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A Platform of Rydberg-Dressed Cesium Atoms for Quantum Control Applications

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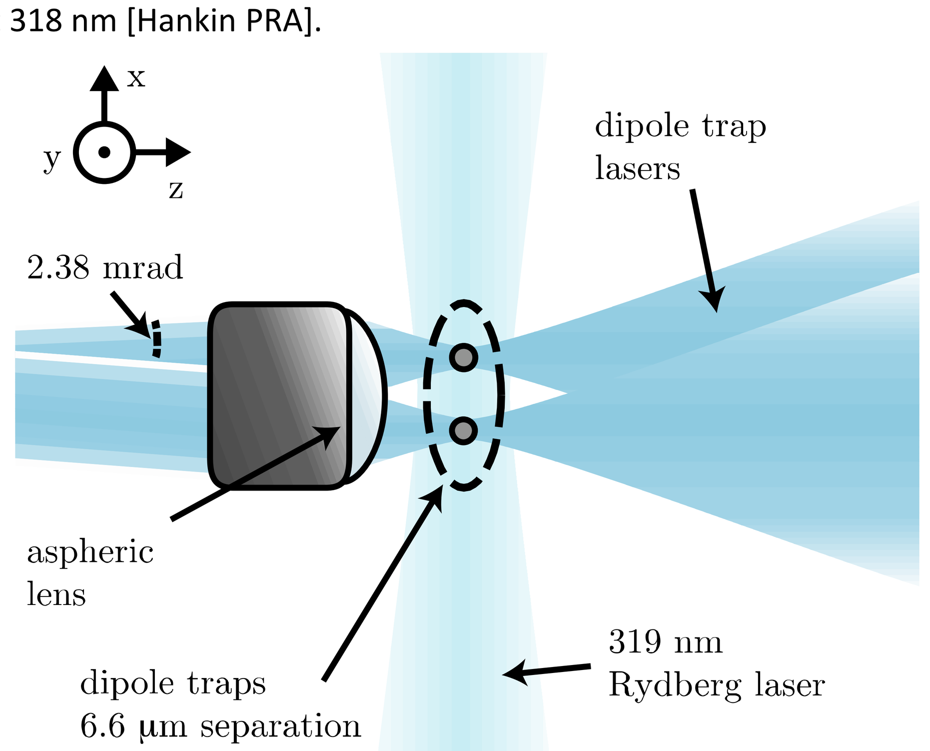
Abstract

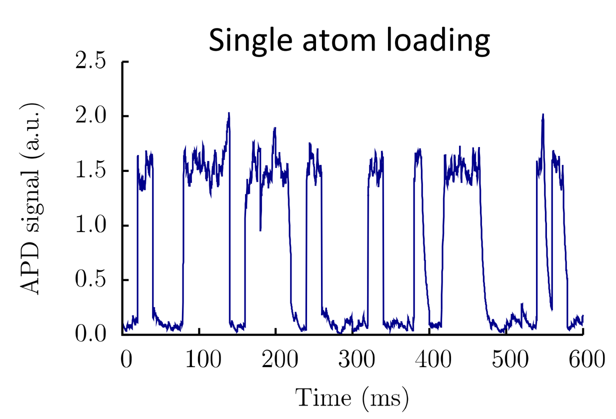
We demonstrate a Rydberg-dressed ground-state blockade that provides a strong tunable interaction energy (~1 MHz in units of Planck's constant) between spins of individually trapped cesium atoms. With this interaction we directly produce Bell-state entanglement between two atoms with a fidelity ≥ 81(2)%, excluding atom loss events, and ≥ 60(3)% when loss is included [arXiv]. Our method is based on a new technique that produces a blockade of Rydberg-dressed ground states. This approach allows single-step, direct entanglement of long-lived ground (clock) states in our cesium atoms. The on-demand interaction we employ—Rydberg-dressed ground states—is a long sought after fundamental capability for numerous proposals spanning from new phases of matter in ultracold quantum gases to spin-squeezed metrology in clocks and quantum computation protocols. We not only clearly measure this elusive Rydberg-dressed interaction, but also employ it to demonstrate high fidelity Bell-state generation. The entanglement generation differs from previous work in a fundamental way; 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 [Keating PRA]. In addition, the interaction we demonstrate is nearly 4 orders of magnitude larger than that produced in the typical experiment based on ultra cold collisions.

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 [Hankin PRA].

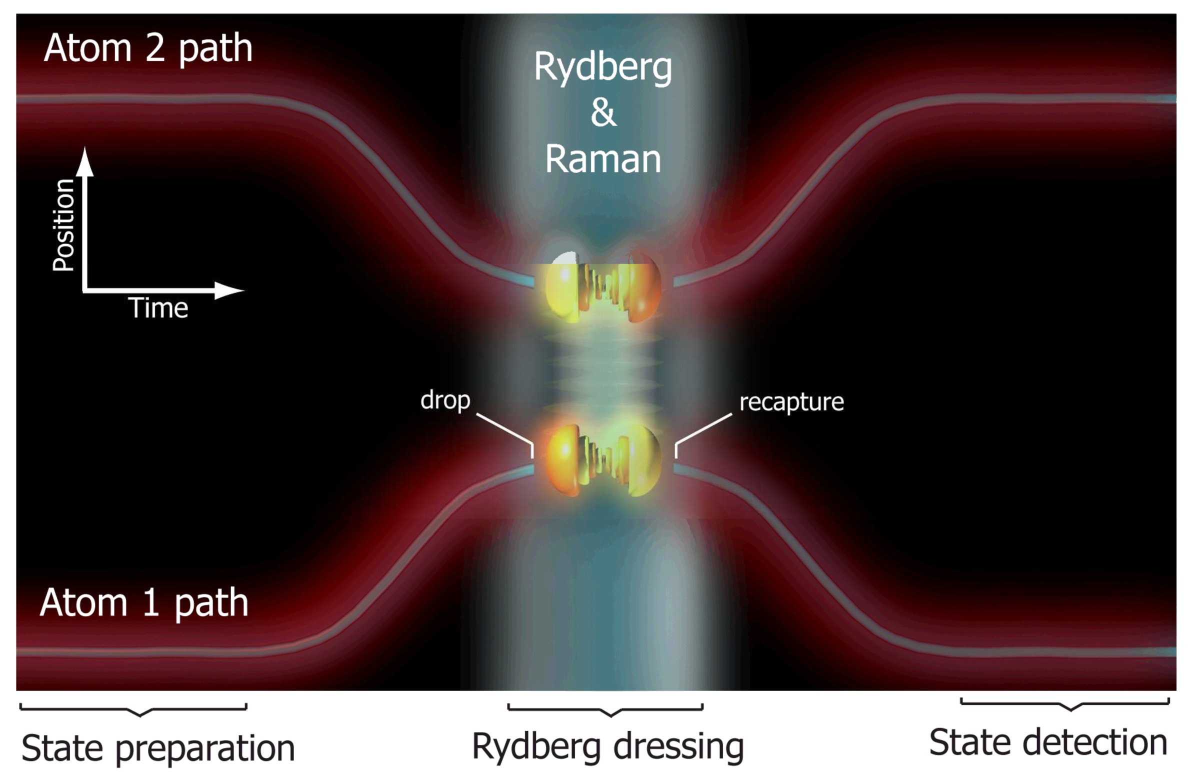


We trap single cesium atoms in optical dipole traps formed by focusing two 938 nm laser beams through a high NA aspheric lens. The relative angle between the two beams is chosen such that the two traps are separated by 6.6 mm during atom loading. We dynamically tune this parameter in our experiment to tune the interaction.



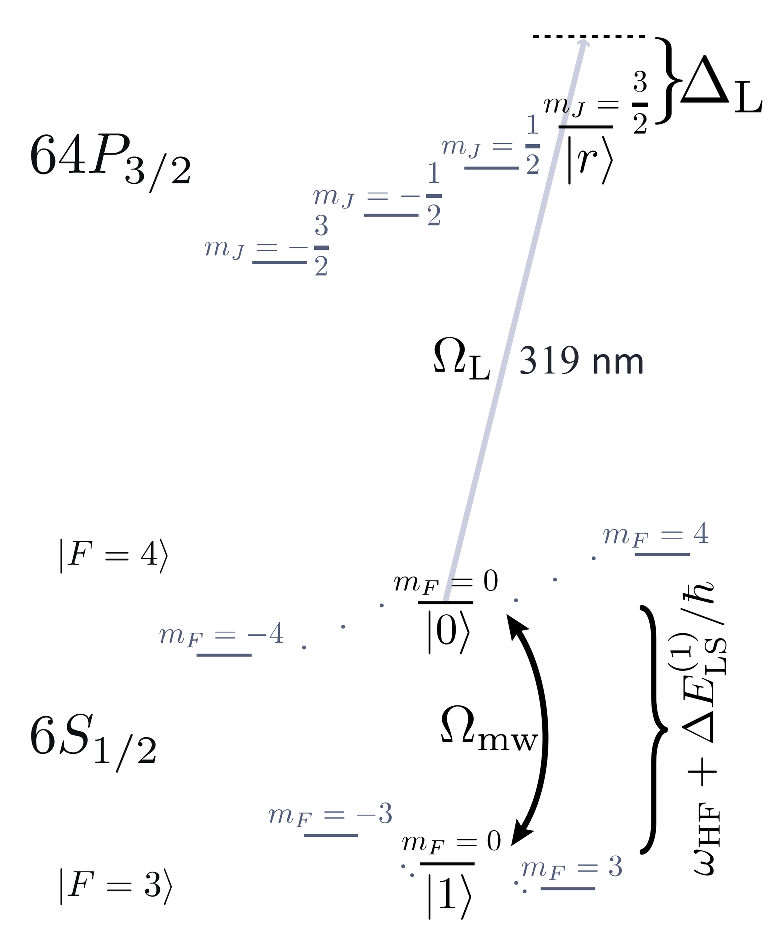
Experiment sequence

In the experimental procedure, two Cs atoms are initially 6.6 μm apart, and held by optical tweezers. After qubit-state preparation, the two trapped atoms translate toward each other with an average speed of 9 mm/sec (18 nm step every 2 μs) by ramping the modulation frequencies of the AOM. At the target distance, the Rydberg dressing laser at 319 nm 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.



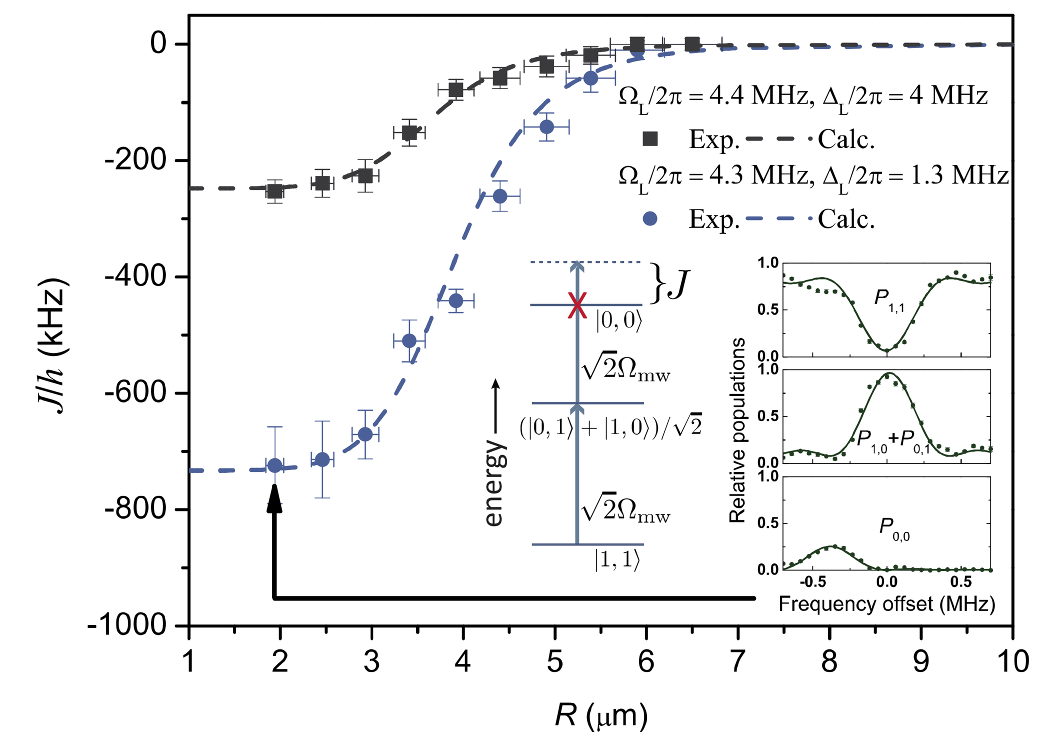
Rydberg-Dressed States

A near resonant laser that couples the ground and Rydberg states together perturbs the system, changing its eigenstates. These new eigenstates called light-dressed states or Rydberg-dressed states add Rydberg character to the ground state. This method transfers the dipole-dipole interactions that occurs between Rydberg states into the ground state without directly exciting the Rydberg state. Relevant energy level diagram for the ^{133}Cs atom. The qubit states $|0\rangle$ and $|1\rangle$ are encoded in the clock states of the Cs hyperfine sublevels $|F=4,m_F=0\rangle$ and $|F=3,m_F=0\rangle$. The Rydberg dressing laser, detuned Δ_L from $|64P_{3/2},m_J=3/2\rangle$, strongly interacts with the $|F=4\rangle$ hyperfine manifold. Here, $\omega_{HF} + \Delta E^1_{LS}/\hbar$ is the hyperfine splitting summed with the single-atom light shift due to the 319-nm laser. A two-photon stimulated Raman transition drives Rabi oscillations between $|0\rangle$ and $|1\rangle$ at a rate Ω_{mw}.



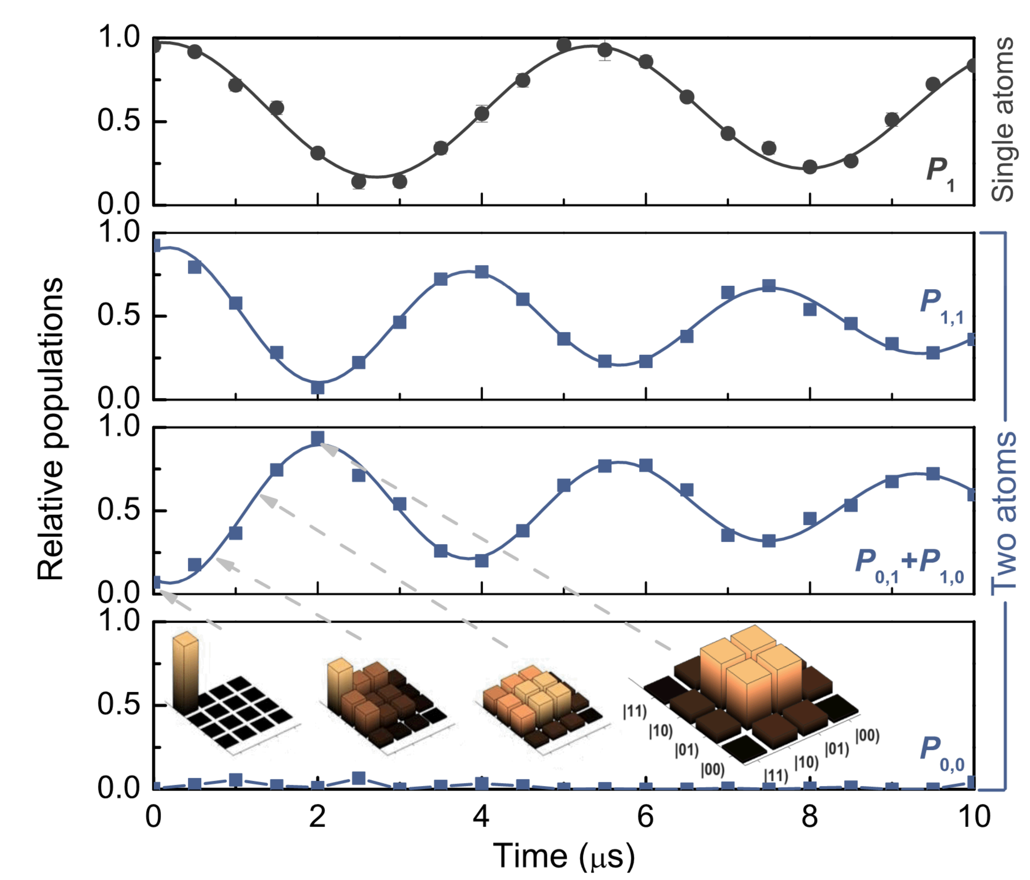
Rydberg-dressed ground state interaction

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.



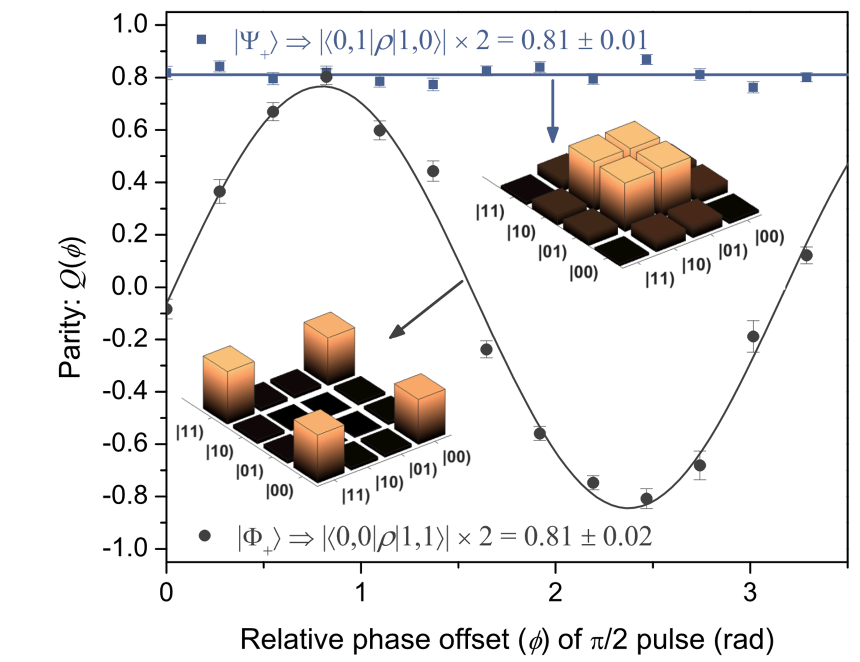
Generating entanglement directly

Top panel: Rabi oscillations of a single Rydberg-dressed Cs qubit. Lower three panels: two-atom data with Rydberg-dressed ground-state blockade ($J/h \approx 750$ kHz). There is a √2 enhancement of the microwave Rabi rate Ω_{mw} and excitation to state $|0,0\rangle$ is strongly suppressed due to the transition blockade. Simulated density matrices are shown for various pulse times. The maximum Bell state $|\Psi_+\rangle$ entanglement is generated at around 2 μs.}



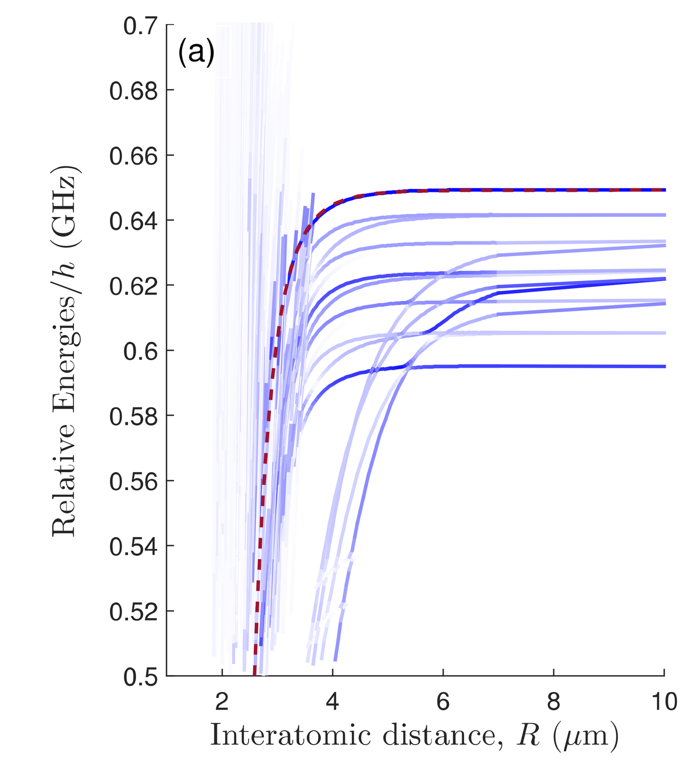
Entanglement verification

A global $\pi/2$ 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.

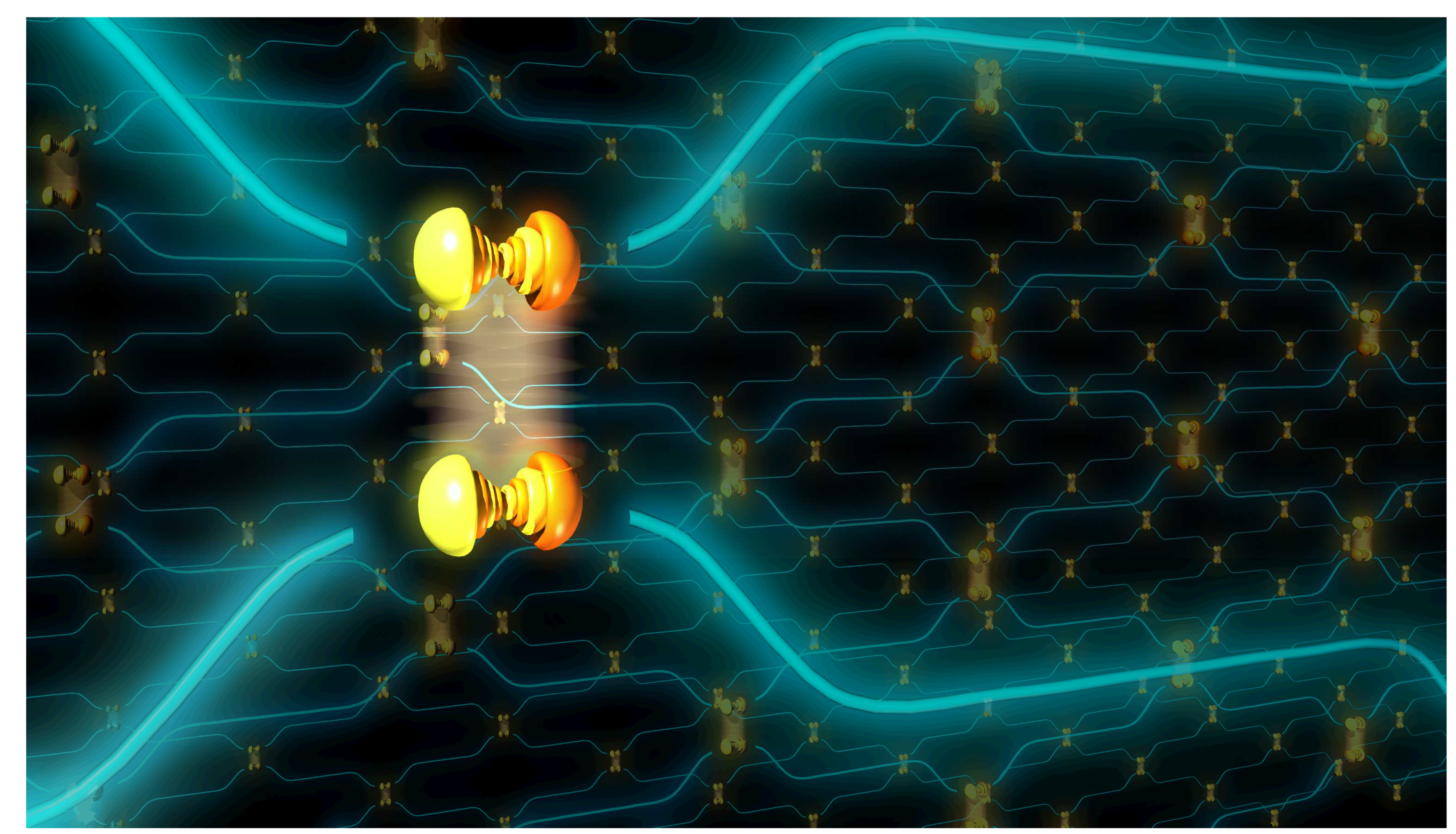


2- atom Rydberg energy levels

Calculated sublevels of $64P_{3/2}$ with $|\mathbf{E}|$ =6.4 V/m and $|\mathbf{B}|$ = 4.8 G. The vertical axis is the energy offset from the center of gravity of 64P. The red dashed curve is the fitting result of our selected two-atom Rydberg state $|m_j = 3/2, m_j = 3/2\rangle$.



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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