# Researchers see signs of interactive form of quantum matter

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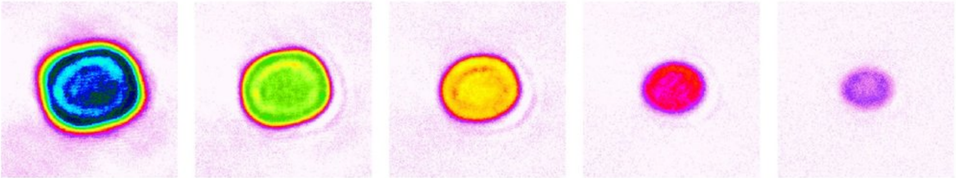

False-color images showing variations in atom numbers (1 to 5 atoms, left to right) and density in different lattice cells of JILA's strontium lattice atomic clock. JILA researchers observed shifts in the clock's frequency that arise from the emergence of multi-particle interactions when three or more atoms occupy a single cell. Credit: Ye Group/JILA

JILA researchers have, for the first time, isolated groups of a few atoms and precisely measured their multi-particle interactions within an atomic clock. The advance will help scientists control interacting quantum matter, which is expected to boost the performance of atomic clocks, many other types of sensors, and quantum information systems.

The research is described in a *Nature* paper posted early online Oct. 31. JILA is jointly operated by the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder.

NIST scientists have been predicting "many body" physics and its benefits for years, but the new JILA work provides the first quantitative evidence of exactly what happens when packing together a few fermions—atoms that cannot be in the same quantum state and location at the same time.

"We are trying to understand the emergence of complexity when multiple particles—atoms here—interact with each other," NIST and JILA Fellow Jun Ye said. "Even though we may understand the rules perfectly on how two atoms interact, when multiple atoms get together there are always surprises. We want to understand the surprises quantitatively."

Today's best tools for measuring quantities such as time and frequency are based on control of individual quantum particles. This is the case even when ensembles of thousands of atoms are used in an atomic clock. These measurements are approaching the so-called standard quantum limit—a "wall" preventing further improvements using independent particles.

Harnessing of many-particle interactions could push that wall back or even break through it, because an engineered quantum state could suppress atom collisions and protect quantum states against interference, or noise. In addition, atoms in such systems could be arranged to cancel each other's quantum noise such that sensors would get better as more atoms were added, promising significant leaps in precision and data-carrying capacity.

In the new research, the JILA team used their three-dimensioned strontium lattice clock], which offers precise atom control. They created arrays of between one and five atoms per lattice cell, and then used a laser to set the clock "ticking," or switching at a specific frequency between two energy levels in the atoms. JILA's new imaging technique was used to measure the atoms' quantum states.

The researchers observed unexpected results when three or more atoms were together in a cell. The results were nonlinear, or unpredicted based on past experience, a hallmark of multi-particle interactions. The researchers combined their measurements with theoretical predictions by NIST colleagues Ana Maria Rey and Paul Julienne to conclude that multi-particle interactions occurred.

Specifically, the clock's frequency shifted in unexpected ways when three or more atoms were in a lattice site. The shift is different from what one would expect from summing up various pairs of atoms. For example, five atoms per cell caused a shift of 20 percent compared to what would normally be expected.

"Once you get three atoms per cell, the rules change," Ye said. This is because the atoms' nuclear spins and electronic configurations play together to determine the overall quantum state, and the atoms can all interact simultaneously instead of in a pair-wise fashion, he said.

Multi-particle effects also appeared in crowded lattice cells in the form of an unusual, rapid decay process. Two atoms per triad formed a molecule and one atom remained loose, but all had enough energy to escape the trap. By contrast, a single atom is likely to remain in a cell for a much longer time, Ye said.

"What this means is, we can make sure there is only one atom per cell in our atomic clock," Ye said. "Understanding of these processes will allow us to figure out a better path for making improved clocks, as particles inevitably will interact if we pack enough of them nearby to improve signal strength."

The JILA team also found that packing three or more atoms into a cell could result in long-lived, highly entangled states, meaning the atoms' quantum properties were linked in a stable way. This simple method of entangling multiple atoms may be a useful resource for quantum information processing.

**More information:** A. Goban, R.B. Hutson, G.E. Marti, S.L. Campbell, M.A. Perlin, P.S. Julienne, J.P. D'Incao, A.M. Rey,and J. Ye. 2018. Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock. *Nature*. Advance Online Publication Oct. 31. DOI: 10.1038/s41586-018-0661-6 , www.nature.com/articles/s41586-018-0661-6

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