# QUANTUM PHYSICS NEWS LETTER 30-MAY-2024

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**It is a quantum fractal algorithmic universe**

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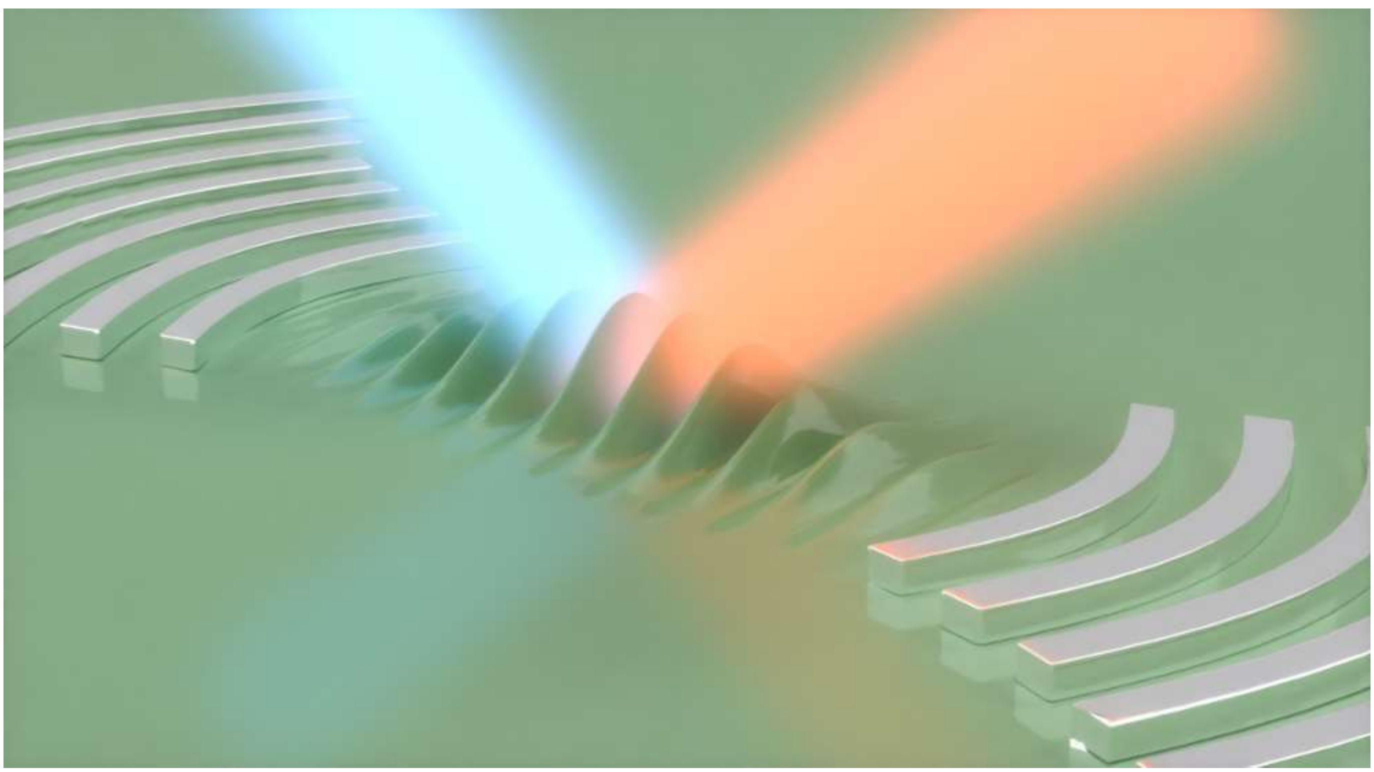
# New Surface Acoustic Wave Techniques Could Lead To Surfing A Quantum Internet

**Researchers at the** University of Rochester **used surface** acoustic waves **to overcome a significant obstacle in realising a quantum internet.**

In a new study published in *Nature Communications*, scientists from Rochester's Institute of Optics and Department of Physics and Astronomy describe a technique for pairing particles of light and sound that could be used to faithfully convert information stored in quantum systems—qubits—to optical fields, which can be transmitted over long distances.



MAKING WAVES: Beams of light, shown in orange and blue, are shined on a surface acoustic wave resonator, where their interactions are controlled by a precisely designed cavity. Inside this echo chamber, the light becomes strongly coupled with the surface acoustic waves. Illustration by Arjun Iyer / University of Rochester

## What are surface acoustic waves?

Surface acoustic waves are vibrations that glide along the exterior of materials like a wave in the ocean or tremors along the ground during an earthquake. They are used for a variety of applications—many of the electrical components of our phones have surface acoustic wave filters—because they make very precise cavities that can be used for precise timing in uses like navigation. But scientists have begun using them in quantum applications as well.

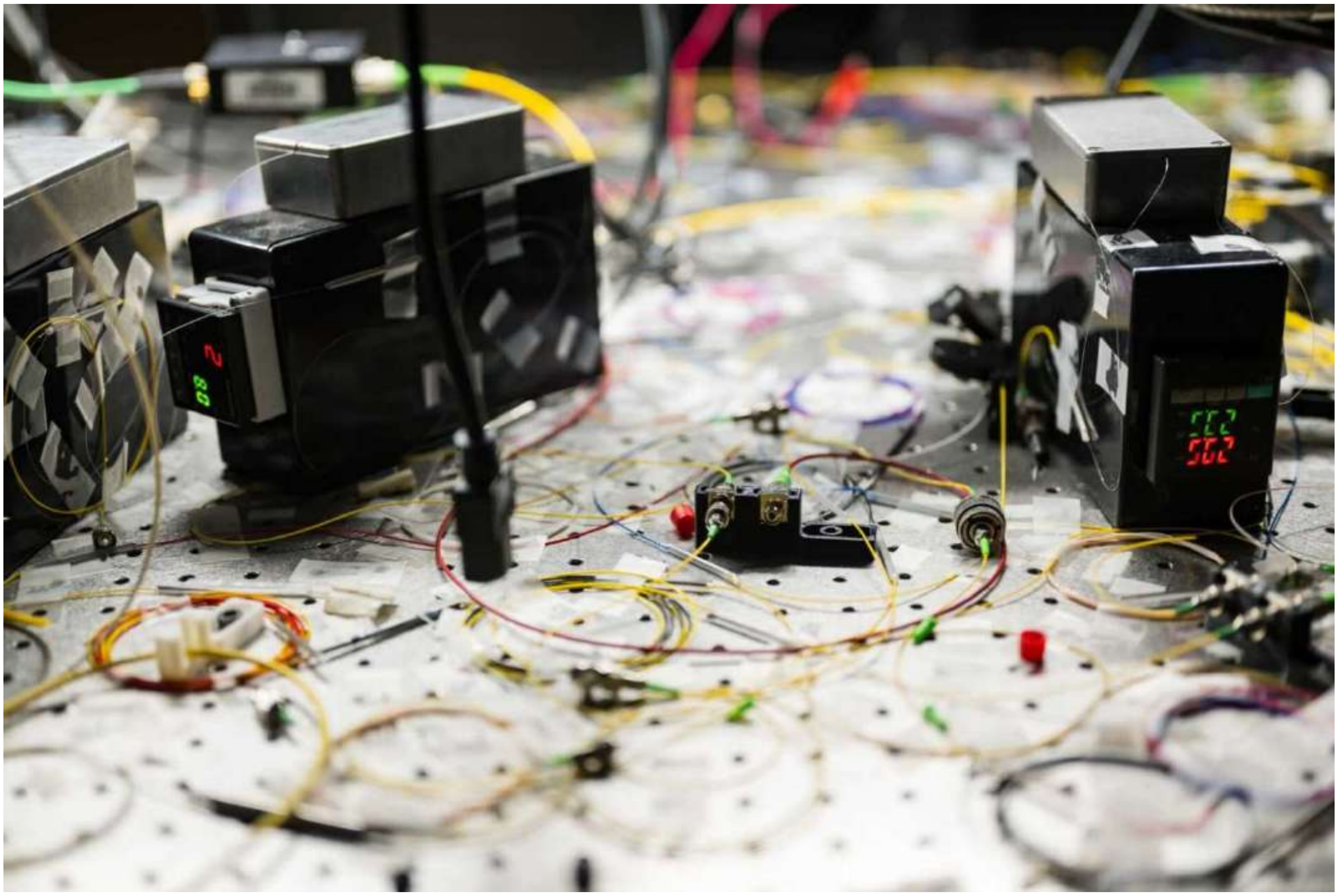
"In the last 10 years, surface acoustic waves have emerged as a good resource for quantum applications because the phonon, or individual particle of sound, couples very well to different systems," says William Renninger, associate professor of optics and physics.

Using existing methods, surface acoustic waves are accessed, manipulated, and controlled through piezoelectric materials to turn electricity into acoustic waves and vice versa. However, these electric signals must be applied to mechanical fingers inserted into the middle of the acoustic cavity, which cause parasitic effects by scattering phonons in ways that have to be compensated for.

## Using light to manipulate surface acoustic waves

Rather than coupling the phonons to electric fields, Renninger's lab tried a less invasive approach, shining light on the cavities and eliminating the need for mechanical contact.

"We were able to strongly couple surface acoustic waves with light," says Arjun Iyer, an optics PhD student and first author of the paper. "We designed acoustic cavities, or tiny echo chambers, for these waves where sound could last for a long time, allowing for stronger interactions. Notably, our technique works on any material, not just the piezoelectric materials that can be electrically controlled."



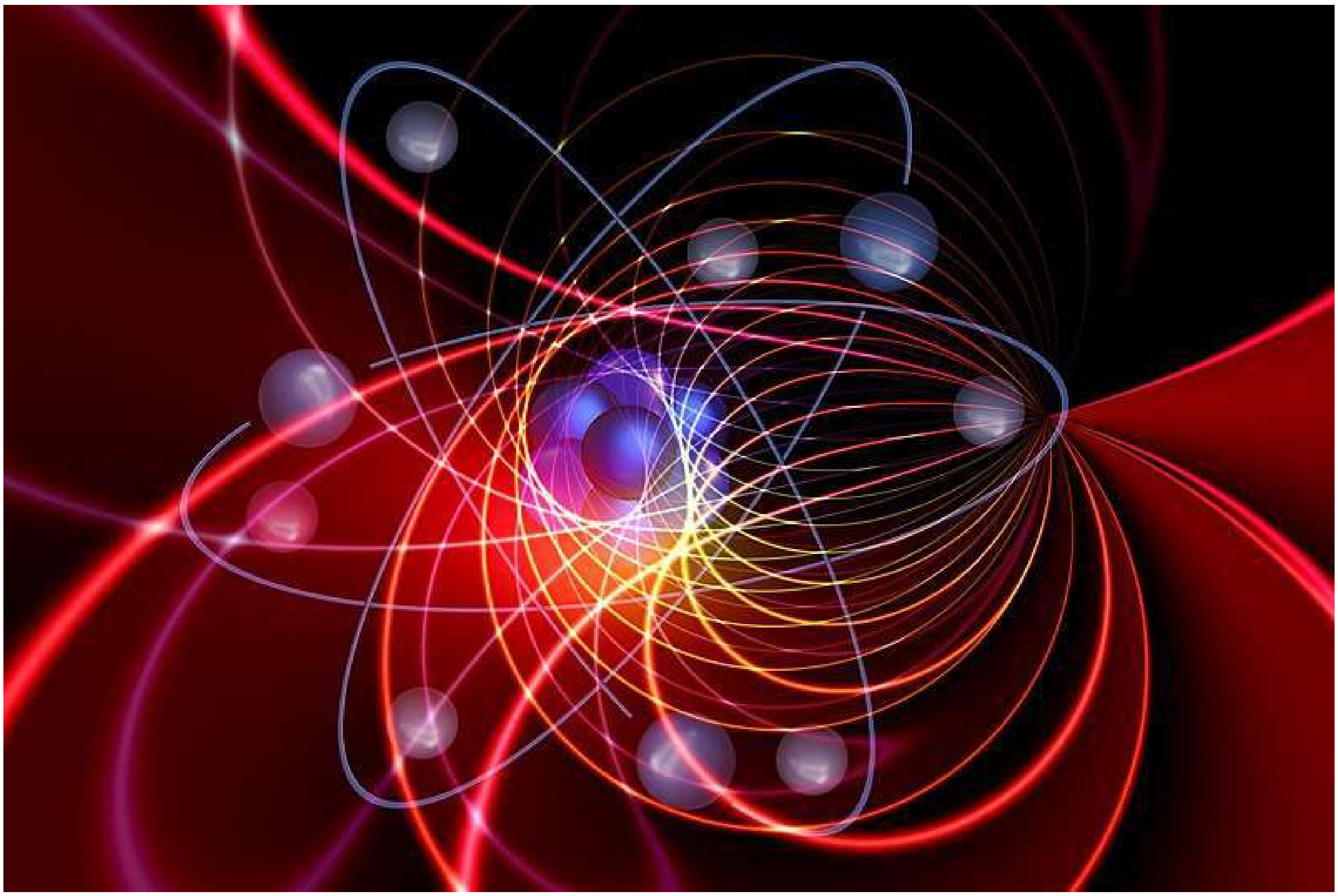
QUANTUM LEAP? "In the last 10 years, surface acoustic waves have emerged as a good resource for quantum applications because the phonon, or individual particle of sound, couples very well to different systems," says optics professor William Renninger. Image credit: University of Rochester photo / J. Adam Fenster

Renninger's team partnered with the lab of Associate Professor of Physics John Nichol to make the surface acoustic wave devices described in the study. In addition to producing strong quantum coupling, the devices have the added benefits of simple fabrication, small size, and the ability to handle large amounts of power.

Beyond applications in hybrid quantum computing, the team says its techniques can be used for spectroscopy to explore the properties of materials as sensors and to study condensed matter physics.

# Scientists Make Quantum Breakthrough In 2D Materials

**Scientists have discovered that a 'single atomic defect' in a layered 2D material can hold onto quantum information for microseconds at room temperature, underscoring the potential of 2D materials in advancing quantum technologies.**



The defect, found by researchers from the Universities of Manchester and Cambridge using a thin material called Hexagonal Boron Nitride (hBN), demonstrates spin coherence—a property where an electronic spin can retain quantum information—under ambient conditions. They also found that these spins can be controlled with light.

Up until now, only a few solid-state materials have been able to do this, marking a significant step forward in quantum technologies.

The findings published in *Nature Materials*, further confirm that the accessible spin coherence at room temperature is longer than the researchers initially imagined it could be.
Carmem M. Gilardoni, co-author of the paper and postdoctoral fellow at the Cavendish Laboratory at the University of Cambridge, where the research was carried out, said: “The results show that once we write a certain quantum state onto the spin of these electrons, this information is stored for ~1 millionth of a second, making this system a very promising platform for quantum applications.

“This may seem short, but the interesting thing is that this system does not require special conditions – it can store the spin quantum state even at room temperature and with no requirement for large magnets.”

Hexagonal Boron Nitride (hBN) is an ultra-thin material made up of stacked one-atom-thick layers, kind of like sheets of paper. These layers are held together by forces between molecules, but sometimes, there are tiny flaws between these layers called ‘atomic defects’, similar to a crystal with molecules trapped inside it. These defects can absorb and emit light that we can see, and they can also act as local traps for electrons. Because of the defects in hBN, scientists can now study how these trapped electrons behave, particularly the spin property, which allows electrons to interact with magnetic fields. They can also control and manipulate the electron spins using light within these defects at room temperature – something that has never been done before.
Dr Hannah Stern, first author of the paper and Royal Society University Research Fellow and Lecturer at The University of Manchester, said: “Working with this system has highlighted to us the power of the fundamental investigation of new materials. As for the hBN system, as a field we can harness excited state dynamics in other new material platforms for use in future quantum technologies.

“Each new promising system will broaden the toolkit of available materials, and every new step in this direction will advance the scalable implementation of quantum technologies.”

Prof Richard Curry added: “Research into materials for quantum technologies is critical to support the UK’s ambitions in this area. This work represents another leading breakthrough from a University of Manchester researcher in the area of materials for quantum technologies, further strengthening the international impact of our work in this field.”

Although there is a lot to investigate before it is mature enough for technological applications, the finding paves the way for future technological applications, particularly in sensing technology.

The scientists are still figuring out how to make these defects even better and more reliable and are currently probing how far they can extend the spin storage time. They are also investigating whether they can optimise the system and material parameters that are important for quantum-technological applications, such as defect stability over time and the quality of the light emitted by this defect.

# Developed Compiler Acceleration Technology For Quantum Computers

**The new method is based on a probabilistic approach and reduces the time to search for the optimal sequence by several orders of magnitude.**

The National Institute of Information and Communications Technology (NICT, President: TOKUDA Hideyuki, Ph.D.), RIKEN (President: GONOKAMI Makoto, Ph.D.), Tokyo University of Science (President: Dr.ISHIKAWA Masatoshi), and the University of Tokyo (President: FUJII Teruo, Ph.D.) succeeded in developing a technique to quickly search for the optimal quantum gate sequence[*1] for a quantum computer using a probabilistic method[*2].

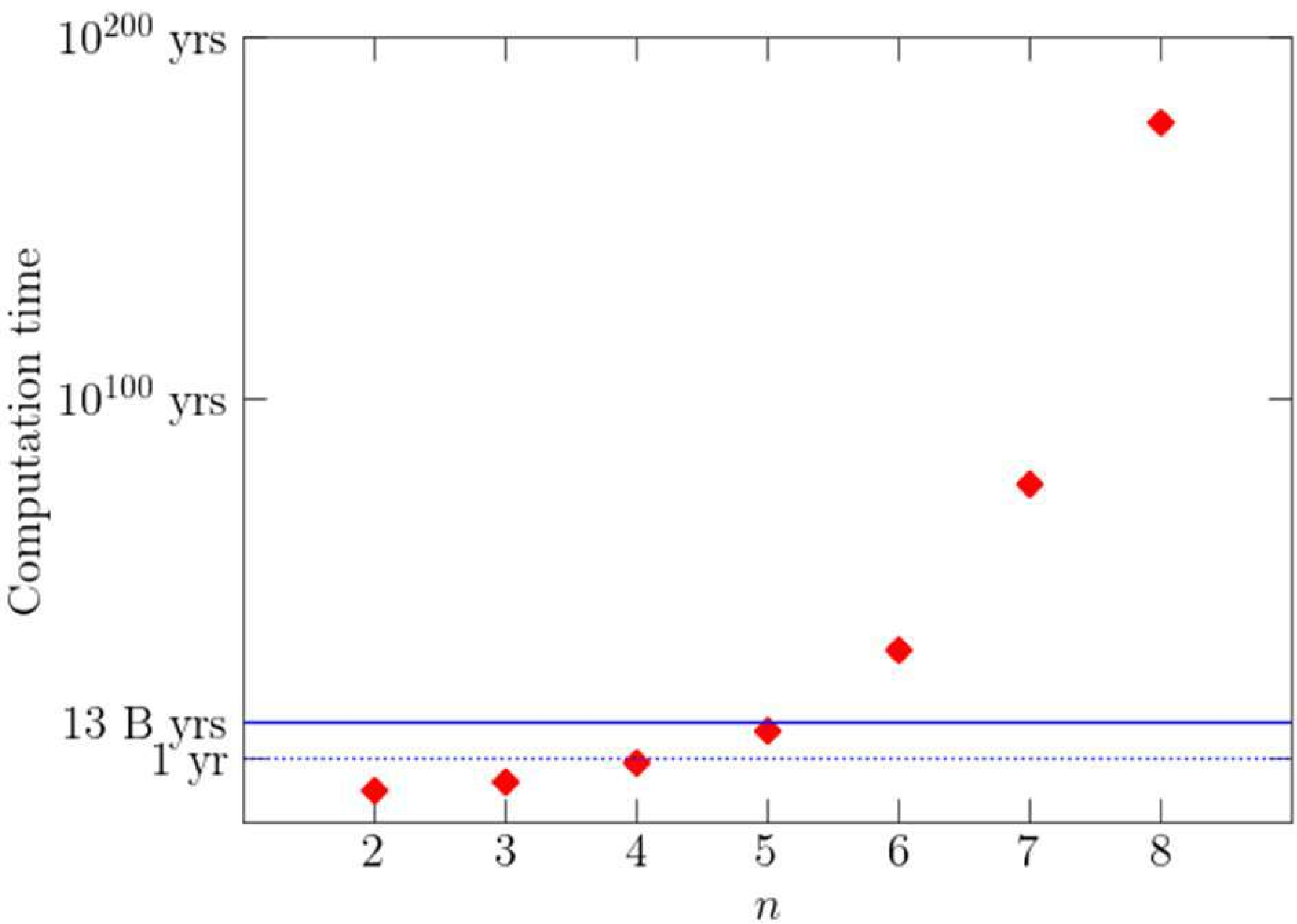



Figure 1 Estimated calculation time when performing a search to optimize the fidelity F for every gate arrangement using GRAPE to prepare the state of n qubits. The solid blue line is the time from the universe's beginning to the present (13.7 billion years).

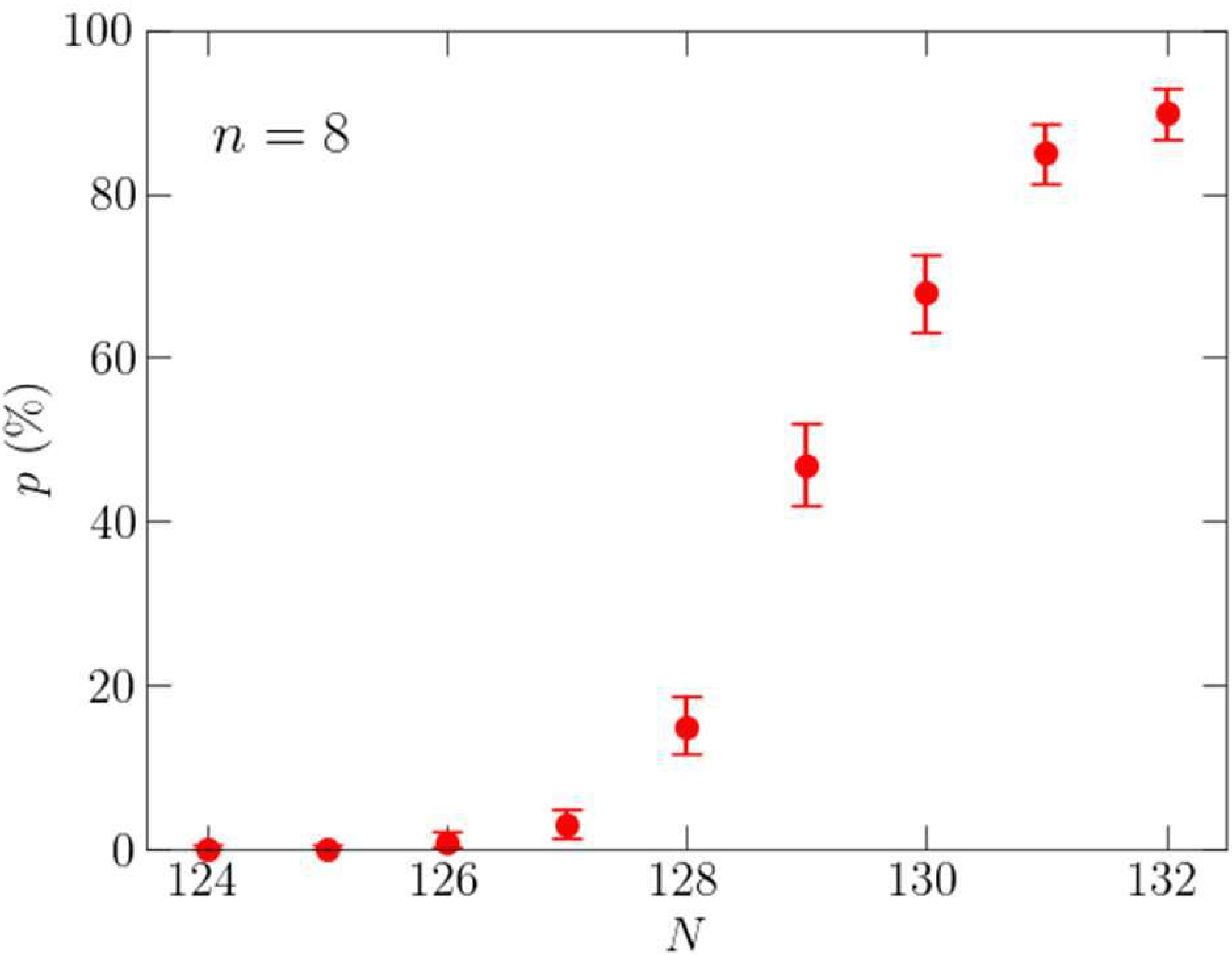



Figure 2 The appearance rate of optimal quantum sequences with F=1 calculated using the supercomputer Fugaku. N is the number of 2-qubit gates used for state preparation (green vertical line in Figure 4 in the Glossary). This figure is for the case of n=8 qubits. The appearance rate of F=1 at values of N that slightly exceed the theoretical lower bound*7 of N=124 increase rapidly.

To make a quantum computer perform a task, it must use a compiler to convert instructions written in a programming language into a sequence of gate*3 operations on quantum bits, or qubits for short. We previously applied optimal control theory (GRAPE*4 algorithm) to an exhaustive search to develop a method to identify the theoretically optimal gate sequence*5, but as the number of qubits increases, the number of possible combinations increases.

As the number increases explosively, an exhaustive search becomes impossible. For example, if we were to perform an exhaustive search to find the optimal gate sequence for generating an arbitrary quantum state of 6 qubits, it would take longer than the universe's age using the fastest classical computer currently available.

Therefore, we succeeded in developing a method to search for the optimal quantum gate sequence using a probabilistic approach. Using the supercomputer Fugaku, we confirmed and demonstrated that a new probabilistic random search method can be used to search for the optimal quantum gate sequence for the above problem in a few hours.

This new method is expected to speed up quantum computer compilers, become a useful tool for practical quantum computers, and improve the performance of quantum computer devices. It can also be applied to optimize quantum information processing at quantum relay nodes, so it is expected to contribute to realising the quantum Internet and reducing environmental impact.

This result was published in the American scientific journal “Physical Review A.“
Quantum computers, which are currently under development, are expected to have a major impact on society. Their benefits include reducing the environmental burden by reducing energy consumption, finding new chemical substances for medical use, accelerating the search for materials for a cleaner environment, etc. One of the big problems for quantum computers is that the quantum state is very sensitive to noise, so it is difficult to maintain it stably for a long time (maintaining a coherent quantum state).

For best performance, operations must proceed within a time that allows the quantum state to remain coherent. However, apart from the special case where the number of qubits is very small, no good method has been known to find the optimal quantum gate sequence. A solution that avoids the difficulty of the explosive increase in the number of possible gate sequences even in large-scale quantum computations and allows efficient searches within the time and computational resources that can be performed on classical computers has been awaited.

The research team introduced a probabilistic method to develop a systematic method that can efficiently search for the optimal quantum gate sequence within the execution time and computational resources.

When a computer stores and processes information, all information is converted to a string of bits with values of 0 or 1. A quantum gate sequence is a computer program written in a human-readable language after it has been converted so that it can be processed by a quantum computer (see Figure 4 in the Glossary). The quantum gate sequence consists of 1-qubit gates and 2-qubit gates. The best sequence is the one with the fewest gates and shows the best performance (the number of red squares and green vertical lines is the smallest in Figure 4 in the Glossary).

Figure 1 shows the estimated calculation time when a search is performed to optimize the fidelity[*6] F on the fastest classical computer for every gate arrangement using the

optimal control theory algorithm GRAPE for preparing n qubit states. The solid blue line is the so-called age of the universe (13.7 billion years). As the number of qubits increases, the number of possible combinations increases explosively, so at n=6, the total calculation time exceeds the age of the universe.
Analysis of all possible sequences for small qubit numbers reveals that there are many optimal quantum gate sequences (shown in Figure 5 in the Appendix). This suggests the possibility of expanding to large quantum tasks and finding the optimal quantum gate sequence using a probabilistic search method rather than an exhaustive search.

Figure 2 shows the appearance rate (p) of sequences with fidelity F=1 for the preparation of a state consisting of n=8 qubits, which was investigated using the supercomputer Fugaku. The rate p is expressed as a function of the number of 2-qubit CNOT gates (N) in the sequence. It is clear that the probabilistic method is very efficient because the F=1 occurrence rate increases rapidly when the lower limit of N (N=124) is exceeded. For example, the appearance rate of F=1 at N=129, which is a little over N=124, is over 50%, so if you search for a gate arrangement twice, you will find a quantum sequence that has F=1 at least once on average (see Table 1 in the Appendix). In this way, it has been found that by using a probabilistic method, it is possible to search for optimal quantum gate sequences several orders of magnitude faster than when searching using an exhaustive search method.
The developed systematic and probabilistic method to provide optimal quantum gate sequences for quantum computers is expected to become a useful tool for practical quantum computers and speed up quantum computer compilers. It is expected to improve the performance of quantum computing devices (see Figure 3) and contribute to the development of quantum nodes in the quantum internet and the reduction of environmental burden.

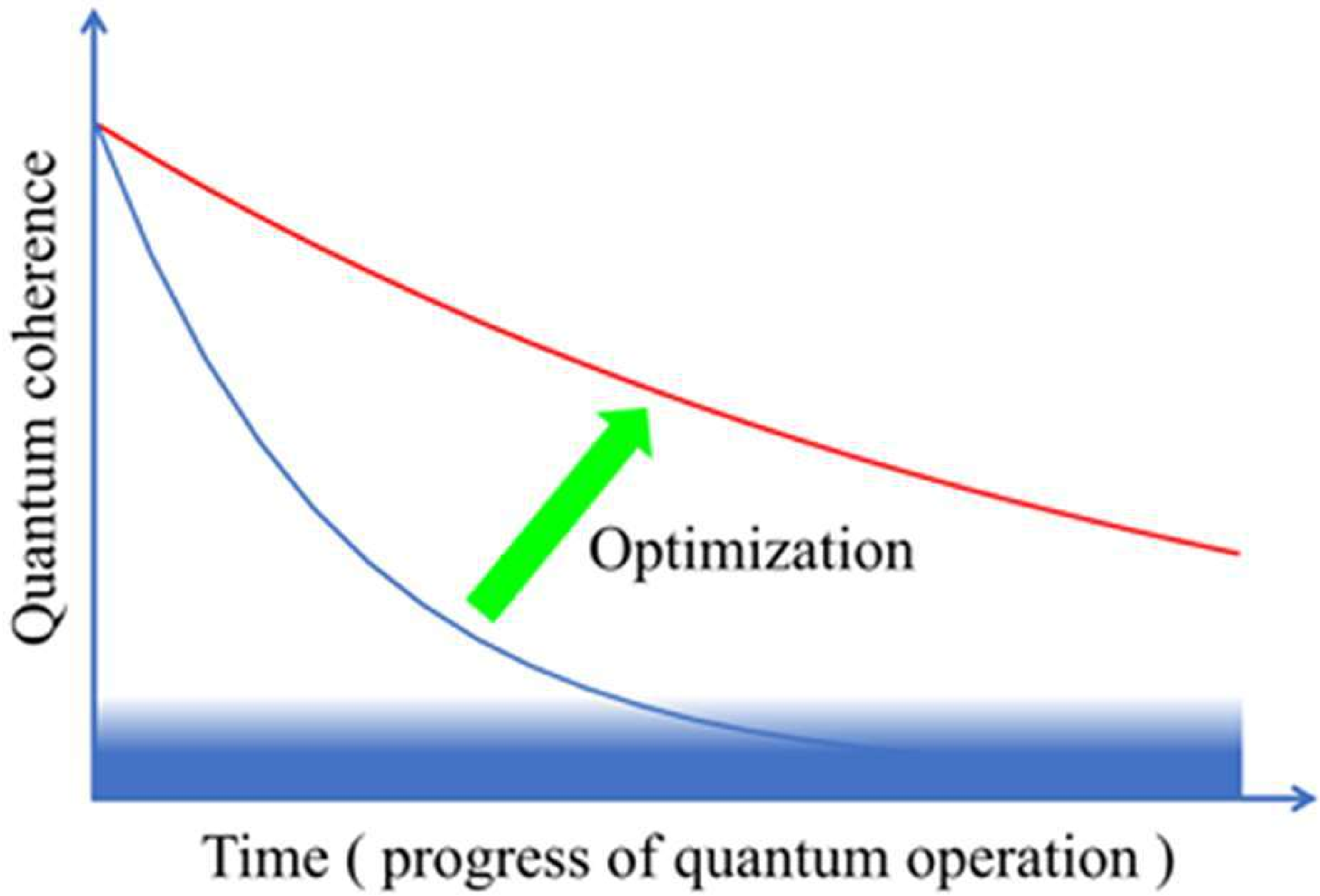



Figure 3 Improving quantum computer performance (conceptual diagram). Quantum computer coherence declines over time. If the coherence gets too low, the information in the quantum computer becomes meaningless. By optimizing the operation of quantum computers, more information can be processed before quantum coherence*8 falls below the utility threshold.

In the future, the research team will integrate the results obtained in this study with machine learning approaches and apply them to optimize the performance of quantum computers, aiming to further speed up quantum compilers and create a database of optimal quantum gate sequences.

## *Glossary*

*1 Quantum gate sequence

A set of instructions that specify the steps for gate *3 operations to be performed on multiple qubits. In Figure 4, the six horizontal blue lines represent six qubits, with the input on the left and the output on the right. Operations are executed from left to right. Each red square represents a 1-qubit gate, and each green vertical line connecting two blue lines represents a 2-qubit gate. A quantum gate sequence consists of a sequence of 1-qubit gates and 2-qubit gates, but the optimal sequence is the one that achieves high performance with the smallest number of gates.

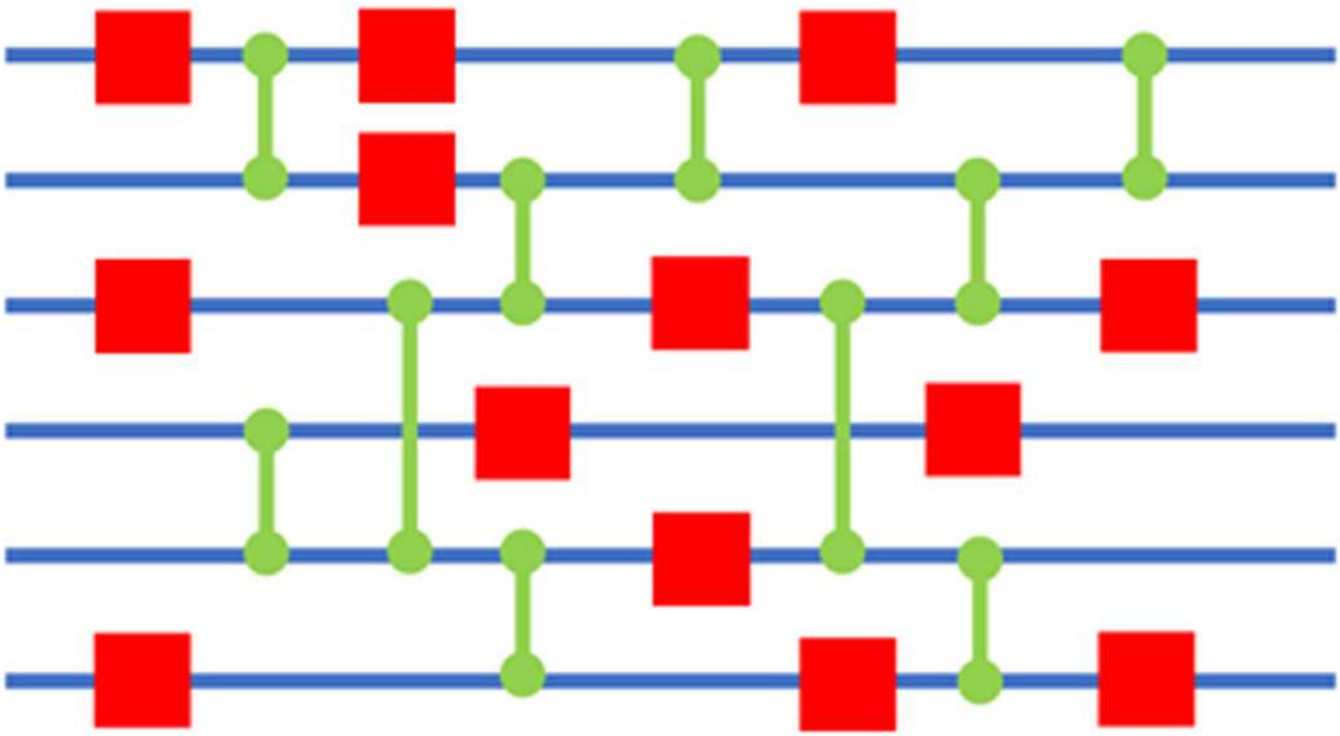


Figure 4 Quantum gate sequence (conceptual diagram)

*2 Probabilistic approach
A computational method that randomly tries possible solutions and may succeed or fail. If there are many solutions, probabilistic methods may perform better than methods that analyze all possible solutions.

*3 Gate
A simple operation performed on one or two bits of information. Several recent studies have proposed improved methods (recipes) for constructing sequences of quantum gates that perform various quantum tasks. However, these recipes do not necessarily yield the shortest sequence of quantum gates.

*4 GRAPE
The abbreviation of GRadient Ascent Pulse Engineering. A numerical algorithm that uses the principles of optimal control theory to find the optimal pulse to control a quantum system.

*5 Developed a method of applying optimal control theory (GRAPE[*4] algorithm) to an exhaustive search to identify the theoretically optimal gate sequence.
Press Release dated September 2, 2022,

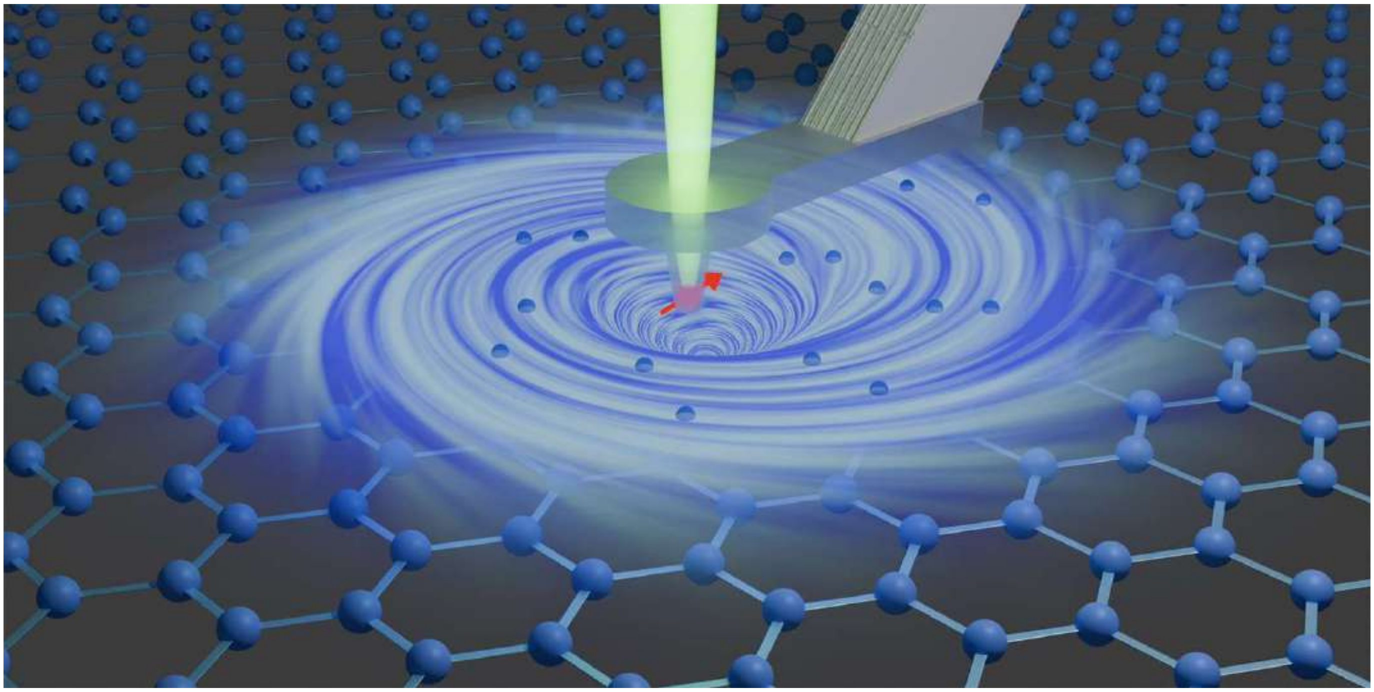
*6 Fidelity
A measure of the "closeness" of two quantum states. It represents the probability that one quantum state passes the test of being identified as another quantum state. If two quantum states are identical, the fidelity between them is equal to 1 (F=1). The fidelity has also been generalized for use as a measure of "closeness" between two unitary operators.

*7 Theoretical lower bound that gives F=1
The minimum number of CNOT gates required in a quantum gate sequence to obtain fidelity F=1. In the case of n-qubit state preparation, as the number of qubits (n) increases, the number of representable state parameters also increases, as shown in the "Number of CNOT gates ($N_{CNOT}$)" column in Table 1 of the Appendix.
The CNOT gate is a type of two-qubit gate. It serves to flip the state of the second qubit (target qubit) if and only if the first qubit (control qubit) is |1>.

*8 Quantum coherence
A number between 0 and 1 that represents how much the quantum information has been degraded by device noise or other imperfections. The quantum coherence index equals 1 when the information is first input into the quantum processor and is still intact. If the quantum coherence index is equal to zero, it means that the original information is completely lost.
One of the biggest issues that need to be addressed in the further development of quantum computers is how to cope with the gradual loss of information (the inability to maintain a coherent quantum state) caused by the noise inside the computer.

# Electron Vortices In Graphene Detected At Room Temperature

**For the first time, researchers at ETH Zurich have made visible how** electrons form vortices **in a material at room temperature. Their experiment used an extremely high-resolution quantum sensing microscope.**



Using a magnetic field sensor (red arrow) inside a diamond needle, researchers at ETH imaged electron vortices in a graphene layer (blue). Illustration by Chaoxin Ding / ETH Zurich

When an ordinary electrical conductor – such as a metal wire – is connected to a battery, the electrons in the conductor are accelerated by the electric field created by the battery. While moving, electrons frequently collide with impurity atoms or vacancies in the crystal lattice of the wire, and convert part of their motional energy into lattice vibrations. The energy lost in this process is converted into heat that can be felt, for example, by touching an incandescent light bulb.

While collisions with lattice impurities happen frequently, collisions between electrons are much rarer. The situation changes, however, when graphene, a single layer of carbon atoms arranged in a honeycomb lattice, is used instead of a common iron or copper wire. In graphene, impurity collisions are rare and collisions between electrons play the leading role. In this case, the electrons behave more like a viscous liquid. Therefore, well-known flow phenomena such as vortices should occur in the graphene layer.

Reporting in the scientific journal external pageSciencecall_made, researchers at ETH Zurich in the group of Christian Degen have now managed to directly detect electron vortices in graphene for the first time, using a high-resolution magnetic field sensor.

## Highly sensitive quantum sensing microscope

The vortices formed in small circular disks that Degen and his co-workers had attached during the fabrication process to a conducting graphene strip only one micrometre wide. The disks had different diameters between 1.2 and 3 micrometres. Theoretical calculations suggested that electron vortices should form in the smaller, but not in the larger disks.

To make the vortices visible the researchers measured the tiny magnetic fields produced by the electrons flowing inside the graphene. For this purpose, they used a quantum magnetic field sensor consisting of a so-called nitrogen-vacancy (NV) centre embedded in the tip of a diamond needle. Being an atomic defect, the NV centre behaves like a quantum object whose energy levels depend on an external magnetic field. Using laser beams and microwave pulses, the quantum states of the centre can be prepared in such a way as to be maximally sensitive to magnetic fields. By reading out the quantum states with a laser, the researchers could determine the strength of those fields very precisely.

“Because of the tiny dimensions of the diamond needle and the small distance from the graphene layer – only around 70 nanometres – we were able to make the electron currents visible with a resolution of less than a hundred nanometres”, says Marius Palm, a former PhD student in Degen’s group. This resolution is sufficient for seeing the vortices.

## Inverted flow direction

In their measurements, the researchers observed a characteristic sign of the expected vortices in the smaller discs: a reversal of the flow direction. While in normal (diffusive) electron transport, the electrons in strip and disc flow in the same direction, in the case of a vortex, the flow direction inside the disc is inverted. As predicted by the calculations, no vortices could be observed in the larger discs.

“Thanks to our extremely sensitive sensor and high spatial resolution, we didn’t even need to cool down the graphene and were able to conduct the experiments at room temperature”, says Palm. Moreover, he and his colleagues not only detected electron vortices, but also vortices formed by hole carriers. By applying an electric voltage from below the graphene, they changed the number of free electrons in such a way that electrons no longer carried the current flow, but rather by missing electrons, also called holes. Only at the charge neutrality point, where there is a small and balanced concentration of both electrons and holes, the vortices disappeared completely.

“At this moment, the detection of electron vortices is basic research, and there are still lots of open questions”, says Palm. For instance, researchers still need to figure out how collisions of the electrons with the graphene’s borders influence the flow pattern, and what effects are occurring in even smaller structures. The new detection method used by the ETH researchers also permits taking a closer look at many other exotic electron transport effects in mesoscopic structures – phenomena that occur on length scales from several tens of nanometres up to a few micrometres.

# Did A Magnetic Field Collapse Trigger The Emergence Of Animals?

**Evidence suggests a weak magnetic field millions of years ago may have fueled the proliferation of life.**

The Ediacaran Period, spanning from about 635 to 541 million years ago, was a pivotal time in Earth's history. It marked a transformative era during which complex, multicellular organisms emerged, setting the stage for the explosion of life.

WINDOW ON THE PAST: Fossil impression of Dickinsonia, an example of Ediacaran fauna, found in present-day Australia. Image credit: Shuhai Xiao, Virginia Tech

But how did this surge of life unfold and what factors on Earth may have contributed to it?

Researchers from the University of Rochester have uncovered compelling evidence that Earth's magnetic field was in a highly unusual state when the macroscopic animals of the Ediacaran Period diversified and thrived. Their study, published in *Nature Communications Earth & Environment*, raises the question of whether these fluctuations in Earth's ancient magnetic field led to shifts in oxygen levels that may have been crucial to the proliferation of life forms millions of years ago.

According to John Tarduno, the William Kenan, Jr. Professor in the Department of Earth and Environmental Sciences, one of the most remarkable life forms during the Ediacaran Period was the Ediacaran fauna. They were notable for their resemblance to early animals—some even reached more than a meter (three feet) in size and were mobile, indicating they probably needed more oxygen compared to earlier life forms.

"Previous ideas for the appearance of the spectacular Ediacaran fauna have included genetic or ecologic driving factors, but the close timing with the ultra-low geomagnetic field motivated us to revisit environmental issues, and, in particular, atmospheric and ocean oxygenation," says Tarduno, who is also the Dean of Research in the School of Arts & Sciences and the School of Engineering and Applied Sciences.

## Earth's magnetic mysteries

About 1,800 miles below us, liquid iron churns in Earth's outer core, creating the planet's protective magnetic field. Though invisible, the magnetic field is essential for life on Earth because it shields the planet from solar wind—streams of radiation from the sun. But Earth's magnetic field wasn't always as strong as it is today.

Researchers have proposed that an unusually low magnetic field might have contributed to the rise of animal life. However, it has been challenging to examine the link because of limited data about the strength of the magnetic field during this time.

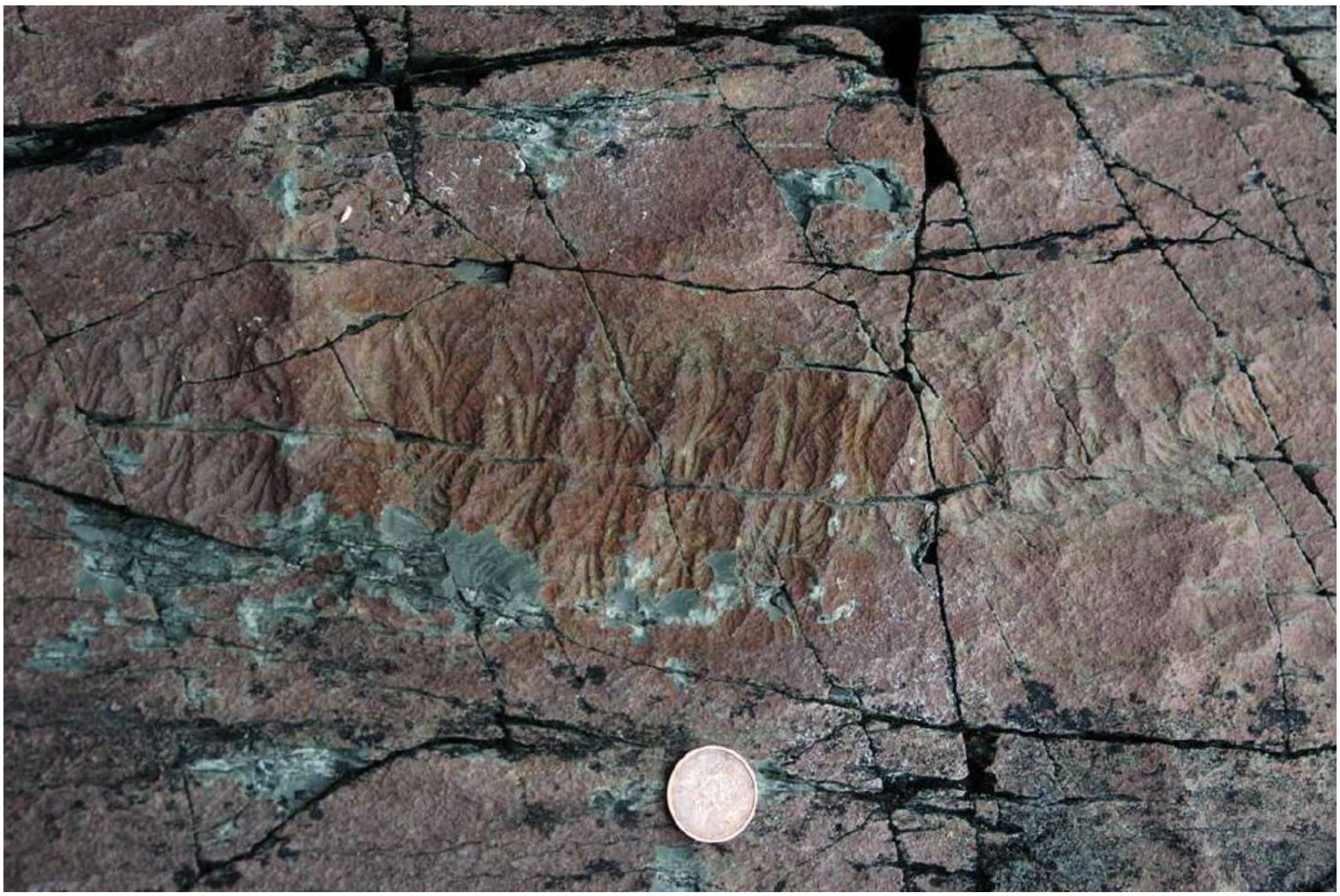
Tarduno and his team used innovative strategies and techniques to examine the strength of the magnetic field by studying magnetism locked in ancient feldspar and pyroxene crystals from the rock anorthosite. The crystals contain magnetic particles that preserve magnetization from the time the minerals were formed. By dating the rocks, researchers can construct a timeline of the development of Earth's magnetic field.

Leveraging cutting-edge tools, including a $CO_2$ laser and the lab's superconducting quantum interference device (SQUID) magnetometer, the team analyzed with precision the crystals and the magnetism locked within.

**A weak magnetic field**

Their data indicates that Earth's magnetic field at times during the Ediacaran Period was the weakest field known to date—up to 30 times weaker than the magnetic field today—and that the ultra-low field strength lasted for at least 26 million years.

A weak magnetic field makes it easier for charged particles from the sun to strip away lightweight atoms such as hydrogen from the atmosphere, causing them to escape into space. If hydrogen loss is significant, more oxygen may remain in the atmosphere instead of reacting with hydrogen to form water vapor. These reactions can lead to a buildup of oxygen over time.



HARD COPY: Fossil impression of Fractofusus, an example of Ediacaran fauna, found in what is now Newfoundland, with a Canadian penny nearby for scale. Image credit: Shuhai Xiao, Virginia Tech

The research conducted by Tarduno and his team suggests that during the Ediacaran Period, the ultraweak magnetic field caused a loss of hydrogen over at least tens of millions of years. This loss may have led to increased oxygenation of the atmosphere and surface ocean, enabling more advanced life forms to emerge.

Tarduno and his research team previously discovered that the geomagnetic field recovered in strength during the subsequent Cambrian Period, when most animal groups begin to appear in the fossil record, and the protective magnetic field was reestablished, allowing life to thrive.

“If the extraordinarily weak field had remained after the Ediacaran, Earth might look very different from the water-rich planet it is today: water loss might have gradually dried Earth,” Tarduno says.

**Core dynamics and evolution**

The work suggests that understanding planetary interiors is crucial in contemplating life’s potential beyond Earth.

“It’s fascinating to think that processes in Earth’s core could be linked ultimately to evolution,” Tarduno says. “As we think about the possibility of life elsewhere, we also need to consider how the interiors of planets form and develop.”

END OF NEWS LETTER

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