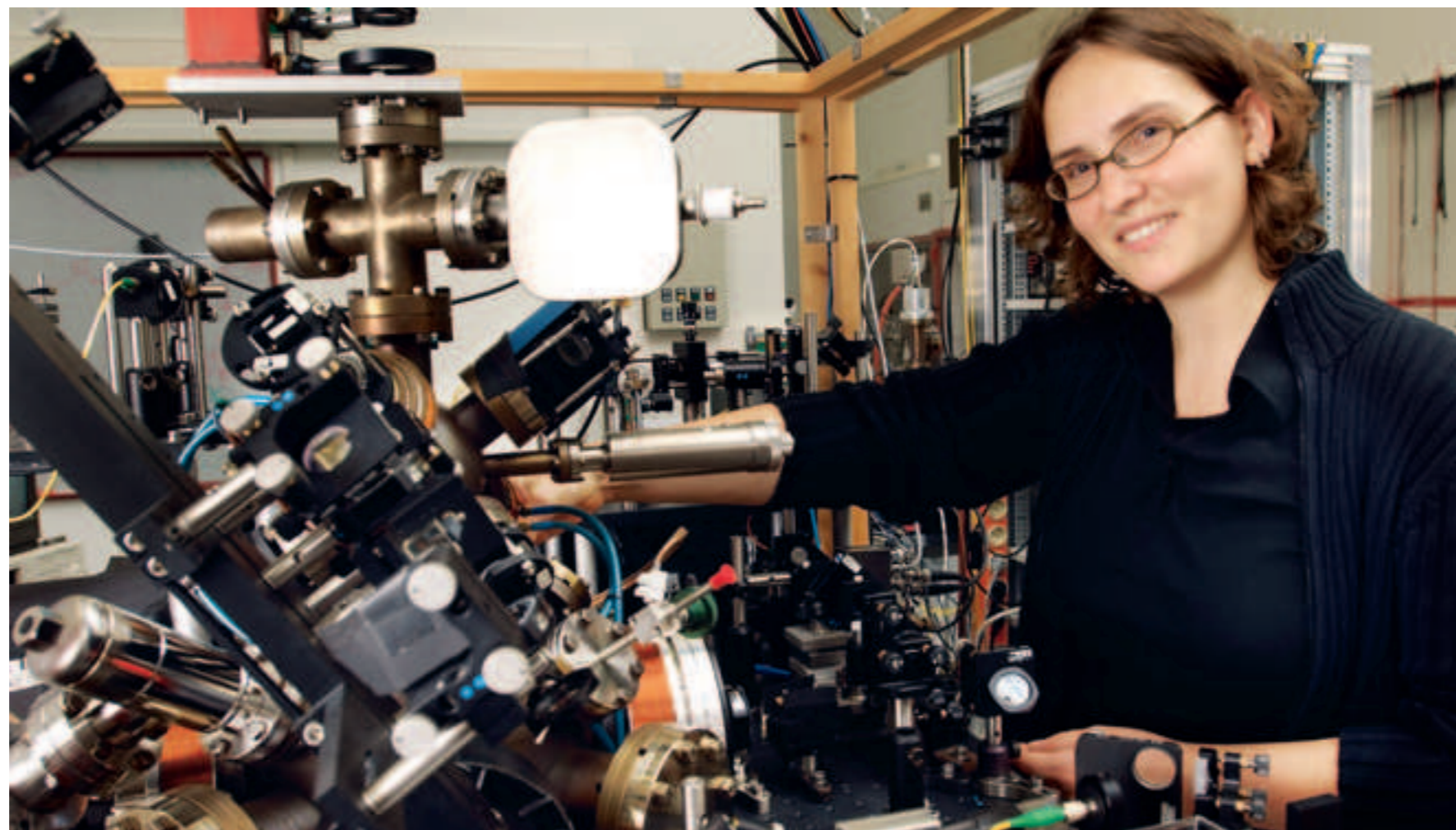


Duel in the Quantum World

*Quantum cryptography already exists, researchers have been working with quantum dots, and the quantum computer is eventually supposed to become part of our daily lives. It is not easy for the normal human intellect to conceive of the new technologies: events in this most miniature of worlds are too abstract. Nevertheless, the future has already begun at the **MAX PLANCK INSTITUTE OF QUANTUM OPTICS** in Garching and the **MAX PLANCK INSTITUTE FOR SOLID STATE RESEARCH** in Stuttgart.*



A photon pistol can't be loaded as quickly as a revolver: Tatjana Wilk must precisely align every laser she beams into the vacuum chamber.

Fortunately, Tatjana Wilk does not have to draw her pistol in a duel. Not only would she have to transport it in a truck and then need days to put it together, but the magazine alone would probably take up more space than the German chancellor's desk, and it's packed higher than humans are tall with optical and electronic devices.

What the gun finally produces when Wilk, a physicist from the Max Planck Institute of Quantum Optics

in Garching, pulls the trigger is one of the smallest bullets in existence: a harmless photon. That's why the photon pistol is not suitable for a shoot-out. However, it is suitable for performing calculations and transmitting information. At least, that is what the physicists who are developing quantum information technology firmly believe.

Not only can they envisage photons one day operating in a quantum computer with bits and bytes – a job

that electrons do in conventional PCs – but they are also conducting research into quantum cryptography. This technology applies the laws of quantum mechanics to the key for an encrypted message as it travels from sender to recipient. Then no one could acquire possession of this key unnoticed (box, page 43). This technology could ensure better security for the data transactions with which banks transfer amounts running into the billions every day. The

first devices that work on this principle are already on the market.

"Quantum cryptography functions only when each bit of the key is stored on precisely one photon," says Tatjana Wilk. Above all, this means that each light pulse that transports a bit must not consist of more than one photon. The first commercially available quantum cryptographs create the single photons statistically. They weaken laser pulses so much that they contain, on

average, only a fraction of a photon, so it is highly probable that they do not contain more than one. However, this also means that most pulses are so weakened that they disappear and no longer contain any light. It thus takes a long time for the key for a message to reach the recipient.

With the photon pistol that Tatjana Wilk and her colleagues have constructed under the leadership of Gerhard Rempe, this process would presumably be faster – and certainly

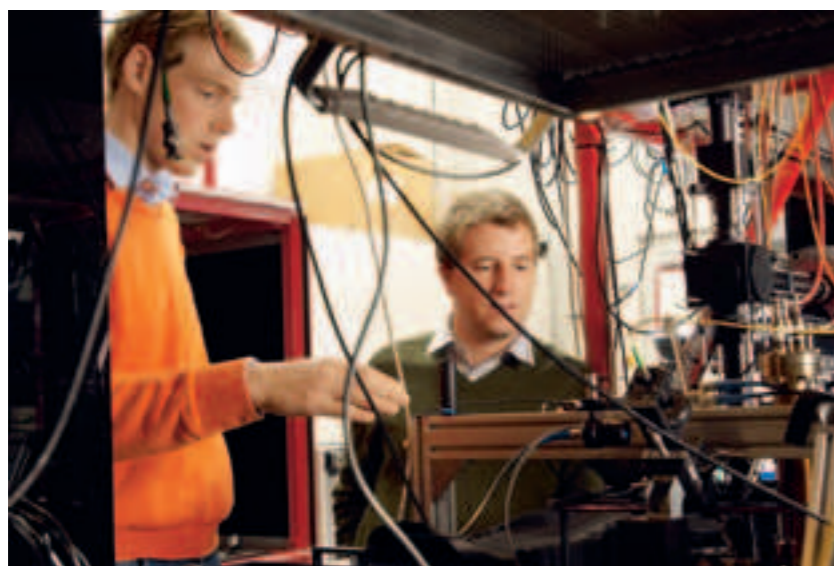
more elegant. "We know that each shot from our photon pistol contains exactly one photon. And we can aim the shot at a target," says Wilk. However, to achieve this, the Garching-based physicist has to do more than just hold a filter in front of a laser. First, she loads a very thin gaseous cloud of rubidium atoms into a magneto-optical trap in which a magnetic field and gentle nudges from the photons of a laser beam cool the particles down to a few millionths of a degree above absolute zero.

When she switches the trap off, the atoms trickle through an optical resonator – two mirrors positioned opposite each other. The diameter of the two mirrors is merely that of a small tablet, and the distance between them is even less. They sit in the center of a vacuum chamber on a table with the surface area of a shower tray.

SINGLE LIGHT PARTICLES LIGHT UP IN TIME

Glass fibers lead to the chamber, which resembles a diving bell, from a system that is just over twice the size. The laser pulse speeds through one of the glass fibers. It excites an atom just as it falls through the resonator, thus loading the pistol, which immediately shoots. "The color of the light emitted is determined by the distance between the two mirrors," says Wilk. Only whole waves of light fit into the resonator. Light waves that are too large or too small are never even created. This limits the colors in which the atom can light up.

"Producing a single photon is a fundamentally different issue from creating a photon on average," says Gerhard Rempe, in whose department Tatjana Wilk does her experi-



15...16...17 seconds – record: That is how long Markus Hijlkema and Bernhard Weber kept an atom suspended in a resonator. The scientists in Garching used multiple cooling mechanisms to keep an atom still for so long.

ments. On average, a photon is created from a weakened conventional pulse in which the individual light particles are created as randomly as raindrops fall. “However, we direct a conventional light pulse at the atom in the resonator – and out comes a quantum mechanical pulse.” A characteristic of this single photon pulse is that it does not light up randomly, but in a precise rhythm specified by the physicists in Garching. “We are now looking at what is possible with these light pulses. At the moment, we’re making photons that are about one kilometer long. Eventually, we will pass our findings on to engineers,” says Rempe.

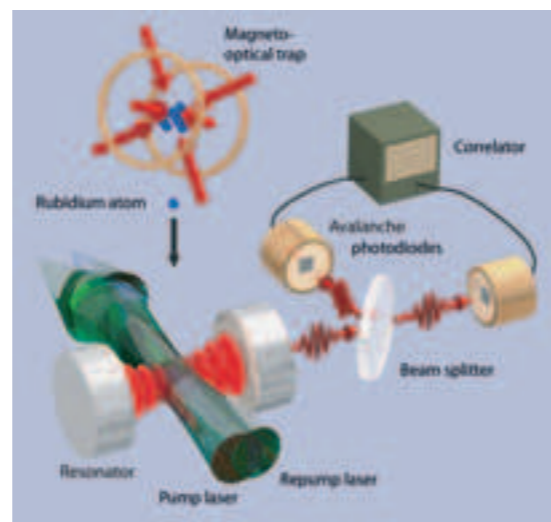
In the meantime, Tatjana Wilk and some of her colleagues are coaxing, for example, polarized photons from the atoms on their path through the resonator. The light waves turn to the right and to the left, alternating neatly. “The direction of the resonance is very suitable for coding bits,” says Wilk. Not only is this essential for transmitting digital signals, but a quantum computer could also store and process its smallest computing unit in this physical property.

Right-polarized light could then stand for one and left-polarized light for zero, for example. Making light spin in this way also creates the possibility of entangling photons from two photon pistols. This, in turn, is a step without which quantum information technology can’t function. “That’s what we’re working on at the moment,” says Tatjana Wilk.

COMPUTING AT ABSOLUTE ZERO

To entangle light particles from photon pistols, Markus Hijlkema and Bernhard Weber are working a couple of laboratories away on a counterpart to Wilk’s photon source. Their research would make it possible to have greater control over the pistol. To do this, they need to trap single

Shooting in free fall: A rubidium atom falls out of the magneto-optical trap through the resonator. The photon shot escapes through the right-hand mirror.



atoms in a resonator. Unlike in Tatjana Wilk’s device, an atom would not fire in free fall, but while it is trapped between the mirrors. Controlling atoms in this way is essential for a quantum computer. Irrespective of whether a computer of this kind works with atoms, molecules or ions – physicists are currently working on all three options – the particles must be cold. Very cold: at most, fractions of a degree Celsius above absolute zero.

This means that the particles must stand almost completely still, just as Hijlkema, Weber and their colleagues immobilize atoms in a resonator. They have already immobilized rubidium atoms for 17 seconds. On an atomic timescale, that is a small eternity. They are experimenting with different mechanisms to stop and control the atoms. They use three different cooling techniques to confine the particles between the mirrors. The atoms have already been through cooling in the magneto-optical trap that Tatjana Wilk also uses. From this standard version of a refrigerator for atoms, the physicists transport the test subjects of their experiments into the resonator with a dipole trap. Here, too, they use the electromagnetic field of a laser. This field reshapes the electron shell of the atoms to a dipole, which the laser simultaneously attracts.

Using an electromagnetic gripper arm, the physicists maneuver the particles 14 millimeters into the resonator. This is where it all really starts happening. The distance between the mirrors of the resonators is adjusted so that only light with certain frequencies can move backwards and forwards. Furthermore, two laser beams meet in the center of the mirror chamber. One serves as a dipole trap to hold the atoms; the other excites the atom so that it can emit a photon into the resonator. However, the frequency of the exciting laser is slightly lower than would fit in the resonator. Therefore, the light radiated by the atom needs a little more energy. It takes this energy from the movement of the atom, which thus becomes slower – and colder.

Physicists call this effect “Doppler cooling.” It acts both along the resonator axis and at right angles to it in the direction of the exciting laser beam. Finally, the rubidium atom also loses energy in the “Sisyphus cooling” effect. The particle prefers to stay at the antinodes of the standing wave that forms in the resonator, where its potential energy is minimal – similar to Sisyphus, who undoubtedly would have preferred to stay at the foot of his fateful mountain.

A COMPUTER AS BIG AS A SMALL TOWN

And just as Sisyphus had to roll a stone up a mountain, a hot atom always oscillates away from its preferred position. It runs up against an energetic mountain and loses kinetic energy. Ultimately, it packs this energy on top of the energy of the photons emitted. In this way, the atom finally becomes so cold that its movement is determined only by quantum mechanical fuzziness.

In quantum cryptography, just a few of these atoms in the resonator could transmit reliable signals. However, to link thousands of quanta into a network requires a bit more miniaturization. Currently, the sys-

COMPUTING WITH LIGHT

The quantum computer is intended to solve a few problems a lot more quickly than conventional computers, which would take months or even years. One example would be reducing large numbers to their prime factors – an operation that banks use to encrypt electronic money transactions. In a quantum computer, the calculations would be performed by, not transistors, but quantum bits, or qubits for short: atoms, molecules, photons or, in general, particles that are governed by the laws of quantum mechanics.

A quantum computer will be faster because a group of these particles does not behave as our view of the world leads us to expect. For example, two photons become a quantum mechanical system when they are entangled with each other. They are then no longer independent of each other and can either be both right polarized or both left polarized. This means that their light waves spin to either the left or the right. They do not choose a direction until someone observes them – that is, measures their direction of spin. Until that moment, the true state corresponds to an overlap of both possibilities.

“That is a problem only for our Western view of the world,” says Tobias Schätz, whose quantum simulator is intended to work with a chain of entangled atoms. “The Dalai Lama doesn’t have a problem with it.” His world view is based on the principle of Yin and Yang. Nothing is purely good or purely bad.

In physics, this principle is known as superposition – and a quantum computer is inconceivable without it. For two entangled photons, it means that they can simultaneously encode two zeroes and two ones, and can also perform calculations in both channels. One such computing operation could consist in using lasers or filters to systematically influence the vibration planes in photons.

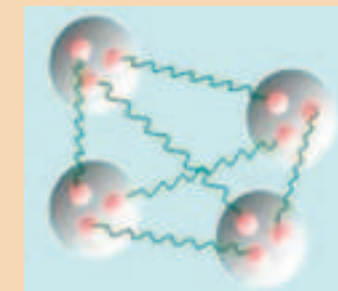
But there is one problem: after the calculation, it must be possible to read the results of the parallel processes. Unfortunately, in this respect, the entangled particles conform to the Western world view. As soon as a physicist measures the polarization of two entangled photons, they must commit themselves to either left or right.

In many cases, the results of the other computing channels are lost – but not always. Physicists have devised measurement rules to record more than one result from the parallel calculations – and it really was possible to reduce large numbers to their individual factors much more quickly.

It also seems possible to solve another problem of quantum computing. A quantum mechanical state is a very volatile affair, often remaining intact for only fractions of a second. The quantum calculation must thus be completed in an instant. But now lasers create pulses that are thousands or millions of times shorter than the lifetime of many states that are relevant to quantum computers. Since lasers control the steps of a quantum calculation, they can, in theory, complete thousands of calculations on a quantum mechanical state.

Ignacio Cirac, Director at the Max Planck Institute of Quantum Optics, and his colleagues have contributed significantly to simplifying the theoretical description of quantum states of several qubits. For example, they created PEPS, which stands for projected entangled pair states. Instead of finding the actual state of a group of particles, the physicists create a model of the state: they assume that each particle in the real system is made up of several particles, just like a neutron is composed of several quarks. Together, the quarks determine the properties of the neutron. In the case of PEPS, they choose entangled pairs as components, as they are mathematically easier to deal with than real particles.

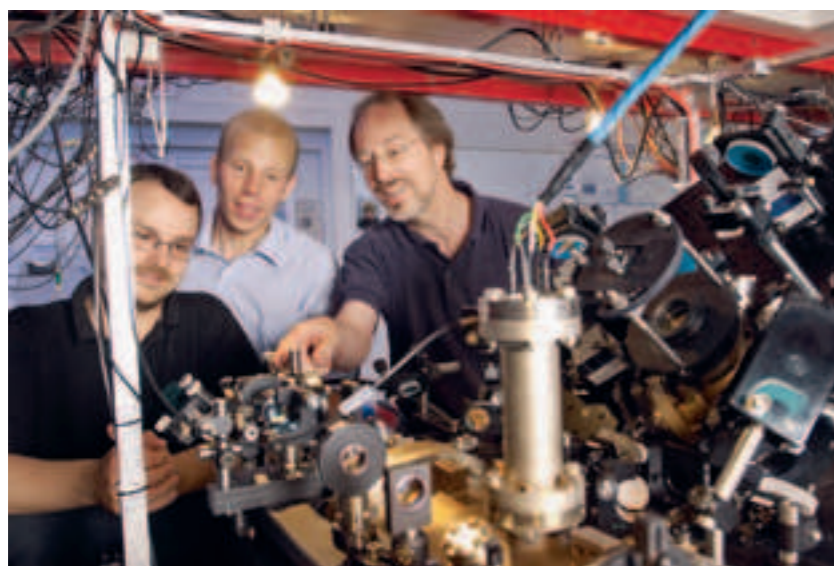
This model could not only simplify quantum calculations, but solid-state physicists should also be able to solve some of their problems more easily. They usually observe very complex systems that consist of innumerable particles. The models with which they currently describe these systems often fail when they want to explain high-temperature superconductivity, for example. PEPS could help them with this.



Quantum physicists have PEPS: these models break down real particles into entangled pairs.

tem required to capture a single atom in the resonator fills an entire laboratory. A quantum computer would be the size of a small town. Consequently, even Gerhard Rempe says that “Whether we will ever really build a quantum computer from atoms in resonators remains to be seen. However, we can carry out many fundamental investigations on

individual atoms.” Physicists are therefore pursuing other approaches to building a quantum mechanical supercomputer. For example, atoms that physicists immobilize in optical lattices, similar to an egg carton, take up far less space than tens of thousands of atoms in resonators. The atoms settle in potential troughs that form from the electromagnetic



Even if it doesn't look like it: Thomas Volz, Niels Syassen and Gerhard Rempe (from left) are standing in front of an optical egg carton that they are creating from laser beams in the steel chamber on the right-hand side of the picture. In the potential troughs, they are joining rubidium atoms to form molecules.

waves of superimposed laser beams. In the lattice, they are about as slow and as cold as in a resonator. And physicists already have some ideas about how the particles on the lattice can communicate with each other – a prerequisite for solving arithmetical problems.

Polar molecules would be even better suited than atoms to handle bits in the lattice, because they are better at communicating from lattice position to lattice position. Their atomic composition gives such molecules positive and negative ends that allow them to interact with each other. “We haven't gotten that far yet, but we recently created non-polar molecules for the first time from two rubidium atoms at the lattice

positions,” says Niels Syassen, who is working on the experiment in Rempe's department.

To this end, the scientists filled very cold and highly diluted rubidium gas into the optical egg carton such that a maximum of two atoms occupied a potential trough. Then they applied a magnetic field to this arrangement. By very slowly altering its strength, they forced the molecules into a partnership. After the magnetic field reaches a certain strength, it is more favorable for the atoms to combine than to remain single. As soon as the researchers reduced the magnetic field, the partners separated again.

Such a collection of molecules floating in an optical lattice could

also form the core of a quantum simulator. Ignacio Cirac, a Director at the Max Planck Institute of Quantum Optics working on the theory of quantum information processing, has already proposed an explanation for how the particles isolated in a lattice assume several states simultaneously. Physicists refer to this as superpositioning. It is a requirement for participating in quantum information processing, as it is the only way they can carry out several computing operations simultaneously in one step (box, page 41). To allow the atoms to group in this quantum mechanical fashion, Ignacio Cirac first wants to split their identities. Physicists can manipulate an atom so that it is caught in either a light lattice with waves that spin to the right or a light lattice in which the waves spin to the left. However, quantum mechanics gives the atom the option of both until someone actually measures which light it reacts to. There are thus two virtual atoms where conventional thinking holds that there is just one. Each of the two virtual atoms can even be manipulated separately: an optical lattice of right-polarized light can move only the associated virtual part of the atom. The other remains where it is – even though both constitute one particle.

ATOMS WITH SPLIT IDENTITIES

In this way, the physicists could move one form of the atom to the neighboring position on the lattice,

which is occupied by the opposite-poled version of its neighbor. By interacting with each other, the two virtual particles become entangled – which is one way to achieve a superposition.

Now it should be possible to perform quantum computing with them – at least in theory. In practical terms, physicists are not yet able to address individual particles in a lattice to store information on them or read information from them. They normally use lasers to change and read the state of a particle, but there are no lasers fine enough to single out one of the closely packed particles in an optical lattice.

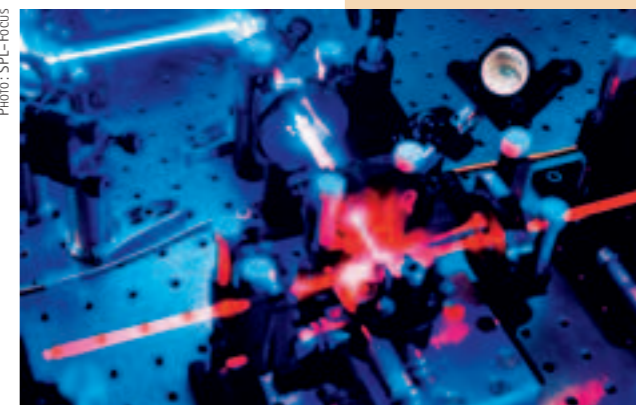
IONS SIMULATE QUANTUM PHENOMENA

This is where the approach pursued by Tobias Schätz and his working group is particularly strong. He wants to trap a chain of magnesium ions in an alternating electrical field in order to entangle them to form a quantum simulator. The ions are intended to arrange themselves in the trap with approximately 3 micrometers' distance between them so that they can be addressed separately with a laser. Using perhaps a handful of ions, Schätz and his colleagues want to work through the instructions for an experiment that likewise comes from Ignacio Cirac's department.

Their first objective is a quantum simulator – a slimmed-down version of a quantum computer. A quantum simulator could, in the relatively near future, help physicists understand high-temperature superconductivity, for example. “We want to use a known quantum mechanical system to simulate an unknown quantum mechanical system,” says Tobias Schätz. In some respects, a quantum simulator works in the same way as a quantum computer. However, some of the particularly tricky technical problems do not arise, such as how the collected information can be defined separately in a superposition.

In their experiment, Schätz and his colleagues would like to discover what happens in the ion system in a specific magnetic transition. Each separate ion behaves like a small bar magnet. The north and south poles of adjacent magnets repel each other. That is why they arrange themselves so that the north pole of a magnet always lies next to the south pole of its neighbor – if a stronger magnetic field does not align all the bar magnets parallel, as in a piece of iron: north pole to north pole and south pole to south pole.

Photo: SPL-FOCUS



A quantum ion trap processes information with laser light – it can be seen, but not heard.

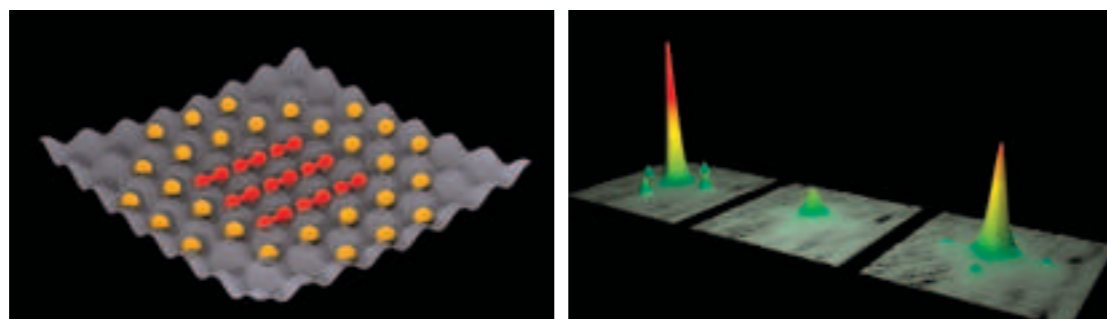
Several methods are possible for this. The first commercial quantum cryptographs work on the basis that the zero and the one, the smallest information units in digital data traffic, can be translated into the properties of light particles in two ways: either in a horizontally or vertically polarized basis, or in a plus 45 degree or minus

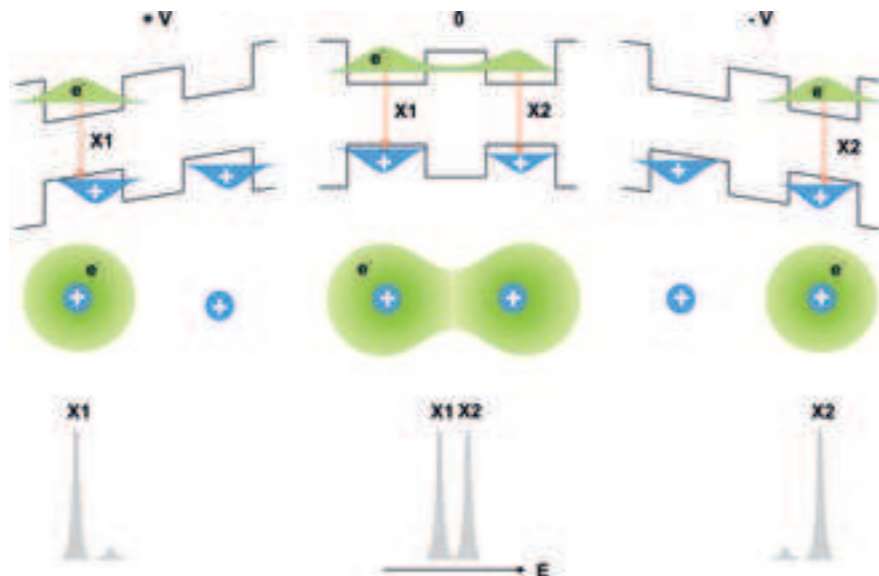
45 degree polarized basis. Without knowing in which of the two bases the sender sends a bit, the key can't be intercepted without being noticed. Sender and recipient send or measure in bases they select at random. They then compare the bases and only use the bits that the recipient has measured in the same basis in which the sender sent them.

In addition, entangled photons can be used to protect the key against unauthorized access. The photons decide on a measurement value simultaneously, even when they are light years apart – a phenomenon that Albert Einstein referred to as “spooky action at a distance” and therefore rejected. In the meantime, there has been experimental proof of it, but some physicists admit openly that they do not understand it, although they are getting used to it. Using a recipe from Ignacio Cirac, Danish physicists even recently entangled atoms with photons – in a quantity and over a distance never before achieved.

But complete entanglement is almost impossible to achieve. The sender sends the key bits with a certain theoretically defined error rate. Anyone who tries to intercept the photons will increase the error if they prepare a similar photon and send it to the real addressee. The sender and recipient can compare the error rate – if it is higher than expected, they have exposed a spy.

A fixed-term partnership: Rubidium atoms (red) in an optical lattice enter into a bond (left image) – and separate again, depending on how Gerhard Rempe's colleagues alter the magnetic field. The atoms create an interference pattern with satellite peaks only when they are separated (right image).





The application of voltage shifts the energy level in artificial molecules (top). The electron then stays with one of the two partners (center), and one of the two peaks in the spectrum of the artificial molecule disappears – a single photon source has been created (bottom).

A quantum computer, on the other hand, would require almost a hundred thousand. It might be best to organize such a host of quantum bits in a solid state – in the form of quantum dots. They each consist of a few thousand atoms. A group of this nature assumes the characteristics of a single artificial atom that can store one bit.

Oliver Schmidt and his colleagues at the Max Planck Institute for Solid State Research in Stuttgart have already developed a regular pattern of several million quantum dots on a surface. In artificial atoms, as in their real counterparts, electrons swirl around a positive particle that semiconductor physicists refer to as a hole. These electrons rotate with a spin that, in simple terms, is equivalent to their angular momentum and that determines the behavior of a particle in a magnetic field. Physicists illustrate the spin with an arrow pointing upwards or downwards. It seems obvious to describe one of the directions with zero and the other with one. One and zero could, however, also be assigned to the base state and an excited state into which an electron is put when bombarded by a laser.

To bring the benefits of the quantum computer to bear, the quantum

dots must interact – this is the only way in which they can create the superposition that is the crux of all quantum computations. “Together with scientists from the University of Stuttgart, we recently linked two self-organizing quantum dots that were adjacent to each other on a surface,” says Oliver Schmidt, the head of the working group at the Max Planck institute in Stuttgart.

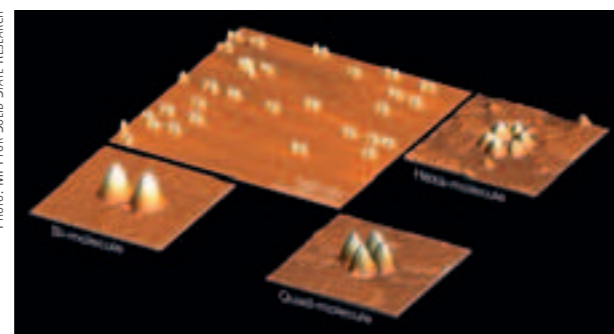
A PHOTON PISTOL WITH THE CALIBER OF YOUR CHOICE

The researchers created an artificial molecule from two artificial atoms. To do this, they used a newly developed technology to create two little piles of indium arsenide about 8 nanometers apart on the substrate, so that the quantum dots grew close together out of the substrate like two sugar cones. “Electrons jump be-

tween the two quantum dots,” says Schmidt. The quantum dots assume a shared state in which they “talk to each other.”

However, not only do the two quantum dots carry on exchanges between themselves, they can also communicate externally. To do this, they use the lingua franca of the quantum world: light. “This is in the special form of single photons,” says Schmidt. Like their photon-pistol-wielding colleagues at the institute in Garching, the Stuttgart physicists make their quantum dots emit one photon shot after another. They also do this at high temperatures – at least on the atomic physicists’ scale: quantum dots deliver individual photons at around 200 degrees below zero, a long way from absolute zero. This means that a source of single photons of this nature could be cooled with liquid nitrogen at a reasonable price. The researchers apply electrical voltage to a molecule of quantum dots and vary it, thus influencing the wavelength of the emitted light – just as if they were altering the caliber of their photon pistol.

So maybe the Max Planck physicists should, in fact, be prepared for a duel of photon shooters. The outcome would be open – in two respects: “Whether photons, molecules or quantum dots will, in the end, be performing the calculations in a quantum computer is still uncertain,” says Ignacio Cirac. Either way, he is working to ensure that there are no theoretical limits to any of the approaches. PETER HERGERSBERG



Oliver Schmidt and his colleagues collected molecules made of indium arsenide quantum dots on a gallium arsenide surface. They have linked as many as six of the artificial atoms together.

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