Rydberg atoms can be used to produce magnetic crystals in an optical lattice

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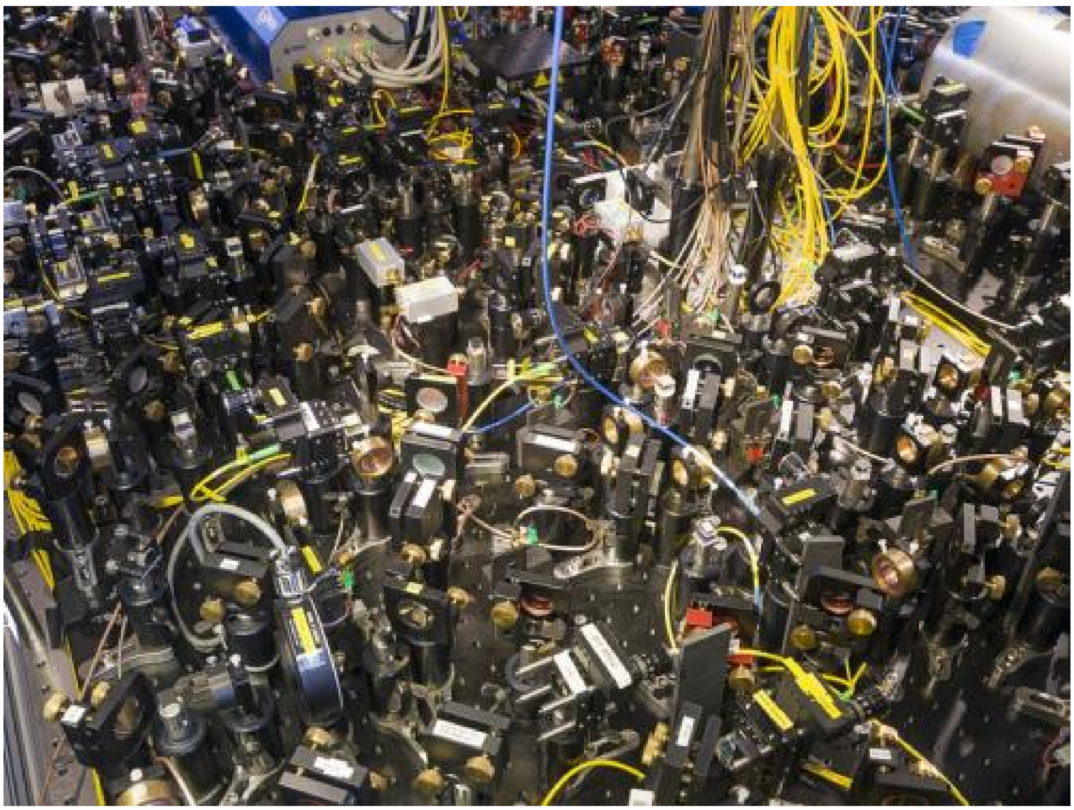


Growing artificial crystals: In this jumble of optical instruments, researchers from the Max Planck Institute of Quantum Optics use laser beams to create an optical lattice in which they trap rubidium atoms. Using a further laser, they excite a few of the atoms to become Rydberg atoms, which then form a magnetic quantum crystal. Credit: Axel Griesch

It is a situation familiar from one's own living environment: relations between neighbours can be intense, yet also characterised by sensitivities. Complex quantum systems can be imagined in a similar way – especially when magnetism is involved. A team headed by Christian Groß in the department of Immanuel Bloch, Director at the Max Planck Institute of Quantum Optics in Garching, is investigating such a system, which takes its inspiration from the crystals of magnetic solids. However, the artificial crystal produced by the researchers in Garching consists of a lattice of laser light that traps rubidium atoms. The researchers pump up some of these atoms using special laser light, turning them into exotic, gigantic atoms. These form quantum crystals whose behaviour can answer fundamental questions not only about magnetism.

Normal magnetism, as occurs in iron, for example, resembles the situation on an estate of terraced houses during a soccer World Cup match. The live broadcast is being watched in every home and as soon as the national team scores a goal, collective roars of delight can be heard through the open windows. In crystalline solids, which include normal magnets, the atoms contributing to the magnetism are ordered in a way which resembles rows of terraced houses. Specific electrons in these atoms align in one direction like tiny compass needles. They join together to form a collective magnetism, just as the shouts of joy from the houses swell to a mighty collective roar.

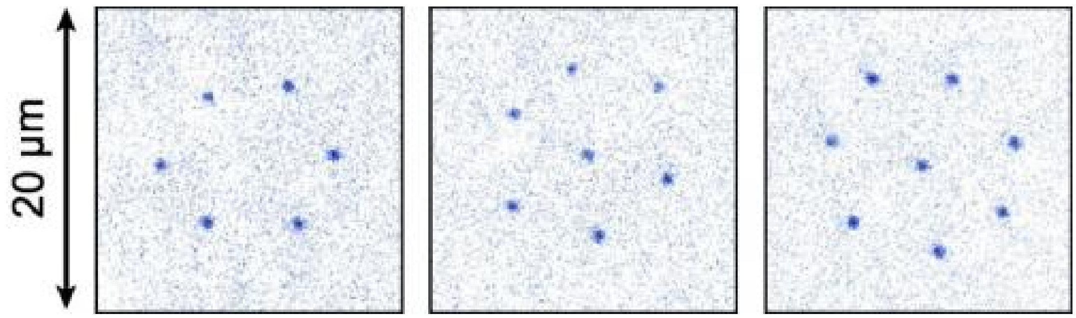
This familiar magnetism is called ferromagnetism, after the Latin word ferrum for iron. There are other forms as well: in antiferromagnetism, adjacent electronic compass needles align themselves in opposite directions. This corresponds to an estate of terraced houses in which every other neighbour is a supporter of the other football team – and the match ends in a draw.

Physicists learn a great deal when they tinker with

quantum systems

There are many other intermediate forms of magnetism between these two magnetic extremes. Moreover, these collective quantum effects play an important role in other physical phenomena as well, for example in superconductivity: a state in which some materials conduct electricity without resistance at low temperatures. This is the reason why investigating these effects is so important. But real crystals whose atoms are connected permanently with each other have several disadvantages: it is difficult to look deep into them in experiments, and gigantic numbers of atoms and electrons are always involved. Above all, researchers can exert very little influence on the interactions which lead to a collective phenomenon such as magnetism. Yet it is precisely this tinkering around with quantum systems that enables physicists to learn a great deal about the quantum world.

This is why scientists are putting their hope in artificial crystals with a manageable number of atoms which are easily accessible. Above all, the interactions between them can be wonderfully manipulated. Christian Groß's team in Garching is working with such a system. It consists of a cloud of between 250 and 700 rubidium atoms which are frozen at very low temperatures. The individual atoms are easy to trap, as they move relatively slowly. The particles are trapped by a lattice of laser beams: one atom is caught at each crossing point, creating an order resembling a crystal. And most importantly: by cleverly irradiating the crystal with additional laser light, the physicists can now manipulate the interactions between the atoms – and even the atoms themselves.



Growth of a quantum crystal: The thicker blue dots are giant atoms in the Rydberg state which form a quantum crystal. The geometry of the growing crystal changes stepwise from left to right with every Rydberg atom added. The largest quantum crystal with eight atoms can be seen on the right. Credit: Science 2015 / Max Planck Institute of Quantum Optics

"This is a very tidy system in which we can study the individual processes at the quantum level in detail," says Christian Groß. This new quantum tool is so flexible and powerful that it has already set itself apart from the pure simulation of real solid state crystals. This especially applies to the latest research work of the team headed by the postdoc.

Magnetic interactions as vuvuzela collective

Together with the theoretical physicists in Thomas Pohl's Group at the Max Planck Institute for the Physics of Complex Systems in Dresden, the Garching-based researchers asked themselves the following question: What would happen if the interaction between magnetic atoms in the quantum collective was very long range? With normal magnetism, this interaction is limited to short distances: it is primarily the immediate neighbours that have a mutual effect on each other. Returning to our hypothetical estate of terraced houses, a long range would correspond to a situation where every tenth neighbour had a vuvuzela which they could use to join together for a particularly loud noise collective across the intervening houses. If, however, the neighbours in between were now also to reach for their vuvuzelas, the peace would be shattered so lastingly that it would no longer be possible to establish order on the estate.

The quantum system with which Groß and his team have now formed a completely new type of magnetic crystal behaves in a very similar way. To this end, the researchers in Garching irradiated the atoms trapped in the light lattice with a special laser light. With its energy, they pumped up some of the atoms – in simple terms – so they became exotic, giant atoms. Like those with vuvuzela on the estate, these Rydberg atoms are able to affect other atoms across many neighbouring atoms.

"A giant atom of this type is a thousand times bigger than a normal atom," explains Groß. Its outermost electron is extremely far away from the nucleus and turns the giant atom into a kind of antenna. It can thus affect other Rydberg atoms, which also act as antennas, so that they form a common, crystalline order – just like the vuvuzela owners joining up for coordinated tooting across many houses. "The atoms remain in the Rydberg state for only a few millionths of a second," explains Groß: "But in the quantum world, this is an extremely long time." It is sufficient for an attractive order.

Giant atoms form a magnetic crystal

Similar to baking cookies, the Garching-based researchers cut out either elongated or circular shapes from the cloud of several hundred rubidium atoms trapped in the light lattice, and in these shapes they pump up individual atoms with their laser to turn them into Rydberg atoms. The elongated shapes gave rise to one-dimensional chains of giant atoms that together formed a magnetic crystal; the circular disks produced two-dimensional crystals of up to eight Rydberg atoms. It turned out here that the size of this cut-out determined how many giant atoms were involved in the magnetism. The distance between them always remained the same and corresponded approximately to ten atoms of the light lattice. With the one-dimensional cut-out, two, then three, finally four Rydberg atoms formed a quantum crystal in stages.

It is also important to be aware that normal magnetism knows only two states on the quantum level of individual electrons in solids: like rotary switches, the electrons can only click into place when they are parallel or antiparallel to the magnetic field applied. In the Garching system, Rydberg atoms represent the switching state of parallel to the magnetic field; antiparallel, in contrast, corresponds to the rubidium atoms in the light lattice when they are not excited to giant atoms. The special laser light enables the physicists to switch specifically between these two quantum states.

The researchers in Garching are thus in perfect control of their system. They have thereby created a tool which they can use to investigate the collective behaviour of these quantum systems in more detail. The aim is not only to obtain a deeper understanding of magnetism: in principle, this tool can reproduce the behaviour of many complex quantum systems . As "quantum simulators", they can perhaps even help to answer fundamental questions in other fields, such as particle physics for example.

More information: "Crystallization in Ising quantum magnets." *Science*, 27 March 2015; DOI: 10.1126/science.1258351

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