The interference of many atoms, and a new approach to boson sampling

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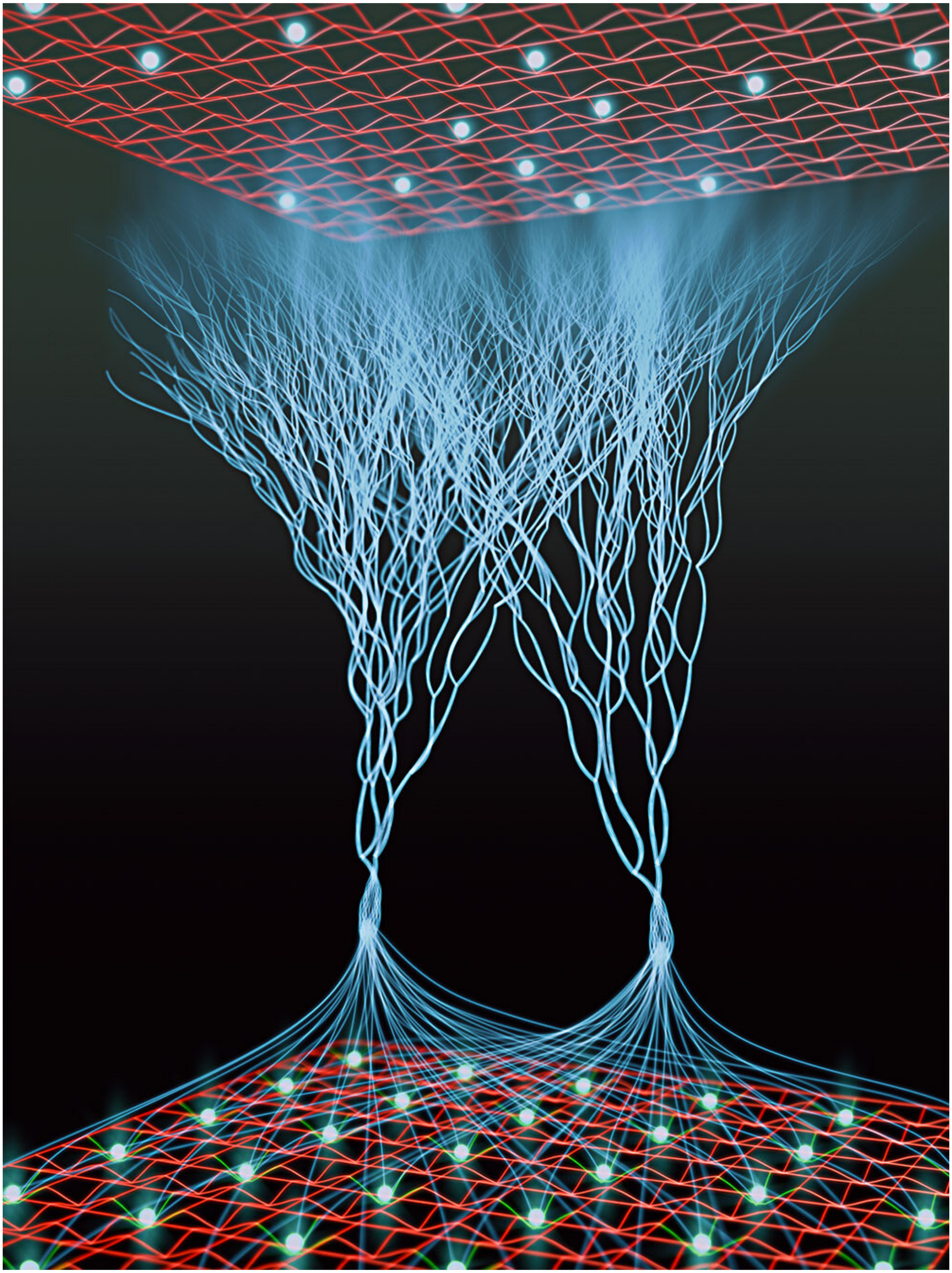

Atoms in an optical lattice perform a "quantum walk" where they experience many different quantum phenomena, such as superposition or tunneling as they move around the lattice. Credit: Alex Downham, Default Interactive and Steven Burrows/JILA

In daily life, when two objects are "indistinguishable," it's due to an imperfect state of knowledge. As a street magician scrambles the cups and balls, you could, in principle, keep track of which ball is which as they are passed between the cups. However, at the smallest scales in nature, even the magician cannot tell one ball from another.

True indistinguishability of this type can fundamentally alter how the balls behave. For example, in a classic experiment by Hong, Ou, and Mandel, two identical photons (balls) striking opposite sides of a half-reflective mirror are always found to exit from the same side of the mirror (in the same cup). This results from a special kind of interference, not any interaction between the photons. With more photons, and more mirrors, this interference becomes enormously complicated.

Measuring the pattern of photons that emerges from a given maze of mirrors is known as "boson sampling." Boson sampling is believed to be infeasible to simulate on a classical computer for more than a few tens of photons. As a result, there has been a significant effort to perform such experiments with actual photons and demonstrate that a quantum device is performing a specific computational task that cannot be performed classically. This effort has culminated in recent claims of quantum advantage using photons.

Now, in a recently published paper in *Nature*, JILA Fellow and NIST Physicist and University of Colorado Boulder Physics Professor Adam

Kaufman and his team, along with collaborators at NIST (the National Institute of Standards and Technology), have demonstrated a novel method of boson sampling using ultracold atoms (specifically, bosonic atoms) in a two-dimensional optical lattice of intersecting laser beams.

Using tools such as optical tweezers, specific patterns of identical atoms can be prepared. The atoms can be propagated through the lattice with minimal loss, and their positions detected with nearly perfect accuracy after their journey. The result is an implementation of boson sampling that is a significant leap beyond what has been achieved before, either in computer simulations or with photons.

"Optical tweezers have enabled ground-breaking experiments in many-body physics, often for studies of many-interacting atoms, where the atoms are pinned in space and interacting over long distances," says Kaufman. "However, a large class of foundational many-body problems—so-called 'Hubbard' systems—arise when particles can both interact and tunnel, quantum mechanically spreading out in space. Early on in building this experiment, we had the goal of applying this tweezer paradigm to large-scale Hubbard systems—this publication marks the first realization of that vision."

Techniques for better control

To achieve these results, the researchers used several cutting-edge techniques, including optical tweezers—highly focused lasers that can move individual atoms with exquisite precision—and advanced cooling methods that bring the atoms near absolute zero temperature, minimizing their movement and allowing for precise control and measurement.

Similar to how a magnifying glass creates a pinprick of light when focused, optical tweezers can hold individual atoms in powerful beams of light, allowing them to be moved with extreme precision. Using these tweezers, the researchers prepared specific patterns of up to 180 strontium atoms in a 1,000-site lattice, formed by intersecting [laser beams]() that create a grid-like pattern of potential energy wells to trap the atoms. The researchers also used sophisticated laser cooling techniques to prepare the atoms, ensuring they remained in their lowest energy state, thereby reducing noise and decoherence—common challenges in quantum experiments.

NIST physicist Shawn Geller explained that the cooling and preparation ensured that the atoms were as identical as possible, removing any labels, such as individualized internal states or motional states, that could make a given atom different from the others.

"Adding a label means the universe can tell which atom is which, even if you can't see the label as an experimenter," says first author and former JILA graduate student Aaron Young. "The presence of such a label would change this from an absurdly hard sampling problem to one that's completely trivial."

A matter of scaling

For the same reason that boson sampling is hard to simulate, directly verifying that the correct sampling task has been performed is not feasible for the experiments with 180 atoms. To overcome this issue, the researchers sampled their atoms at various scales.

According to Young, "We do tests with two atoms, where we understand very well what's happening. Then, at an intermediate scale where we can still simulate things, we can compare our measurements to simulations involving reasonable error models for our experiment. At large scale, we can continuously vary how hard the sampling task is by controlling how distinguishable the atoms are and confirm that nothing dramatic is going wrong."

Geller adds, "What we did was develop tests that use physics we know to explain what we think is happening."

Through this process, the researchers were able to confirm the high fidelity of the atom preparation and later evolution of the atoms' quantum states in comparison to previous boson sampling demonstrations. In particular, the very low loss of atoms compared to photons during the atoms' evolution precludes modern computational techniques that challenge previous quantum advantage demonstrations.

The high-quality and programmable preparation, evolution, and detection of atoms in a lattice demonstrated in this work can be applied in the situation where the atoms interact. This opens new approaches simulating and studying the behavior of real, and otherwise poorly understood, quantum materials.

"Using non-interacting particles allowed us to take this specific problem of boson sampling to a new regime," says Kaufman. "Yet, many of the most physically interesting and computationally challenging problems arise with systems of many interacting particles. Going forward, we expect that applying these new tools to such systems will open the door to many exciting experiments."

More information: www.nature.com/articles/s41586-024-07304-4

Provided by JILA

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