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Scientists set the stage for quantum chemistry in space on NASA's cold atom lab

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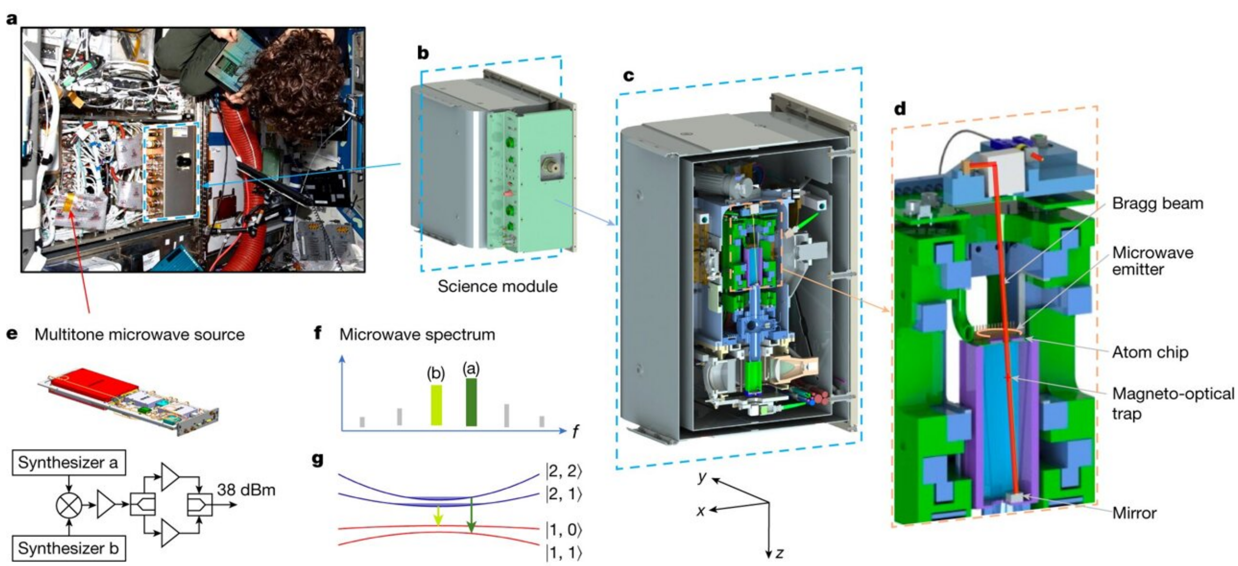

CAL on-orbit hardware upgrades. Credit: *Nature* (2023). DOI: 10.1038/s41586-023-06645-w

For the first time in space, scientists have produced a mixture of two quantum gases made of two types of atoms. Accomplished with NASA's Cold Atom Laboratory aboard the International Space Station, the achievement marks another step toward bringing quantum technologies currently available only on Earth into space.

Physicists at Leibniz University Hannover (LUH), part of a collaboration led by Prof. Nicholas Bigelow, University of Rochester, provided the theoretical calculations necessary for this achievement. While quantum tools are already used in everything from cell phones to GPS to medical devices, in the future, quantum tools could be used to enhance the study of planets, including our own, as well as to help solve mysteries of the universe and deepen our understanding of the fundamental laws of nature.

The new work, performed remotely by scientists on Earth, is described in *Nature*.

With this new capability, it is now possible to study not only the quantum properties of individual sorts of atoms, but also quantum chemistry, which focuses on how isotopes of different atomic elements interact and combine with each other in a quantum state. Researchers will be able to conduct a wider range of experiments with Cold Atom Lab and learn more about the nuances of performing them in microgravity. That knowledge will be essential for harnessing the one-of-a-kind facility to develop new space-based quantum technologies.

Quantum chemistry

The physical world around us depends on atoms and molecules staying bound together, according to an established set of rules. But different rules can dominate or weaken depending on the environment the atoms and molecules are in—like microgravity. Scientists using the Cold Atom Lab are exploring scenarios where the quantum nature of atoms dominates their behaviors. That can mean that instead of acting like solid billiard balls, the atoms and molecules behave more like waves.

In one of those scenarios, the atoms in two- or three-atom molecules can remain bound together but grow increasingly far apart, almost as though the molecules are getting fluffy. To study these states, scientists first need to slow the atoms down. They do this by cooling them to fractions of a degree above the lowest temperature matter can reach and far colder than anything found in the natural universe: absolute zero, or minus 273 degrees Celsius.

Physicists have created these fluffy molecules in cold atom experiments on the ground, but they are extremely fragile and either break apart quickly or collapse back down to a normal molecular state. For that reason, enlarged molecules with three atoms have never been directly imaged. In microgravity the fragile molecules can exist for longer and potentially get larger, so physicists are excited to start experimenting with the Cold Atom Lab's new capability.

These types of molecules likely don't occur in nature, but it's possible they could be used to make sensitive detectors that can reveal subtle changes in the strength of a magnetic field, for example, or any of the other disturbances that cause them to break apart or collapse.

A modern mystery

"We now have, for example, completely new ways of testing the equivalence principle of Einstein, one of the most fundamental assumptions of fundamental physics," says Naceur Gaaloul from the Institute of Quantum Optics at LUH and co-author of the new study. The famous principle holds that gravity affects all objects the same regardless of their mass. It is a principle that many physics teachers will demonstrate by putting a feather and a hammer in a sealed vacuum chamber and showing that, in the absence of air friction, the two fall at the same rate.

Using an instrument called an atom interferometer, scientists have already run experiments on Earth to see if the equivalence principle holds true at atomic scales. Using a quantum gas with two types of atoms and an interferometer in the microgravity of the space station, they could test it with more precision than what's possible on Earth. Doing so, they might learn whether there's a point where gravity doesn't treat all matter equally, indicating the general theory of relativity contains an (albeit small) error.

The equivalence principle is part of Albert Einstein's general theory of relativity, the backbone of modern gravitational physics, which describes how large objects, like planets and galaxies, behave. But a major mystery in modern physics is why the laws of gravity don't seem to match up with the laws of quantum physics, which describe the behaviors of small objects, like atoms. Both fields have proven to be correct again and again in their respective size realms, but physicists have been unable to unite them into a single description of the universe as a whole.

Looking for features of gravity not explained by Einstein's theory is one way to search for a means of unification or learn about the nature of dark energy, the mysterious driver behind the accelerating expansion of the universe.

Better sensors

Scientists already have ideas to go beyond testing fundamental physics in microgravity. They have also proposed space-based experiments that could use an atom interferometer and quantum gases to measure gravity with high precision in order to observe mass variations on Earth. What they learn could lead to the development of precision sensors for a wide range of applications such as geophysics, climate research or space inertial navigation.

The quality of those sensors will depend on how well scientists understand the behavior of these atoms in microgravity, including how those atoms interact with each other. The introduction of tools to control the atoms, like magnetic fields, can make them repel each other like oil and water or stick together like honey. Understanding those interactions is a key goal of the Cold Atom Lab and its successor BECCAL, a joint project of NASA and the German Aerospace Agency (DLR).

More information: Ethan Elliott, Quantum gas mixtures and dual-species atom interferometry in space, *Nature* (2023). DOI: 10.1038/s41586-023-06645-w.
www.nature.com/articles/s41586-023-06645-w

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