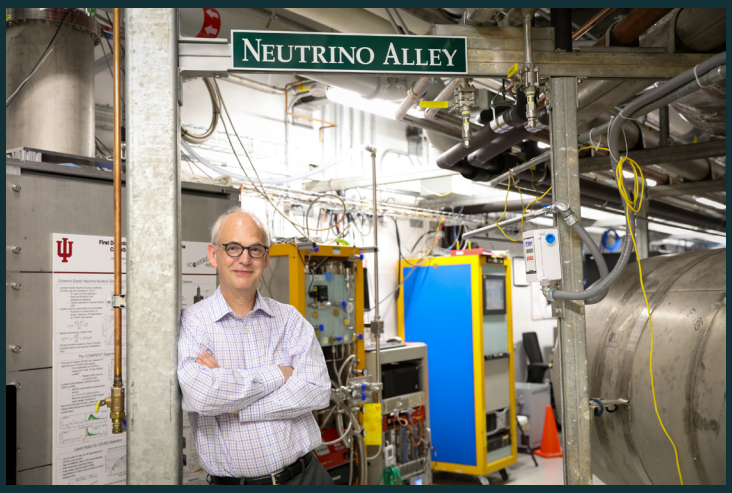
Sometimes a system's quantum properties can make it astonishingly sensitive to effects like magnetic fields, temperature or gravity. Such systems are candidates for quantum sensors.

These sensors are a boon to researchers when they are looking for something extremely tiny or subtle — say the nearly infinitesimal **ripples in space-time** caused by far-off black hole mergers — or when sensing methods themselves have to be low-energy — or when lasers are used to analyze materials in extremely cold environments or biological samples.

The key to using these systems effectively is to find cases where nonquantum sensors really won't do the job, according to Alberto Marino, leader of ORNL's Quantum Sensing and Computing Group.

Much of the work done by the group focuses on sensors that exploit the quantum properties of light, such as entanglement and squeezing — aspects of quantum mechanics that allow you to measure one property with great sensitivity as long as you're not interested in the accuracy of another, complementary property.

"We need to find the right applications where it makes sense to use quantum sensing," he said. "In many cases you can, for example, just take a classical laser beam and increase the intensity of the light. It's for some particular applications where you're going to have some limitations in the power or measurement time that you can use to probe the system that it starts to make sense to use quantum light to enhance sensors."



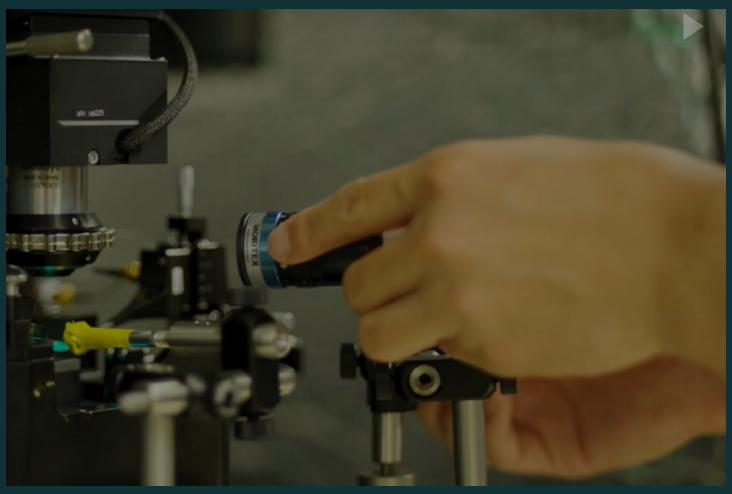
ORNL researchers are turning their quantum sensing efforts to detecting and understanding two of the universe's most elusive substances: dark matter and neutrinos.

Dark matter makes up most of the mass of the universe; we know this in part because galaxies spin faster than they should, given the matter that we can observe.

Yet we really don't know what dark matter is. It doesn't interact with electromagnetic radiation, including visible light, so we can't see it. We know something is there only because it exerts a gravitational force.

"People have a lot of hypotheses of what dark matter is," said Marcel Demarteau, director of ORNL's Physics Division. "But there's only one thing that we know about dark matter, and that is that it interacts gravitationally. That's it."

ORNL researchers are hoping to detect dark matter — whatever it may be — with a tiny silicon device about the weight of a single grain of sugar. The device uses the interference pattern of two laser lights to detect movement of the sensor.



"If you have dark matter that passes by a mass, it will move that mass because the attraction is a gravitational attraction," Demarteau said. "But you have to have an extremely sensitive instrument to detect any kind of deviation."

Neutrinos, on the other hand, are elementary particles so unobtrusive that scientists estimate 100 trillion pass through your body every second. Knowing more about them would help answer some basic questions about the universe, Demarteau said, including why it contains more matter than antimatter.

Even the mass of neutrinos is unknown, he said, despite their being the second most abundant particle in the universe, after photons.

Demarteau noted that ORNL is an ideal place to look for neutrinos because it houses two preeminent neutron scattering facilities — the Spallation Neutron Source and the High Flux Isotope Reactor — which coincidentally produce abundant neutrinos.

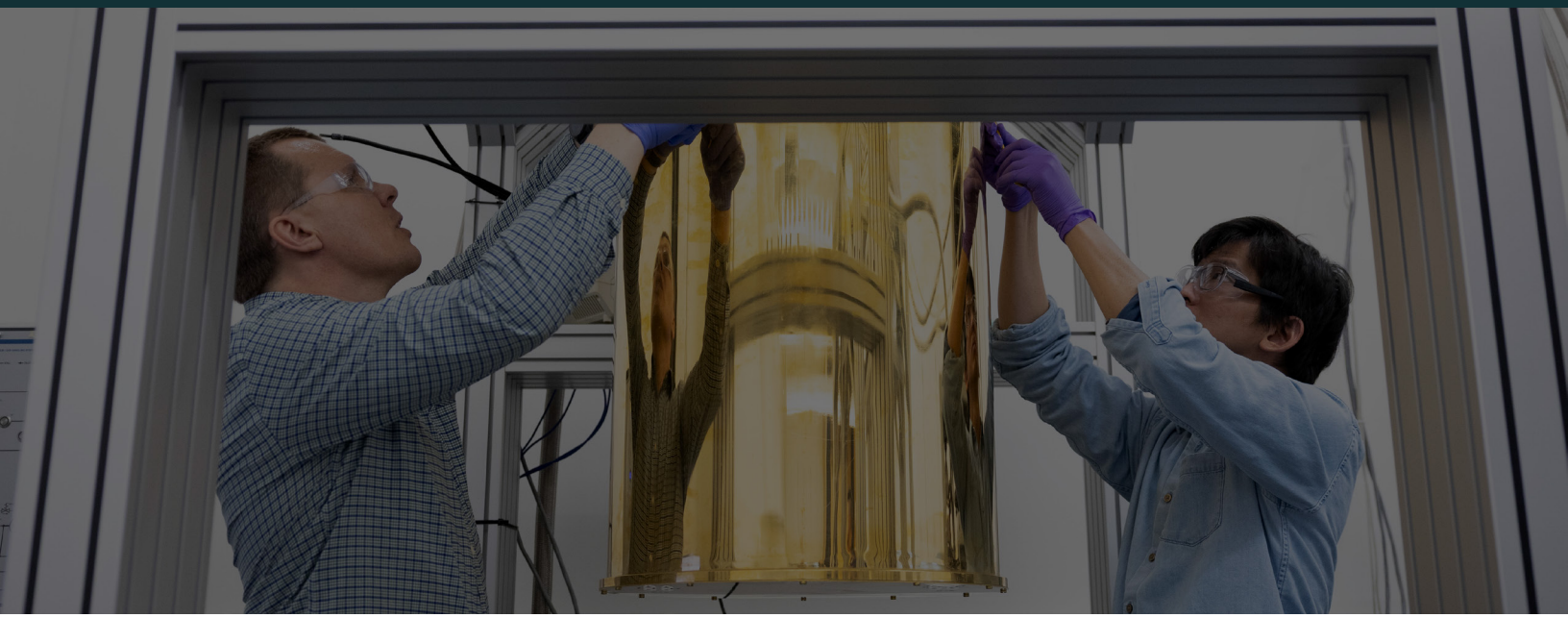
ORNL researchers are working to locate neutrino detectors at these two facilities. In the process, they may answer some important questions.

"We know very little about neutrinos," Demarteau said. "The basic questions: What is their nature? What is their mass? We just don't know."

Quantum sensing should give researchers new information regarding the workings of the universe, Marino noted, but they will also have practical uses.

"From a fundamental point of view, it will allow you to discover new things that you would not be able to discover, or see them better, or learn more things about what you're studying," he said.

"From a practical point of view, there are a lot of applications. For example, in national security, if you could sense something faster, you could detect a threat quicker. For medical applications, if you could detect a disease faster, that would, of course, have consequences."



Preparing for a quantum future

Like the elusive neutrino, there is much that we don't know about quantum science and technology.

For one thing, each area of quantum research depends on the others.

"It's that understanding of the basic interactions in materials that leads to the development of better sensors, that leads to better understanding of how these qubits are behaving in their environment, that leads to better networks and better computers, etcetera," said ORNL's Ben Lawrie of the Quantum Heterostructures Group.

"So, it's a very interconnected ecosystem, where building all of those connections between all of these different areas really does help to accelerate them all and allow us to address problems in basic research and in national security, all in one fell swoop."

The usefulness of quantum science and technology will also depend on how effectively we move information between quantum and classical systems, Peters said.



"It's really important that people understand that all of these quantum things, they go hand in hand with classical things. All quantum protocols that I am aware of require something classical. We distribute quantum signals, and we'll keep them quantum as long as it's useful to keep them quantum. But at the end of the day, if you want a quantum-enabled application, you have to convert that quantum information into classical information for people to consume it."

Whatever quantum science and technology look like in the next few years and beyond, experts agree they're going to be big.

Bennink, the group leader for quantum computational science, sees quantum computers really coming into their own over the coming years. Quantum computers have been available to researchers for the past eight years or so, but to this point they've been too small and too unfamiliar to reach their potential. "

A lot of what's been done since 2017 has been, 'Gee whiz, we've got a new toy.' So [there were] lots of proof-of-principle demonstrations where they've taken a problem and simplified it down to a very, very small problem that these early, limited quantum devices could do.

"Now we're moving to a point where these devices have enough qubits, and the qubits are of sufficient quality, that we can start actually doing something useful. So, I would say the emphasis now for us is going beyond proof-of-principle and finding places where there's actual usefulness in a quantum computer."

Demarteau agreed that applied quantum technologies will make a big splash in the coming decade and beyond.

"One thing that I would like to emphasize is that the potential of quantum is really enormous," he said. "And it could be transformational. And I think it will happen sooner rather than later — if sooner, it's five or 10 years.

"A lot of progress is being made over a very short time. I think we could be at the dawn of a new era."