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Adiabatic Quantum Computing with Neutral Atoms

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Abstract

We are developing, both theoretically and experimentally, a neutral atom qubit approach to adiabatic quantum computing (AQC). It has been shown in [1,2] that neutral atoms trapped in optical far off-resonance traps (FORTs) can be used for two-qubit gates using interactions mediated by electric-dipole coupling of a coherently excited Rydberg state. A similar neutral atom system is attractive for this work due to the long-term coherence of the qubit ground states, the potential of multi-dimensional arrays of qubits in FORT traps and the possibility for strong, tunable interactions via Rydberg-dressed atoms [3]. If these arrays can be designed to encode a desirable computation into the system Hamiltonian one could use these tunable interactions along with single-qubit rotations to perform an AQC. Taking full advantage of Sandia's microfabricated diffractive optical elements (DOEs), we plan to implement such an array of traps and use Rydberg-dressed atoms to provide a controlled atom-atom interaction in atomic cesium. We forecast that these DOEs can provide the functions of trapping as well as the single sight addressing required for AQC.

We will develop this experimental capability to generate a two-qubit adiabatic evolution aimed specifically toward demonstrating the two-qubit quadratic unconstrained binary optimization (QUBO) routine. We are studying the two-qubit QUBO problem to test the immunity of AQC to noise processes in the control interactions as well as dissipation mechanisms associated with the trapping. We are developing our theoretical and experimental capabilities through key collaborations with the University of Wisconsin and the University of New Mexico.

QUBO Hamiltonian with neutral atoms

For 2-qubit QUBO (quadratic unconstrained binary optimization), we adiabatically evolve the Hamiltonian from H_0 to H_f by ramping the parameter s from 0 to 1:

$$H(s) = (1-s)H_0 + sH_Q$$

$$H_0 = \sum_{i=1,2} \frac{A_i}{2}\sigma_x^{(i)}$$

$$H_Q = \sum_{i=1,2} \frac{B_i}{2}\sigma_z^{(i)} + \sum_{\substack{i,j=1,2\\ i\neq j}} \frac{C_{ij}}{4}(1\pm\sigma_z^{(i)})(1\pm\sigma_z^{(j)})$$

microwave rotations

light shifts

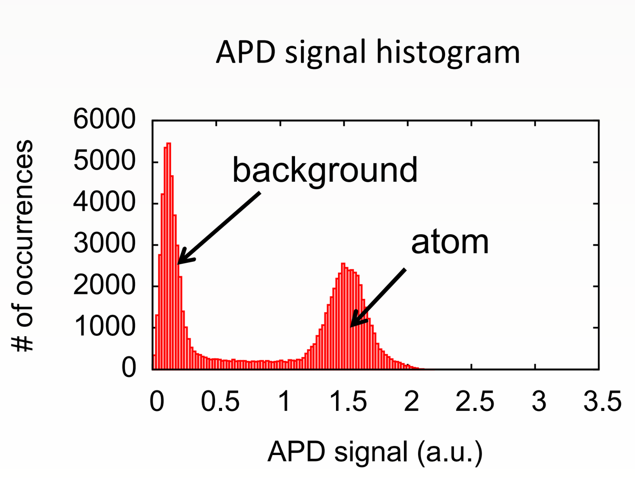
two-atom Rydberg interaction

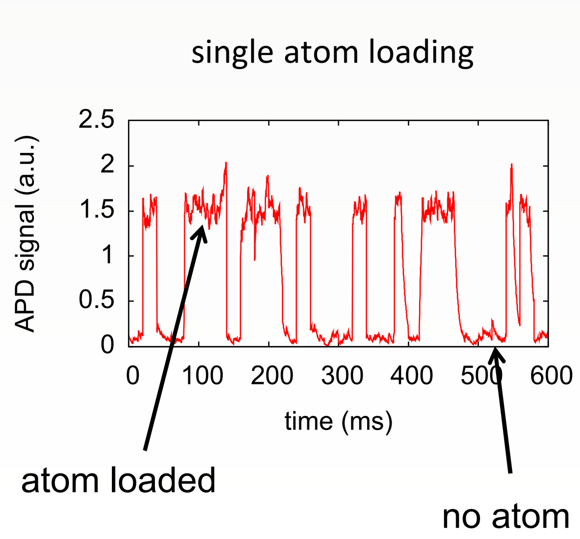
where $\sigma_x^{(i)}$, $\sigma_z^{(i)}$ are Pauli operators that act on individual qubit *i*. We initialize the state in the ground state of H_0 and end the evolution in the ground state of H_Q. The ground state of H_Q is chosen so that it is he solution of the QUBO problem.

Trapping a cesium atom in a far off resonance dipole trap via the collisional blockade

We focus a 938 nm laser into the central region of a magneto-optical trap (MOT). The intensity gradient provided by the dipole trap laser creates an attractive potential centered at the focus of the beam via the resulting spatially dependent light shift. The MOT provides the dissipative cooling force required to cool and load room temperature atoms into the shallow dipole potential (typically 0.5 to 1 mK deep).

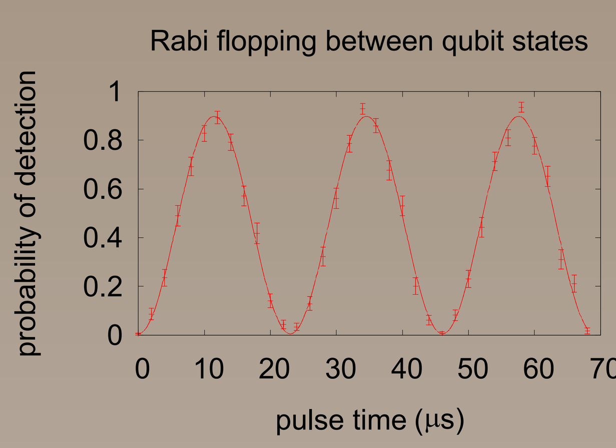
The waist of the dipole trap is roughly 1 to 2 μm ensuring that the trap operates in the 'collisional blockade' regime. Under these conditions the trap is too small to accommodate more than one atom due to light assisted collisions.





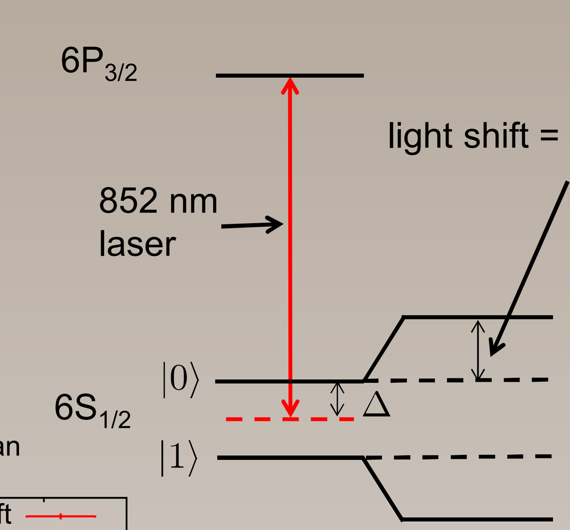
Initial state preparation using microwaves

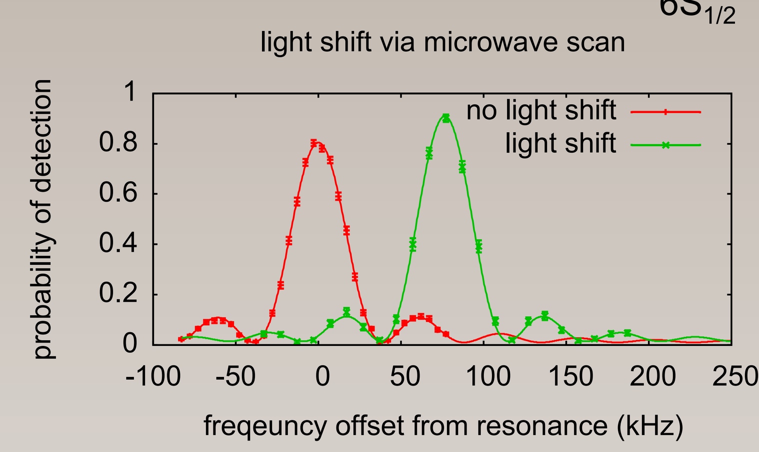
We utilize microwaves resonant with the splitting between the single qubit states (this is 9.192 GHz for the $6S_{1/2}$ ground states of Cesium). This gives us a tool to initialize the individual qubits in the ground state of H_0 via a σ_x rotation.



Linear terms in the QUBO Hamiltonian

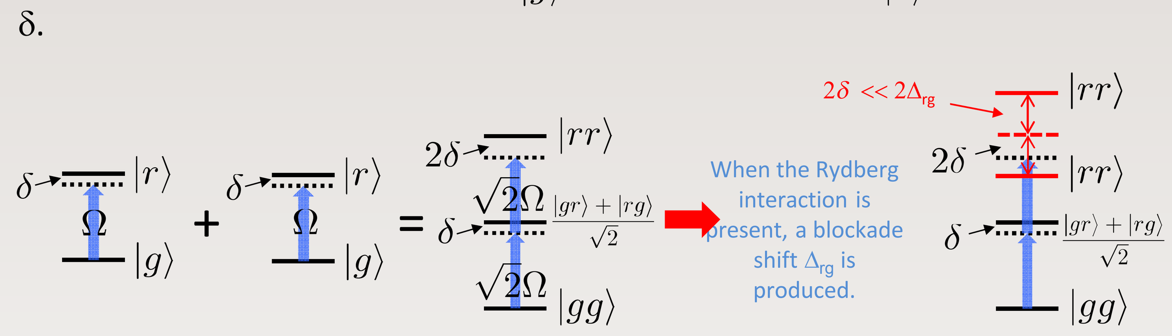
When the laser is tuned far from resonance it acts to shift the energy of the states. This light shift provides the σ_z term in H_Q.





Ground-state interaction via dressed-Rydberg atoms [3] to obtain the quadratic $\sigma_z\sigma_z$ term

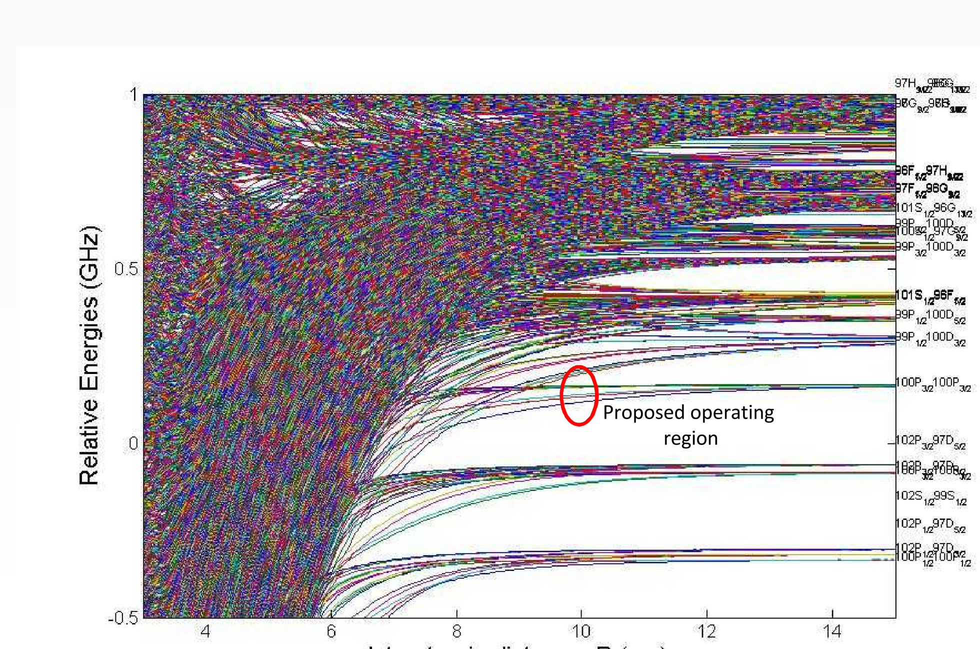
Two atoms are illuminated by the same optical field with Rabi frequency Ω from ground-state $|g\rangle$ to a Rydberg state $|r\rangle$ with the same optical detuning δ.



If the Rydberg laser only interacts with on of the qubit states, then the two atom Rydberg light-shift that appears in addition to the normal single atom light-shift. The result is a tunable two atom interaction term that arises from the Rydberg dipole-dipole interaction:

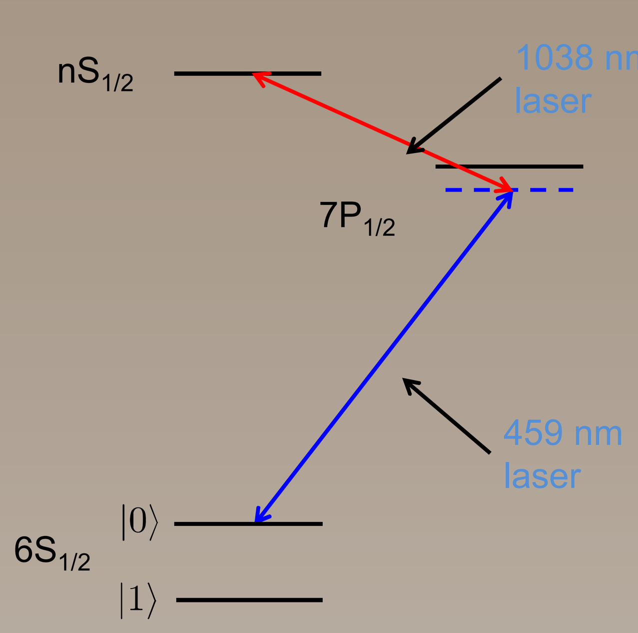
$$J = \frac{\Omega^4}{8\delta^3} - \frac{\Omega^4}{16\delta^5}$$

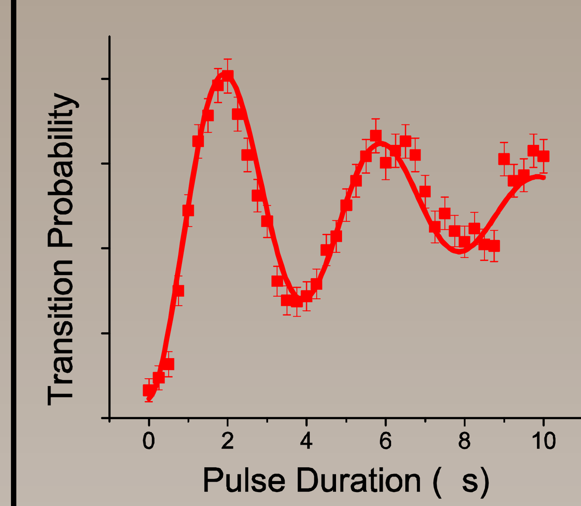
Two-atom Rydberg jungle

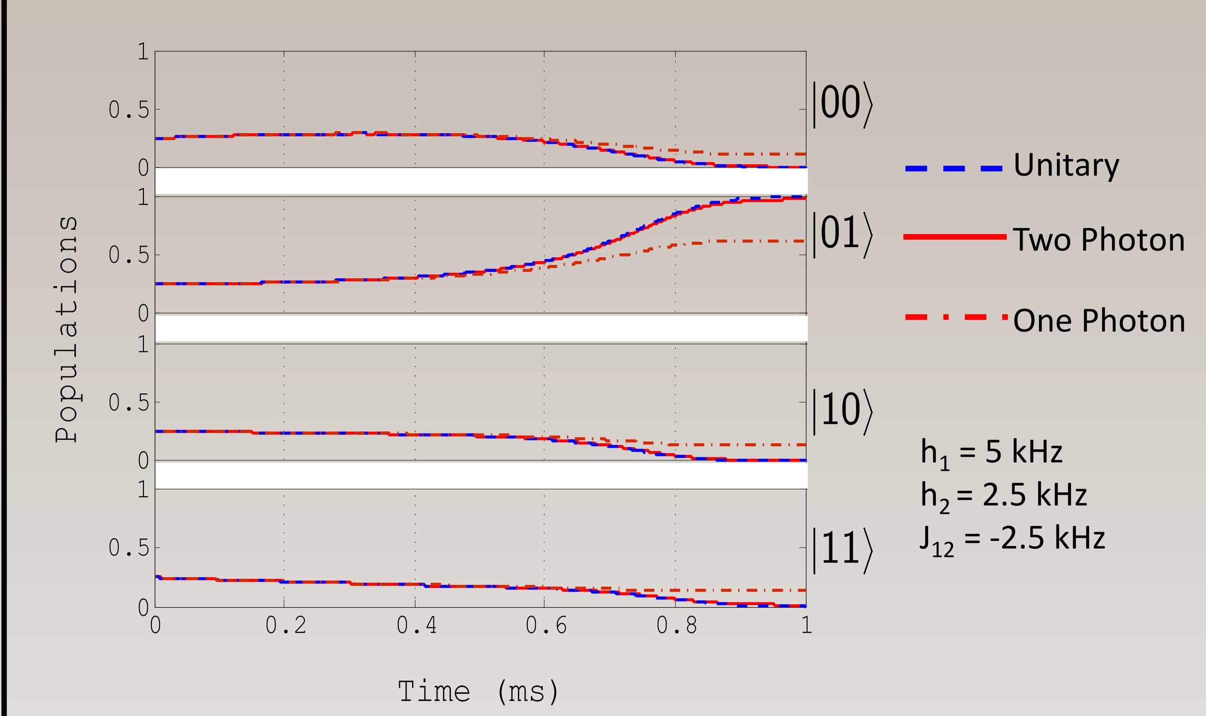


Rabi oscillations to n=45 Rydberg level

We utilize the fact that the Rydberg state is anti-trapped in a red-detuned dipole-trap to perform single atom Rydberg spectroscopy. When the atom is excited to the Rydberg state it is quickly ejected from the trap.





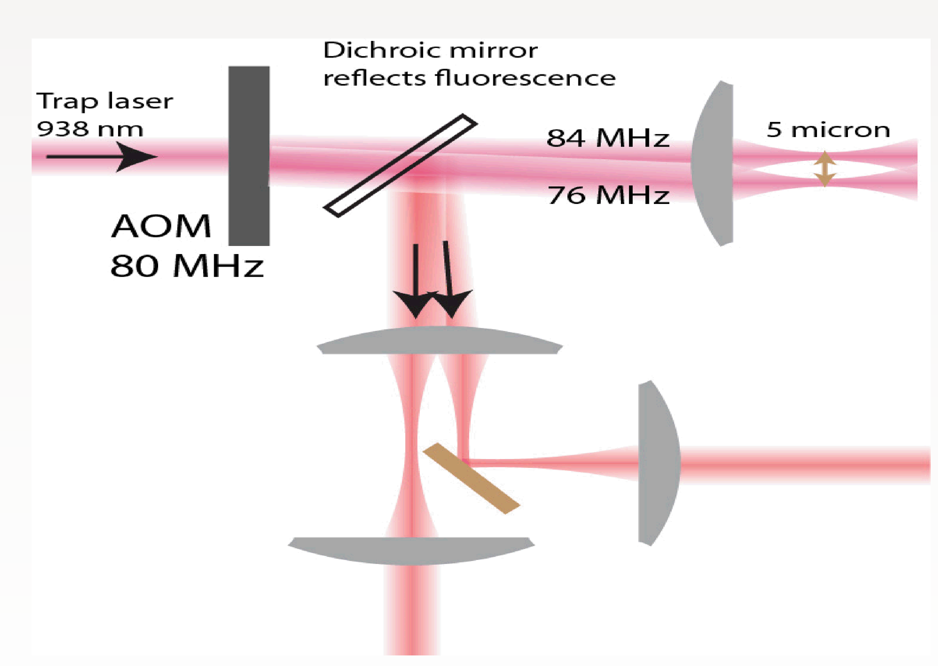


Two-qubit AQC Simulation

Simulation of two-qubit adiabatic evolution including dissipation effects due to photon scattering. Scattering from the 7p state significantly decreases fidelity

- Initialize: μ-wave rotation, followed by a $\pi/2$ phase shift to place state in ground-state in the rotating frame
- Evolve: Ramp up Rydberg and Light shift lasers while simultaneously ramping down μ-waves

Setup



References:

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[2] T. Wilk *et al.*, "Entanglement of two individual neutral atoms using Rydberg blockade," Phys. Rev. Lett., **104**, 010502, (2010).
[3] J.E. Johnson and S. L. Rolston, "Interactions between Rydberg-dressed atoms," Phys. Rev. A, **82**, 033412, (2010).
[4] X. Wu, Gravity Gradient Survey with a Mobile Atom Interferometer, Ph.D. thesis, Stanford University (2009).

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NNSA National Nuclear Security Administration

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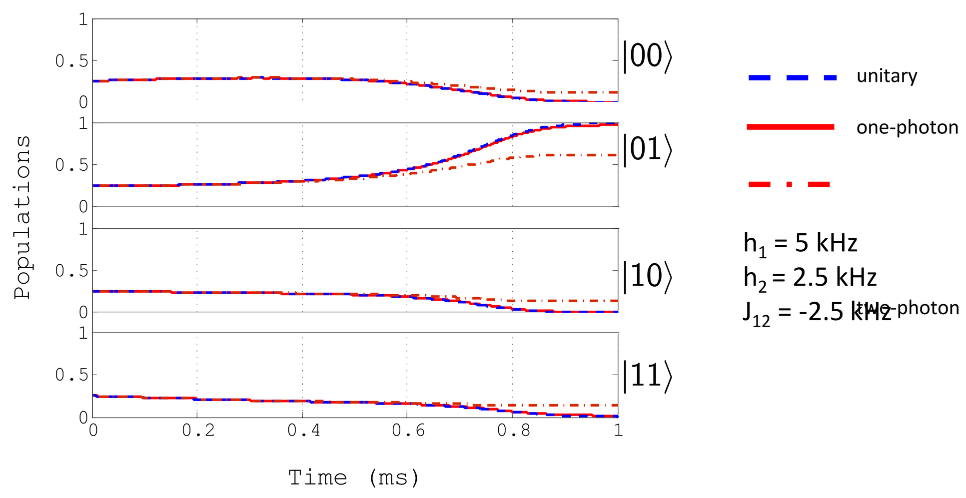

- Initialize: μ-wave rotation, followed by a $\pi/2$ phase shift to place state in ground-state in the rotating frame
- Evolve: Ramp up Rydberg and Light shift lasers while simultaneously ramping down μ-waves

In addition to this, we took advantage of the large dipole moments experienced between Rydberg states with similar principle quantum number to probe higher angular momentum states via 4-photon transitions. The plot below demonstrates the appearance of 4-photon transitions due when the 9.2 GHz microwave oscillator is switched on during the 2-photon Rydberg laser pulse.