Generation and Manipulation of Schrödinger Cat States in Rydberg Atom Arrays

Arjun Kulkarni

Written Report - ECE405

The research paper “Generation and Manipulation of Schrödinger Cat States in Rydberg Atom Arrays” solves a fundamental problem in quantum information science through its development of extensive coherent Schrödinger-cat states using Rydberg atom arrays. The authors focus on developing Schrödinger cat states which represent coherent many-body states that exist between two distinct macroscopic configurations. The superposition state remains fragile because any single qubit error will cause the entire system to transition into a mixed state. The authors focus on Rydberg-atom physics because they want to overcome the current limitation of achieving only small entangled clusters or slow adiabatic protocols that fail to scale properly. The system becomes more sensitive to noise when the number of atoms increases because many-body energy gaps decrease which makes adiabatic preparation slower than natural decoherence processes. The creation of cat states exceeding twelve atoms became unattainable through neutral-atom array systems. The study shows that engineered many-body spectra together with optimal control pulses allow scientists to generate large GHZ states at fast speeds before decoherence destroys the coherence.

Multiple previous methods tried to generate multipartite entanglement between different quantum systems but they all faced major restrictions. The Rydberg blockade functioned as the fundamental protection system which prevented nearby atoms from getting excited when one atom shifted to a Rydberg state. The system enabled scientists to execute two-qubit operations which produced small entangled states but required slow detuning sweeps for system expansion that became less efficient with each additional qubit. Neutral atom experiments achieved two goals by creating small entangled clusters and showing Ising-type interactions but they did not produce extensive coherent superposition states. The generation of GHZ states succeeded in different quantum systems which included trapped ions reaching 14 qubits and microwave cavities producing large photon cat states and superconducting circuits making multi-qubit GHZ states and photon experiments creating small GHZ groups. The platforms failed to scale up through ions because they struggled with ensemble control and lacked the ability to change their interaction patterns like neutral atoms. The concept of GHZ states existed as a proven idea but no method existed to generate extensive GHZ states for systems that combined spatial programmability with individual addressability like Rydberg arrays.

The research faced multiple major obstacles which blocked its advancement at that point. Scientists failed to create big GHZ states through neutral-atom array experiments because they could not perform single-site measurements. The state preparation time became shorter than the rate at which state degradation occurred because of Doppler shifts and Rydberg lifetime restrictions and laser phase instabilities and position variations. The combination of imperfect blockade and restricted laser stability and small spectral gaps made traditional adiabatic methods impossible to use. The existing methods for GHZ state preparation operated at a speed that was too slow because adiabatic ramps took longer than decoherence time periods which matched or exceeded them. The scientific community required an innovative method to generate extensive superposition states in Rydberg ensembles because current methods operated at slow speeds and failed to scale up.

The authors solve these problems through their implementation of two essential concepts which include spectrum engineering of many-body systems and the application of optimized control pulses obtained through RedCRAB algorithm optimization. The first breakthrough achievement used 840-nm beams to generate local light shifts which affected the edge atoms. The many-body spectrum transformation through this method results in two degenerate classical Rydberg excitation patterns $|0101\ldots\rangle$ and $|1010\ldots\rangle$ when the positive detuning becomes large. The two states naturally form the GHZ basis. The authors achieve a clean two-level manifold through their approach which penalizes specific configurations that include edge atom excitation. The RedCRAB algorithm generates an optimal control method which produces a fast 1-μs sequence instead of traditional slow adiabatic sweeps. The system uses diabatic transitions to create GHZ states because it applies beneficial effects through these transitions while preventing harmful effects as spectral gaps in the spectrum become smaller. The generated pulse sequence operates at speeds which exceed decoherence times and delivers better performance than any slow adiabatic method. The combination of these two elements enables Rydberg blockade physics to generate GHZ states which include atoms ranging from 1 to 20.

Scientists start the technical process by using optical tweezers to capture 87Rb atoms before they perform individual atom separation. The qubit states use the $5S_{1/2}$ ground state as $|0\rangle$ and the $70S_{1/2}$ Rydberg state as $|1\rangle$. The two-photon transition between 420-nm and 1013-nm lasers allows a maximum Rabi frequency of $\Omega/2\pi = 5$ MHz. The atoms maintain a distance which produces a nearest-neighbor Rydberg interaction strength of $V/2\pi = 24$ MHz thus creating a strong blockade effect. The preparation sequence begins by placing all atoms in the $|0\rangle$ state. The

840-nm local beams modify the energy levels of the edge atoms to achieve the required antiferromagnetic patterns. The system transitions from the product state to a coherent superposition of alternating-pattern basis states through the application of optimized $\Omega(t)$ and $\Delta(t)$ pulses which are optimized for this process (Figure 1). The system achieves GHZ state formation through the application of staggered 420-nm fields to alternate atoms which enables off-diagonal coherence measurement through parity oscillations. The system reaches its final state through trap activation which allows ground-state atoms to return while Rydberg-state atoms experience repulsion for site-specific computational basis measurement.

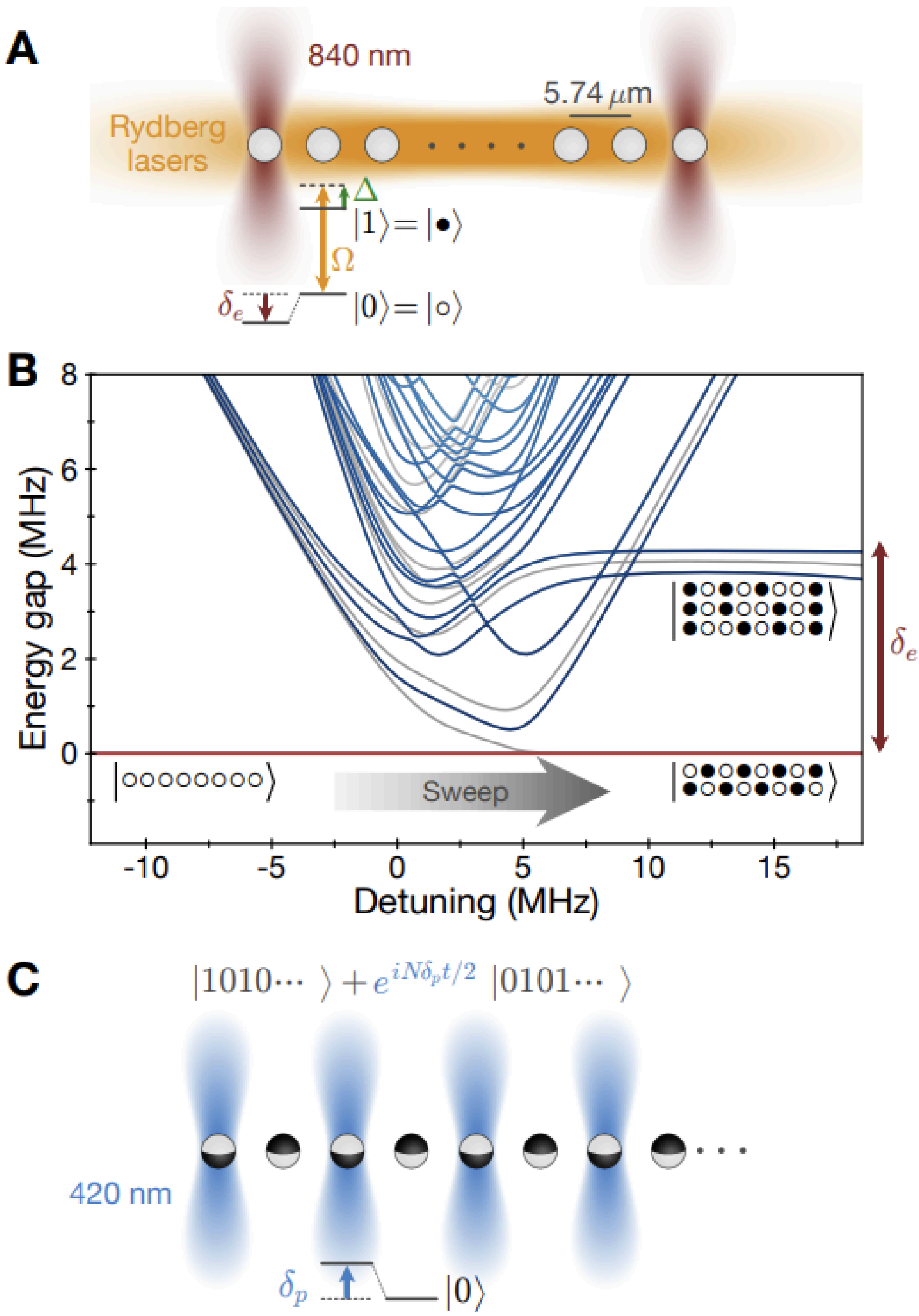
A
840 nm
5.74 μm
Rydberg lasers
Δ
|1⟩=|•⟩
Ω
δ_e
|0⟩=|∘⟩
B
Energy gap (MHz)
8
6
4
2
0
|∘∘∘∘∘∘∘∘∘⟩
Sweep
δ_e
-10
-5
0
5
10
15
Detuning (MHz)
C
|1010··· ⟩ + e^{iNδ_p t/2} |0101··· ⟩
420 nm
δ_p
|0⟩

Figure 1

The experimental setup appears in Figure 1 which was adapted from the research paper. The two-photon Rydberg excitation lasers power the atomic array through atomic array edge position adjustments made by addressing beams. The many-body spectrum in Figure 1B demonstrates the evolution of the initial |000…⟩ state into the GHZ manifold through an adiabatic process when edge atoms experience frequency detuning. The process requires spectrum engineering to stop unwanted configurations which would interfere with the final superposition state.

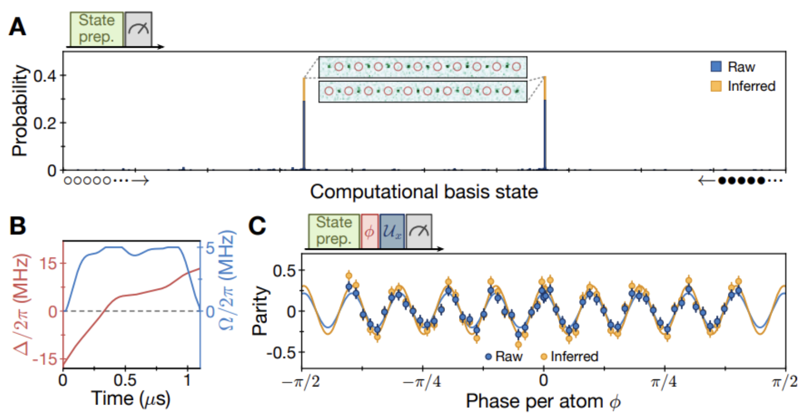

Figure 2

The optimized control pulses which RedCRAB generated appear in Figure 2 (adapted). The Ω(t) and Δ(t) traces demonstrate complex patterns through their fast beginning followed by a gradual middle section and their quick final section. The pulses achieve better fidelity than any linear or adiabatic ramp within a 1.1 µs time period. The right section of the figure shows how the N = 20 GHZ state undergoes coherent phase evolution at a rate that depends on N. The oscillation contrast enables the calculation of the coherence term |c□| which directly affects the GHZ fidelity.

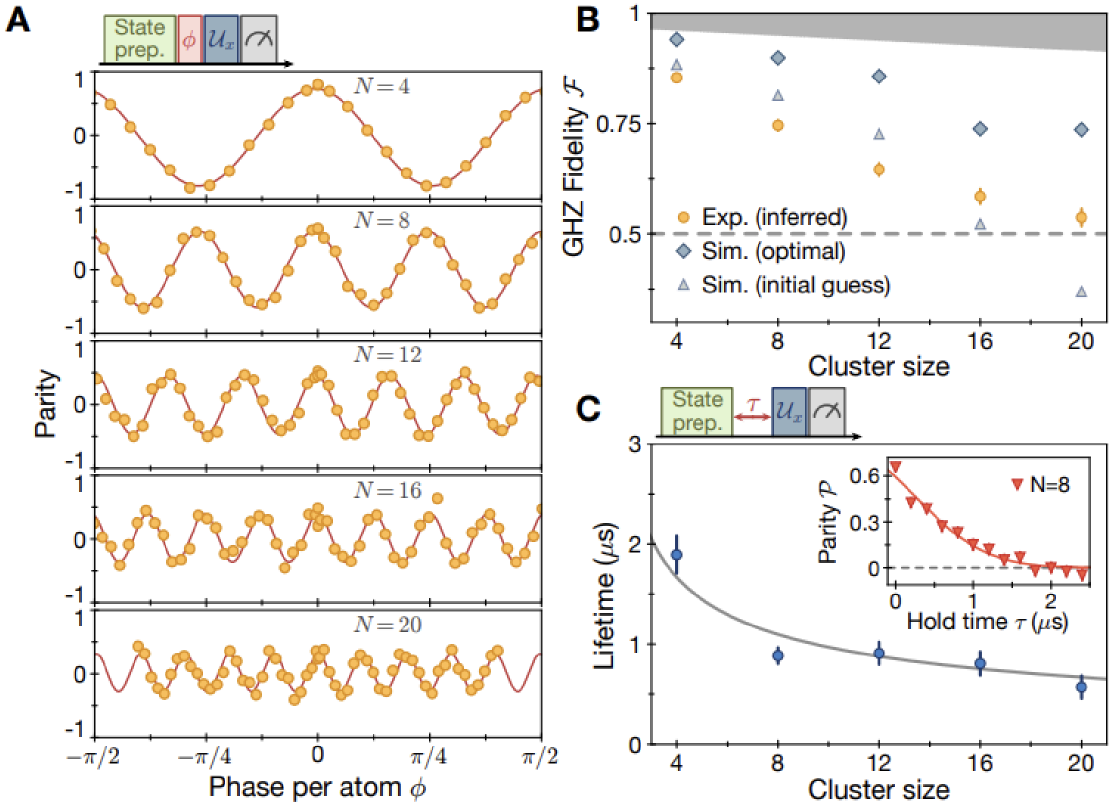

Figure 3

The complete characterization of a 20-atom GHZ state appears in Figure 3 (adapted). The measurement patterns show two major peaks which represent the states $|A_{20}\rangle$ and its opposing alternating pattern. The population inference shows approximately 0.78 after implementing detection error corrections. The system size does not reduce the parity oscillation amplitude so the authors can determine a fidelity of $F \geq 0.542$ which exceeds the 0.5 threshold for GHZ entanglement. The experiment proved the existence of 20-particle entanglement in Rydberg arrays through this achievement which became the largest in this system at that time.

The research results produce multiple effects which affect various academic fields. The research proves that Rydberg atom arrays function as an efficient method to produce strongly connected quantum states at large scales. The research achieves GHZ states with 20 atoms which matches the performance of trapped ions and superconducting qubits while providing geometric control and potential expansion to hundreds of qubits. Scientists can use this research to develop and manage GHZ states which function as vital resources for quantum metrology applications that reach Heisenberg limit phase sensitivity. The research demonstrates how GHZ states allow for entanglement sharing between remote qubits in the array structure which supports quantum networking and modular system development. The research introduces optimal control techniques to many-body quantum simulation which will evolve into QAOA and variational quantum control methods for future quantum devices. The research shows that purposefully designed pulses achieve better results than slow transition methods which proves that algorithmic control will be necessary for building future quantum technology.

Scientists use Hamiltonian engineering with optimal control techniques to achieve fast and extensive quantum superpositions in systems which were previously restricted by decoherence and slow operation times. The discovery proved neutral-atom arrays to be an optimal platform for large-scale quantum information processing which has driven advancements in quantum simulation and quantum computing and quantum-enhanced metrology.