

Magnesium **Simulates** Magnets

*Atoms are unpredictable – at least when they occur in large groups. A conventional computer cannot describe the interaction of as few as 30 atoms correctly, since the quantum mechanical effects make the computation extremely complicated. For this reason, physicists like **TOBIAS SCHÄTZ**, head of an Independent Junior Research Group at the **MAX PLANCK INSTITUTE OF QUANTUM OPTICS**, are developing quantum simulators. The purpose of the simulators is to provide physicists with a better understanding of certain forms of magnetism, for instance, or of high-temperature superconductivity.*

PHOTO: MPI OF QUANTUM OPTICS

After the initial matches of the UEFA EURO 2008™ soccer championship, many observers would have picked the Dutch or Portuguese team to win. Shortly afterward, both were unceremoniously evicted from the tournament. Just as even the most experienced commentators can't predict the course of a game involving 22 soccer players, physicists are unable to foretell the quantum physical behavior of atoms in large groups. They do, however, have one advantage over the soccer commentators: they can simulate the processes that take place in the quantum world.

So researchers hope to simulate such phenomena as magnetism, quantum-critical transitions and high-temperature superconductivity. However, conventional computers used for this purpose rapidly reach fundamental limits. At present, their capacity is limited to around 30 quantum particles, and even the best

computers of the future will probably be unable to cope with any more than 40. Physicists are thus developing quantum simulators as a more powerful alternative.

Among them is Tobias Schätz, who heads an Independent Junior Research Group at the Max Planck Institute of Quantum Optics in Garching. He and his staff recently constructed a simple version of a quantum simulator that can be used to study, for example, magnetic phenomena and high-temperature superconductivity. To achieve this, Schätz and his team exploit a quantum system that they are very familiar with and that can be monitored. Their first aim is to use the simulator to imitate quantum magnets, whose properties they do not yet fully understand.

In an initial experiment, the researchers used the instrument to imitate a two-atom quantum magnet whose behavior they had al-

ready predicted using conventional computers. Since the quantum simulator confirmed these predictions, it was proven to be fundamentally suitable for such studies. In the future, the researchers hope to expand the new device in such a way that it can be used to study more than two particles.

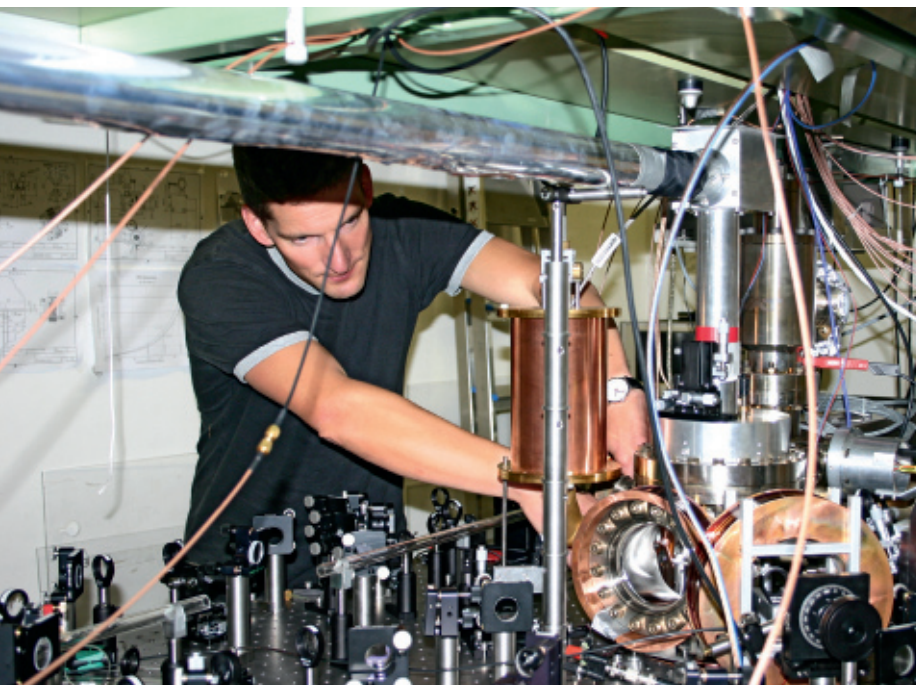
A quantum simulator shares essential properties with the system that it imitates, and is thus suitable for studying such systems. "In addition, we can use it to test how a system behaves when we change only one of its properties and retain all the others," says Tobias Schätz.

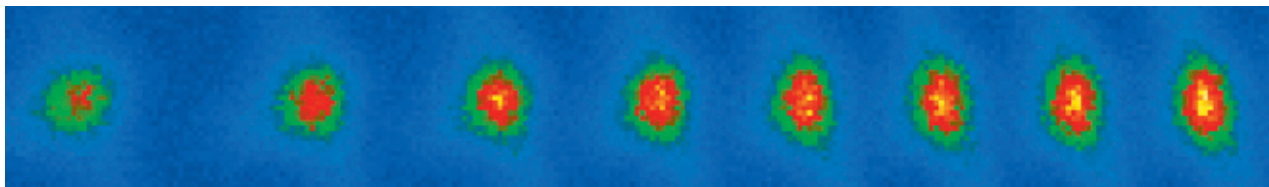
THE SEARCH FOR ZERO RESISTANCE CONDUCTORS

"The possibility of using a quantum simulator to control discrete properties selectively could help us, for example, to one day understand the phenomenon of high-temperature superconductivity and thus to produce materials that can conduct electric current without resistance – even at temperatures of over 40 degrees Celsius." The critical temperature at which a high-temperature superconductor ceases to present resistance depends, among other things, on the distance between the atoms in a solid. This, in turn, is a function of the chemical composition of said solid. However, the chemical composition also influences numerous other properties that have an impact on the superconductivity. "So if we modify the composition of high-temperature superconductors, we don't know whether the different interatomic interval or some other change in the properties is responsible for displacing the critical temperature or, for that matter, whether positive and negative effects cancel each other out," says Schätz.

It will be some time before physicists can actually use quantum simu-

Tobias Schätz must prepare the ion traps (below) carefully in order for the four triangular electrodes to capture the magnesium ions within them (left).





The particles line up neatly for the computational roll call.

lators to study high-temperature superconductivity. The physicists in Garching began by simulating how the magnetic order in a two-atom quantum magnet changes when the two atoms are no longer independent of each other, but become linked.

In a magnetic material such as iron, individual electrons behave like small compass needles or bar magnets, each with a north and a south pole. In a permanent magnet, such as a horseshoe magnet, these minute bar magnets are all aligned in the same direction – physicists call this a ferromagnetic state – and with their combined force, are even able to magnetize and attract another piece of iron.

In a quantum magnet, the situation is unclear, as is often the case in quantum physics. The “compass needles” within the quantum magnet – that is, the elementary magnets – do not become aligned until an attempt is made to determine their orientation. Before this, the compass needle points in two directions at the same time: upward and downward. In a quantum magnet consisting of two atoms, as investigated by Tobias Schätz and his team, the situation is already more complicated, especially when the two magnets interact with each other – so, when they become linked. When this happens, the two elementary magnets tend to align their north poles in the same direction, since this requires the least energy.

What direction will this be, though, when each individual elementary magnet possesses two orientations at

the same time? The result is indeterminate as long as no one examines the magnet. Until that happens, the compass needles point both upward and downward at the same time, and decide on a direction only the instant they are measured. But it is sufficient for a physicist, by conducting a measurement, to force one of the atoms to define its orientation. In the same instant, the magnetic moment of the other atom then assumes the same alignment. This is due to another mysterious phenomenon known as entanglement.

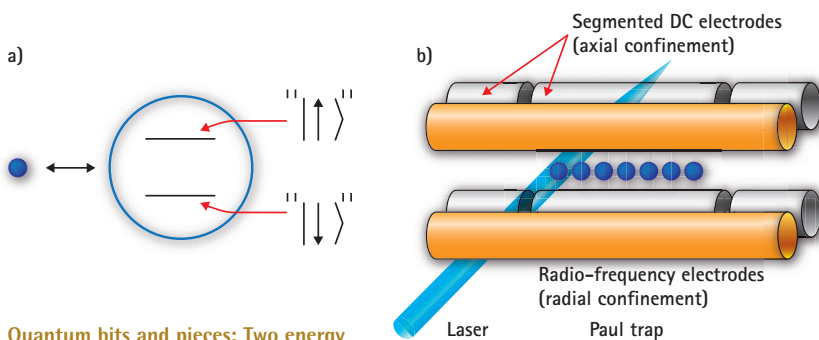
SIMULATED MAGNETIC ORIENTATION

Tobias Schätz and his colleagues have now simulated how the quantum magnet changes from the paramagnetic to the ferromagnetic state. In the paramagnetic state, the two elementary magnets are unaware of each other, and align themselves with an external magnetic field. The Garching-based physicists have now simulated the gradual increase in interaction between the two elementary magnets. The probability then also gradually rises of the two bar magnets aligning themselves ferromagnetically – that is, with the north

poles of both pointing downward and upward at the same time.

The physicists have already used a computer to simulate the behavior of the atoms in a quantum magnet. “This means that we can test whether our simulator works,” says Tobias Schätz. And it does. The physicists have trapped two magnesium ions between a number of electrodes that confine the electrically charged particles by means of electrical forces. The two magnetic orientations are simulated by two energetic levels of the magnesium, between which the electrons hop back and forth. The outer magnetic field is simulated using radio waves, which transport an electron from one level to the other. The physicists beam in the radio waves for just half the time required to turn a compass needle from north to south. In this way, they attain a superposition state in which each compass needle points in both directions at the same time – something that is illogical in classical physics.

The researchers use a laser to simulate the coupling between the two atoms that brings about their ferromagnetic arrangement in the energetically most efficient state. The



Quantum bits and pieces: Two energy levels of an ion (blue) represent spin up and spin down (left). Four electrodes ensure that the quantum bits don't escape during computation; a laser assists in reading the simulation result.

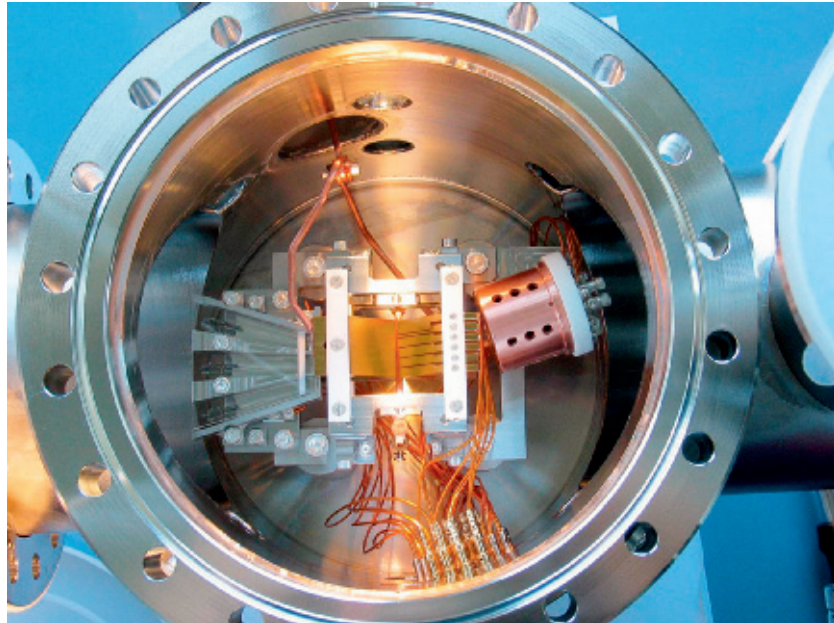
GRAPHIC: CHRISTOPH SCHNEIDER, BASED ON MATERIAL FROM TOBIAS SCHÄTZ / PHOTO: MPI OF QUANTUM OPTICS

laser's electromagnetic field captures the atoms and moves them. The energy of the laser beam, however, lies precisely between the two electronic levels of the magnesium ions. This leads to a phenomenon similar to that which can be seen on a hanging telephone receiver: if the cable is moved slowly back and forth, the receiver swings to and fro in step, but if the hand is moved too quickly, the receiver swings back and forth in the opposite direction to that of the hand.

THE NEXT GOAL: FRUSTRATED SPINS

Following the same principle, the laser used by the physicists in Garching moves magnesium ions whose electrons are at the higher electronic level in the same direction in which it is moving itself. Magnesium ions whose electrons have less energy, on the other hand, are drawn by the laser beam in the opposite direction. What matters now is that less energy is required when both ions migrate in the same direction – that is, when they are in the same electronic state. The observations by the physicists in Garching confirm this: the probability of their laser pushing the two ions in the same direction increases with the intensity of the beam, or in other words, with the coupling strength.

The simulator thus reflects precisely what occurs in a two-atom quantum magnet: the stronger the magnetic coupling between the two



A harmless trap: It can't snap shut until it is sealed with a lid.

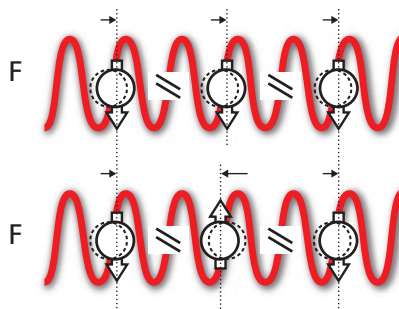
atoms, the more likely they are to assume a ferromagnetic state. This means, however, that when the two compass needles are entangled, they point in the same direction: both simultaneously north and south. The researchers have thus clearly demonstrated entanglement, which Einstein considered “spooky.”

“We now plan to expand our simulator little by little,” says Tobias Schätz. “Even a simulator for a quantum magnet comprising three atoms arranged in a triangle will allow us to conduct interesting physics experiments.” For instance, by carefully adjusting their simulator, Schätz and his colleagues will be able to simulate the antiferro-

magnetic state, in which the elementary magnets are aligned in exactly opposite directions – their north and south poles alternate. But how are the elementary magnets aligned in a triangular quantum magnet? “In this case, the effect is described as spin frustration,” explains Schätz. It is as if two battling soccer players were to be joined by a third player who, upon reaching the two others, forgets which team he belongs to.

“Such spin frustrations may be relevant to high-temperature superconductivity.” When physicists understand this relationship better, they might perhaps also discover why some substances conduct electrical current losslessly, even at relatively high temperatures. This, in turn, would enable them to develop materials that are able to do so at room temperature. For the scientists who achieve it, this goal would be a triumph equivalent to soccer players winning the World Cup.

PETER HERGERSBERG



Divide and conquer: An intense laser beam, displayed as a wave, pushes the ions into the trap (top). The direction in which the laser pushes the particles depends on the electronic state of the ions (upward or downward arrow). The same should also be possible in a two-dimensional ion crystal.

