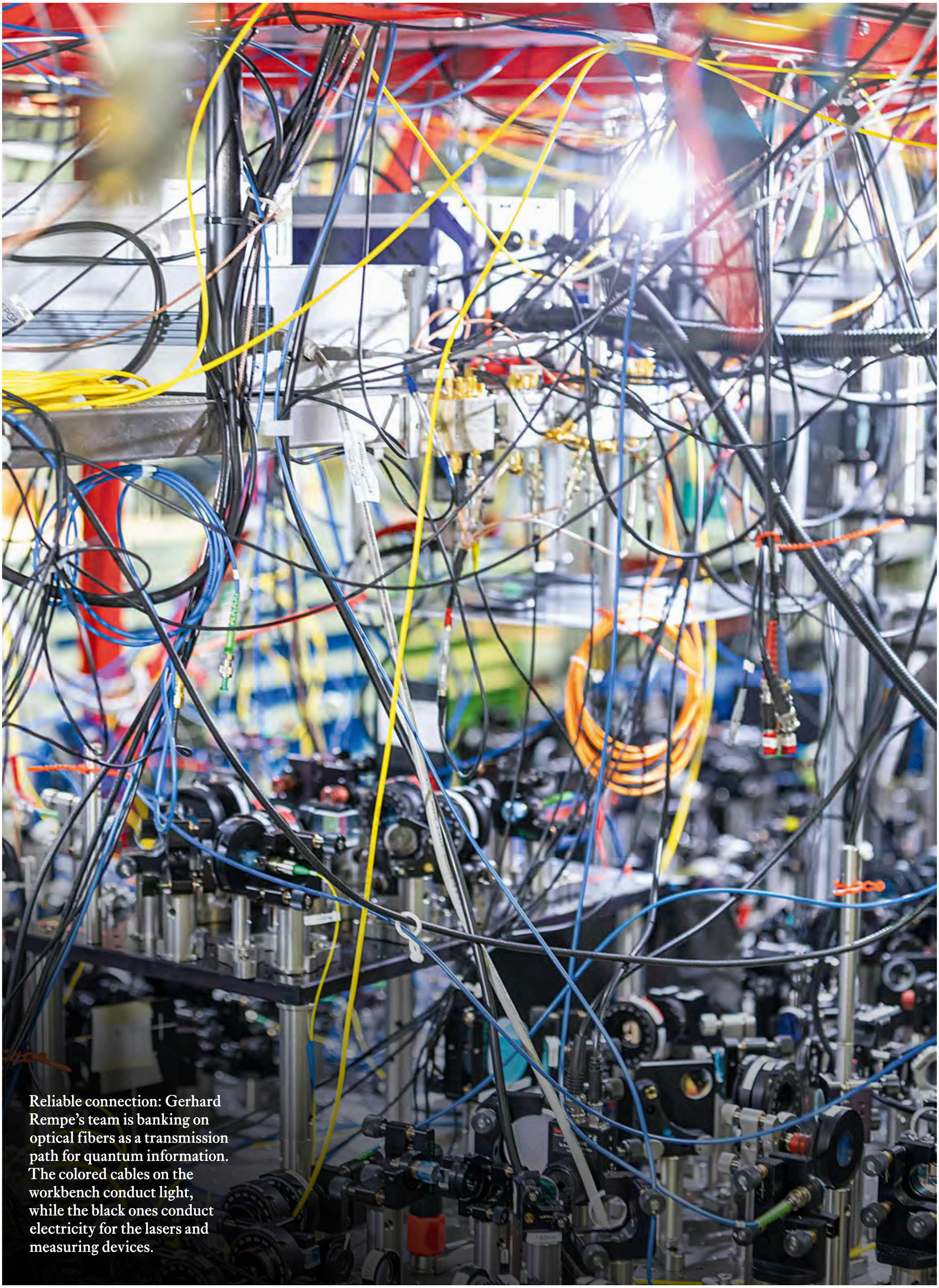

Reliable connection: Gerhard Rempe's team is banking on optical fibers as a transmission path for quantum information. The colored cables on the workbench conduct light, while the black ones conduct electricity for the lasers and measuring devices.

PHOTO: AXEL GRIESCH

THE ARCHITECTURE OF THE QUANTUM INTERNET

TEXT: ROLAND WENGENMAYR

Advances in technology are likely to make cyber-attacks ever more damaging. But at least the transmission of data could become more secure – through quantum communication. This has spurred researchers from around the world to work on its physical principles and technical components. Gerhard Rempe's team at the Max Planck Institute of Quantum Optics in Garching have set their vision even higher: to network quantum computers.

The two bright spots on the screen could represent the future of the quantum internet. "They're two glowing rubidium atoms, captured by a specialized high-resolution camera," explains Stephan Welte, a postdoctoral researcher in Gerhard Rempe's division at the Max Planck Institute of Quantum Optics in Garching. The atoms, just a few tenths of a nanometer (billionths of a meter) in diameter, were suspended in a vacuum in a cavity about half a millimeter wide when the image was taken. This "optical resonator" is formed by two almost perfect mirrors facing each other. Welte's colleague Emanuele Distante explains what this can be used for: "If you fire a photon, a quantum of light, at a minute atom, it is extremely unlikely that the two will ever interact with each other." But this is precisely what they have to do for quantum communication to work. Rempe's group aims to send quantum information by photon mail between senders and receivers composed of atoms or other particles that can store this information. The group hopes that Rempe's approach involving such mirror cabinets will eliminate the obstacle to communication. To achieve this, the two mirrors reflect the photon that is to be sent or received back and forth numerous times within the resonator, rather like a ping-pong ball – "in our case, about twenty thousand times," explains Welte: "This makes it highly likely that the photon will interact with the atom."

Over the course of two decades, Gerhard Rempe and his research team have perfected this mirror trick to the point where they are now using such resonators to develop components for quantum networks of the future. This field of research holds the promise of two advancements: enormously powerful quantum computers and guaranteed tap-proof communications. The latter would immediately be useful in everyday life for such things as online banking. In contrast, we are not likely to come into direct contact with quantum computers in our daily lives. Nevertheless, they would have a profound impact on the world in which we live. They could, for example, solve the "traveling salesman problem" of how to find the shortest route between a large number of different destinations. Such optimization problems that cannot be solved by conventional computers are common in science, engineering, business, and finance.

As quantum computers are costly to build, they are likely to be designed less like computing centers and more like world-wide quantum clouds. That is Gerhard Rempe's vision of the future and it would require a quantum internet. However, quantum computers could also crack the encryption we currently use to transmit data securely. Amazingly, quantum physics provides a solution to this

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problem in the form of quantum cryptography: eavesdroppers on the quantum channel used to distribute the secret key between sender and receiver would inevitably betray themselves.

This explains the huge interest in quantum information technologies in companies such as Google and IBM, which now have a substantial lead on the road to quantum computers. Beyond that, the competition is also on at the state level, above all between China, the U.S., and Europe. In 2018, the U.S. Congress passed the National Quantum Initiative Act, the purpose of which is to provide annually increasing funding to support and focus the wide range of research and development activities within the U.S. Nearly $ 800 million has been budgeted for 2021. The German government plans to provide EUR 2 billion to fund quantum technologies over the next few years, while the State of Bavaria is investing EUR 300 million to transform the Munich area into a “Munich Quantum Valley”. The intention is to create new research opportunities and study programs, as well as to establish new start-ups within the Munich region.

SUMMARY

Even if quantum computers end up breaking the encryption codes we currently use, the quantum internet could protect data transmission against eavesdropping. It could also connect remote quantum computers to form more powerful units.

The U.S., China, Germany and the EU, are all in a race to develop quantum communication. China, for example, has already constructed a 4,600-kilometer fiber-optic network to this end, which however, still uses nodes based on everyday physics which leaves them vulnerable to attack.

Gerhard Rempe’s team aims to transmit information over long distances purely on the basis of quantum physics. The researchers rely on photons as mobile carriers of quantum information and on individual atoms in resonators as stationary elements that act as senders or receivers. Among other advances, they have been developing a quantum repeater.

Fierce international competition

When it comes to delivering strong media messages, China is currently ahead of the pack. Chinese physicists launched the first satellite to conduct experiments for interception-free quantum communications in space in 2017. On the ground as well, they have constructed the largest fiber optic network to date, spanning 4,600 kilometers, to accomplish this goal. Asked how he assesses the current international competition in physics, Gerhard Rempe points out the cultural context of the race. “The laws of physics are the same everywhere, but there is a strong spirit of pragmatism and creativity in places such as the U.S.,” he says. He also considers Europe to be competitively positioned in terms of basic research, with different countries having different strengths. There are some excellent research teams in Germany, especially those that focus on quantum networks and quantum simulators. In fact, Germany is only falling behind when it comes to constructing a freely programmable, universal quantum computer, which is partially due to a lack of funding in the past. Rempe is impressed by the Chinese achievements in terms of management and technical implementation. “But,” he says “their work is less exciting from a conceptual perspective.” In his opinion, Chinese research is still slightly in copycat mode. On the subject of China’s fiber-optic network, he says that: “the network subsystems are based on established off-the-shelf technology but the system as a whole is definitely playing in the first league.”

For Rempe, the term “quantum internet” refers to something much more radical than the simple point-to-point connections currently being implemented. According to him, such a network would eliminate human actors communicating via quantum channels of longer or shorter distances. Humans belong to the macroscopic world, which is subject to the

Tracking of quantum post: the Max Planck physicists trap an atom in two crossed resonators, each formed by two optical fibers. This allows them to verify the existence of a photonic qubit without destroying the quantum information.

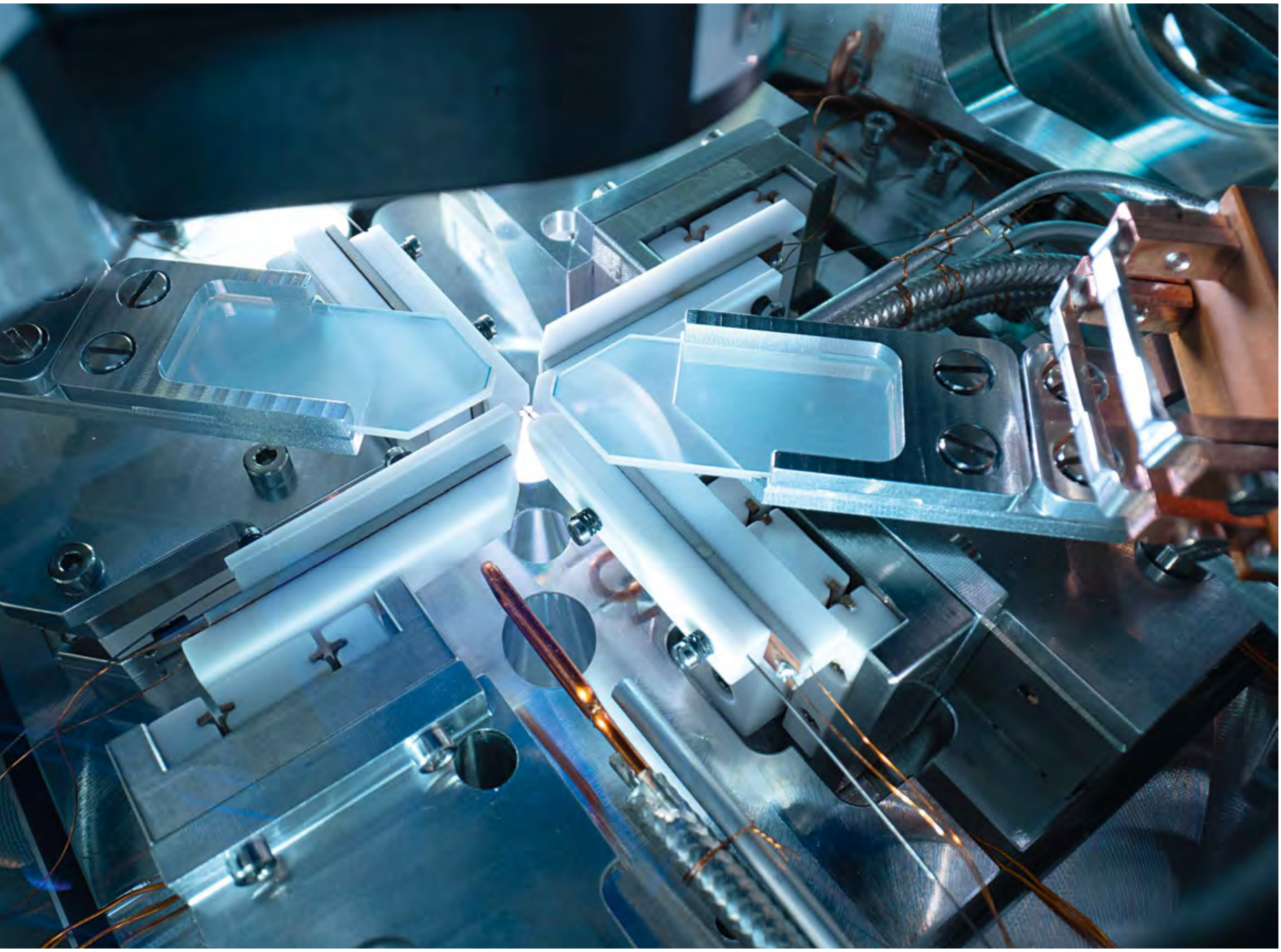

PHOTO: CHRISTOPH HOHMANN (MCQST / LMU MÜNCHEN)

rules of everyday physics, in which no sensitive quantum information can survive. Rempe envisions a future in which true quantum systems, and one day even quantum computers, will be able to communicate with each other over larger distances in a quantum cloud. "That would be Champions League level," he says. He has already taken the initial steps in his laboratories in Garching, and all the involved modules rely on the mirror cabinets.

But, for a layperson to understand what it is all about, one needs to briefly dive into the world of quantum physics – and that is a very strange place. Quantum information is always linked to its physical carrier, such as a quantum of light or photon. Photons transport quantum bits, or qubits for short, as quantum long-distance mail – whether through the atmosphere up into space to a satellite or through an optical fiber to a receiver. The information encoded in the photon can be envisaged as a small pointer extending from the center of a sphere to its surface. The north and south poles of this sphere correspond to the bits used in traditional computers, which can represent either a 0 or a 1. All other points on the sphere represent a superposition of these two states – an increase in possibilities that underlies the computational and storage potential of quantum information. Another crucial factor is that any time the photon is measured, the original superposition of all permissible states collapses to either 0 or 1 in accordance with the probabilistic rules of quantum mechanics. So, any attempt by an eavesdropper to surreptitiously read the quantum information encoded in a passing photon will inevitably be exposed, because the attempt to read the information constitutes a measurement that collapses the superposition which constitutes the actual content of the message. An eavesdropper cannot simply copy the quantum information to a second photon to read it there without being noticed, because,

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by its very nature, quantum information cannot be copied – a fact referred to as the no-cloning theorem. The information can only be transferred, for example from the photon to an atom as a storage medium. The communication deployed in the individual sections of the Chinese network is based on this no-cloning theorem. The problem is that as the length of the fiber increases, so does the number of photons that are lost, which means that trusted nodes need to be interposed within the network – 32 of them in the Chinese implementation. Currently, these nodes that link individual quantum subsections are still subject to everyday physics. “That’s not immune against eavesdropping in the sense of quantum physics,” as Rempe explains, “because an eavesdropper could discover what was happening at the nodes.”

The physicists are hoping to make progress here based on another property of quantum systems, namely entanglement, which allows distant quantum systems to be fused into a single quantum object. To get a feel for entanglement, let us imagine that “Alice” in Munich and “Bob” in Toronto have a pair of quantum dices. Both are tasked with rolling their individual dice a thousand times and writing down the sequence of numbers obtained. In isolation, this sequence will seem completely random for both. However, as soon as they compare their lists, for example via a video call, they start to notice something strange: every time Alice rolled a six, Bob rolled a one – and vice versa. And if the result was not one and six then it was two and five or three and four. The reason is that the two dices were entangled with each other over thousands of kilometers.

Albert Einstein viewed this “spooky action at a distance” as evidence that quantum theory is incomplete. But he was mistaken, because nature operates precisely like this, and entanglement has now been successfully demonstrated in experiments spanning many kilometers. It is this entanglement that nascent quantum information technologies are exploiting as a key resource. In its advanced form, the distribution of quantum keys – quantum cryptography – depends on the extreme sensitivity of entanglement to any external influences. The moment eavesdroppers try to snoop on the quantum channel, they betray themselves due to the immediate collapse of the entangled state. In a future quantum internet, as envisioned by Gerhard Rempe, quantum modules will be capable of entangling with each other via traveling qubits. The modules – which could even be full quantum computers in the future – will serve as intermediate storage devices for quantum information. For Rempe’s team, these memory modules are made of the atoms in the mirror cabinets.

Quantum repeaters for long distances

In the view of the Max Planck Director, any future quantum internet will inevitably be based on a fiber-optic network. Satellite transmission becomes problematic as soon as larger amounts of data are involved, because the atmosphere is no exception to the rule that precious photons sometimes disappear, or because a satellite sinks below the horizon. Compensating for the losses in optical fibers requires a larger quantum network to incorporate some form of repeater, analogous to the repeaters in conventional optical fiber networks. As yet, however, no such quantum repeaters have been developed, although several groups around the world have been researching them for the past 20 years.

The difficulty is due to the fact that a quantum repeater cannot function as an amplifier. In principle, a conventional repeater collects attenuated laser light and transfers the signal received onto a stronger laser beam for reemission. In quantum physics, this would constitute the prohibited process of copying, i.e., the quantum message would have been opened prematurely, rendering it worthless. So, a quantum repeater must be capable of passing on Alice’s highly sensitive entangled message to Bob at a distance, without reading it. More precisely, a quantum state is sent from Alice through to Bob via an entanglement. This process is known as quantum teleportation, although the term, inspired by Star Trek, is frequently misunderstood. Unlike in the science fiction show, it does not mean that matter, including a full-sized Mr. Spock, can be beamed from place to place. It only works for non-material quantum states, in other words, quantum information.

In fact, Gerhard Rempe’s team recently conducted the world’s most successful laboratory experiment on quantum repeaters. A mirror module housing two atoms served as the repeater. This ensemble is placed in the fiber optic path between Alice as the sender and Bob as the receiver. It involves one of the two atoms in the mirror module repeatedly sending an individual photon entangled with the atom to Alice, until one eventually arrives successfully. At the same time and independently, the other atom establishes a connection with Bob. As soon as this is established, both atoms in the mirror module are subjected to what Rempe refers to as a “magical measurement.” This causes the entanglements of the two partial sections to be “glued together” to form an entanglement between Alice and Bob.

Since the two sections have been processed in parallel before this last step, the transmission rate is higher than that of the simple connection without a repeater as soon as a specific section length is exceeded. The experimental setup has not yet achieved this distance: the longest connection path achieved in the laboratory to date was equivalent to a two-kilometer fiber-optic path. The measured results already show that beyond a distance of seven kilometers, the Garching quantum repeater would result in better transmission of photons than a link without a repeater. However, the path to this achievement is still long and hard. Simply extending the distance will not work, as Rempe explains. Prior to that, the researchers will have to solve a number of problems, in particular they will have to reduce losses caused by the magic measurement. Any quantum fiber optic network would then have to include a quantum repeater every few kilometers.

Another crucial tool developed by the team performs the task of a herald. In a network with quantum repeaters, this herald issues a success signal as soon as each section of the link has established entanglement that is subsequently switched through by means of the final magic measurement. The challenge is that the herald is not permitted to carry out a full measurement itself. Metaphorically, its job is to discover if someone is in a room solely by listening, without opening the door. To implement such a herald, Rempe's team has devised a clever arrangement of two crossed resonators. The main resonator, which is aligned in the same direction as the actual communication link, serves as a network node with a memory function. The secondary resonator, which is aligned perpendicular to it, checks as a herald carefully whether the atom in the resonator has stored the incoming qubit.

Network of quantum processors

Rempe and his team can also use their herald method to check whether a photon has arrived at the crossed resonators in an optical fiber. This is essential, in order to establish as quickly as possible whether the quantum mail has been lost in transit. In this context too, the trick is to "sense" the photon, without measuring it directly. Any measurement would destroy the information stored in the photon. Such heralds are part of the toolbox with the aid of which multiple quantum computers could be linked via a quantum network. This is because multiple heralds distributed over the quantum network would enable the rapid detection of whether a photon is still present or has already been lost so that a new transmission attempt could be made if required.

Gerhard Rempe's team has recently taken an important step towards a quantum network with an experiment in which Alice and Bob were already represented by two quantum processors. This experiment consisted of two modules 60 meters apart, comprising atoms in mirror resonators,

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Philip Thomas, Olivier Morin, Gerhard Rempe and Leonardo Ruscio (from left) gather around the table on which the vacuum chamber used in experiments involving individual atoms sits. The lasers needed for this are mounted on the table on the left.

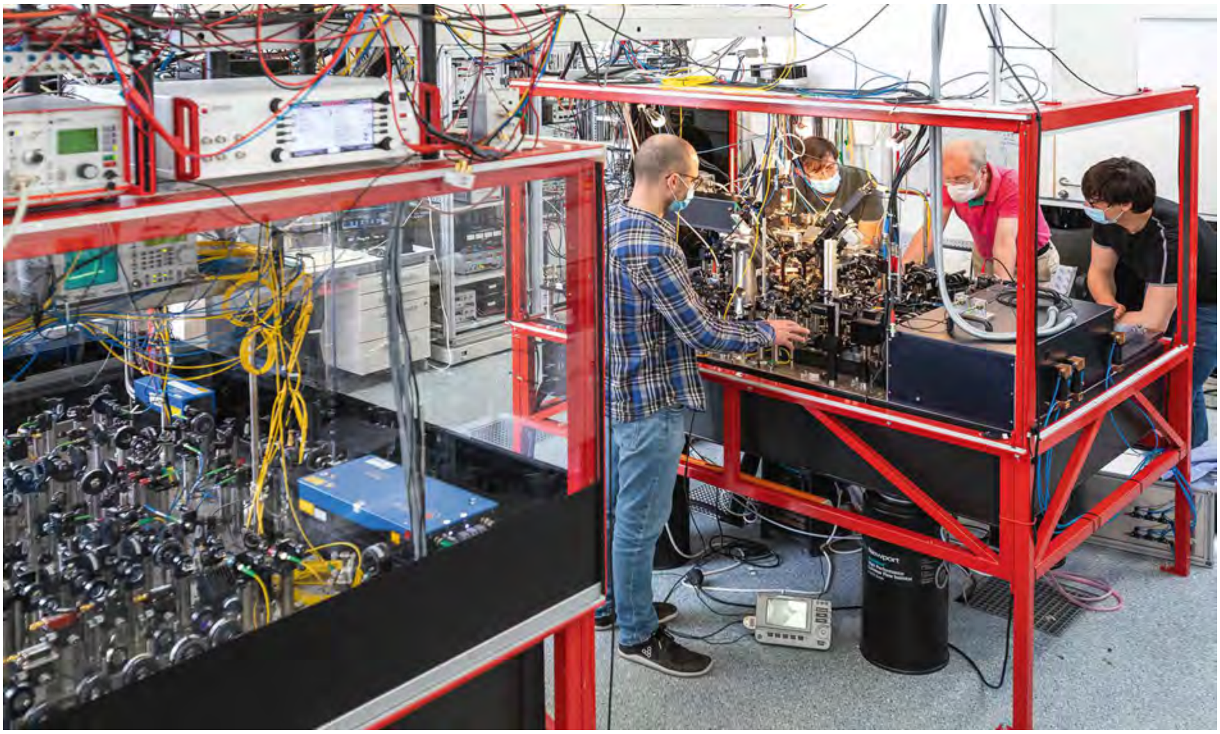
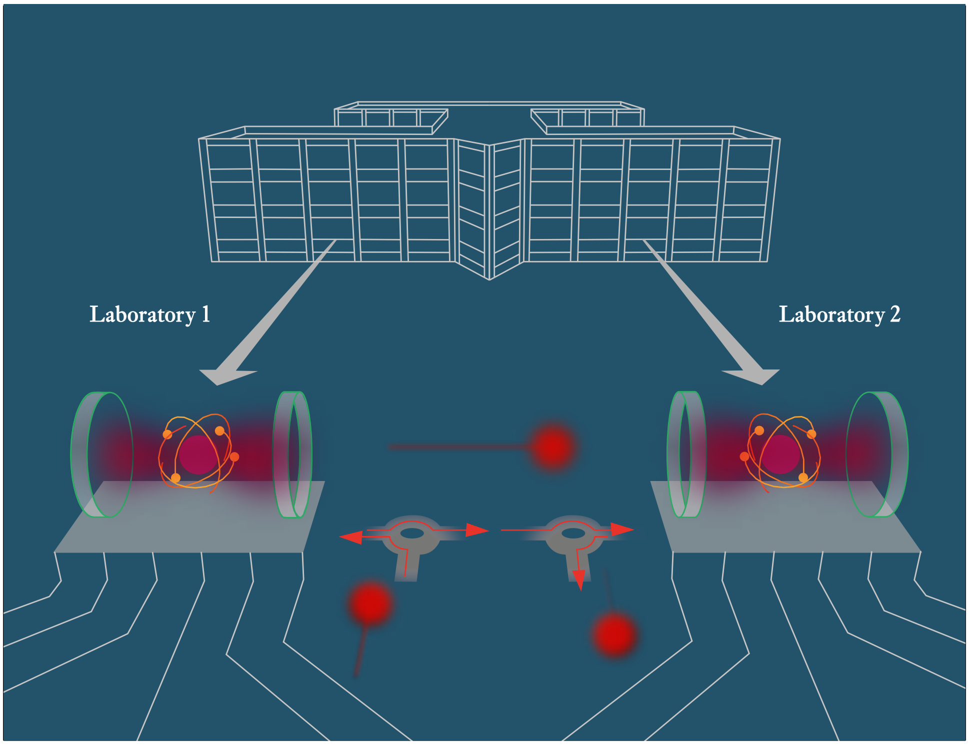


PHOTO: AXEL GRIESCH



Distributed computing: two atoms between pairs of mirrors located in different laboratories perform a joint quantum calculation. This is mediated by photons rather than the electrical signals used in conventional computers.

GRAPHIC: GCO BASED ON A DESIGN BY THE MPI OF QUANTUM OPTICS

connected via an optical fiber. The researchers succeeded in coupling the two atoms in the modules to form a quantum logic gate with a herald via a single photon transmitted through the fiber. The quantum gate can be envisioned as an analog of the logic gates used in conventional electronics, but with optical fibers for photons rather than electronic conductors. Such distributed quantum processors could overcome a key problem of quantum computers: qubits are located in close proximity to each other and can therefore interfere with each other in undesirable ways. This problem could be prevented by a quantum network comprised of distributed processors. Establishing local quantum networks with this kind of function within individual premises is also a much easier initial step than, say, creating a global quantum internet. Such local quantum networks could represent an initial use case.

Recently, Rempe and his team also succeeded in creating the first “random-access memory” for quantum information in the form of two atoms in the mirror cabinet. This type of memory permits unrestricted access to each memory cell, and in the configuration devised by Rempe’s team, these cells are represented by each of the two atoms.

In this way, the researchers are progressively developing quantum communication modules. Rempe’s confidence comes as no surprise. He firmly believes that we will witness the establishment of a true quantum technology long before the end of this century. Among other things, his optimism is based on the history of scientific progress: major discoveries in physics, for instance in optics and mechanics, thermodynamics, electrodynamics, and quantum physics, have always proved to be the economic engines of the following century. They are at the root of countless technical and societal breakthroughs, from trade to mass production and automation.

“Quantum physics has brought us a multitude of major breakthroughs in the form of transistors and lasers, and I believe that the 21st century will be the century of quantum information.”

←

GLOSSARY

QUBITS
The smallest unit of quantum information is known as a qubit. Qubits can not only encode a 0 or a 1, but also states in between. This is expected to make quantum computers much more powerful than conventional computers. The laws of quantum physics also prohibit the copying of quantum information, thus enabling tap-proof communications.

QUANTUM REPEATERS
are designed to enable fragile quantum information to be transmitted over long distances by using quantum entanglement.

ENTANGLEMENT
transforms multiple quantum systems, even spatially separated ones such as photons and atoms in resonators, into a single extended quantum system.