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Entangling Atomic Spins and Jaynes-Cummings ladder with a Rydberg-Dressed interaction

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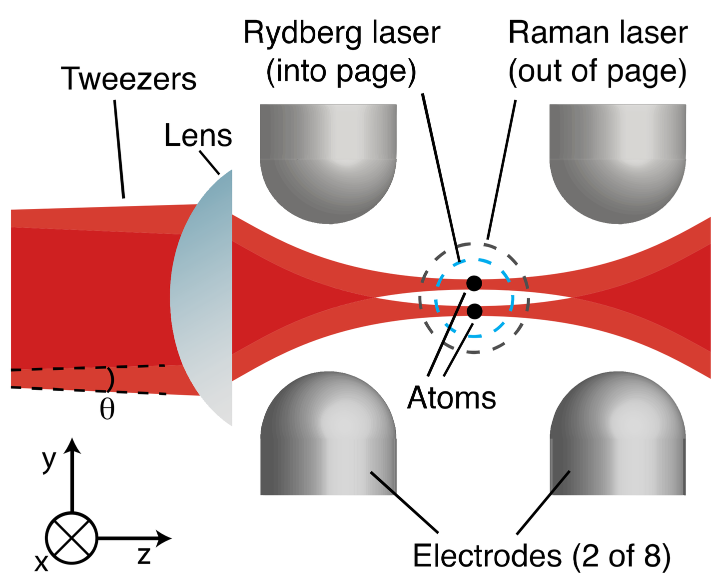
Abstract

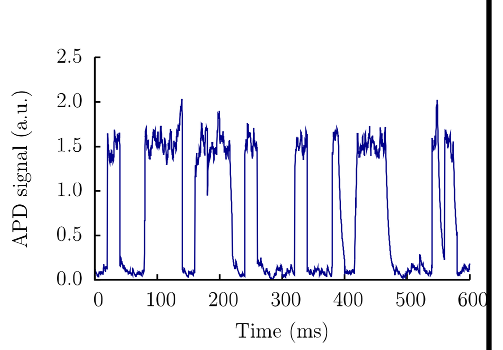
We demonstrate a Rydberg-dressed ground-state blockade that provides a strong tunable interaction energy (~1 MHz), nearly 4 orders of magnitude larger than that in ultra cold collisions, between spins of individually trapped cesium atoms. With this interaction we directly produce Bell-state entanglement between two atoms with a fidelity ≥ 81(2)%, excluding atom loss events, and ≥ 60(3)% when loss is included [1]. Our method is based on a Rydberg-dressed spin-flip blockade which allows single-step, direct entanglement of long-lived ground (clock) states. For the Bell-state entanglement generation, the probability remains entirely in the Rydberg-dressed ground state, freeing the approach from the experimental burden of coherently exciting optical transitions to and from the Rydberg states. In principle Rydberg-dressed atoms are more insensitive to various decoherence mechanisms and lead to a better quantum control fidelity [2]. In addition, we observed Jaynes-Cummings (JC) ladder and its $\sqrt{N}$ nonlinearity of a Rydberg-dressed atomic system. This $\sqrt{N}$ nonlinearity induced by the Rydberg-dressed spin-flip blockade and the symmetric coupling between a Rydberg atom and atomic ensembles in the ground state, and this differentiates single and two microwave photon excitations from Rydberg-dressed state atoms.

Single atom trapping apparatus

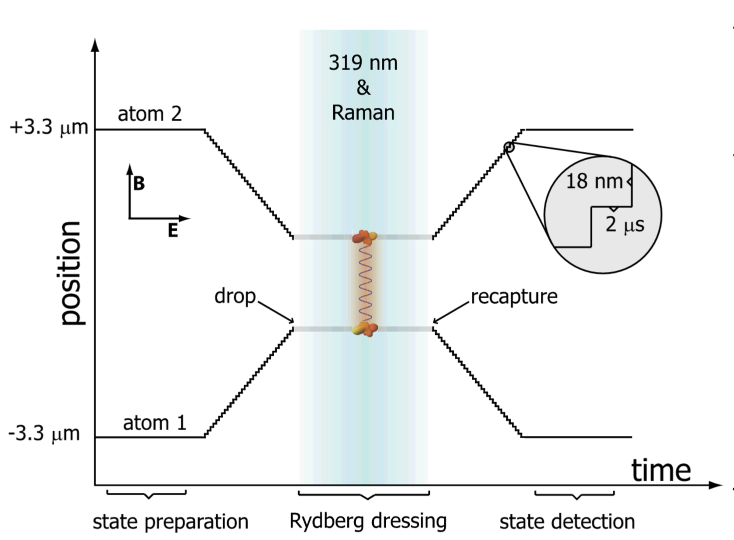
At Sandia, we have established an experimental system allowing us to singly trap Cs atoms and generate Rydberg-dressed states with a direct excitation laser at 318 nm [3]. We trap single cesium atoms in optical dipole traps formed by focusing two 938 nm laser beams through a high NA aspheric lens. The relative angle between the two beams is chosen such that the two traps are separated by 6.6 μm during atom loading. We dynamically tune this parameter in our experiment to tune the interaction.



Single atom loading



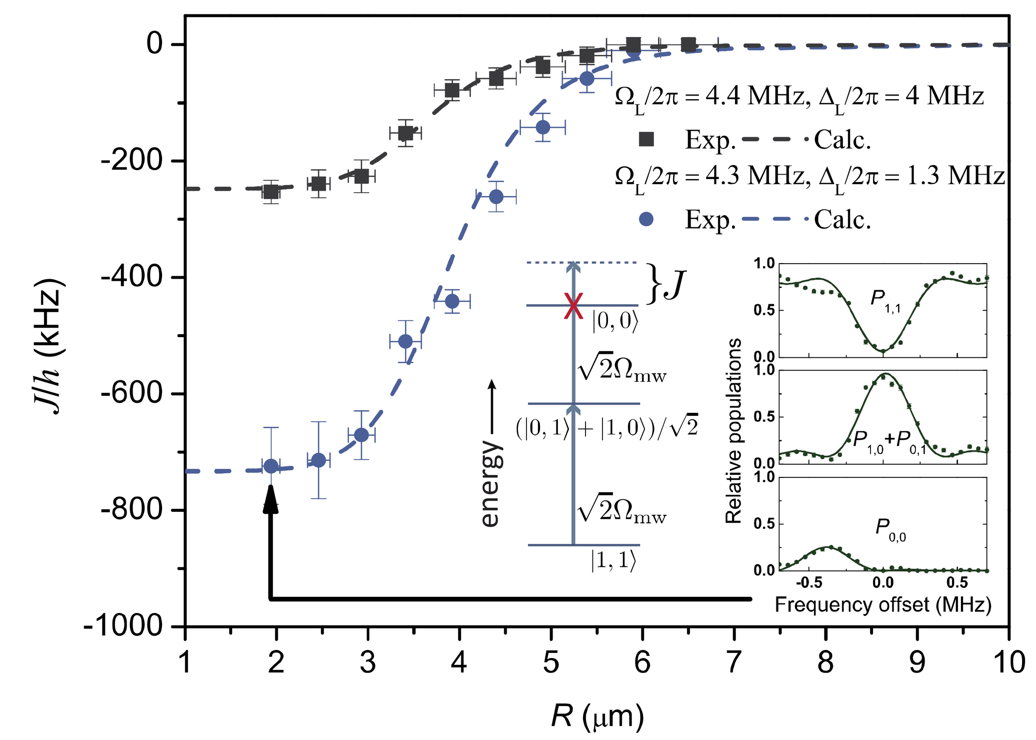
Experiment sequence



Two initially separated Cs atoms held with optical tweezers translate toward each other after state preparation by ramping the AOM modulation frequencies. At the target distance, the 318nm Rydberg dressing laser turns on to illuminate the two atoms simultaneously with a Raman laser. The tweezers are extinguished during this step to eliminate optical perturbation. The two atoms then translate back to the original positions for state detection.

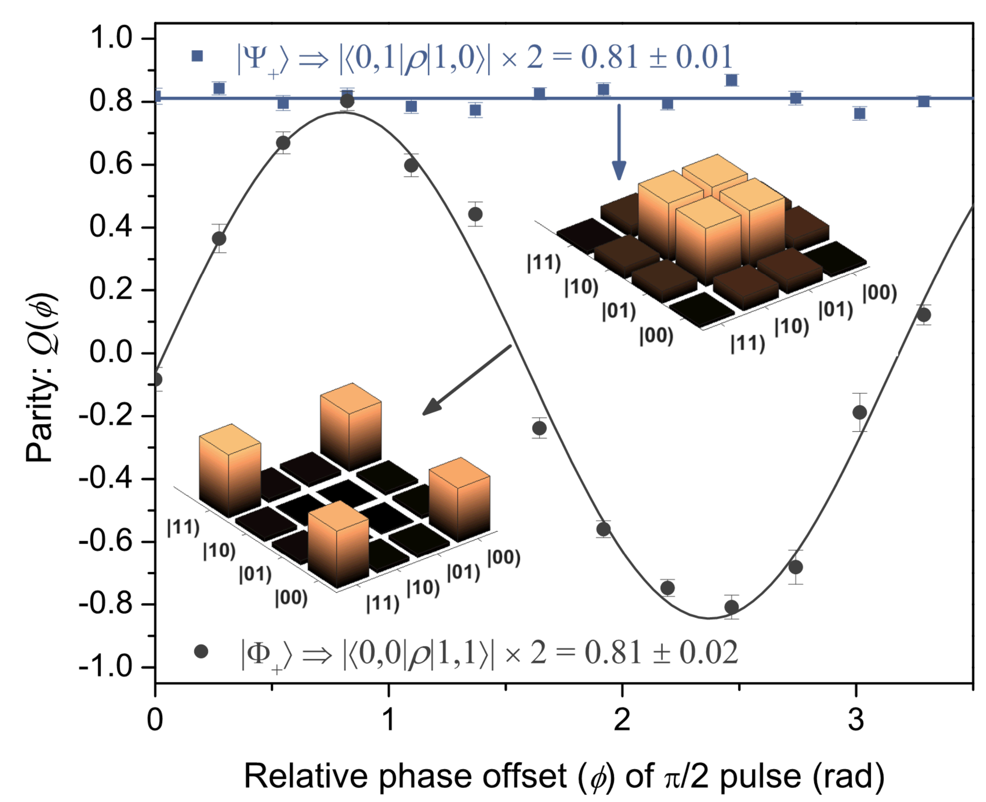
Rydberg-dressed ground state interaction

Scanning the microwave frequency of the stimulated Raman pulse applied to the two trapped Rydberg-dressed ^{133}Cs atoms reveals the ground-state blockade. Insets: if a non-zero J is present, only the transition from $|1,1\rangle \rightarrow (|1,0\rangle$ or $|0,1\rangle)$ is allowed and the transition from $(|1,0\rangle$ or $|0,1\rangle) \rightarrow |0,0\rangle$ is blockaded at the non-interacting, single-atom qubit resonance frequency. The excitation from $|1,1\rangle \rightarrow |0,0\rangle$ is available via an anti-blockade two-photon transition. Therefore, J/h is simply twice the resonance shift of the excitation to state $|0,0\rangle$. The dashed curves are the calculated values based on a detailed model with no free parameters.



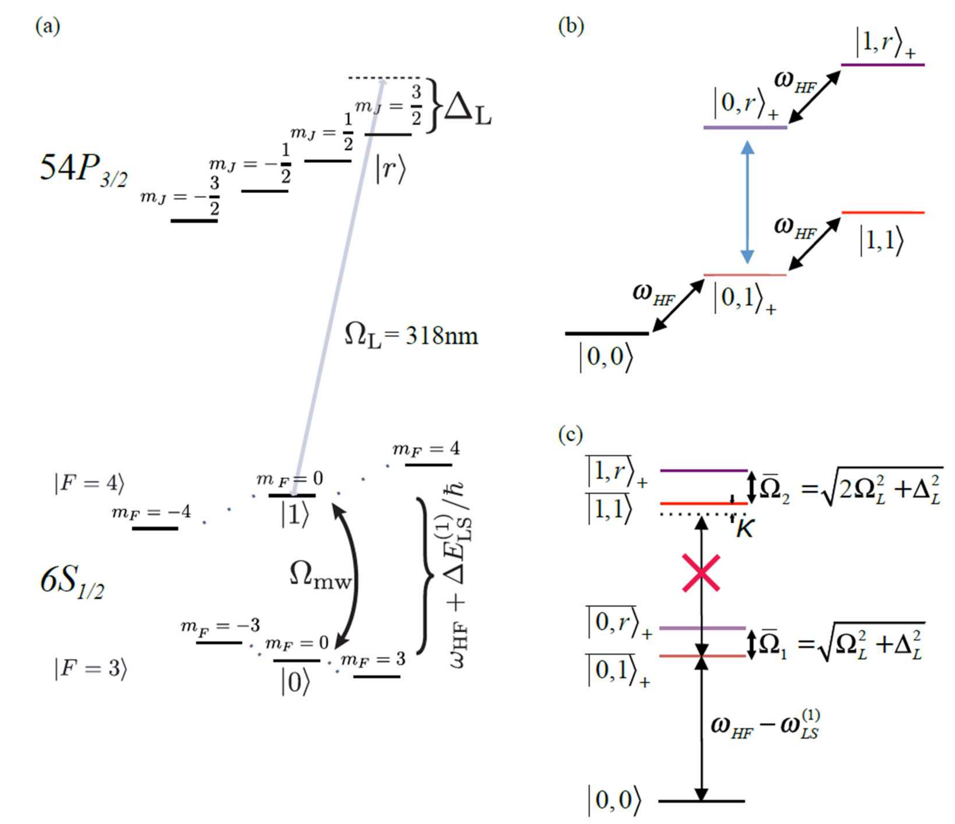
Entanglement verification

A global π/2 pulse is applied to the undressed system after the entangled state is prepared. The data show that both Bell states generated from our experiment have a fidelity ≥ 81(2) %. Here, ρ represents the two-atom density matrix. The insets show the simulated density-matrix populations using conditions similar to the experiment. The parity measurement, $P_{1,1} + P_{0,0} - (P_{0,1} + P_{1,0})$, allows direct determination of the amplitudes of the off-diagonal elements for both entangled states.



Rydberg-Dressed States and JC model

A nearly-resonant Rydberg dressing laser couples the ground and Rydberg states together. This process creates an admixture state having the properties of the Rydberg state and the ground state. This method transfers the electric dipole-dipole interactions between two Rydberg states into the ground states without directly exciting the Rydberg state.

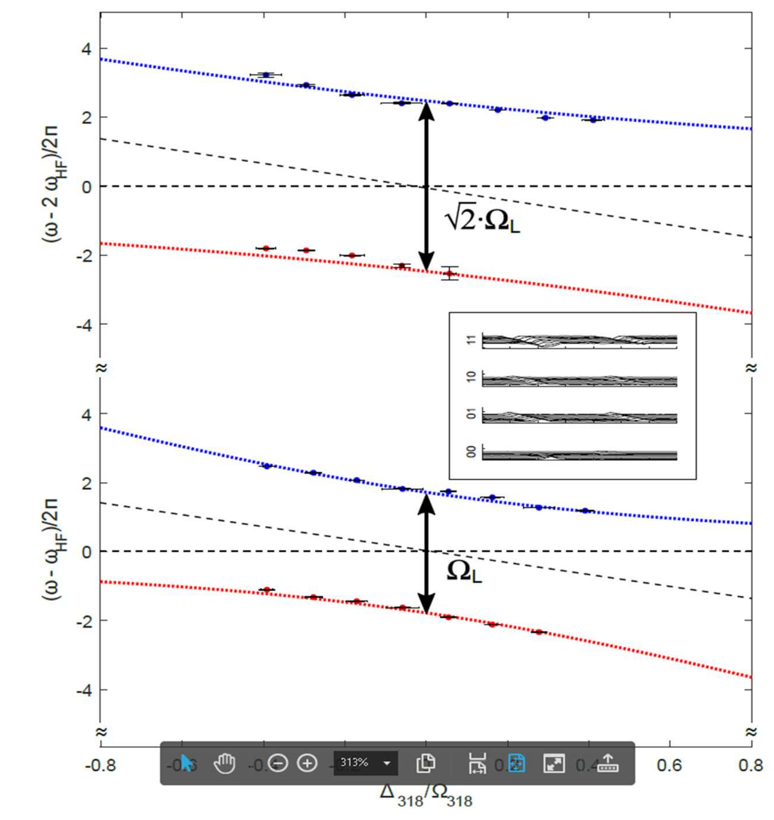


(a) Energy level diagram of the ^{133}Cs atom. The qubit states are $|1\rangle = |6S_{1/2}, F = 4, m_F = 0\rangle$ and $|0\rangle = |6S_{1/2}, F = 3, m_F = 0\rangle$, where Δ_L is the detuning from $|1\rangle$ to $|r\rangle = |54P_{3/2}, m_J = +3/2\rangle$.
(b) Energy level diagram of two bare state atoms, symmetrically coupled. States with `+'-subscript are symmetric superposition, and the state $|r, r\rangle$ is excluded under the assumption of a perfect Rydberg blockade.
(c) Energy level diagram of two-atom dressed states and Jaynes-Cummings model (JCM). If the microwave is tuned to the $|0, 0\rangle \rightarrow |\widetilde{0,1}\rangle_+$ resonance, double spin flips are blockaded, by a microwave detuning κ. This Rydberg-dressed spin-flip blockade results in entanglement, controlled by microwaves in the dressed-ground subspace, and induces the $\sqrt{N}$ nonlinearity by the symmetric coupling between a Rydberg excited atom and the ground state atomic ensembles.

$$\hat{H}_{JC} = \hbar\omega_{HF}\hat{a}_1^\dagger\hat{a}_1 + \frac{\hbar(\omega_{HF}+\Delta_r)}{2}\hat{\sigma}_z + \frac{\hbar\Omega_r}{2}\left(\hat{\sigma}_+\hat{a}_1 + \hat{a}_1^\dagger\hat{\sigma}_-\right)$$

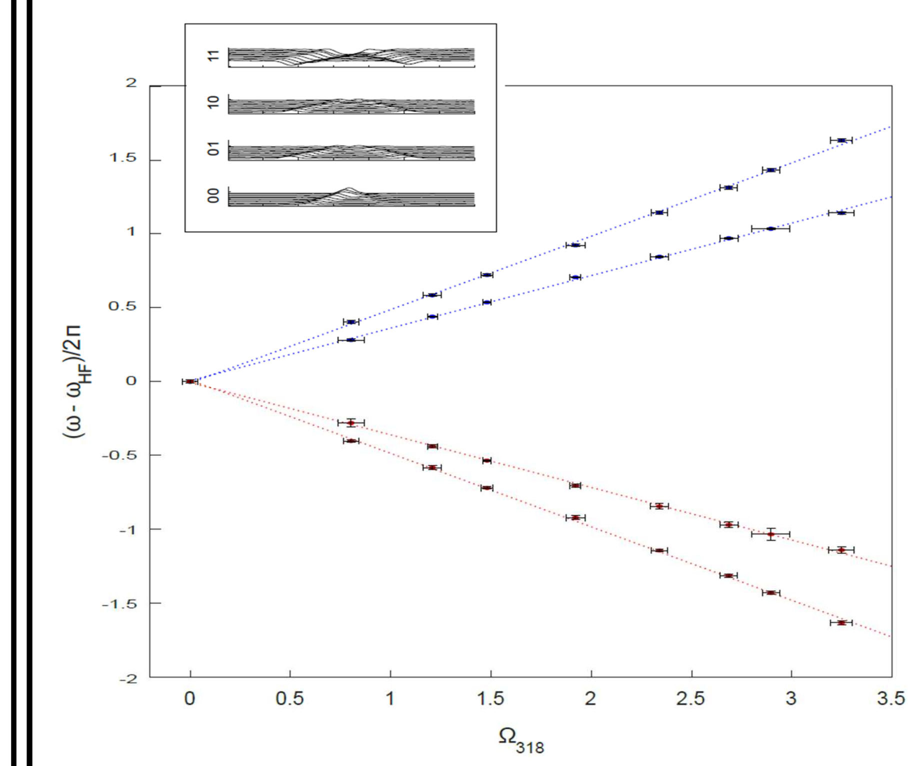
The JCM of Rydberg-dressed atoms can be extended to a many-atom system. For atomic ensembles, the Rydberg-dressed ground state atoms are adiabatically dressed with a Rydberg excited state atom through the EDDI. A Rydberg excited atom from atomic ensembles is symmetrically coupled with the remained ground state atoms in its Rydberg radius, and a second Rydberg excited atom from the remained atoms does not occur due to Rydberg blockade. In this situation, the remained ground state atoms sharing the property of the Rydberg excited state atom are called as the Rydberg-dressed ground atoms. In the theory, we assume the infinite EDDI, which means a perfect Rydberg blockade. This JC Hamiltonian of Rydberg-dressed atoms can be exploited for controlling atomic state toward an arbitrary entanglement state generation and implementing optimal gate operations with atomic qubits.

Jaynes-Cummings ladder



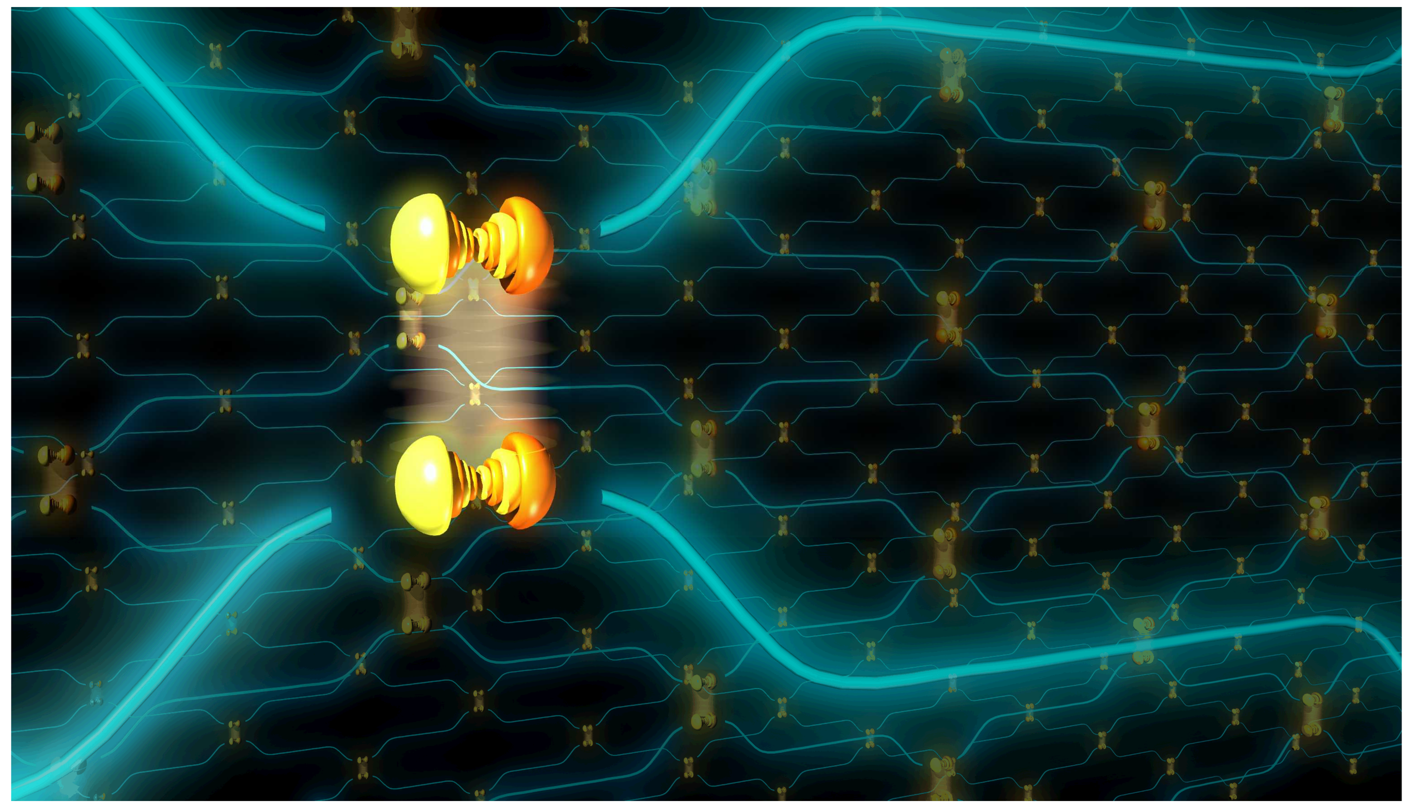
Autler-Townes spectroscopy of single and two Rydberg-dressed ground state atoms was measured with the microwave spectroscopy of two-photon Raman pulses as a function of the Rydberg laser's detuning. As the Rydberg laser's detuning varies, the center position of the split peaks are also shifted. This is caused by the laser-induced light shifts according to the detuning. We confirmed $\sqrt{2}$ nonlinearity of two Rydberg-dressed ground state atoms compared to single Rydberg-dressed ground state atom.

1 and 2-atom Autler-Townes



We measured Autler-Townes splitting of two Rydberg-dressed ground state atoms depending on the Rydberg laser's Rabi frequencies. As we expected, the difference of two slopes between single atom splitting and two atom splitting is $\sqrt{2}$. This shows the nonlinearity of the Rydberg-dressed atomic system.

As numerous proposals suggest, this Rydberg-dressed interaction could be a disruptive capability for controlled interactions of neutral atom systems. The clarity of our demonstration arises partly from the use of a direct transition Rydberg laser and partly from the use of dynamic atom positioning. The direct transition laser from ground to Rydberg state crucially avoids coupling through an intermediate state, avoiding rapid decoherence during the Rydberg-dressing process. The dynamic tuning of our atom spacing allows us to prepare and measure the atoms far apart where they are easily resolved optically, and complimentarily interact them close together where interaction strengths are large. Optimally, large interaction strengths can be achieved with lower principal quantum number Rydberg states, thus reducing sensitivity to external perturbing fields, a common challenge in such experiments. With this dynamic tuning, and strong, coherent interaction in hand, we imagine a large-scale quantum processor as depicted artistically in the graphic below.



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References:

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