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A bridge to the quantum world

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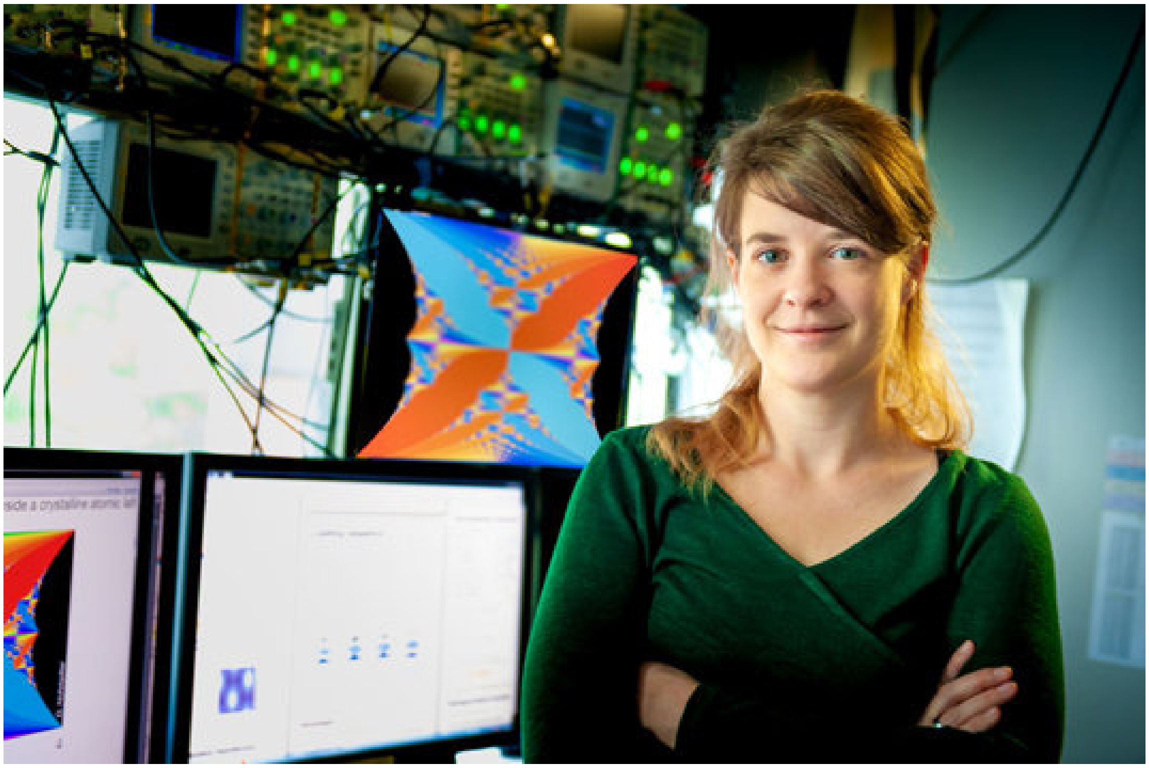

Credit: Ludwig Maximilian University of Munich

Monika Aidelsburger uses a special type of optical lattice to simulate quantum many-body phenomena that are otherwise inaccessible to experimental exploration. She has now been awarded an ERC Starting Grant to pursue this work.

Over the past decade, researchers led by Professor Immanuel Bloch, who holds a Chair in Experimental Physics at LMU, have developed several techniques and strategies to probe the secrets of the quantum world. Much progress has been made, but many phenomena of interest remain unexplored, and theoretical schemes are often difficult to test. Bloch's team is primarily interested in quantum interactions that can be modelled using ultracold gases trapped in optical lattices formed by laser beams. Dr. Monika Aidelsburger, leader of a research group in Bloch's department, has now been awarded a highly endowed Starting Grant by the European Research Council (ERC) to extend this line of work. Her aim is to use ultracold ytterbium atoms trapped in optical lattices to simulate models of quantum behavior in condensed matter on a scale that is three orders of magnitude larger than in real solids.

Indeed, Aidelsburger, who is also part of the Max Planck Institute for Quantum Optics, hopes to take this strategy further, and use it to simulate 'lattice gauge theories', which describe fundamental interactions between particles in terms of 'gauge fields'. In these models, matter fields (substance particles) are depicted as points on a fictitious lattice, and the force fields that act on them are represented by the links between these nodes. Lattice gauge theories are of fundamental significance in many branches of quantum physics. Not only do they form the basis for the Standard Model of particle physics, they can also be applied to the physics that underlies the behavior of strongly interacting electrons in solids, and can account for important phenomena in quantum electrodynamics. Therefore, Aidelsburger's experimental approach to simulating lattice gauge theories in optical lattices would provide a link between classical and quantum physics, and allow analogous simulations of phenomena observed in settings other than solid-state physics. Aidelsburger's research has so far focused on simulating the effects of magnetic fields. "This is because magnetic fields too can be described in terms of gauge fields," she explains. Physicists hope to extend these ideas and apply them to other quantum many-body phenomena that have remained largely inaccessible.

Two long-lived states

The experimental platform is currently being designed and soon the optical tables in Aidelsburger's laboratory will be arrayed with carefully positioned lenses and mirrors, lasers and optical fibers. Controlled manipulations of ultracold atoms in optical lattices have already been successfully used to probe and simulate quantum phenomena that have been observed in condensed-matter systems. These experiments were carried out under conditions in which the atoms can 'tunnel' between lattice sites, although their collective motions are influenced by the global parameters of the lattices. Extension of the strategy to lattice gauge theories will require site-specific control over the motions of the atoms in the lattice.

Setting up such an experiment is extremely demanding, because the symmetries inherent to gauge theories must be precisely reproduced. "A successful implementation necessitates the use of completely new approaches," says Aidelsburger. "This carries a high risk, but having a working quantum simulator of such a model would constitute a tremendous advance." Bloch's team has learned a lot about how to keep quantum gases at temperatures only a smidgen above absolute zero, generate and manipulate optical lattices and control the motions of atoms of various elements such as rubidium, sodium and lithium, to name only a few. Aidelsburger's experiments will use yterrbium (Yb) atoms, because they exhibit two long-lived quantum states, which make them particularly useful for the planned simulations. Strongly focused laser beams will be employed to site- specifically control the motions of the atoms within the lattice. In the simulation, the two atomic states will play both the roles of the matter particles and the particles that mediate the forces that act upon them.

It is technically feasible to couple the motion of the two long-lived states of Yb atoms in the lattice. "This local coupling allows us for the first time to experimentally represent the fundamental building blocks of simple lattice gauge theories in an experimental setting," says Aidelsburger. Moreover, the technique can be straightforwardly extended to larger lattice structures and higher dimensions. This would allow researchers to simulate lattice gauge theories that play an important role in both condensed-matter physics and quantum electrodynamics using tractable experimental procedures. That would be a truly ground-breaking achievement. "Our strategy opens up entirely new experimental opportunities to explore certain phenomena and develop ideas for new theories," says Aidelsburger.

The fine adjustments

The prospect of being able to work for the next few years in Immanuel Bloch's department as a tenure-track professor was one reason why she decided to return to Munich after her spell as a postdoc at the Collège de France in Paris. "Young researchers need such longer-term perspectives," she says, "especially if they wish to carry out such a complex and demanding experimental task." The design and construction of a new system can take up to three years. One begins with simple models, and asks whether their simulation produces results that agree with those obtained with theory, or are compatible with predictions derived using well established numerical methods, such as Monte Carlo simulations. These tests serve as a calibration scale for experiments – and allow researchers to adjust conditions appropriately and gradually increase the level of complexity of the experiments. In addition, the experimental systems must be constantly checked to ensure that they provide a correct description of the phenomena they set out to describe. "This is where close collaboration with theorists in other fields is especially important," says Aidelsburger. "The risks involved are considerable, as this is largely unknown territory for us all. We have to bring very different areas of physics together. It is my fervent hope that the initial experiments with simple models will yield results that find an echo in diverse disciplines."

In the simplest models, the Yb atoms can adopt either of two defined states, the ground state and a single metastable excited state. The aim is to progressively add further states to the system, allowing more complex interactions to be implemented. This would be an important step toward the ultimate goal of using ultracold atoms to simulate the strong nuclear force – the interaction between quarks (the fundamental constituents of atomic nuclei) and gluons (the force particles that hold atomic nuclei together). The latter task will require the implementation of far more complex lattice gauge theories.

Individual cells in two-dimensional optical lattices consisting of 100 × 100 atoms can now be addressed and their occupancies controlled, allowing dynamical effects to be observed in detail. Thus, it is possible to determine whether or not a particular lattice cell is occupied under specific conditions, and the state of every atom in the lattice can be probed practically in real time. With these achievements under their belts, physicists are well on the way to realizing the idea of a quantum simulator that the famous American physicist Richard Feynman formulated in the 1980s. "We hope that our set-up will pave the way to experimentally investigate fundamental issues in quantum chromodynamics," says Aidelsburger – before adding an emphatic qualifier: "But we are still at the very beginning."

Provided by Ludwig Maximilian University of Munich

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