SAND2015-1059C

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

Yuan-Yu Jau

Sandia National Laboratories

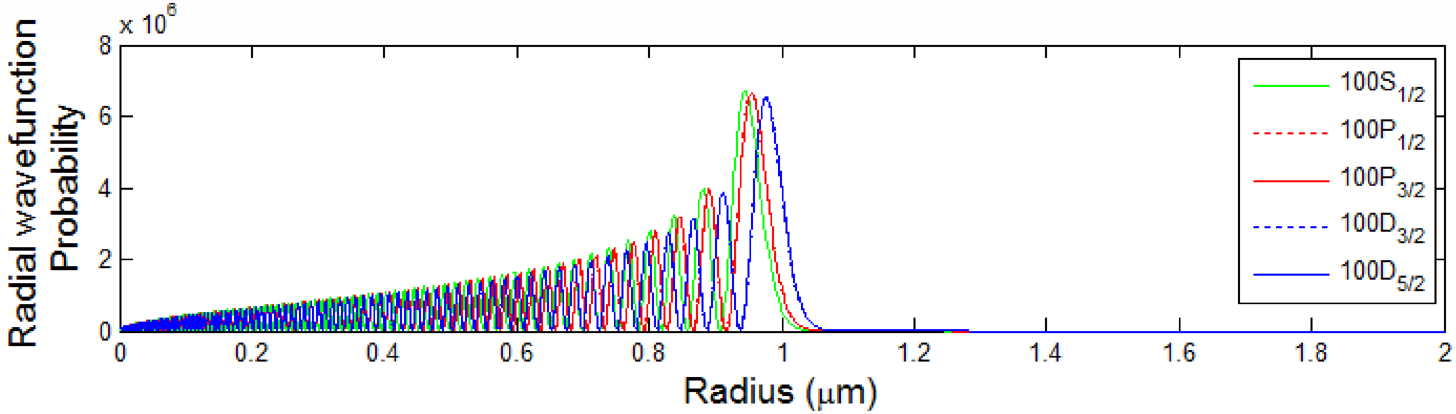
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Overview

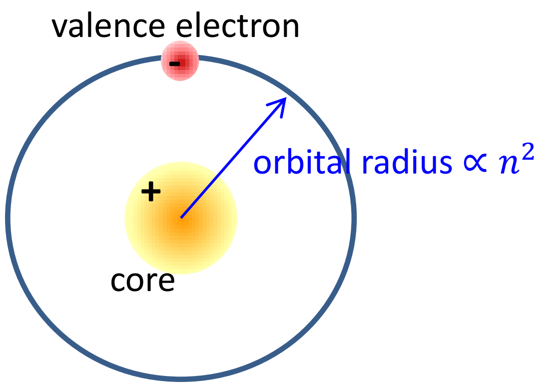
- Taking advantage of Rydberg atoms
- Approach and experiment
- Experimental demonstration of strong ground-state atom-atom interaction
- Experimental demonstration of neutral atom Bell-state entanglement
- Summary and outlook

Strong Electric Dipole Moment

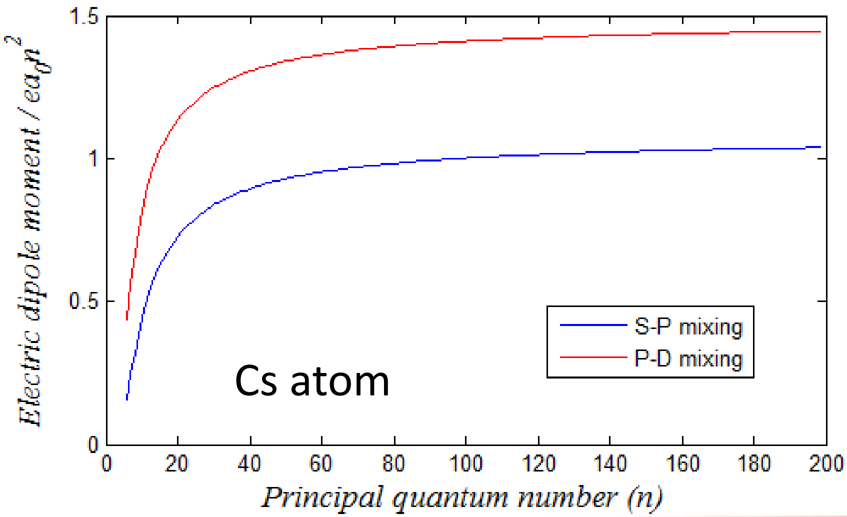
An example of the radial wavefunctions of a Cs atom at $n = 100$:



A Rydberg atom has a strong electric dipole moment.

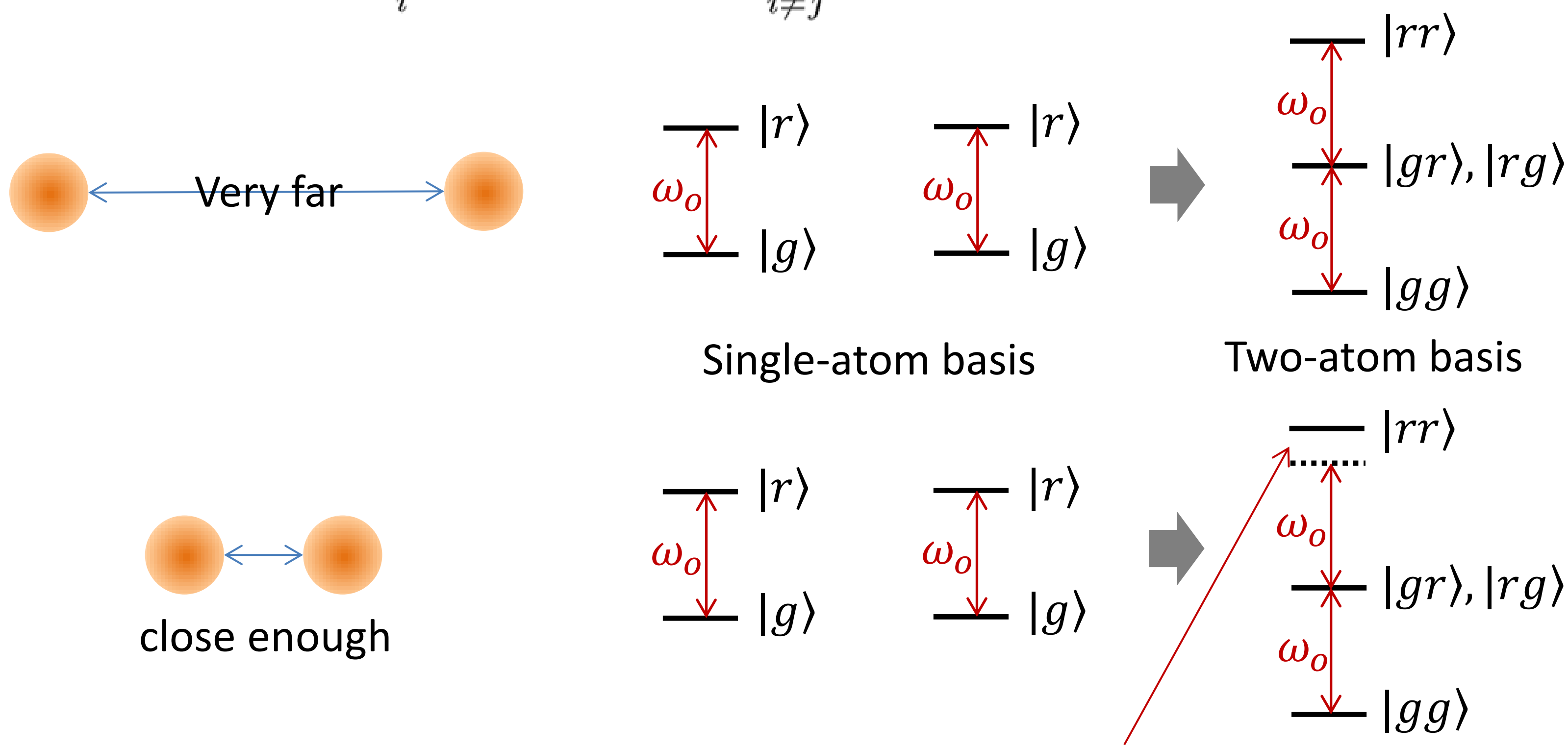


A classical picture of an atom



Blockade & Electric Dipole-Dipole Interaction

$$H_{\text{atoms}} = \sum_i H_0^{(i)} + \frac{1}{4\pi\varepsilon_0 r^3} \sum_{i \neq j} \left(\mathbf{D}^{(i)} \cdot \mathbf{D}^{(j)} - 3\mathbf{D}^{(i)} \cdot \hat{\mathbf{r}}\hat{\mathbf{r}} \cdot \mathbf{D}^{(j)} \right)$$

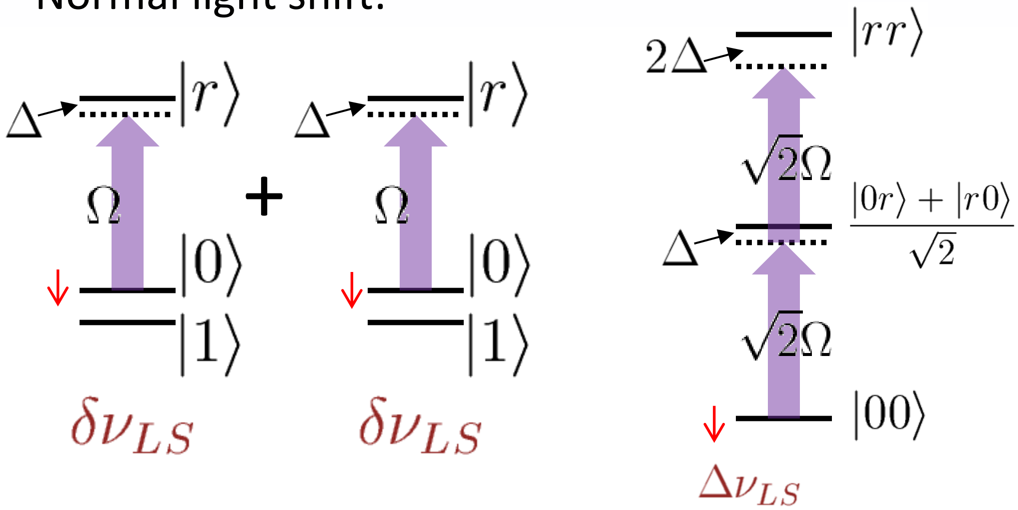


Blockade shift U

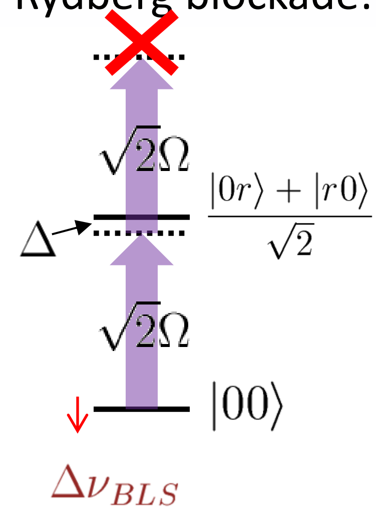
Normally, $1 \leq U \leq 1000$ MHz.

Interaction between Two Rydberg-Dressed Atoms

Normal light shift:



With Rydberg blockade:



$$H_{BLS} = H_{LS} + H_{int} = \begin{bmatrix} 2\delta\nu_{LS} & 0 & 0 & 0 \\ 0 & \delta\nu_{LS} & 0 & 0 \\ 0 & 0 & \delta\nu_{LS} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} J & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{for} \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix}$$

$$J = \Delta\nu_{BLS} - \Delta\nu_{LS} = \frac{\Omega^4}{8\Delta^3} - \frac{3\Omega^6}{16\Delta^5} + \frac{35\Omega^8}{128\Delta^7} - \cdots$$

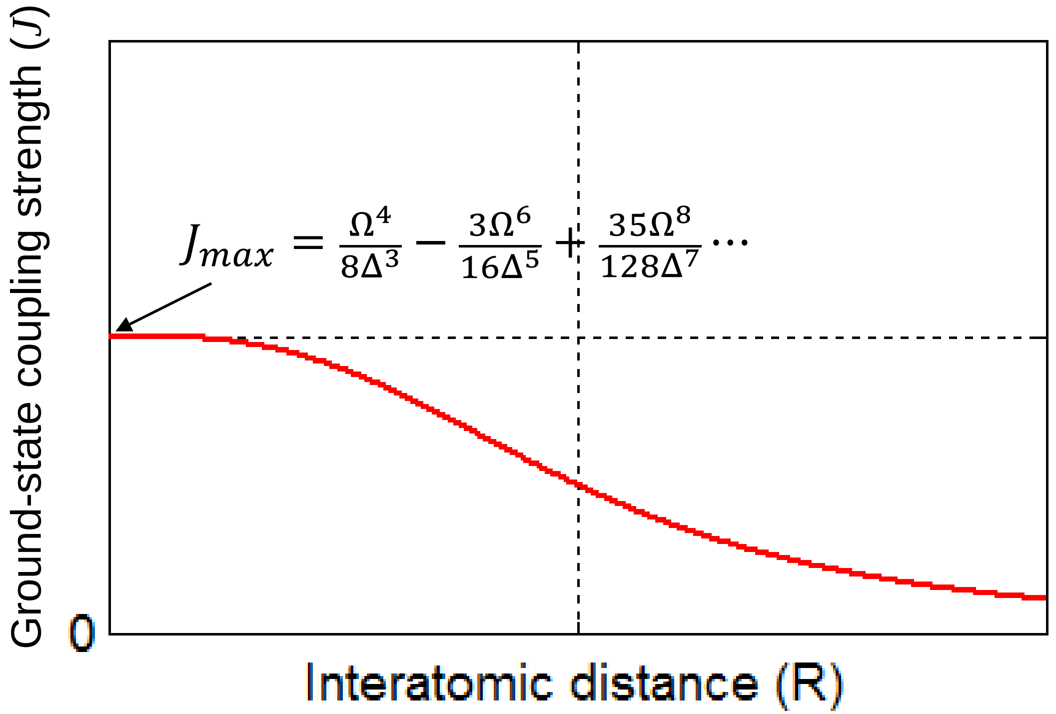
$$H_{int} = \frac{J}{4}(\sigma_z^{(1)} + 1)(\sigma_z^{(2)} + 1)$$

Sandia National Laboratories

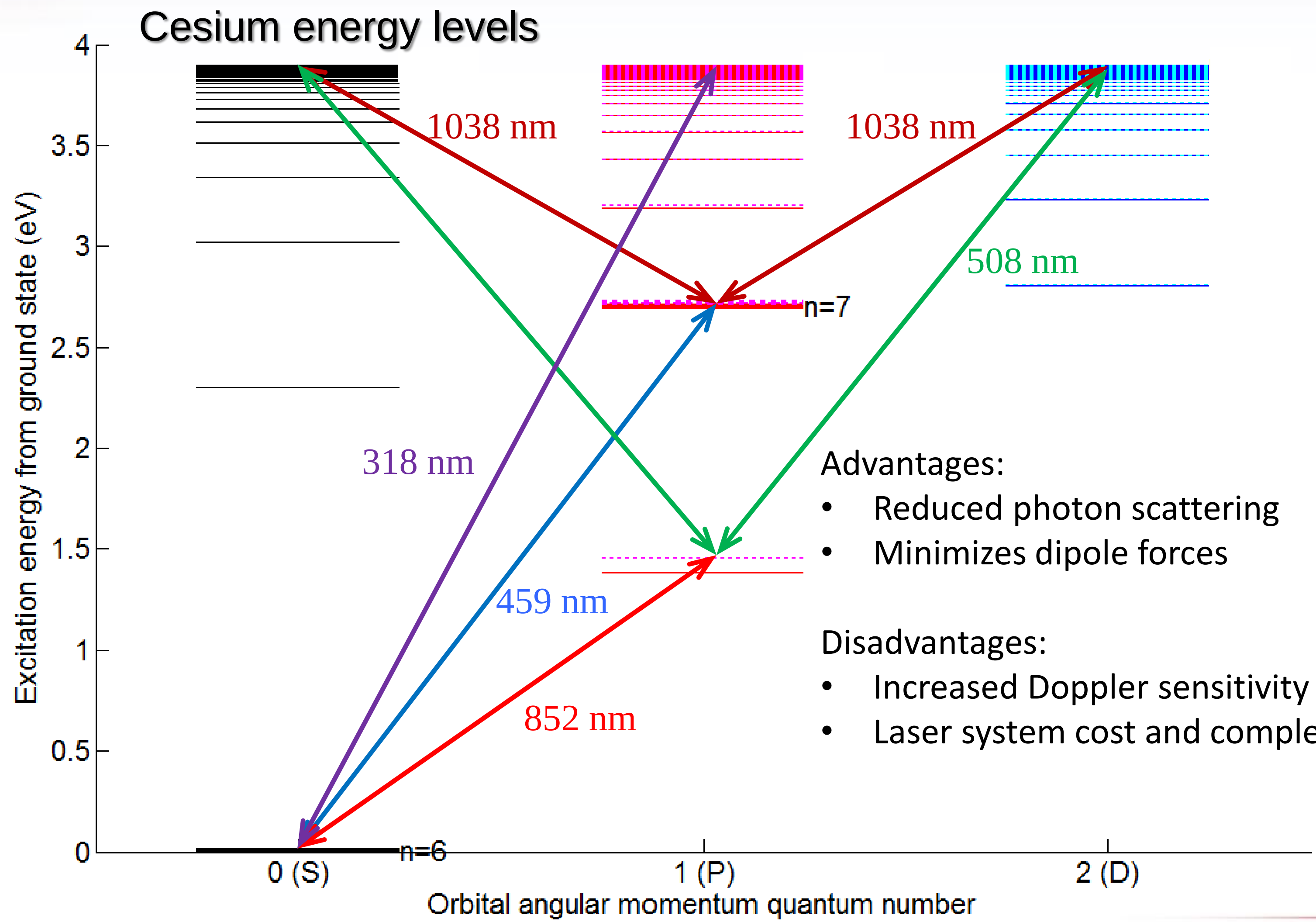
Advantages of Rydberg-Dressed Atoms

Tunable interaction strength (J), low sensitivity to atom motion, and effectively strong ground-state interactions.

$$H_{int} = \sum_{ij} \frac{J_{ij}}{4} (\sigma_z^{(i)} + 1)(\sigma_z^{(j)} + 1)$$



Our Approach to Rydberg Dressing



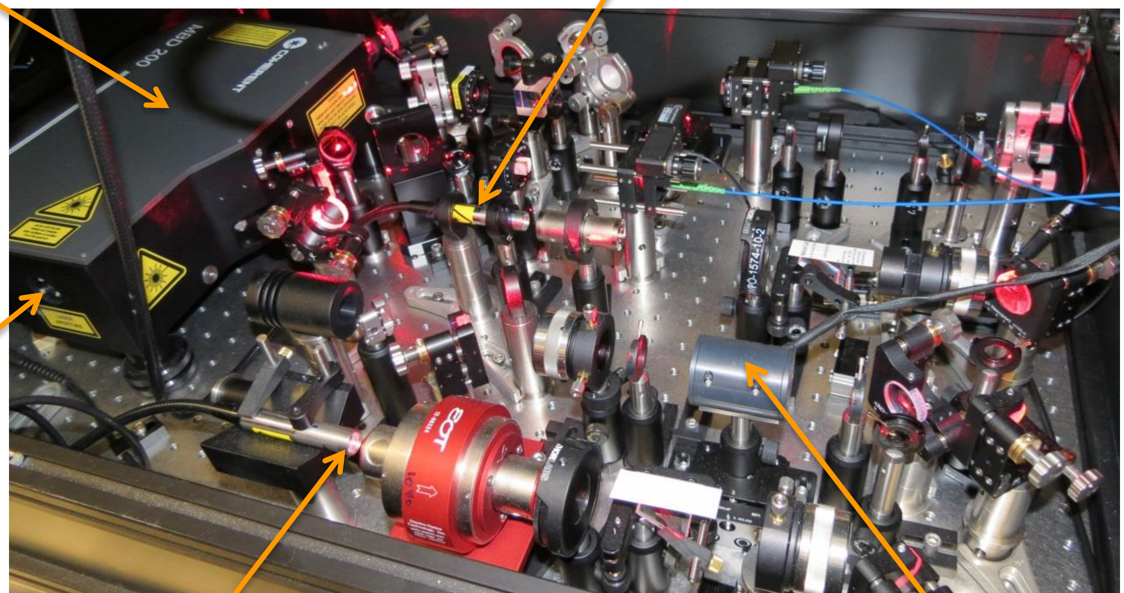
Advantages:
- Reduced photon scattering
- Minimizes dipole forces

Disadvantages:
- Increased Doppler sensitivity
- Laser system cost and complexity

318-nm Rydberg Excitation Laser

Doubling cavity

1575 nm, 5 W



200 mW, 318 nm

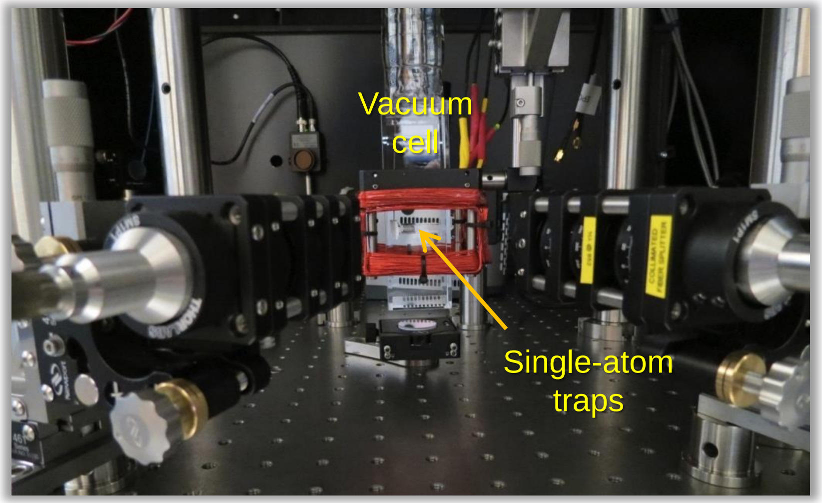
1070 nm input, 5 W

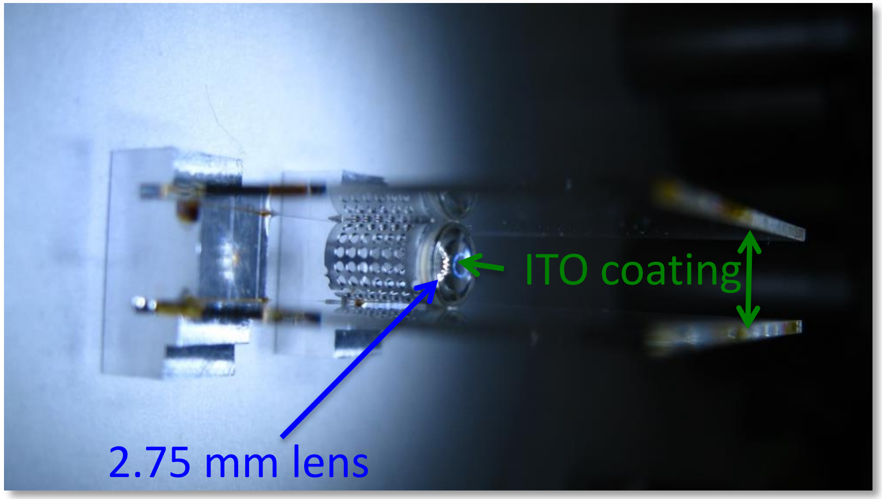
Sum-frequency mixing

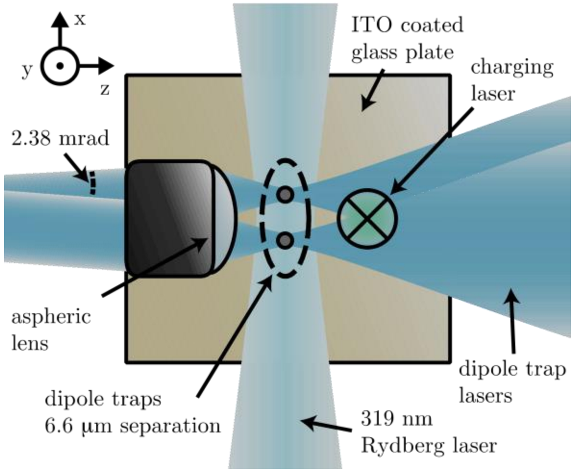
Hankin, *et. al*. “Two-atom Rydberg blockade using direct 6S to nP excitation,” Phys. Rev. A, 89, 033416 (2014)

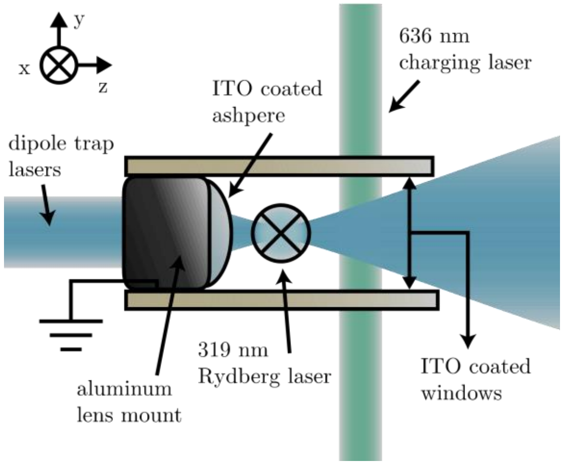
Sandia National Laboratories

Experimental Setup

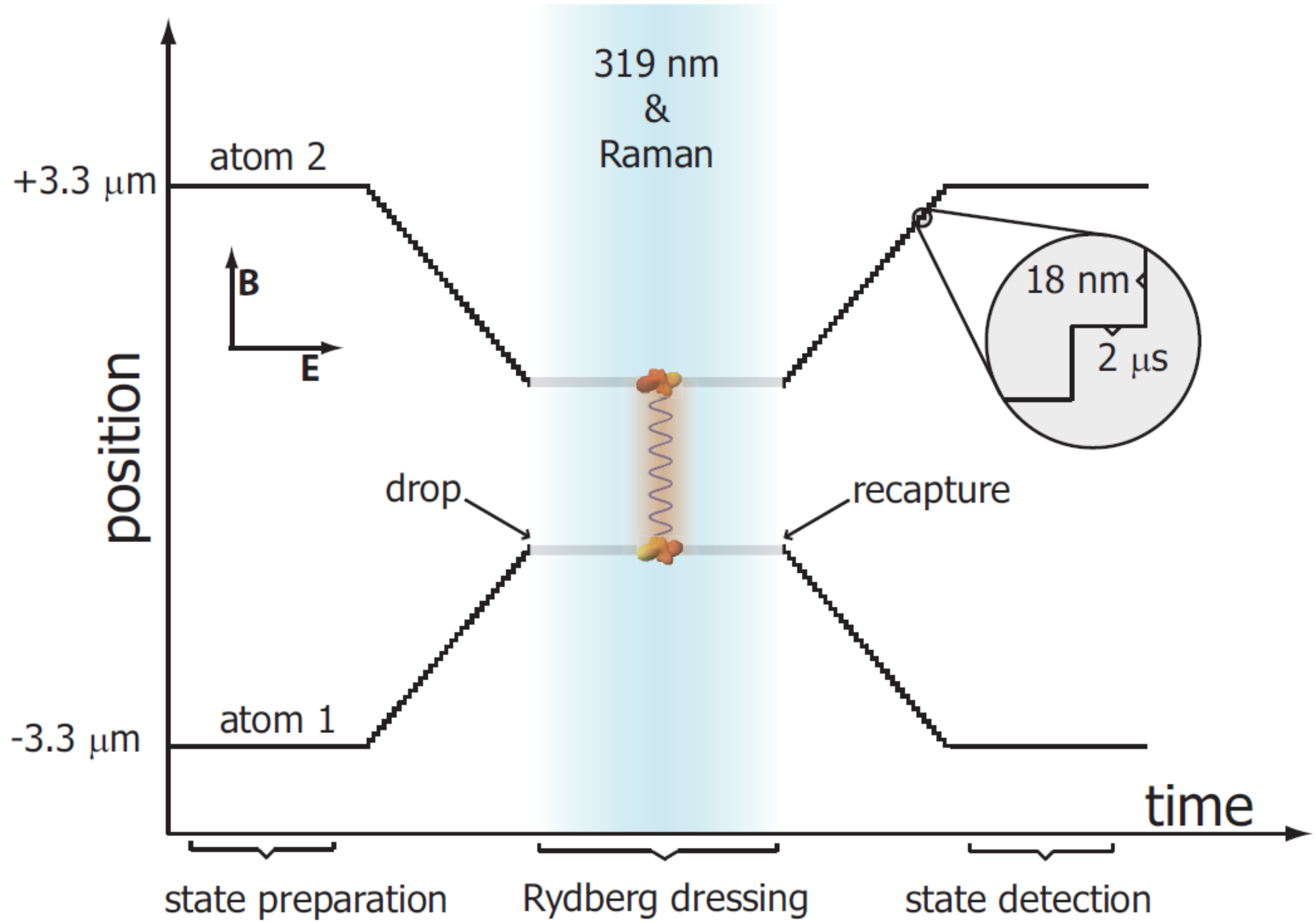






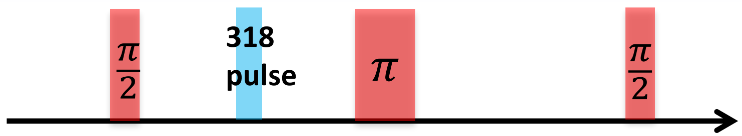


Experimental Sequence

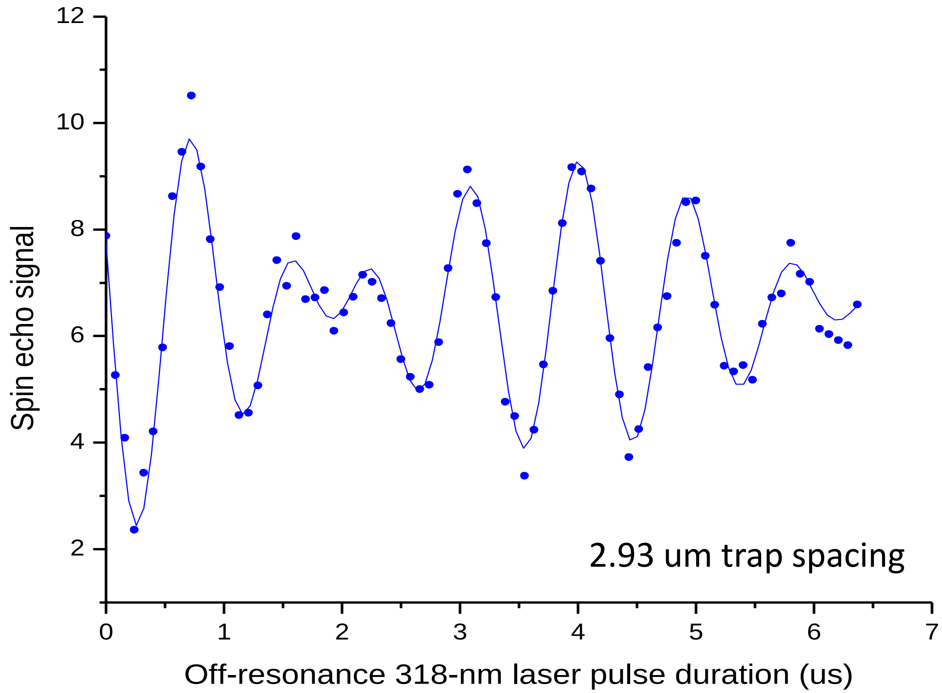


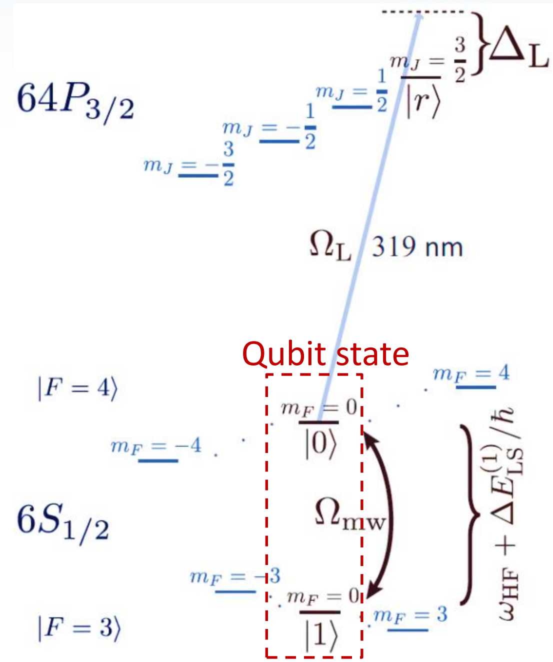
First Evidence of Rydberg-Dressed Interaction

Microwave transition is via Raman laser

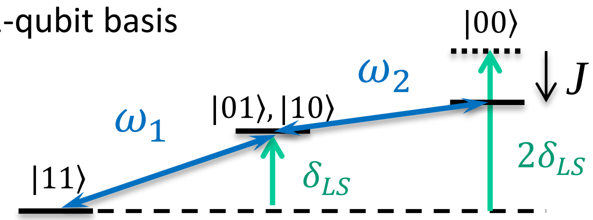


318-nm laser dressed spin echo sequence



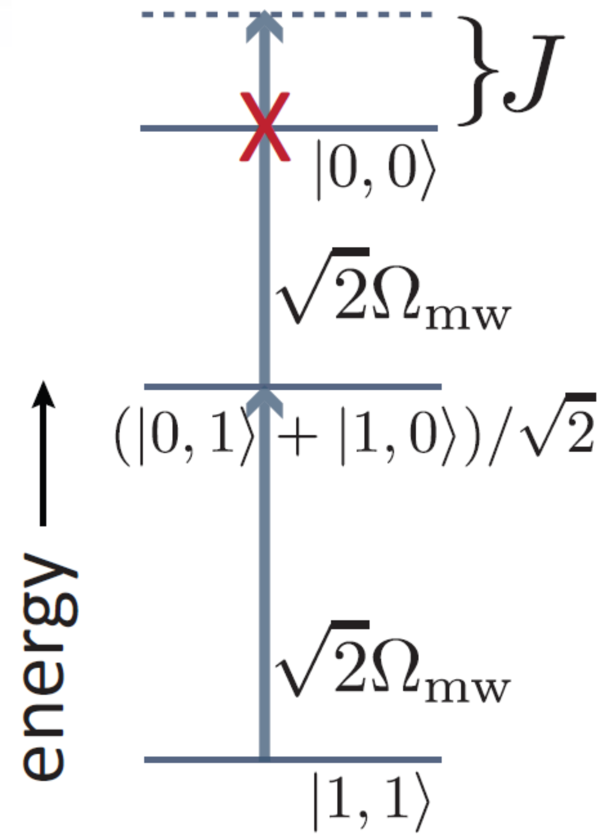


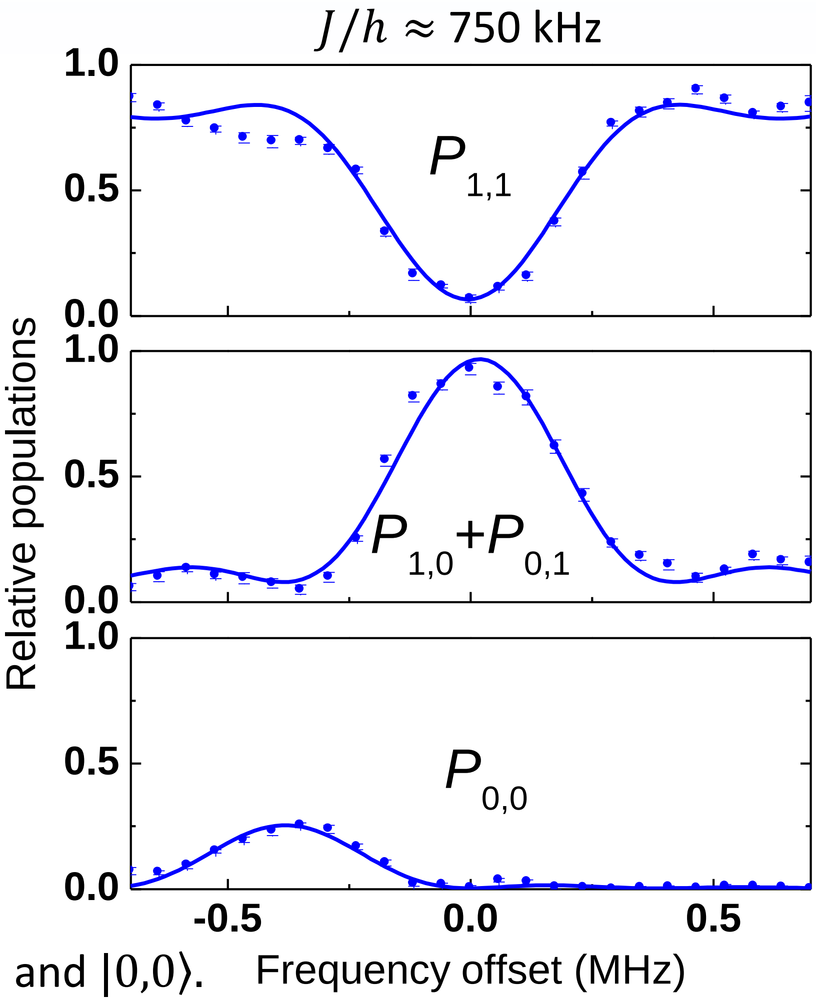
2-qubit basis



A frequency beat note is generated if $\omega_1 \neq \omega_2$

Two-Qubit Microwave Resonances

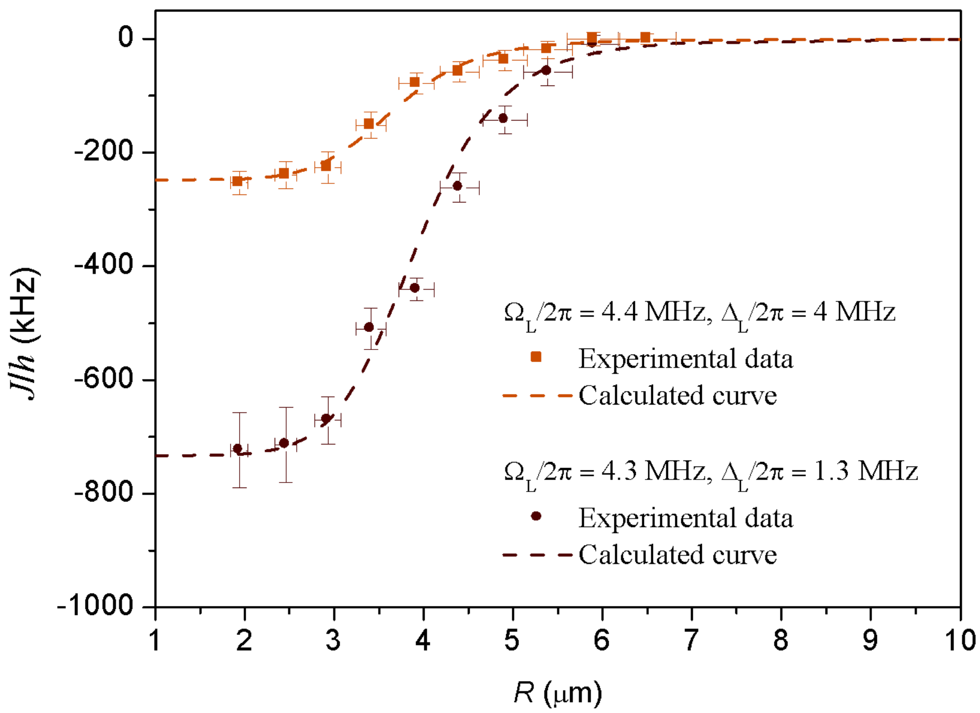


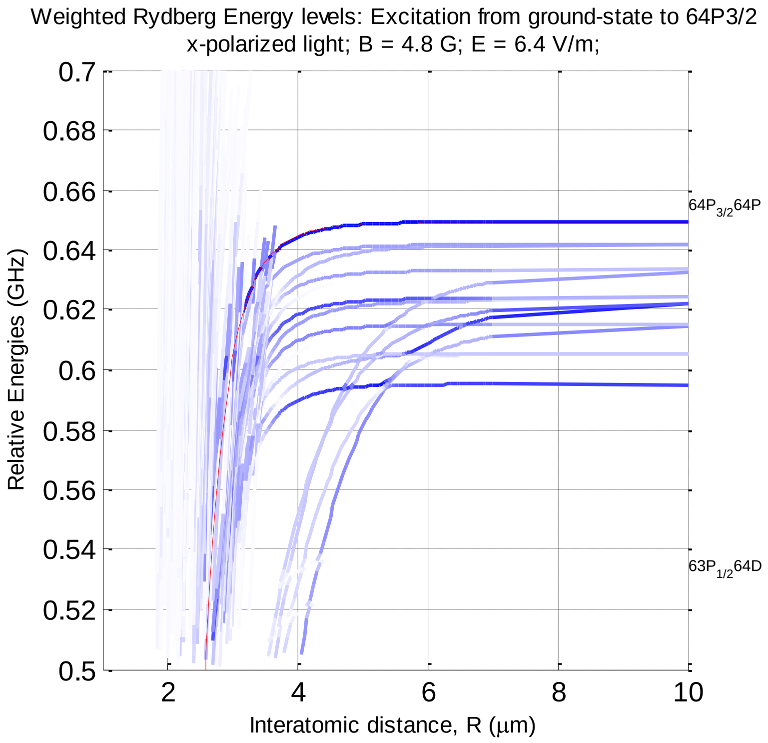


$P_{1,1}$, $P_{1,0}$, $P_{0,1}$, and $P_{0,0}$ denote relative populations of state $|1,1\rangle$, $|1,0\rangle$, $|0,1\rangle$, and $|0,0\rangle$.

J vs *R*

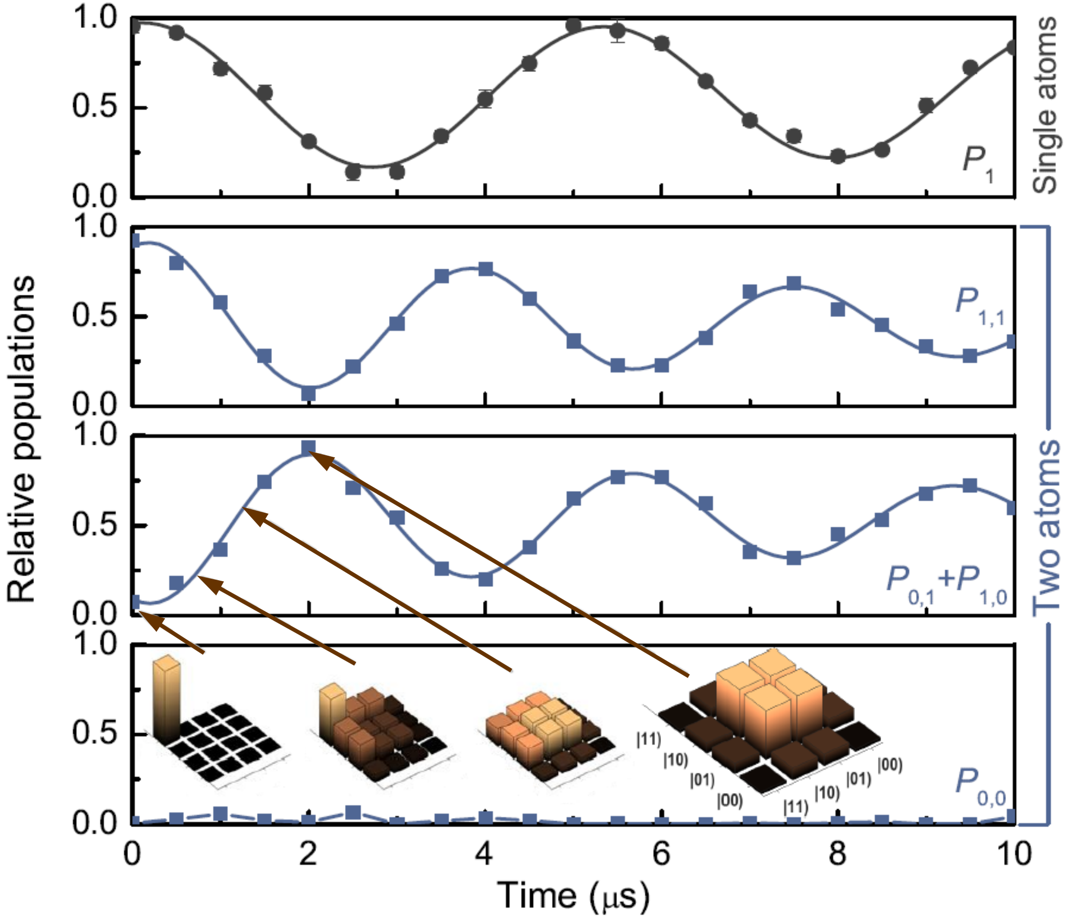
Direct measurement of two-qubit interaction strength *J* as a function of two-atom separation with two conditions.





Producing Bell-State Entanglement

Initial state is $|1\rangle$ or $|11\rangle$, then apply 318-nm and Raman lasers
Experimental data with $J/h \approx 750$ kHz



Single-atom Rabi oscillation: $|1\rangle \leftrightarrow |0\rangle$

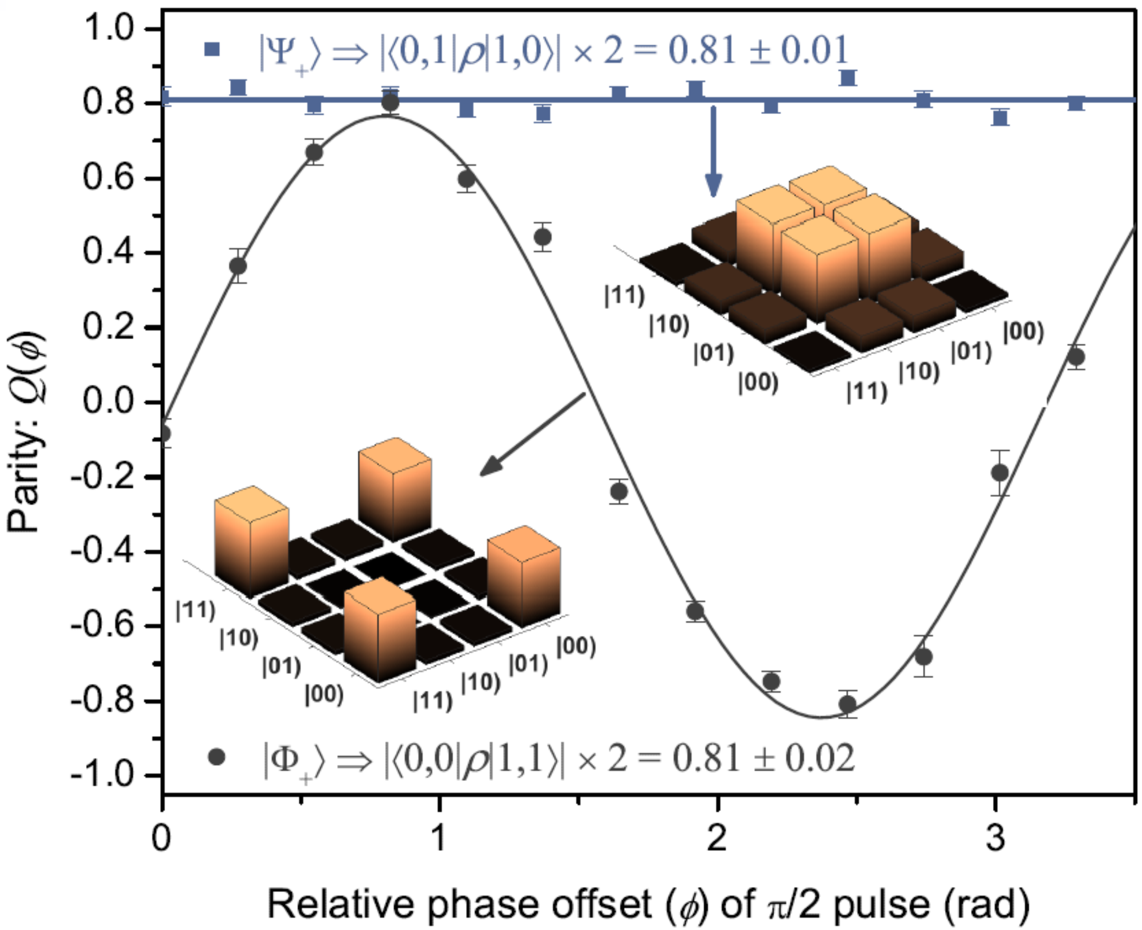
Two-atom Rabi oscillation: $|11\rangle \leftrightarrow (|10\rangle + |01\rangle)/\sqrt{2}$

- $\sqrt{2}$ times faster
- No significant population being transferred to $|00\rangle$
- Bell state $|\Psi_+\rangle$ is produced at $t = \pi/\sqrt{2}\Omega_{mw}$

Sandia National Laboratories

Entanglement Fidelity ≥ 81%

Verify the entanglement via parity measurements



Prepare two Cs atoms in Bell state $|\Psi_+\rangle$ or $|\Phi_+\rangle$

Apply a global $\pi/2$ rotation with a given phase

Perform parity measurement $Q = P_{11} + P_{00} - (P_{01} + P_{10})$

Obtain the two-qubit entanglement fidelity F, where $Q \leq F \leq 1$.

Sandia National Laboratories

Summary and Outlook

- We have demonstrated effective ground-state interaction $J/h \sim 1$ MHz via Rydberg dressing technique.
- We experimentally show neutral-atom entanglement with a fidelity ≥ 81±2%.
- With two-atom survival probability is about 74% and about 10-Hz data rate, we produce 6 entangled pairs per second.
- Multi-atom entanglement can be achieved based on the similar approach.
- Universal quantum gate control can be realized with individual addressing of the trap atoms.
- We will implement adiabatic Rydberg dressing to improve the quantum control fidelity. (see Tyler Keating's poster for more details.)

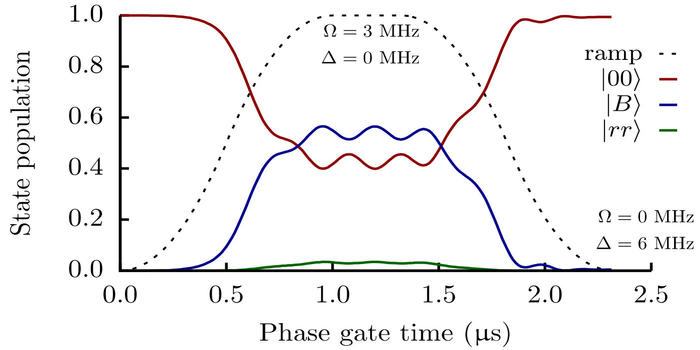
Team Members:

Aaron Hankin (Sandia, currently at NIST)

Grant Biedermann (Sandia)

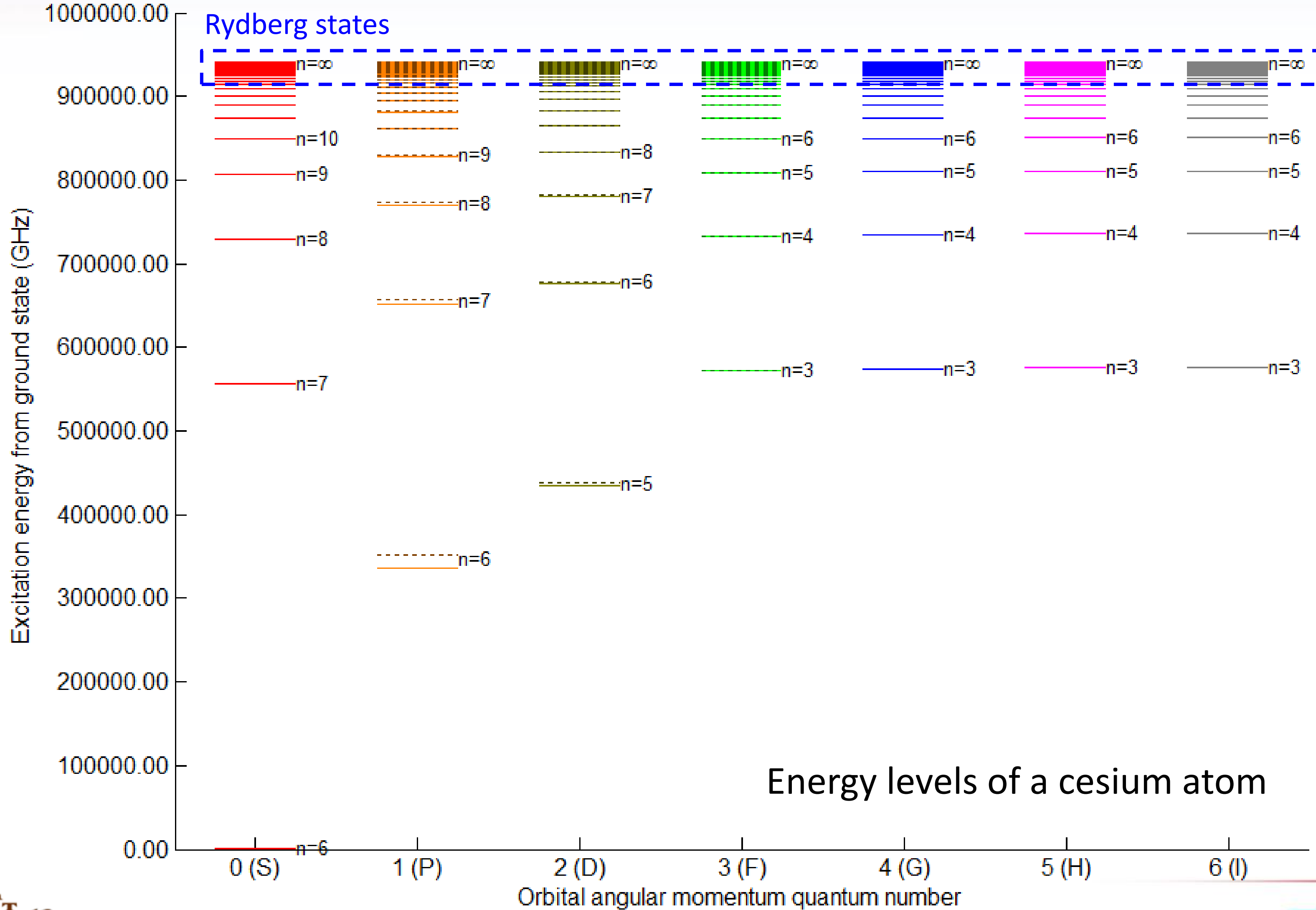
Bob Keating (UNM)

Ivan Duetsch (UNM)



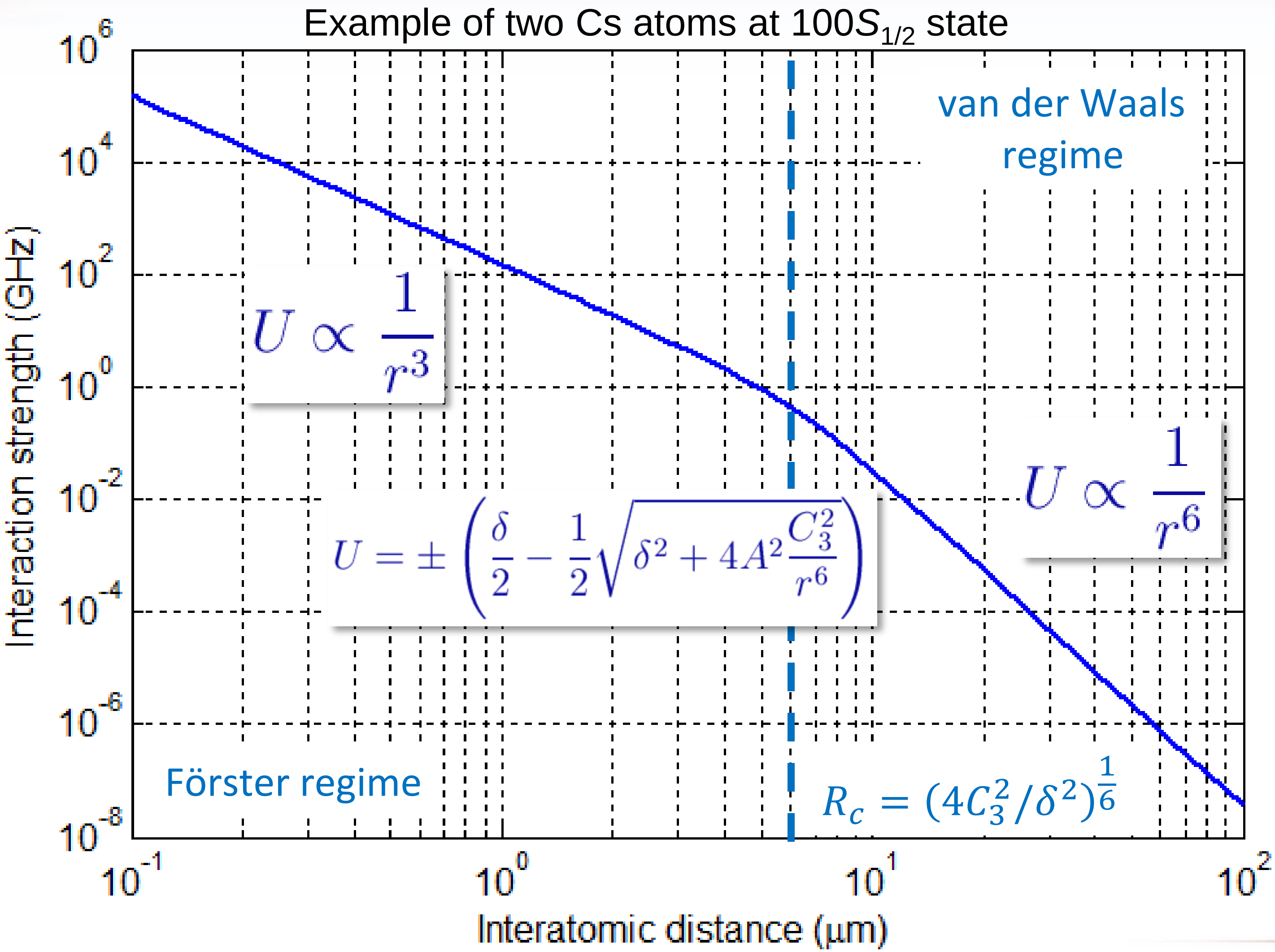
BACK UP SLIDES

Atomic Rydberg States



Energy levels of a cesium atom

Blockade Strength vs Interatomic Distance



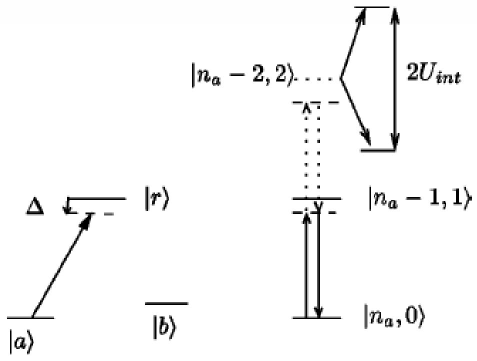
Ideas of Rydberg Dressing

PHYSICAL REVIEW A, VOLUME 65, 041803(R)

Spin squeezing of atoms by the dipole interaction in virtually excited Rydberg states

Isabelle Bouchoule and Klaus Mølmer
Institute of Physics and Astronomy, University of Aarhus, DK 8000 Aarhus C, Denmark
(Received 7 May 2001; revised manuscript received 31 August 2001; published 10 April 2002)

We show that the interaction between Rydberg atomic states can provide continuous spin squeezing of atoms with two ground states. The interaction prevents the simultaneous excitation of more than a single atom in the sample to the Rydberg state, and we propose to utilize this blockade effect to realize an effective collective spin Hamiltonian $J_x^2 - J_y^2$. With this Hamiltonian the quantum-mechanical uncertainty of the spin variable $J_x - J_y$ can be significantly reduced.



PHYSICAL REVIEW A **82**, 033412 (2010)

Interactions between Rydberg-dressed atoms

J. E. Johnson and S. L. Rolston
Joint Quantum Institute, Department of Physics, University of Maryland and National Institute of Standards and Technology, College Park, Maryland 20742-4111, USA
(Received 15 June 2010; published 14 September 2010)

We examine interactions between atoms continuously and coherently driven between the ground state and a Rydberg state, producing "Rydberg-dressed atoms." Because of the large dipolar coupling between two Rydberg atoms, a small admixture of Rydberg character into a ground state can produce an atom with a dipole moment of a few debye, the appropriate size to observe interesting dipolar physics effects in cold atom systems. We have calculated the interaction energies for atoms that interact via the dipole-dipole interaction and find that because of blockade effects, the R dependent two-atom interaction terms are limited in size and can be R independent up until the dipolar energy is equal to the detuning. This produces R dependent interactions different from the expected $1/R^3$ dipolar form that have no direct analogy in condensed-matter physics and could lead to interesting quantum phases in trapped Rydberg systems.

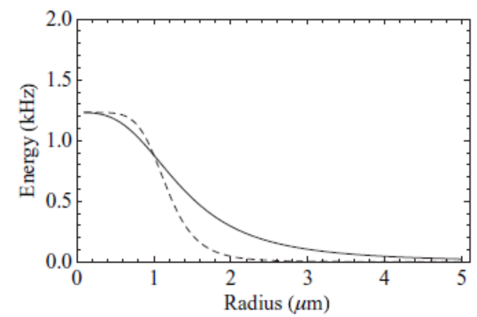
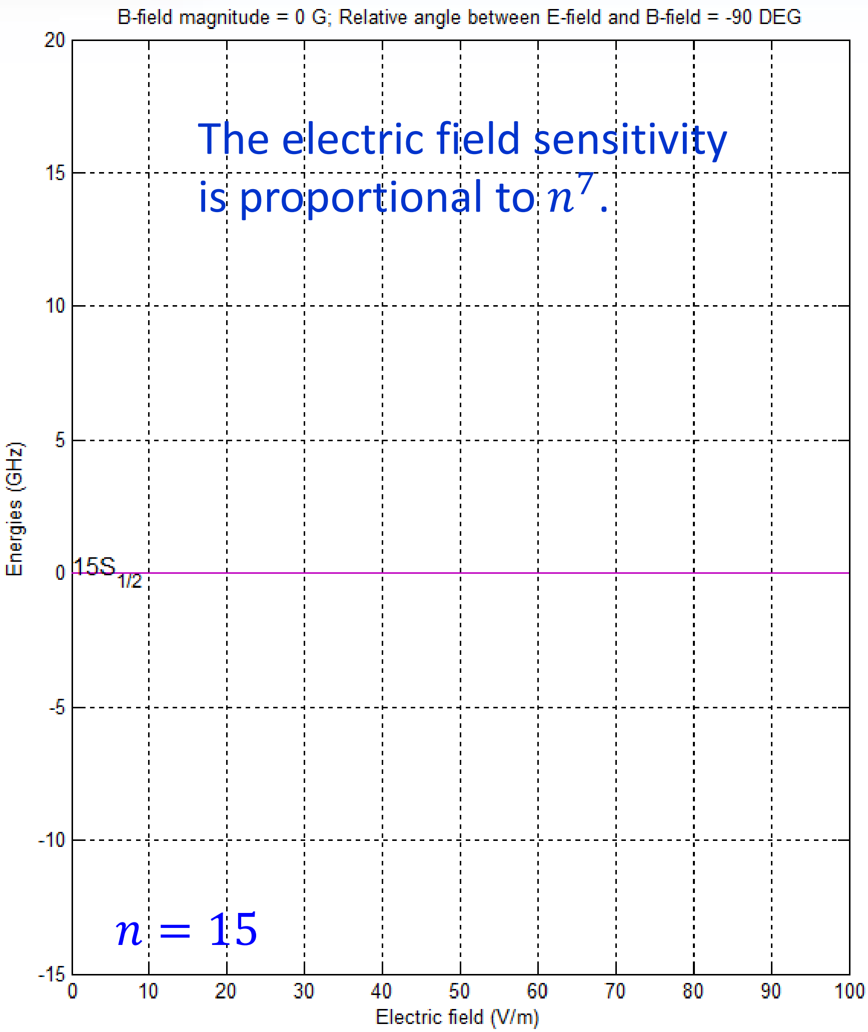


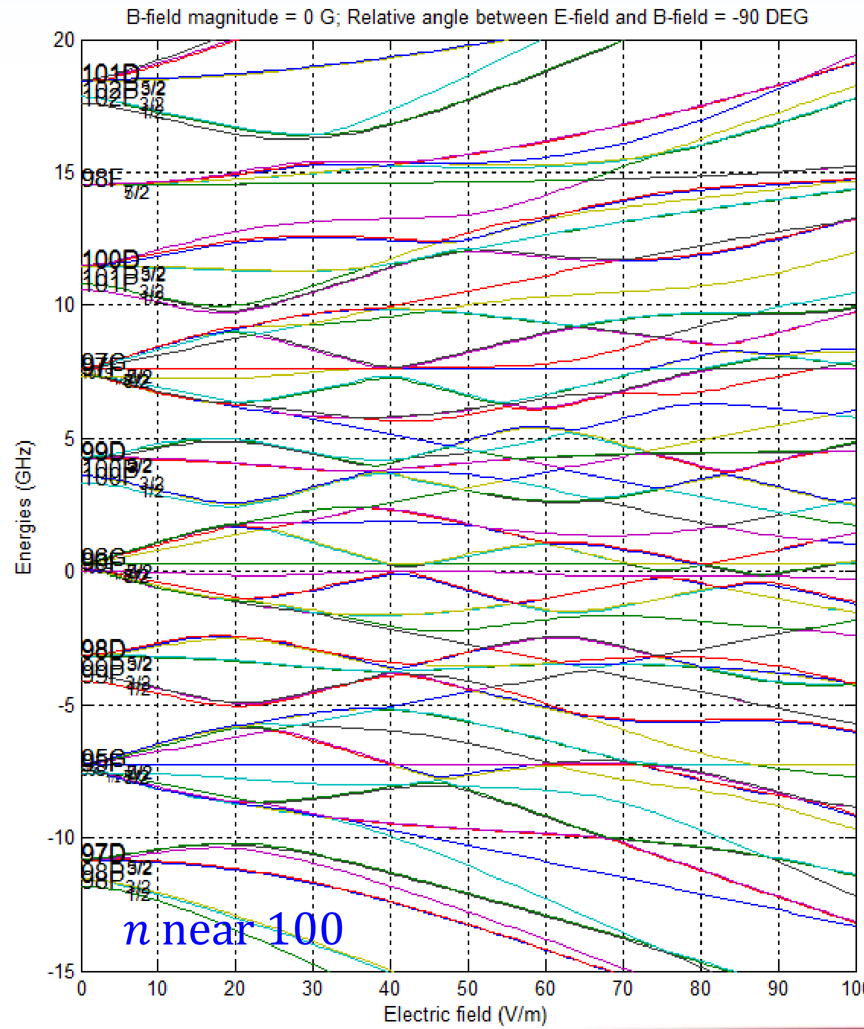
FIG. 3. The energy of the dressed state, for two different interactions: the dipole-dipole that varies as $1/R^3$ (solid) and the Van der Waals that varies as $1/R^6$ (dashed) for $\delta/2\pi = 100$ MHz, $c_3/2\pi = 1000$ MHz μm^3, and $c_6/2\pi = 500$ MHz μm^6.

Sandia National Laboratories

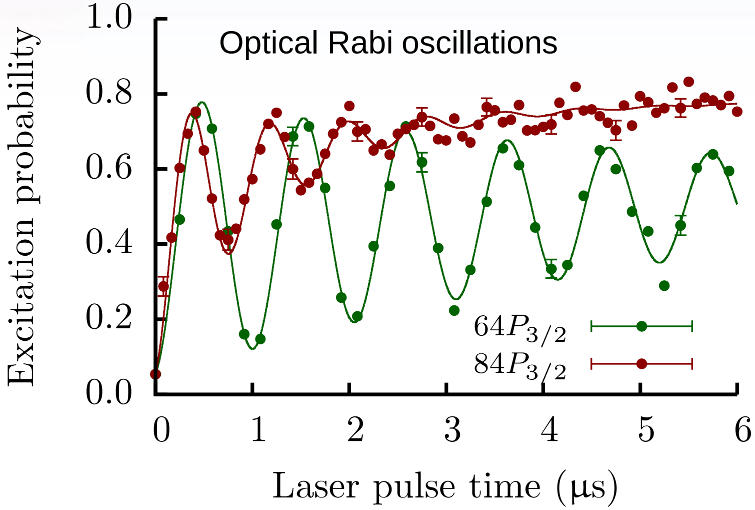
Electric-Field Sensitivity of Rydberg States

The electric field sensitivity is proportional to n^7.





Rydberg-State Lifetime



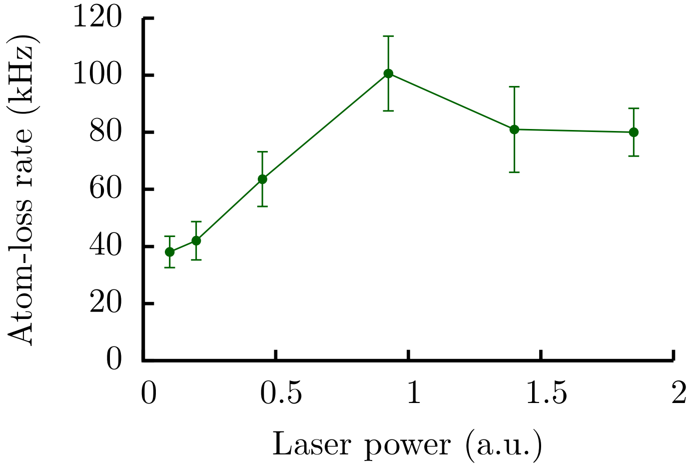
Calculated lifetimes:

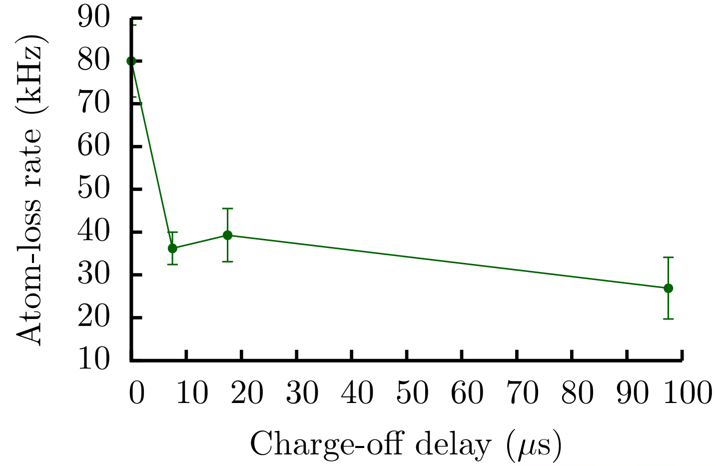
	$84P_{3/2}$	$64P_{3/2}$
T_1 =	270 μs	150 μs

Measured lifetimes:

	$84P_{3/2}$	$64P_{3/2}$
T_1 =	0.8(1) μs	15(4) μs

Illumination of laser beams on the ITO coated glass surface is reducing the Rydberg state lifetime!





Sandia National Laboratories

Dynamically Tuning the Optical Tweezers

Preparing atoms at normal trapping separation

Bring the atoms closer for strong Rydberg interactions

Return to the normal position for signal detection