Long-lived pionic helium: Exotic matter experimentally verified for the first time

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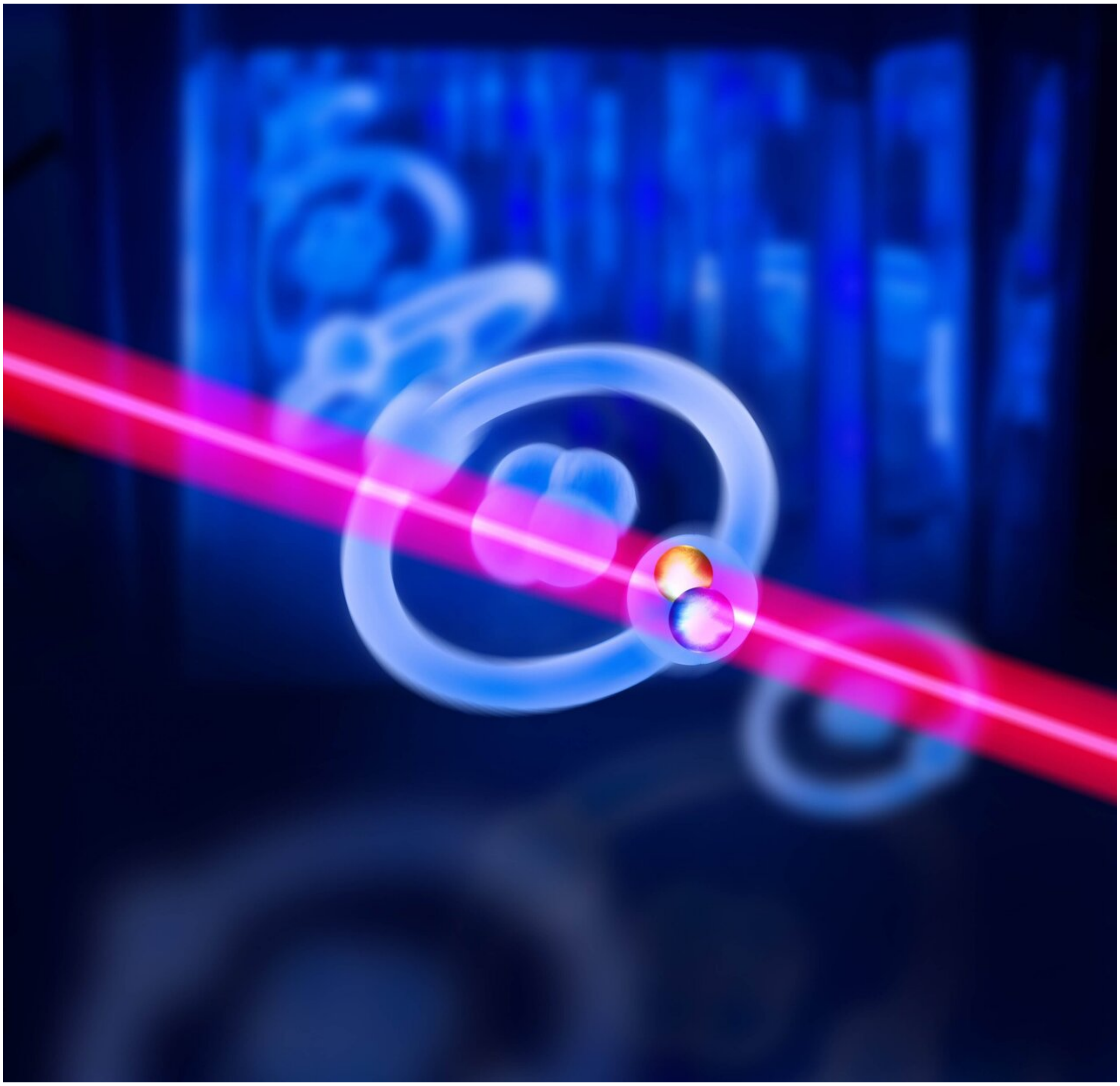

Artistic impression of the pionic helium atom irradiated by a laser beam. Credit: Max Planck Institute of Quantum Optics

Exotic atoms in which electrons are replaced by other subatomic particles of the same charge allow deep insights into the quantum world. After eight years of ongoing research, a group led by Masaki Hori, senior physicist at the Max Planck Institute of Quantum Optics in Garching, Germany, has now succeeded in a challenging experiment: In a helium atom, they replaced an electron with a pion in a specific quantum state and verified the existence of this long-lived "pionic helium" for the very first time. The usually short-lived pion could thereby exist 1000 times longer than it normally would in other varieties of matter. Pions belong to an important family of particles that determine the stability and decay of atomic nuclei. The pionic helium atom enables scientists to study pions in an extremely precise manner using laser spectroscopy. The research is published in this week's edition of *Nature*.

For eight years, the group worked on this challenging experiment, which has the potential to establish a new field of research. The team experimentally demonstrated for the first time that long-lived pionic helium atoms really exist. "It is a form of chemical reaction that happens automatically," explains Hori. The exotic atom was first theoretically predicted in 1964 after experiments at that time pointed toward its existence. However, it was considered extremely difficult to verify this prediction experimentally. Usually, in an atom, the extremely short-lived pion decays quickly. However, in pionic helium, it can be conserved in a sense so it lives 1000 times longer than it normally does in other atoms.

The "smoking gun"

The challenge the team struggled with for eight years was proving that such a pionic helium atom exists in a tank filled with extremely cold, superfluid helium. In the helium atom, the pion behaves like a very heavy electron. It can only jump between discrete quantum states, like climbing steps on a ladder. The team had to find a long-lived state and a very special quantum leap which they could excite with a laser and which would kick the pion into the helium nucleus and destroy the atom. Then the team could detect the debris from the breakup of the nucleus as a "smoking gun" (see figure). However, the theoreticians couldn't exactly predict at which light wavelength the quantum leap would occur. So the team had to install three complex laser systems, one after the other, until they were successful.

"This success opens up completely new ways to investigate pions with the methods of quantum optics," Hori says. The researchers used laser spectroscopy, one of the most precise tools in physics. Pions in quantum states can thus be studied with much more precision than ever before.

A new window into the quantum cosmos

The pion belongs to the particle family of the so-called mesons. Mesons mediate the strong force between the building blocks of atomic nuclei, neutrons and protons. Although protons with the same electrical charge repel each other violently, the stronger nuclear force binds them together to form the atomic nucleus. Without this force, our world would not exist. Mesons are fundamentally different from protons and neutrons, which are each made up of three quarks, whereas mesons consist of only two quarks.

The experiment used the most powerful pion source in the world, located at PSI. Since the risk of failure was very high and there were numerous failures along the way, the group needed long-term support from PSI and the Max Planck Society (MPG). The PSI provided beam time with pions, the technical groups of CERN provided an important part of the equipment, and the MPG provided a long-date research enabling environment. The project was financed by an ERC grant (European Research Council).

Dr. Hori hopes that his research opens a new window into the quantum cosmos of particles and forces.

More information: Masaki Hori et al. Laser spectroscopy of pionic helium atoms, *Nature* (2020). DOI: 10.1038/s41586-020-2240-x

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