RYDBERG ATOMS

A spotlight on circular states

Circular Rydberg states provide an ideal resource for large scale quantum computing and simulation that These circular states can be controlled using coherent optical pulses, providing a route to programmable quantum hardware.

Neutral atoms are an attractive candidate for the development of scalable quantum hardware, due to the ability to create large arrays of qubits with individually focused beams [1]. A route to couple the qubits is through highly excited Rydberg states, which offer strong and long-range interactions to create tuneable spin-models [2] or perform quantum gate operations [3]. However, a major limitation to the reliability of current experimental platforms arises from the short lifetime (less than 1ms) of optically accessible Rydberg states [4]. Reporting in *Nature Physics*, Andrea Muni and co-authors [10] have now demonstrated how to ease this obstacle by manipulating circular Rydberg states — highly excited states with maximal angular and magnetic quantum numbers.

Circular states provide an isolated two-level system with long radiative lifetimes of 10-100 ms, which can be further extended by protecting the atoms using a cavity to suppress the spontaneous decay channels [5]. These states have been used in pioneering studies of cavity quantum electrodynamics (QED), enabling non-destructive readout [6]. To date, experiments using circular Rydberg states have predominantly used alkali atoms with only a single valence electron. Once excited to the circular states, the use of microwave fields permits coherent control and manipulation. But, due to the fundamental millimetre-scale wavelength of microwaves, it is impossible to achieve control over individual atoms, which would enable programming of the atomic states.

Using alkaline-earth atoms like Sr can overcome this limitation, thanks to the second optically active valence electron they provide. This enables both optical trapping and coherent optical manipulation of the circular Rydberg states for quantum computing [7] and simulation [8] applications. Experiments using low angular momentum Rydberg states of Sr have previously demonstrated high fidelity entanglement with arrays of optically trapped Rydberg atoms [9]. However, for these low angular momentum states the optical excitation of the inner valence electron causes rapid auto-ionization — the spontaneous emission of the outer Rydberg electron. In their experiment, Muni and colleagues achieved coherent optical manipulation of circular Rydberg states of Sr, which have negligible auto-ionization rates because of their high orbital angular momentum.

The team prepared the atoms by optically exciting one valence electron to a low orbital angular momentum Rydberg state and applying microwave and radiofrequency pulses to transfer it to a high angular momentum circular state (Fig.1). The electrostatic coupling between the inner (core) and outer (Rydberg) valence electrons results in a shift of the Rydberg state energy. This is due to the variation of the core charge distribution as the inner electron changes state. Muni and co-workers measured the circular state microwave resonance shift as they optically transfer the inner electron between different states, providing a mechanism to achieve optical control of the Rydberg electron.

In turn, the electrostatic coupling also leads to a shift in the energy of the core electron, caused by the varying charge distribution of the outer Rydberg electron. Muni and colleagues proved this by applying a two-photon transition between magnetic sublevels of the ionic core and observing a shift in frequency dependent upon the circular Rydberg state. This effect may lead to non-destructive readout of circular states, by making the state transfer of the inner electron conditional on the circular Rydberg state.

Finally, the team demonstrated coherent optical control of the Rydberg state by performing an interferometric Ramsey measurement. Using a pair of time-separated microwave pulses between circular Rydberg states, they first prepared and then probed the phase of the resulting superposition state. When applying a 2π rotation of the inner core electron through a two-photon optical pulse between the two microwave pulses, the atomic wavefunction accumulates a global π-phase shift resulting in an inversion of the output interference fringes. This observation confirms that optical excitation of the core electron can coherently control the circular states and provides a route to local qubit control not possible with microwave transitions alone.

These results demonstrate the potential for state-selective and spatially resolved control and non-destructive readout of circular Rydberg states. The work of Muni and colleagues represents a significant step towards the implementation of scalable and programmable platforms for quantum computing and simulation using arrays of optically trapped alkaline earth atoms.

References

[1] E. Ebadi et al., *Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator,* Nature **595**, 227 (2021)

[2] A. Browaeys and T. Lahaye, *Many-body physics with individually controlled Rydberg atoms,* Nature Phys. **16**, 132 (2020).

[3] M. Saffman, T. G. Walker, and K. Mølmer, *Quantum information with Rydberg atoms,* Rev. Mod. Phys. **82**, 2313 (2010).

[4] M. Saffman, *Quantum computing with atomic qubits and Rydberg interactions: progress and challenges,* J. Phys. B **49**, 202001 (2016).

[5] D. Kleppner, Inhibited Spontaneous Emission, Phys. Rev. Lett. 47, 233 (1981)

[6] Raimond, J. M. and Brune, M. and Haroche, S., *Manipulating quantum entanglement with atoms and photons in a cavity*, Rev. Mod. Phys. **73**, 565 (2001)

[7] S. R. Cohen and J. D. Thompson, *Quantum Computing with Circular Rydberg Atoms*, PRX Quantum **2**, 030322 (2021).

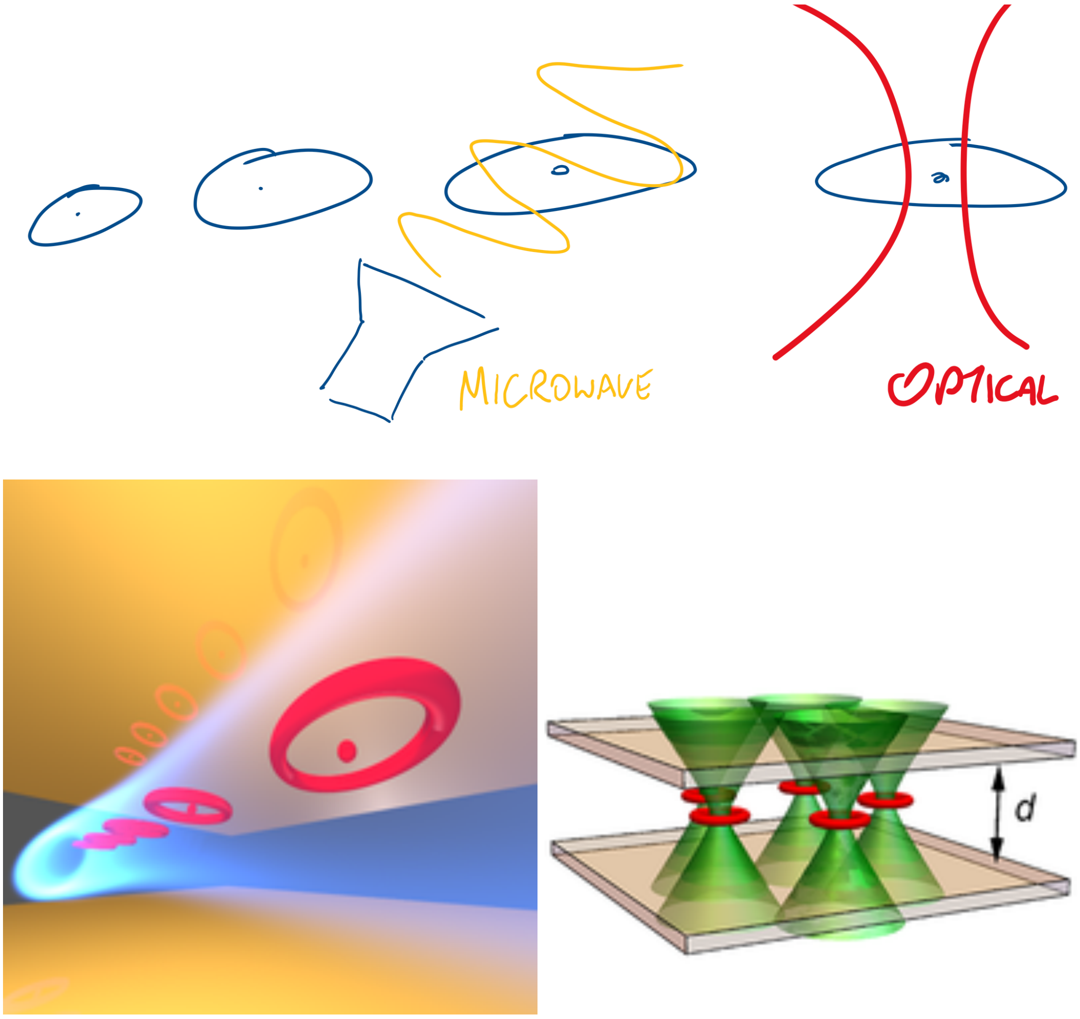
[8] T. L. Nguyen et al., *Towards Quantum Simulation with Circular Rydberg Atoms*, Phys. Rev. X **8**, 011032 (2018).

[9] I. S. Madjarov et al., High-fidelity entanglement and detection of alkaline-earth Rydberg atoms, Nature Phys. **16**, 857 (2020)

[10] A. Muni et al., *Optical coherent manipulation of alkaline-earth circular Rydberg states,* Nature Phys. ? (2022)

Proposed Fig (see sketch): A beam of circular states (similar to the image below) but with a microwave horn (see Fig 1 in paper) showing a propagating microwave and then a tightly focused optical beam showing local addressing, also similar to picture below.

Figure 1: Coherent control of circular Rydberg states



A beam of alkaline earth atoms prepared in circular Rydberg states. An outer electron is coherently controlled using microwaves and an optically active inner core electron is locally addressed with a tightly focused laser beam. Electrostatic coupling of the valence electrons enables coherent optical control and non-destructive, state-selective readout of the Rydberg electron.

Author information

Affiliations

University of Strathclyde, Glasgow, United Kingdom

Jonathan Pritchard

Corresponding author

Correspondence to Jonathan Pritchard (*jonathan.pritchard@strath.ac.uk*).

Competing interest

The author declares no competing interests.