Stretched quantum magnetism uncovered by quantum simulation

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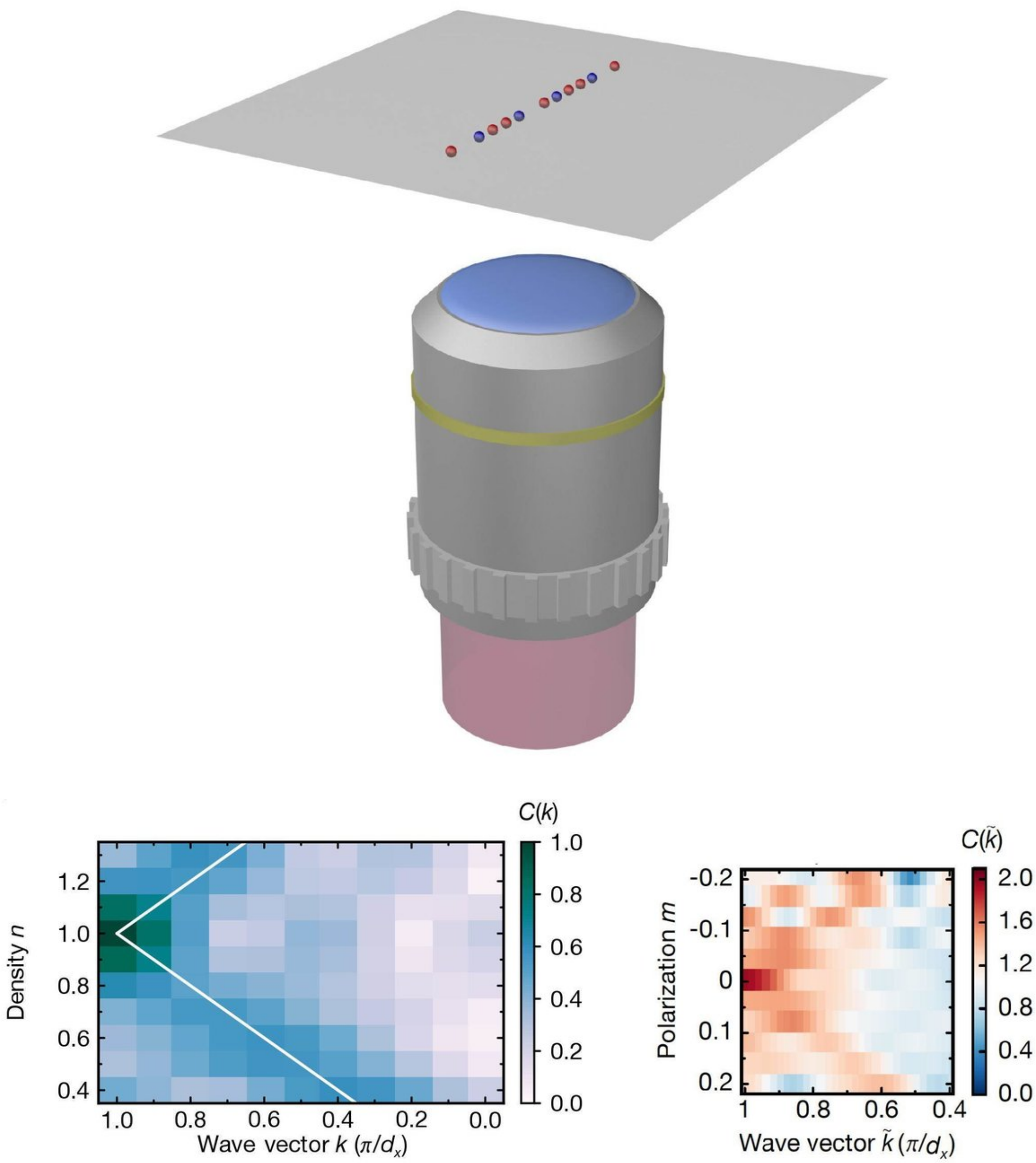

Quantum gas microscopy of Hubbard chains reveals incommensurate spin correlations. | Top: Synthetic Fermi-Hubbard chains are realized by trapping a spin mixture of lithium-6 atoms in optical lattices (red and blue spheres denote up and down spins). Imaging the system with sin-gle-particle and single-spin resolution using a quantum gas microscope allows one to study individually the effects of doping and spin polarization on spin correlations. | Bottom: The Fourier transforms of the spin correlations reveal the change in periodicity of the magnetic correlations with density and polarization, in excellent agreement with the predictions of the Luttinger liquid theory. Credit: Max Planck Institute of Quantum Optics

By studying ultracold atoms trapped in artificial crystals of light, Guillaume Salomon, a postdoc at the Max-Planck-Institute of Quantum Optics and a team of scientists have been able to directly observe a fundamental effect of one-dimensional quantum systems. By detecting the atoms one-by-one, the team observed a stretching of the magnetic ordering when diluting the atoms in the lattice. The study was conducted this year in the Division led by Immanuel Bloch, a director at the Max Planck Institute of Quantum Optics and professor at the Ludwig Maximilians University in Munich. The new findings are relevant, for example, in connection to high-temperature superconductors that conduct electricity without loss.

"One crucial problem related to high-temperature superconductivity is to understand the interplay between magnetism and doping, from which exotic electronic phases can emerge. However, our knowledge is highly dependent on the dimensionality of the system, and quantum gas experiments can help to bridge the gap between one and two dimensions," says Guillaume Salomon, who has been involved in research in this field since 2014.

In the current study, the scientists at the Max Planck Institute of Quantum Optics, together with researchers from the physics departments of the Ludwig Maximilians University and the University of Trento trapped a cloud of lithium-6 atoms at 7 nanokelvin in a light crystal to realize a well-controlled and clean Fermi-Hubbard model.

The Fermi-Hubbard model is the simplest model for electronic systems in which interactions play an important role (i.e. strongly correlated systems). It describes spin up or spin down atoms in a lattice which repulsively interact only if they are located in the same site. When there is on average one atom on each site, antiferromagnetic ordering occurs where spins on neighbouring sites are anti-aligned.

When the system is diluted, the number of atoms in the lattice is reduced (doped) and the periodicity of this magnetic ordering changes similar to an accordion that gets stretched. Instead of finding opposite spins on neighbouring sites, one will find them anti-aligned at larger distances on average. The spin correlations are then said to be incommensurate. Such an effect is also expected to occur when the numbers of up and down spins differ (spin polarization).

The scientists used a technique called spin-resolved quantum gas microscopy, which allows one to image both the positions and spins of all the atoms simultaneously, and to measure spin correlations. They observed the emergence of such incommensurate spin correlations, which were found to vary linearly with doping and polarization, in excellent agreement with theoretical predictions.

"The most fascinating part of this research project has been the disentanglement of the effects of spin-polarization and doping on spin correlations in one dimension where spin-charge separation occurs. The ability to measure all the spins and particle positions in a strongly correlated quantum many-body system allows us to compute arbitrary correlation functions akin to numerical studies on a computer and to quantitatively test fundamental predictions despite the finite temperature of our systems," Salomon explains.

"At the end of this study, we observed in the doped Fermi-Hubbard model fundamental differences between one dimension and two dimensions. Our results are an important benchmark for further studies of the dimensional crossover regime, about which very little is known until now," adds Christian Gross, who heads the research group.

More information: Guillaume Salomon et al. Direct observation of incommensurate magnetism in Hubbard chains, *Nature* (2018). DOI: 10.1038/s41586-018-0778-7

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