Interview with Gerhard Rempe about the fascination of and prospects for quantum information technology

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Gerhard Rempe, Director at the Max Planck Institute of Quantum Optics in Garching near Munich. Credit: Axel Griesch

Gerhard Rempe, Director at the Max Planck Institute of Quantum Optics in Garching, and his colleagues investigate the fundamentals of quantum information technology.

The researchers have learned to control individual atoms and photons, or light particles, and the interactions between the two in a very precise way. They trap individual atoms in resonators which are essentially comprised of two extremely good mirrors. By bringing one photon to interact with one atom in the resonator they store information in the atom in the form of individual bits, read the bit out again and transfer it to another atom. Recently, they even logically linked one atom with one photon and thus executed a fundamental computing step. Here we talk to Gerhard Rempe about what fascinates him in these experiments, the difficulties he and his team have to overcome in the work, the prospects he sees for quantum information technology, and how difficult it is to communicate some peculiar aspects of quantum physics to lay people.

Professor Rempe, how did you explain your work to your children when they were young?

Gerhard Rempe: It was very difficult. I could just about get to the superposition state where one quantum particle can exist in two states simultaneously before its properties are measured. But I didn't get very far with the entanglement of two particles. I tried to demonstrate the effect with dice.

Can you try this again for us?

With a die, the numbers on opposite sides always add up to seven. The six is opposite the one, for example. So if I see one number, I immediately know the other one. There is a similar situation when I measure the properties of entangled particles. The crazy thing about entanglement is that the result of a measurement also depends on the type of measurement - we say that we can rotate the base. Maybe it's easier if you imagine you were to put your head on one side so that you could simultaneously see something of the numbers on the opposite sides. This leads to a new, rotated "number", whose "opposite number" always automatically rotates with it. But you might notice that it's very difficult to explain this with analogies. Quantum physics is not illustrative, because our ideas are characterised by everyday life and quantum physics does not apply here.

One probably has to accept that your work exceeds many people's power of imagination. But it is not only the concept of your research that is difficult to understand. Your experiments also seem to be technically inconceivable. After all, you work with individual atoms and individual photons.

Nowadays, I could say it's not difficult, because now we can do it. But I started on this 20 years ago. And in retrospect you're right: we had to travel a long, but exciting road until we achieved control over individual and very different particles such as atoms and photons. And we also had to have vast amounts of technology available. When research develops over such a long time it is fantastic to be in the Max Planck Society, because here it's possible to pursue long-term research projects and know that the funding is secure.

The perseverance obviously paid off.

At conferences we hear appreciative comments again and again. But some doctoral students who we would like to take on are afraid to join us because our experiments are too demanding for them. For others, it's precisely this aspect which is attractive, of course.

Which problems did you have to overcome in order to control such tiny particles like atoms and photons?

Careful: the atoms may be extremely small, but our photons certainly are not. They extend over several hundred metres, but move extremely fast, of course. Because they extend over such a large space, we can choose their frequency, meaning their colour, with extreme precision.

This is another property of quantum objects that takes some getting used to, the fact that not all of their properties can be determined with the best possible accuracy. Can you tell us something about other challenges in your experiments?

We trap our atoms between two mirrors which are very close to one other. In the beginning, the mirrors were always in our way when we wanted to get to the atom with laser beams in order to cool it or influence its state.

How did you solve this problem?

We developed special cooling techniques for this, for example. A few cooling methods exist for atoms in free space. This was one of the things for which David Wineland received the 2012 Nobel Prize for physics, for example. We, in contrast, take into account the special radiation properties of the atom in the resonator, which are different to those in free space. The atom sees itself between the mirrors maybe one million times. We exploit this to cool the atom.

Why are you interested in the system of one atom in a

resonator?

There are two reasons for this. On the one hand, I am really a laser physicist. I built a laser as part of my diploma thesis. And what is a laser? A medium between two mirrors that I excite and which amplifies light. At some stage I asked myself what the limits were here. Can I also build a laser from one atom between two mirrors? Nobody has really succeeded in doing this as yet. One problem is that the further I reduce the number of atoms between the mirrors, the better these mirrors have to be.

And the second reason?

If I work with such a simple system that comprises only one atom and one photon with one frequency with one polarisation and one wavelength, I can investigate many fundamental questions. You might think that nothing much happens in such a simple system, but in fact there's a lot going on.

And what actually happens?

The most important thing is that the interaction between light and matter becomes nonlinear. If the interactions were linear, the atom would simply react twice as strongly to double the light intensity, for example. But this is not the case for one individual atom. If I offer the atom a photon, it is absorbed by the atom. The atom makes the transition from the ground state into an excited state. If the second photon now arrives, the atom can no longer absorb it, since it is already excited. It can only emit. So what was originally an absorber has now become an emitter. A single photon can therefore completely turn around the radiation properties of a medium which consists of only one atom. This is not possible with a medium consisting of many atoms, of course. From this point of view, a reduction to individual particles is not a limitation, but an opportunity. Because one atom and one photon communicate much more intensively with each other.

What role does the resonator play in this process?

Without the resonator it would be impossible for me to hit the atom correctly. The atom is much smaller than a light beam, even if I focus it to an optimum. This makes it very unlikely that the photon will meet the atom and the two of them start an intensive dialogue. The photon is reflected again and again between the mirrors, so that the probability that the photon interacts with the atom is increased considerably.

The experimental obstacles in your research are obviously difficult to overcome. What is your long-term goal?

The road we take does not always run in a straight line, sometimes we look to the left and right. It's like being in the mountains, where it is sometimes also possible to drift off into particularly beautiful scenery away from the real route.

And the quantum computer is the peak?

People always mention the quantum computer, I don't know why. It's just one of the possibilities which quantum information technology provides us with. We still have no idea if and when there will be one.

So what is your alternative objective?

We don't want to compute, but communicate. My long-term goal is a quantum Internet that has a high capacity, spans large distances and is not susceptible to eavesdropping, so that the NSA can no longer listen in, for example.

They are probably very interested in quantum computing...

... because a quantum computer can quickly crack classic encryptions. But you can't do this with quantum cryptography without someone noticing what you are doing. It's even possible to buy quantum cryptography nowadays, but it works only over a few kilometres and only between two parties. Our hybrid system using one photon and one atom in a resonator makes it possible to transmit quantum information securely over large distances and also to communicate between several parties.

In what way is your system particularly well suited for this?

On the one hand, I need photons. They are the only possible information carriers across large distances, because I can't really pack my atom into a suitcase and carry it from A to B. Photons are good for the transfer, very good even, but unfortunately they are forever getting lost. I therefore need to amplify the information if I want to send it over large distances. But I can't amplify quantum information like classic information. This is why I need a quantum repeater...

... an amplifier which maintains the quantum character of the information.

... precisely, and for this I then need a quantum storage device, and our atoms represent the best possible way of achieving this. These quantum storage devices would be important not only for the quantum repeater, but also for many other applications.

What is your thinking at present, for example?

Such a storage device is very important if I want to establish a connection between three or more parties where synchronisation is crucial. If I only want to transmit information from A to B, everything runs sequentially. But if a third party is involved, it needs to know when it should transmit its information. Until then it needs to hold on to the information, and for this it needs a storage device. These connections between several partners are commonplace in the Internet. So the key word is scalability.

The possibility to combine many systems which work on a small scale to a larger system.

Precisely! A system is scalable if the technical difficulties for the expansion increase only linearly, while the possibilities increase exponentially. The full potential of entangled systems for quantum computing, for example, can only be fully exhausted in larger systems. Some proposals for a quantum computer are not scalable, however.

Can you give an example of this?

When you arrange ions in a chain, you've already produced quantum logic gates, in other words logic operations. This has been possible with up to 14 ions so far. But if I address an ion at one end of the chain, I have to transport the information for this through the whole chain in order to send it to the other end.

The longer the chain, the easier it is for the

information to get lost.

That's correct. Maybe it's possible to add one more ion, just like you can always squeeze another handkerchief into a suitcase. But at some stage, that's it. This system is therefore not scalable as it is. Our system in contrast is scalable.

It is therefore theoretically possible to combine it with itself as often as you want. Can we already foresee when we will have a quantum Internet which cannot be intercepted?

That's difficult. The history of the world does not follow a straight line. If there is a surprise tomorrow, we may all be doing something different the day after tomorrow. This isn't a disaster, because in basic research especially we're looking for the surprises - it would actually be boring without them. So my conclusion is: let's wait and see!

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