Ultrafast quantum simulation of large-scale quantum entanglement

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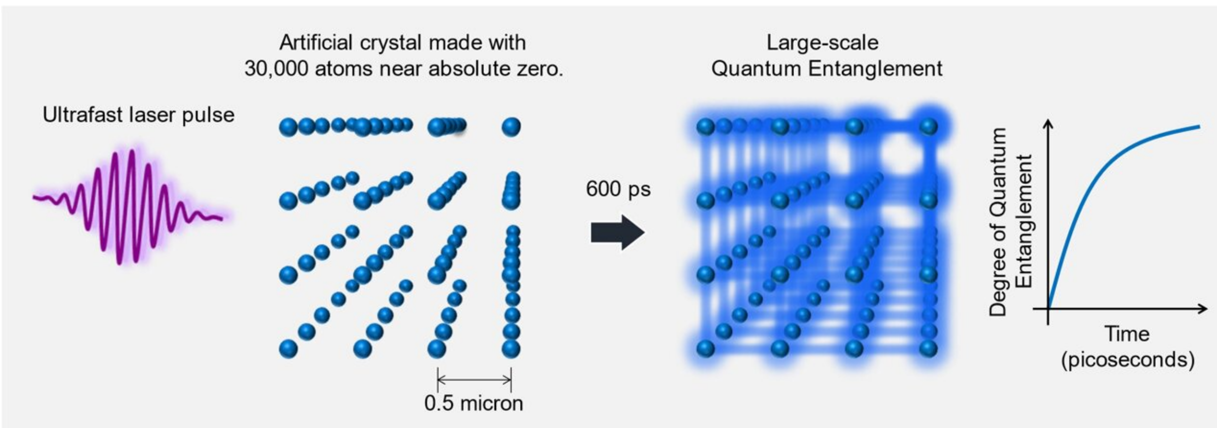

Credit: NINS/IMS

A research group led by Professor Kenji Ohmori at the Institute for Molecular Science, National Institutes of Natural Sciences are using an artificial crystal of 30,000 atoms aligned in a cubic array with a spacing of 0.5 micron, cooled to near absolute zero temperature. By manipulating the atoms with a special laser light that blinks for 10 picoseconds, they succeeded in executing quantum simulation of a model of magnetic materials.

Their novel "ultrafast quantum computer" scheme demonstrated last year was applied to quantum simulation. Their achievement shows that their novel "ultrafast quantum simulator" is an epoch-making platform, as it can avoid the issue of external noise, one of the biggest concerns for quantum simulators. The "ultrafast quantum simulator" is expected to contribute to the design of functional materials and the resolution of social problems.

Their results were published online in *Physical Review Letters*.

Quantum technology, which has seen intensified competition in development in recent years, such as quantum computers, quantum simulators, and quantum sensors, is a qualitatively new technology that takes advantage of the "wave nature" of electrons and atoms. Since quantum technology has the potential to revolutionize functional materials, pharmaceuticals, information security, artificial intelligence, etc., huge investments are being made around the world.

A quantum simulator is a device that simulates the complex behavior of electrons and other microscopic particles in a solid by mapping them onto a highly controllable model material. It is expected to solve problems that would take an infinite amount of time even with the fastest supercomputer, thus bringing about disruptive innovation to solve social problems such as logistics and traffic congestion, and in developing superconductive and magnetic materials.

On the other hand, quantum states created by quantum mechanical particles, such as electrons and atoms, are easily degraded by noise from the external environment and lasers, which makes it difficult to develop quantum computers.

In 2022, a research group led by Professor Kenji Ohmori at the National Institutes of Natural Sciences realized an ultrafast two-qubit gate that operates in only 6.5 nanoseconds using cold atoms, improving the speed of the two-qubit gate by two orders of magnitude as compared to conventional cold-atom approach, thus paving the way for the realization of an ultrafast quantum computer that can ignore the effects of noise.

If their ultrafast approach can be applied to quantum simulations, it is also expected to solve the issue of noise and to realize a highly reliable and innovative quantum simulator.

Research results

The research group performed ultrafast quantum simulations of a model of magnetic materials by preparing an atomic array of 30,000 atoms, cooled to near absolute zero and manipulating them at high precision using a laser pulse that blinks for only 10 picoseconds.

The ultrafast quantum simulator succeeded in simulating the formation of quantum entanglement (the topic of the Nobel Prize in Physics last year), which is a correlation unique to quantum mechanical particles, in 600 picoseconds, the fastest in the world. The ultrafast quantum simulator applies the novel "ultrafast quantum computer" scheme to a quantum simulator: it circumvents the Rydberg blockade effect with an ultrafast laser.

Overcoming the noise issue and achieving high speed and accurate controls are the keys to reliable quantum simulation. The world's fastest quantum simulation realized by the group is three orders of magnitude faster than conventional simulators and is more than 1,000 times faster than noise, allowing the noise effects to be ignored.

Quantum entanglement, a peculiar correlation that appears in quantum mechanical particles such as atoms and electrons that constitute matter, is a concept essential for understanding the "quantum" world, while it is considered extremely difficult to measure in large-scale systems and real materials.

This achievement, which simulates the formation of large-scale "quantum entanglement" at an ultrafast timescale, is expected to contribute to the development of quantum technology by understanding "quantum entanglement," an essential resource for quantum computers and quantum networks, in future large-scale systems close to the practical level.

In addition, quantum simulations of magnetic materials are expected to advance our understanding of the origin of physical properties of materials such as magnetism. It will also provide guidance for the design of next-generation devices and functional materials that exhibit dramatic functionality through the use of quantum mechanical effects.

The experiment was conducted using rubidium atoms. First, 30,000 gaseous rubidium atoms were cooled to an ultralow temperature of fewer than 10 millionths of one Kelvin using laser cooling. Then, an artificial crystal was prepared by arranging the atoms at a 0.5-micron spacing in a cubic array using an optical lattice.

They then irradiated ultrashort laser pulses that blink for only 10 billionths of a second to excite electrons trapped in the 5S orbitals of atoms into giant 35D electron orbitals (Rydberg orbitals) and observed what happens to the artificial crystal. The researchers observed the formation of "quantum entanglement," a correlation unique to quantum mechanical particles, on a timescale of a few hundred picoseconds due to the strong interaction between the distant atoms.

Future development and social significance of this research

The ultrafast quantum simulation of magnetic materials achieved with the cold-atom platform was realized using the unique scheme developed by the same research group to manipulate an array of 30,000 atoms with an ultrafast laser. The research group has demonstrated that the ultrafast quantum simulator is a revolutionary platform.

The innovative ultrafast quantum simulator developed by the research group is expected to be further upgraded in the future to elucidate the origin of physical properties of materials such as magnetism, to provide guidelines for designing quantum materials that exhibit dramatic functions (next-generation devices and functional materials that utilize quantum mechanical effects), and thus to bring innovation to materials research.

It is also expected to contribute to the development of quantum technology by understanding quantum entanglement, an indispensable resource for quantum computers and quantum networks, in a large-scale system close to the future practical level. Furthermore, it is expected to develop as a tool for solving social issues such as logistics, traffic congestion, and electric power transportation, which are difficult to solve even with supercomputers, by using quantum mechanical effects.

More information: V. Bharti et al, Picosecond-Scale Ultrafast Many-Body Dynamics in an Ultracold Rydberg-Excited Atomic Mott Insulator, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.123201

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