A new strategy to implement a high-fidelity mixed-species entangling gate

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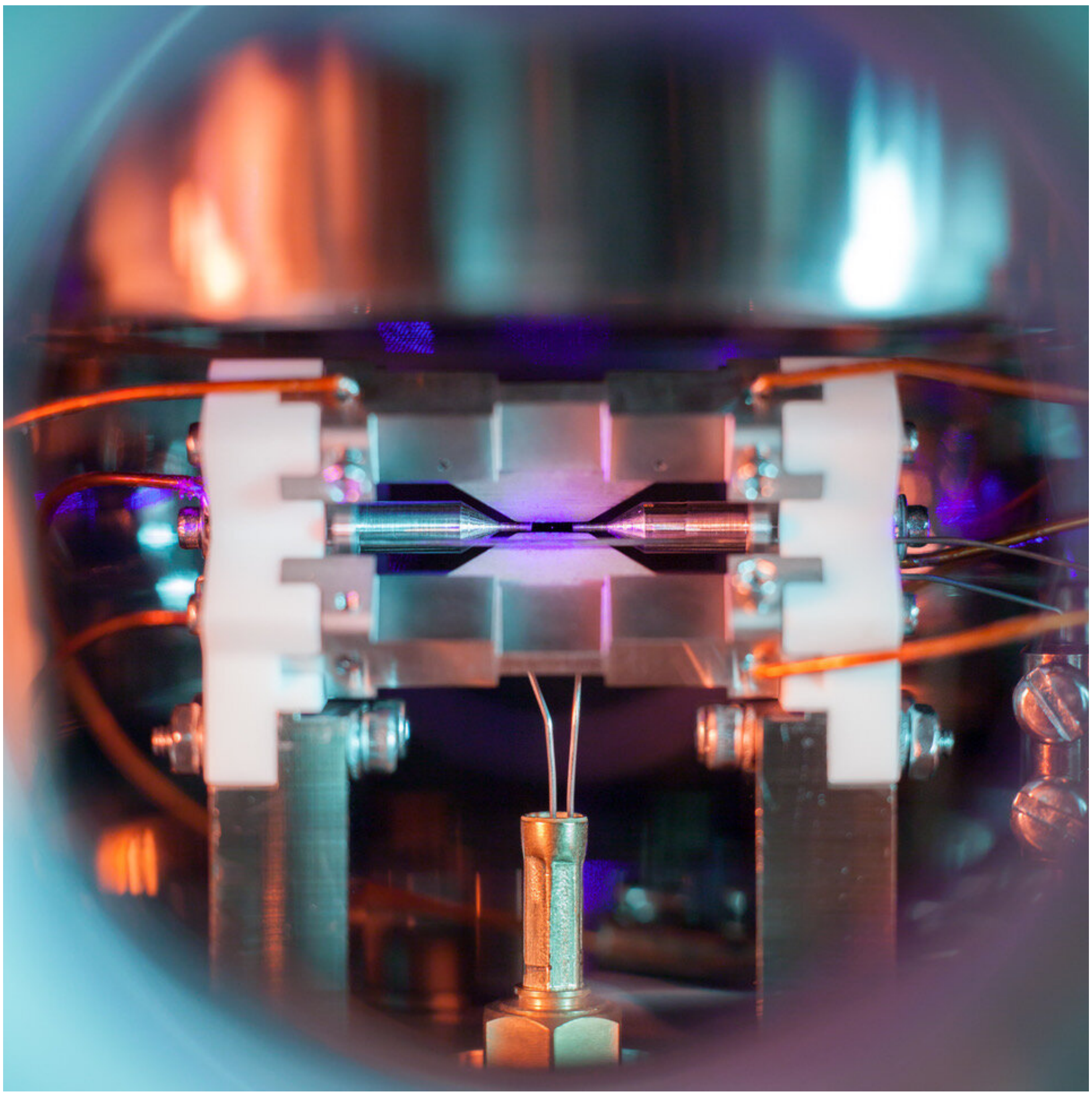

Credit: D. P. Nadlinger.

In recent years, research teams worldwide have been trying to create trapped ion quantum computers, which have so far proved to be among the most promising systems for practical quantum computing implementations. In these computers, trapped ions serve as quantum bits that are entangled in order to perform advanced computations.

On a quest to develop scalable trapped ion quantum computers, researchers at the University of Oxford have recently implemented a two-qubit entangling gate between two distinct atomic elements, calcium and strontium. In their study, featured in *Physical Review Letters*, they used a gate mechanism that requires only a single laser, which they had previously tested on two different calcium isotopes.

One of the greatest challenges in the development of trapped ion quantum computers is scalability (i.e., finding ways to apply approaches that achieved promising results on a few qubits to thousands or even millions of qubits). In fact, simply adding new qubits to a quantum computing system often results in a rapid decrease in performance, as it introduces new errors and makes it harder to interact with a single qubit without affecting some of the others.

To overcome this challenge, the research team at University of Oxford used two methods known as modularization and optical networking. Essentially, their goal was to have ions in separate ion traps and vacuum systems, which are only connected through optical fibers.

This approach limits crosstalk between qubits, retaining only interactions that are desirable and can be controlled by the researchers. This means that once a system that works well is identified, more of the same can be added, as new ones will not impact the overall performance.

"For this approach, but also other strategies to improve scalability, using different ion species is very useful," Vera M. Schäfer, one of the researchers who carried out the study, told Phys.org. "First of all, because different ions have different strengths and weaknesses. For example, we use one ion species that is a very good memory and logic ion—that means it can store information for a very long time (50s compared to tens of milliseconds for 'normal' trapped ion qubits), and we get very small errors when performing calculations with this ion species; the other species is much better (and faster) at coupling to photons. Secondly, because a problem with trapped ions is that they slowly heat up over time. If we have two different species, we can use the second species to cool the ions during a calculation, which diminishes the heating problem."

To use different species for realizing trapped ion quantum computing applications, researchers should be able to transfer information between these species. This can be done by producing what is known as a two-qubit gate.

In one of their past studies, Schäfer, Amy Hughes and her colleagues successfully performed a two-qubit gate between different calcium isotopes. Implementing such a gate between entirely different atomic elements, however, would be far more useful. This is because different elements have very different characteristics and display distinct transition frequencies.

As a result, when performing an operation on one species using laser technology, the other species would remain entirely unaffected. Simultaneously, however, as the two elements may also have different masses, controlling their motion can be far more complicated.

"In our previous work, we performed the gate on two different isotopes of calcium with a single laser, which was quite a natural decision because most transition frequencies are still quite close in different isotopes," Schäfer said. "However, we noticed that for strontium, the element that is best suited to use together with calcium, the transition frequencies aren't that far apart, and [we thought] that maybe we could use the same scheme that worked for different isotopes for different elements."

The similarity between the transition frequencies of calcium and strontium greatly simplified the problem at hand, ultimately allowing the researchers to achieve higher fidelities than those attained when producing other mixed-element gates. Their successful implementation of a mixed species gate could be a significant step forward in the realization of large-scale quantum computing, while also allowing researchers to simultaneously leverage the properties of two different elements.

"The basic idea behind trapped ion entangling gates is to create a correlation between the ions' qubit states via their motion, which is strongly coupled as they repel each other due to their charge," Schäfer said. "Laser light can couple to the ions' motion and, for example, push them in a certain direction. We can apply laser light that couples differently to ions in opposite qubit states, e.g., it will push an ion in state |1>, but pull an ion in state |0>. Thus, for some qubit state combinations the common motion will be canceled and for others enhanced, and we can use that to create entanglement."

Many researchers who previously implemented mixed-species two-qubit entangling gates used different lasers to manipulate different elements. To do this, however, the researchers must ensure that the two lasers are well synchronized and calibrated so that they have a similar effect on the two different ion species.

Schäfer, Hughes and their colleagues, on the other hand, only used a single laser. This means that while they did not need to synchronize it in any particular way, they also had fewer degrees of freedom available for calibration and had to identify a position that would allow it to couple both species in a similar way. As mixed-species crystals are more sensitive to particular external effects (e.g., stray electric fields), the researchers had to be more careful during the calibration than they would when implementing a single species gate.

"The gate was implemented using a pair of laser beams (at about 402 nm), that can couple to and excite the motion of both calcium and strontium simultaneously," Schäfer explained. "We used three different methods to characterize the gate performance: measuring the output state after a single gate and comparing it to the ideal output; running a sequence of gates similar to an algorithm with and without interleaving our gate and comparing the magnitude of errors between the two; and running sequences that enhance different types of errors to characterize the nature of our error sources."

To evaluate their gate's performance, the researchers used three methods known as partial-state tomography, randomized benchmarking and gate set tomography. Partial-state tomography consists of implementing a single gate and then measuring its output state.

"This is the simplest and most commonly used method," Schäfer said. "Because on average we only get an error in two out of 1,000 gates, we have to do this many times to get an accurate estimate of the gate error, and it is harder to distinguish between how many errors were caused by the gate itself and how many by the readout of the final state, compared to the second method we used."

Randomized benchmarking, the second evaluation strategy used by Schäfer, Hughes and their colleagues, entails the implementation of several consecutive gates while inserting different types of gates in between them to continuously change the input state, after which each gate is applied. Subsequently, the researchers compared the error between only this random sequence and a sequence where their gate was intermittently introduced between the random gates.

"Randomized benchmarking is better suited to measure very small errors, because we perform lots of gate operations before we read out the final state, and the result is more comparable to the expected performance in a real algorithm," Schäfer said.

Finally, gate set tomography, the last method used by the researchers to evaluate their gate, tries to quantify and characterize errors produced when a gate is implemented. To do this, it produces sequences that are designed to increase the effect of specific types of errors in order to quantify the total amount of error of each type. The information gained from using this technique is useful for theorists who are trying to develop more efficient error-correction schemes.

"I think that mixed-species work sometimes has the reputation of being quite complex and difficult and hard to do well," Schäfer said. "Our work showed that by choosing the right scheme, we can actually perform mixed species gates almost as well as single species gates. There are also a few things that one might worry about initially, that turned out to be completely irrelevant in this scheme."

The recent study carried out by Schäfer, Hughes and their colleagues could ultimately contribute to the creation of new trapped ion quantum computing approaches that are easier to scale up. In the future, it could also serve as an inspiration for other research groups who are trying to implement mixed species entangling gates, providing some guidance on how to best achieve this.

"We are now testing a different mixed species entangling gate mechanism, and want to compare their advantages, disadvantages and requirements to be able to choose the best scheme for given circumstances," Schäfer said. "We also want to implement this mixed species gate on our ion-photon entangling experiment, to demonstrate its use for building a scalable trapped ion quantum computer and use it to perform entanglement distillation."

More information: Benchmarking a high-fidelity mixed-species entangling gate. *Physical Review Letters* (2020). DOI: 10.1103/PhysRevLett.125.080504.