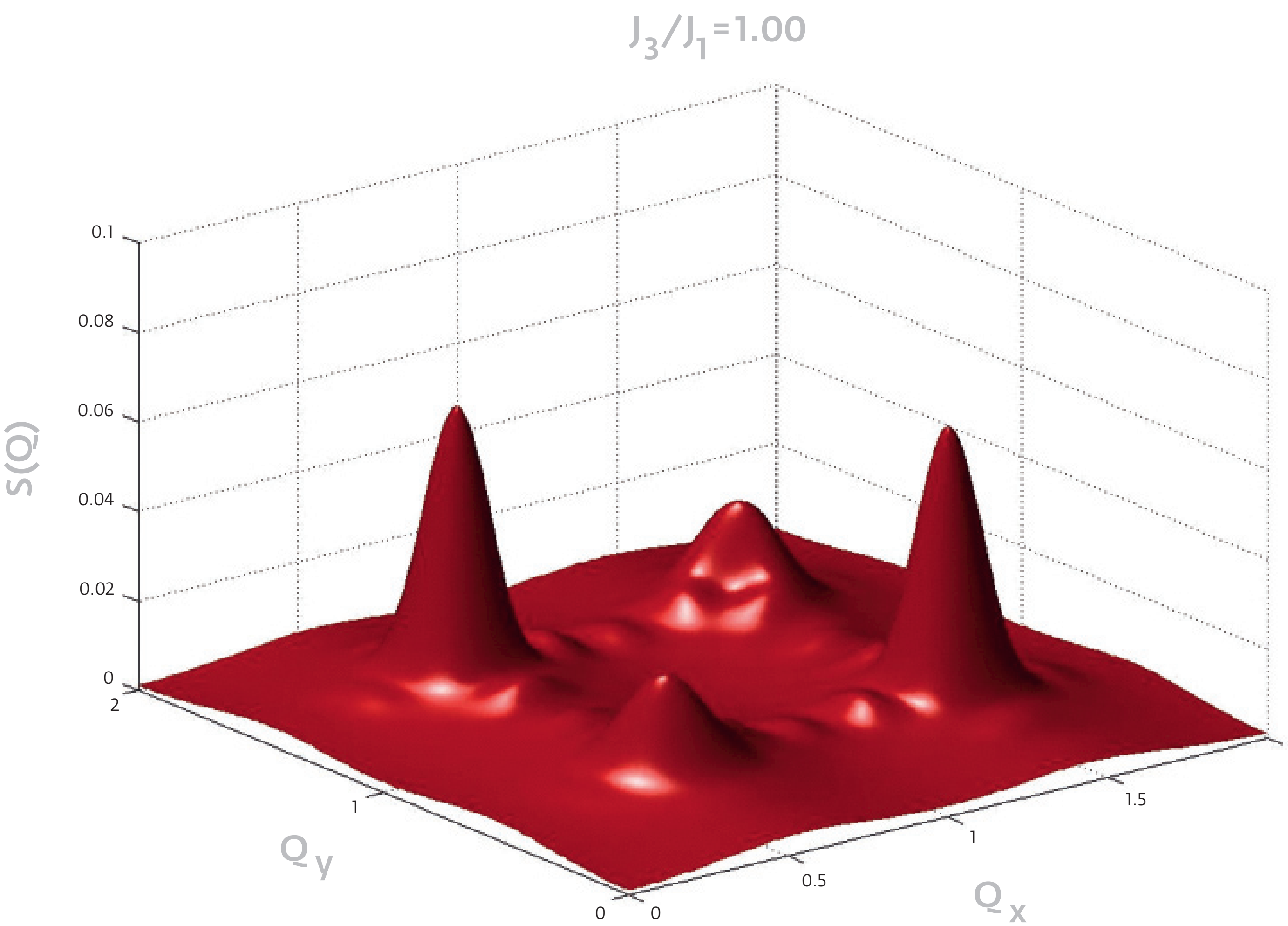
Taming
Quantum Ghosts

Many aspects of quantum physics are mystifying and puzzling: particles can be in two places at once and combine characteristics that are mutually exclusive. **Ignacio Cirac**, Director at the **Max Planck Institute of Quantum Optics** in Garching, is developing ideas for using these mysterious quantum phenomena to process information.

TEXT **BRIGITTE RÖTHLEIN**



A theory for difficult cases of magnetism: Colleagues of Ignacio Cirac calculate how the magnetic moments of electrons (spins) interact when the north and south poles of these tiny magnets can't always dodge each other. The height of the peaks indicates the intensity of the interaction. They deduce the magnetic order from the symmetry of the graph.

Graphic: MPI of Quantum Optics

The yellow leather chairs in Ignacio Cirac's office still exude a hint of Spanish sun even when the sky outside is heavily hung with dark clouds and rain dampens the summer atmosphere. Here at the Max Planck Institute of Quantum Optics on the Garching research campus, the Spanish-born theorist contemplates the problems of quantum physics.

"Right from the start, quantum mechanics has had a puzzling side," says the 44-year-old institute director and physics professor, describing the situation: "Scientists such as Einstein, Bohr and others considered this aspect like a curious game, like something that isn't actually true at all." In recent years, physicists are giving more thought to the practical aspects of this mysterious side of quantum physics, and modern technology even allows them to conduct related experiments. "In this way, we can now put these mysteries to the test, all these strange effects of nature," says Cirac.

For the average citizen with any common sense, what happens in the quantum world – the world of the very small – sounds more like a fairytale anyway: particles that transform into waves and vice versa; particles whose location and speed can't be measured simultaneously; energy that occurs only in packets. Physicists call these phenomena duality, uncertainty relation and quantization.

PARTICLES SEEM TO COMMUNICATE TELEPATHICALLY

They are not fairytales, but the foundations of our modern world. Without these astonishing phenomena, there would be no computers, no lasers, and no magnetic resonance imaging today – there would not even be an ordinary television. The things that seem so inexplicable and puzzling to those with common sense have since been proven in practice a million times over.

But there is a part of quantum mechanics that still remains a mystery: Particles that seemingly communicate by telepathy. Hypothetical cats that are simultaneously dead and alive (see box "A Cat in a Box"). Cold matter that behaves contrary to all known laws of nature. There are scientific names for these phenomena, too, but thus far they have remained pure decriptions: entanglement, superposition of states, superconductivity, superfluidity. While some of the rules of these phenomena are known, in many cases, it is not known how they come about and on which theory they are based.

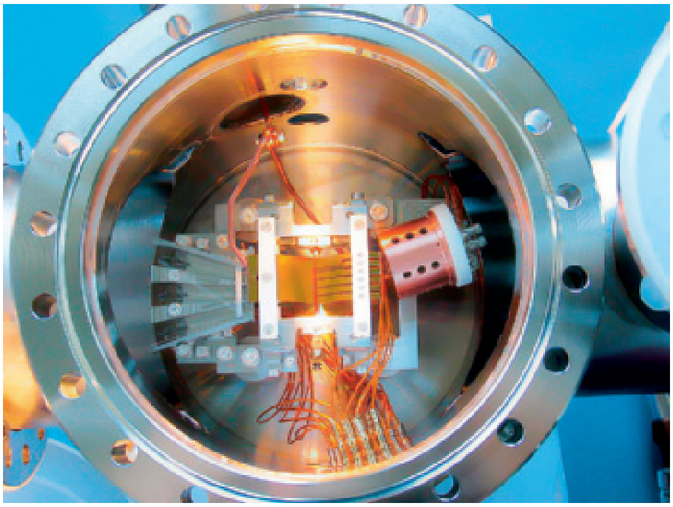
A good 15 years ago, some researchers changed their perspective and considered the secrets as challenges. Cirac is one of them. "So we said: There is a nature that behaves very strangely. This is not only a chal-

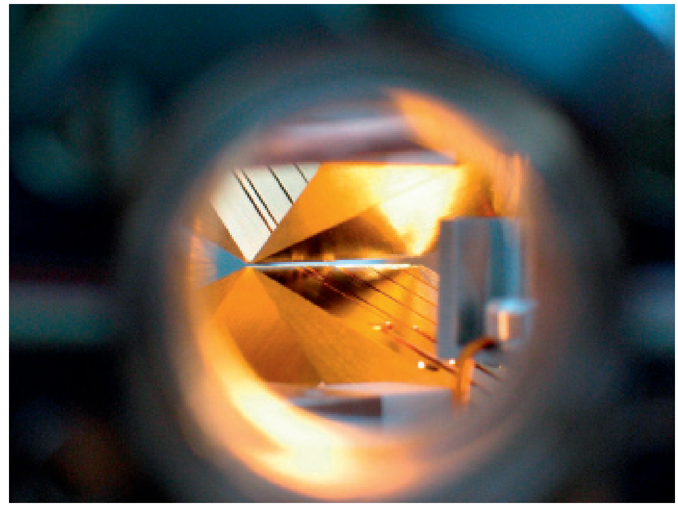
A CAT IN A BOX

Erwin Schrödinger illustrated the phenomenon of superposition with a thought experiment: Imagine a box that you can't see into and from which no sound can escape. In this box is a cat. Next to it is a physical apparatus that will bring about its certain death: A radioactive compound will eventually experience the decay of an atom. When the atom decays, it will trigger, via a Geiger counter, an electrical impulse that will cause a hammer to fall onto a small bottle containing poison. The poison escapes from the smashed bottle – and the cat dies.

Since no information can escape from the box, it can't be determined whether the radioactive decay has already resulted in the cat's death, as radioactive elements do not decay at a fixed time, but rather only with a certain probability within a certain time span.

During the time in which the decay will probably occur, no external observer can say whether the cat is still alive or is already dead, because no one knows precisely when the radioactive atom will decay. Thus, from a logical viewpoint, the cat is simultaneously alive and dead. Or neither. It is in a superposition state between life and death. Of course one can determine at any time whether the cat is still alive or already dead by opening the box, but that would destroy the superposition.





lenge for our philosophical thinking, but we can also use the phenomena for something." Building a quantum computer, for instance, or securely encrypting messages. This led to a revolution in thinking. Physicists like Ignacio Cirac now dare to approach taboos that once intimidated even such people as Albert Einstein.

ENTANGLEMENT FACILITATES QUANTUM GATES

"It all began in 1994 at a conference in Boulder, Colorado," recalls Rainer Blatt, who, as an experimental physicist at the University of Innsbruck, works very closely with Cirac. "There, my Austrian colleague Peter Zoller, Ignacio Cirac and I met British physicist Arthur Ekert, who presented the idea that, in a quantum computer, as in a conventional computer, one needs a set of fundamental gates that can execute certain logical decisions." As soon as they were available, any computing operation could be done by a sequence of these fundamental gates. Zoller and Cirac took up this idea and, within a few weeks, wrote down how it could be realized.

Unlike a conventional computer, a quantum computer works with the superposition of various states, so-called qubits (see box "Quanta You Can Count On"). These offer the advantage of allowing many calculations in parallel in a single step, since all states are calculated simultaneously. However, each measurement means intervening in the system and destroys the superposition. Physicist Erwin Schrödinger illustrated this phenomenon in 1935 with his image of the cat that is simultaneously dead and alive. But how can logical operations be linked without measuring the state of the qubits and thus destroying them? In 1994, Cirac and Zoller came up with the idea how one can entangle the state of a qubit with a movement and thus be able to entangle qubits without measuring them.

QUANTA YOU CAN COUNT ON

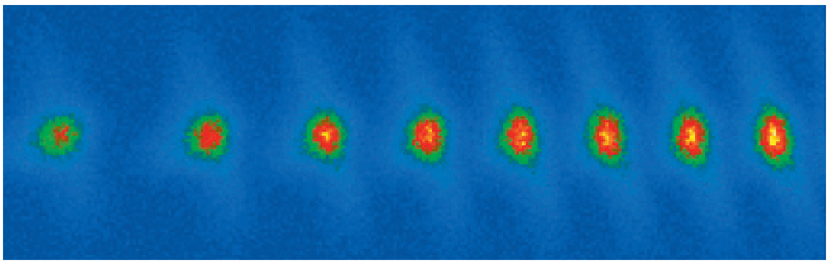
It is well known that digital information is composed of bits. In a conventional computer, a bit can take on the value 0 or 1, which is represented by the charge state of an electronic device. There are states in quantum mechanics as well, corresponding to 0 or 1, such as the excitation state of an atom or the direction of rotation of a rotating particle, called the spin. An excited atom, for example, could stand for 1, and one in the ground state for 0. Bits in the quantum world have come to be known as qubits.

Quantum mechanical objects, however, are not always in an unambiguous state, but can appear to be in a superposition of all possible states simultaneously. Thus, a qubit can simultaneously encode 0 and 1. So two qubits take on the four states 00, 01, 10 and 11 – simultaneously. The number of possible combinations increases rapidly; 32 qubits already yield four billion. This variety is to be put to use in a quantum computer: each computing operation would then take place in all states simultaneously. With two qubits, four values are automatically calculated simultaneously, and with 32 qubits, four billion values.

However, the superposition of the states collapses as soon as the system is disrupted. At the moment of measurement, physicists describe reality precisely: only a single state remains, namely the measured value.

left | Looking into an ion trap: Charged atoms are trapped between the four electrodes (detail image at right). Traps like this can be used to construct quantum gates in which the states of atoms are entangled with their movement.

below | The ions in a trap line up in a row; they must be kept in absolute motionlessness for entanglement to occur.



The entanglement of two objects is a phenomenon that Albert Einstein had already referred to as "spooky action at a distance" and that exists only in the quantum world: two entangled quantum objects are always in the same state – no matter how far apart they are. Translated into quantum gates, this means that, if one of the qubits is excited, it causes a movement, and if it is not excited, it doesn't. Observing the movement does not destroy the superposition in the qubits.

In 2001, David Wineland's group in Colorado realized a quantum gate, implementing the ideas of Cirac and Zoller for the first time in an experiment. Shortly thereafter, Rainer Blatt in Innsbruck succeeded with this, too. His team used ion traps to build a quantum gate. For this, the physicists use suitable electromagnetic fields to trap charged atoms in a small vacuum chamber and manipulate them with lasers, thus entangling their states with movements. This method is now established practice, and entanglement can be created practically at the touch of a button using the Cirac-Zoller method – a process that previously seemed unthinkable.

Before this, one could find only particles that were entangled naturally. "In a non-linear optical crystal, two entangled photons can be generated, for example, by the incidence of a high-energy quantum," explains Ignacio Cirac. But how can three entangled photons be produced, or 30, as would be needed for a quantum computer? He and his colleagues thus proposed a way to intentionally entangle ions. "Today, we can say: Tell me what state your particles are in and we'll give you a procedure for entangling as many of them as you want," says Cirac.

COMPUTATIONS – LED OUT OF ISOLATION

Experimental physicists have a choice of many theoretical proposals for experiments. However, since Ignacio Cirac enjoys an outstanding reputation among experts, he and his group of 30 theorists also always successfully gain partners for experiments for current projects. In this way, in July 2009, Cirac and two former colleagues proposed a new theory that questions a further principle of the quantum world. Several teams are now working on proving it experimentally.

It was previously believed that the qubits in a quantum computer had to remain free of disturbances from external actions in order to keep their superposition intact. That is why the system must be completely isolated from the outside world, making interim measurements impossible. Researchers call this undesired contact with the environment dissipation. Only when the calculation is complete do the experimenters

ENTANGLEMENT IN THE TRAP

To entangle the state of an atom with a movement, Ignacio Cirac and Peter Zoller proposed the following method: Arrange several ions in an ion trap in the form of a chain and bring them into a state of absolute motionlessness. This is easier said than done. To achieve this, several cooling methods must be combined, including laser cooling and sideband cooling. The ion chain constitutes a harmonic oscillator, which possesses internal quantum states. When it is in the absolute ground state, the chain is absolutely motionless, although Coulomb interaction is still present between the ions.

When this absolute ground state is reached, an ion can be brought into an excited state by manipulating it with a suitable laser impulse. If this is done the right way, one can use quantum logic means to ensure that a movement occurs between the ions in the trap due to Coulomb interaction. In this way, there is not only a transition between excitation states, but also a kick that causes the ion to move. The movement is very small – just a few nanometers. But it means that the entire chain now begins to oscillate.

In principle, the system doesn't even know which ion generated the movement. This not knowing is also a kind of superposition. So one can say that the internal state has been entangled with the external movement of the ions. The optical transition was converted into a movement state.

Graphik: MPI of Quantum Optics

It takes only a board and a pen to draft great ideas. Ignacio Cirac develops theories that experimental physicists implement in practice.

read out the result, by taking a measurement – and destroying the superposition. “But now we have found that one can observe the system and still make quantum calculations,” says Cirac: “This proposal contradicts all previous concepts of a quantum computer.”

However, the researchers must make the observation in a very specific way. Then, although the superpositions will collapse, they will do so in a way that leads to the problem’s solution. How this might look in practice is still not clear. In any case, in 2009, the European Union set up a three-year research project called Quevadis to promote relevant experiments. “Ultimately, there are two basic types of quantum computers,” Cirac sums up. “The one requires complete isolation, the other, full dissipation.” In the end, perhaps it will be possible to combine the advantages of both types.

SIMULATORS FOR QUANTUM SYSTEMS

And there is yet another project that Ignacio Cirac is pursuing: He is helping to realize an idea that the legendary physicist and Nobel laureate Richard Feynman touched on as far back as 1981. Feynman doubted that the world could be described precisely with a conventional computer: “I am not happy with all the analyses that go with just classical theory, because nature is not classic, dammit. And if you want to make a simulation of nature you’d better make it quantum mechanical and by golly it is a wonderful problem.” Now, research groups around the world are working on this “wonderful problem” – among them the theoreticians at the Max Planck Institute of Quantum Optics: they want to simulate quantum systems.

THE MICROCOSM IS BECOMING PREDICTABLE

Cirac explains the basic principle using the classical simulations that are common today: “Let’s say you want to design an aircraft and see whether it can fly before you build it. You simulate all the major components on the computer, and with suitable equations, you can make a prediction.” Computers can simulate a lot of things this way. “But no conventional computer can simulate the quantum systems in our microscopic world,” says the physicist.

The behavior of atoms at very low temperatures, for instance: Will they conduct electricity or not, will they display superconductivity? Conventional computers fail here – this calls for quanta. It need not be an actual quantum computer – a simpler quantum system is sufficient as long as it can be controlled to such an extent that, at low temperatures, it behaves like a group of atoms. Then it can be used to make predictions about the unknown system (see MaxPlanckResearch, 1/2009, page 32 ff.).

Currently, the focus is on the question of why some materials exhibit superconductivity even at relatively high temperatures – that is, why they conduct electricity without resistance at relatively high temperatures. “We hope our quantum simulators will help us find out why high-temperature superconductivity exists,” says Cirac. As soon as the mechanism is clear, it may be possible to systematically build such materials to conduct electricity loss-free at temperatures that also facilitate broad application.

There are still adventures and surprises in physics, even in theory. Ignacio Cirac is very satisfied with this situation. “I always tell people who don’t do research themselves: Imagine that you go on a journey and you discover a stone that no one has ever seen before. It feels great. And we get this feeling every day.” ◂

GLOSSARY

Superposition
Particles don’t take on one state, but rather all possible states at once – until a measurement destroys the superposition.

Entanglement
Two or more particles form a joint system, and measuring one particle instantaneously affects its entangled partners – regardless of how far apart the particles are from one another.

Superconductivity
Below the so-called transition temperature, which is usually below minus 260 degrees Celsius, many metals conduct electricity without resistance. Physicists understand this conventional form of superconductivity very well, but this is not yet true for the unconventional form of superconductivity. It occurs, for example, in copper-oxide ceramics, where the record holder loses its electrical resistance at a mere minus 110 degrees Celsius.

Superfluidity
This phenomenon was first observed with two isotopes of helium. Due to quantum mechanical effects, a liquid or a gas flows without friction.

Photo: Axel Griesch