

RYDBERG ATOMS

A boost to Rydberg quantum computing

Systems of neutral atoms are gradually gaining currency as a promising candidate for realizing large-scale quantum computing. The achievement of a record-high fidelity in quantum operation with alkaline-earth Rydberg atoms is a case in point.

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Quantum computing recently attracted a tremendous amount of attention. While the platforms that have claimed the early headlines are trapped ions and superconducting qubits, other physical systems, such as neutral atoms, also remain viable as candidates for realizing scalable universal quantum computers. Writing in *Nature Physics*, Ivaylo S. Madjarov and colleagues have now demonstrated single- and two-qubit operation fidelities higher than 0.99 on a platform of reconfigurable arrays of strontium Rydberg atoms¹. This result is competitive with fidelities achieved with trapped ions (>0.999) and superconducting qubits (>0.99), and potentially opens a new chapter in quantum computing based on neutral atoms.

Like classical computers, quantum computers execute algorithms by performing a sequence of logic-gate operations on a set of two-state objects, referred to as qubits. However, unlike a classical bit, a qubit can also be in a superposition of its two '0' and '1' states. More importantly, two or more qubits can be made entangled, and this quantum entanglement is the crucial resource for realizing quantum logic gates. A universal quantum computer capable of solving problems intractable with classical computers would need hundreds of these fragile qubits and hundreds of thousands of delicate gate operations. This puts stringent requirements on the precise preparation, control and detection of a basic gate set, as well as the scalability to a large ensemble of qubits. The latter is especially challenging, since the fidelity of gate operations reduces rapidly if crosstalk and unwanted interaction between increasing numbers of qubits cannot be eliminated.

Neutral atoms, as one of the many experimental platforms being developed for quantum computational applications² — including ions, electron/nuclear spins and photons, to name a few — exhibit attractive features. Besides those common to atomic systems, such as long decoherence times and accurate state manipulation,

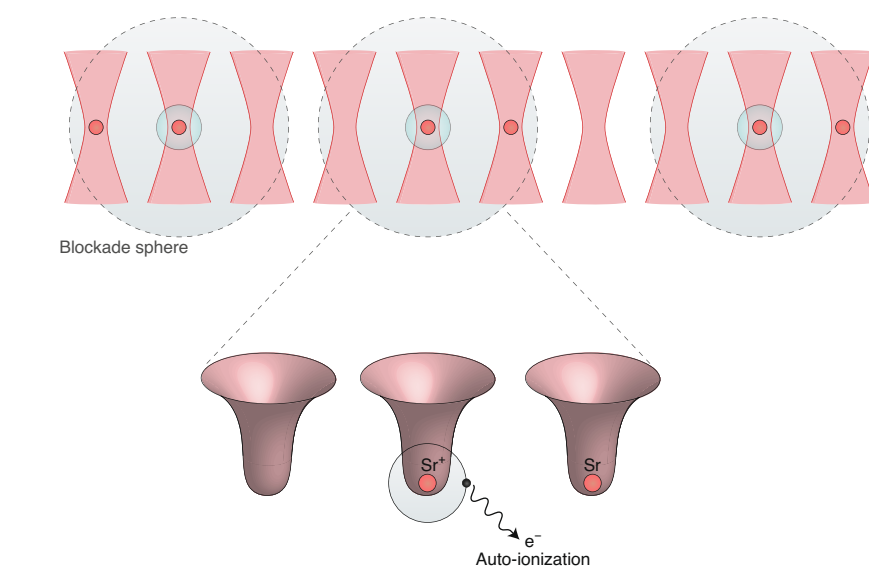


Fig. 1 | Entanglement and detection of strontium Rydberg qubits in a reconfigurable tweezer array.

Atoms can be shuffled in the tweezer array into any desirable configurations. Due to Rydberg blockade, the two atoms within the blockade radius are made into an entangled state, where one atom is in the ground state and the other in the Rydberg state (indistinguishable until detection). A strontium-ion core with one valence electron could still feel the trapping potential of an optical tweezer, even if the Rydberg electron provides an anti-trapping effect. The detection of a Rydberg atom is done by auto-ionizing the Rydberg electron, where the ion left behind is dark to the detection laser.

their scalability is particularly promising. Neutral atoms can be arranged in a large one-, two- or three-dimensional array, and be addressed individually by laser beams for qubit operations with little crosstalk to quantum states of nearby atoms³. For such an architecture, the gate protocols utilizing highly excited (Rydberg) states are currently the most favourable ones among various schemes conceived for entangling two neutral-atom qubits⁴. The huge polarizability and dipole moment of Rydberg atoms allow them to strongly interact with each other over a distance of a few micrometres. More specifically, the interaction-induced Rydberg blockade, which prevents more than one Rydberg excitation for a pair of atoms within a certain distance, is an ideal mechanism for conditional logic (for example,

'controlled-NOT' gates), as the state of a first atom — excited or not — dictates the excitation of a second atom.

Rydberg blockade between two individual atoms was first demonstrated in 2009 (refs. ^{5,6}), and used to realize two-atom entanglement by the same groups. Since then, efforts have been made to enhance the gate fidelity as well as to increase the number of qubits. In addition to the more established techniques — such as loading ultracold atoms into an optical lattice via a superfluid-to-Mott-insulator transition — assembling individually trapped atoms one-by-one into a large reconfigurable array has been actively pursued using optical tweezers. In this approach, the spacing of tweezers in an array can be varied within a few micrometres, which offers

great flexibility in manipulating atoms individually. An ensemble of atoms trapped in such a tweezer array is particularly suitable for exploring quantum physics and applications based on long-range Rydberg interaction.

This tweezer-array approach was successfully implemented in 2016 with a few tens of alkali atoms (now reaching defect-free arrays of more than 100 atoms), and has been subsequently used to study quantum magnetism as well as quantum computational applications⁷. Notably, the two-qubit Rydberg gate fidelity was improved to a high value of 0.97 on this platform, after mitigating various noise sources⁸. Only in the last few years, the technique of optical tweezer arrays has been extended to trapping alkaline-earth atoms⁹.

In their latest work¹, Madjarov and colleagues have demonstrated the quantum entanglement of alkaline-earth Rydberg atoms arranged in arrays, and achieved the control and detection of single and entangled Rydberg qubits with fidelities surpassing all previously reported results. This was accomplished using several novel techniques unique to alkaline-earth atoms (Fig. 1). First, by preparing a metastable clock state of a strontium atom as the ground state, the work realized

single-photon coupling between the two levels of Rydberg-ground state qubit in contrast to the two-photon excitations used in alkali-atom Rydberg qubits. The notable technical step avoids the issue of intermediate state scattering, which usually has to be suppressed using high-power far-detuned lasers. More importantly, the energy structure of two valence electrons makes it possible to implement a very efficient detection of Rydberg states via a coupling to an auto-ionizing channel. This new scheme greatly improved the detection fidelity compared to that obtained by the conventional method relying on the loss of Rydberg alkali atoms from optical tweezers. Finally, the authors demonstrated a high-fidelity two-qubit entanglement with tweezer potentials kept on. While the prospect of implementing Rydberg gates in the presence of optical traps still need to be further investigated¹⁰, this experiment already constituted a very encouraging step in overcoming the challenges associated with switching on and off tweezers in sequential gate operations.

Scalable Rydberg atom arrays have proven to be a promising platform for quantum science. The high-fidelity manipulation and detection of alkaline-earth Rydberg atoms accomplished by Madjarov

and colleagues certainly provides further affirmation and inspiration in exploring this system both for quantum computing and for quantum simulation of many-body spin systems. Moreover, the demonstrated entanglement between qubits of Rydberg-clock states paves the way towards Rydberg-based quantum-enhanced metrology. We can anticipate many new exciting results in all these directions coming from this fascinating physical system of Rydberg atom arrays. □

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References

1. Madjarov, I. S. et al. *Nat. Phys.* <https://doi.org/10.1038/s41567-020-0903-z> (2020).
2. Ladd, T. D. et al. *Nature* **464**, 45–53 (2010).
3. Weiss, D. S. & Saffman, M. *Phys. Today* **70**, 44 (2017).
4. Saffman, M., Walker, T. G. & Molmer, K. *Rev. Mod. Phys.* **82**, 2313–2363 (2010).
5. Urban, E. et al. *Nat. Phys.* **5**, 110–114 (2009).
6. Gaëtan, A. et al. *Nat. Phys.* **5**, 115–118 (2009).
7. Browaeys, A. & Lahaye, T. *Nat. Phys.* **16**, 132–142 (2020).
8. Levine, H. et al. *Phys. Rev. Lett.* **123**, 170503 (2019).
9. Browaeys, A. *Physics* **11**, 135 (2018).
10. Wilson, J. T. et al. Preprint at <https://arxiv.org/abs/1912.08754> (2019).