Exploration of entangling quantum logic gates in the presence of noise and laboratory constraints

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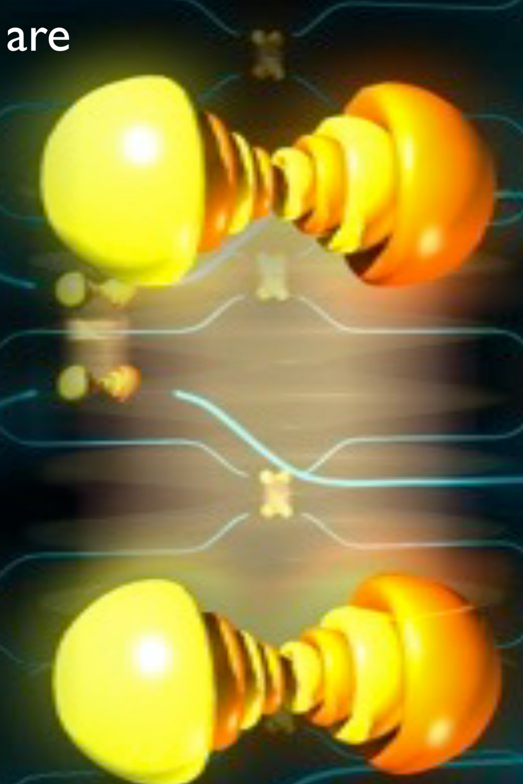
Abstract

Neutral atoms in tweezer arrays have rapidly advanced as a platform for quantum computing in the last decade. As the fidelities in single and two-qubit gates have improved and larger arrays are demonstrated, protocols and applications best suited for this maturing platform are being investigated. We report on progress toward experimental implementation of various gates, including a novel microwave-driven spin-flip logic gate proposed earlier this year [1] and an adiabatic gate. The first presents several advantages, such as going beyond the perfect blockade regime [2], while the second takes advantage of the stability of the hyperfine states by mapping the typical dipole-blockade physics onto these states. Both contribute to the quest to develop gates which are robust to noise and therefore promise higher fidelity.

Rydberg Entanglement

- DC polarizability $\alpha(0) \propto n^7$
- Induced electric dipole-dipole interaction $\propto 1/r^6$
- The quantum state of nearby atoms are dependent on each other via this interaction



Neutral Atom Quantum Computing

- Defect-free arrays of hundreds of atoms demonstrated
- Fidelity still needs improvement:
  Current: 99.5% [3]
- Our aim: seek gates and protocols best suited to this platform to improve performance

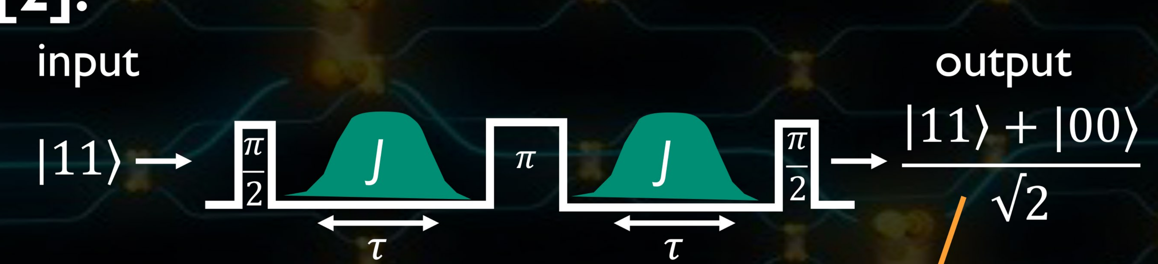
Adiabatic Entangling Gate

- Interaction J is the difference between bare-atom light shifts and the two-atom light shift with the dipole interaction:

$$J = \Delta E_{LS}^{(2)} - 2\Delta E_{LS}^{(1)}$$

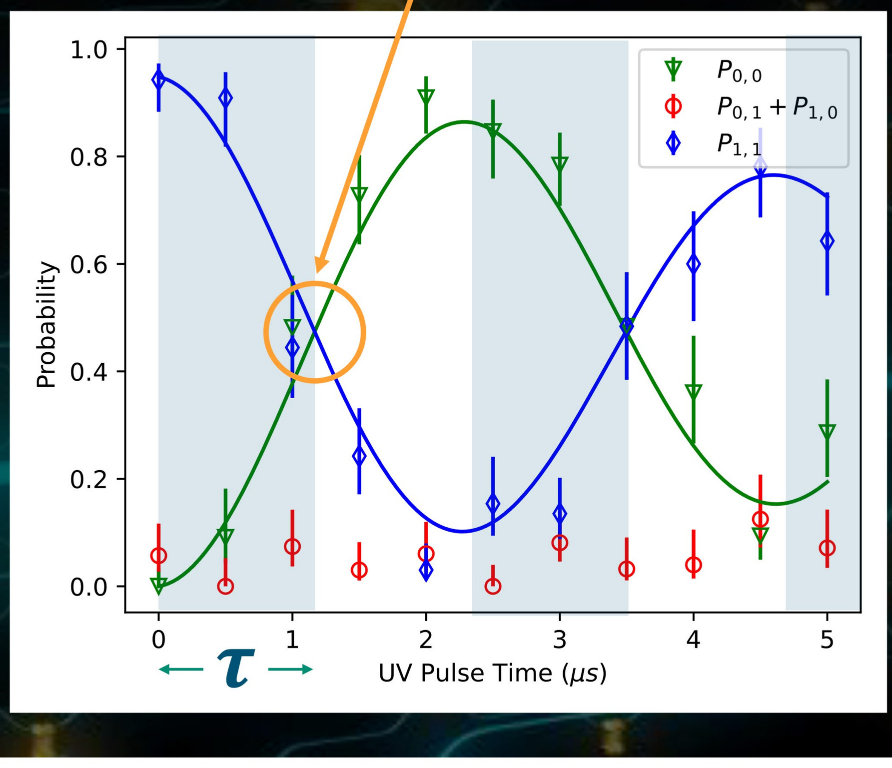
$$J \approx \frac{\hbar}{2}\left[\Delta \pm \left(\sqrt{\Delta^2 + 2\Omega^2} - 2\sqrt{\Delta^2 + \Omega^2}\right)\right]$$

Protocol [2]:



Result (preliminary):

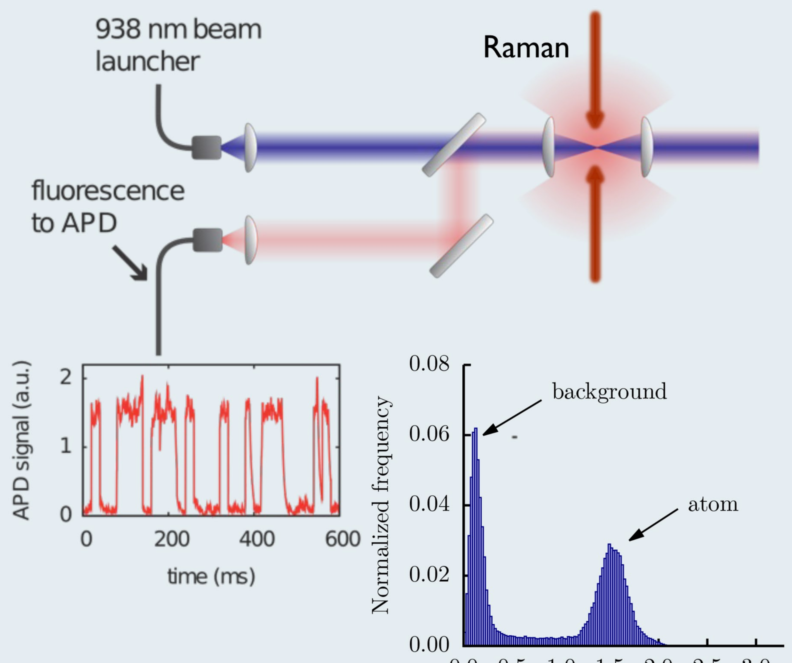
Estimate gate dephasing:
$\sqrt[4]{P_{11}(4\tau)/P_{11}(t=0)} \approx 94.4\%$
Parity:
$Q = P_{1,1} + P_{0,0} - (P_{0,1} + P_{1,0})$
Contrast = 87% raw, 88% corrected
(50% = entangled)



Applying the pulse sequence above for varying times τ yields a measure of the pulse time for entanglement and an estimate of the gate dephasing rate

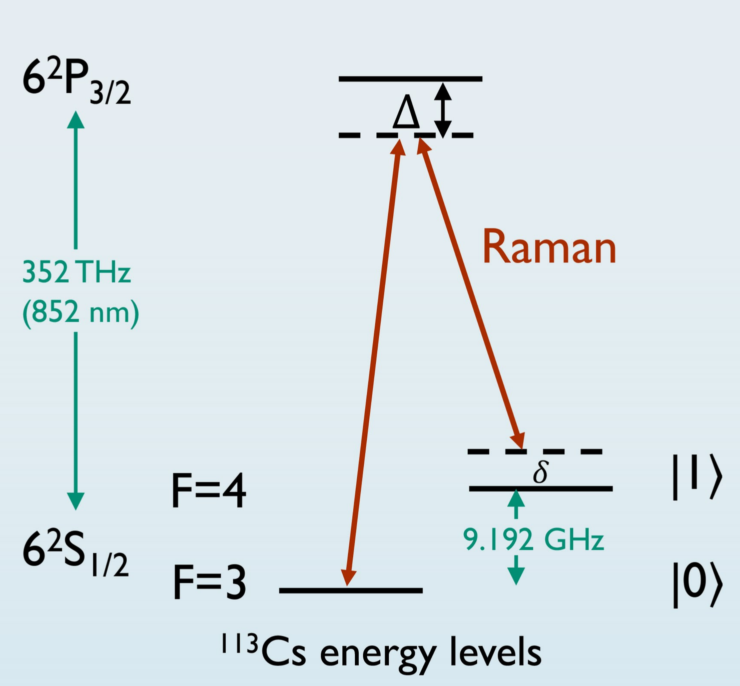
Controlling Individual Atoms in the Lab

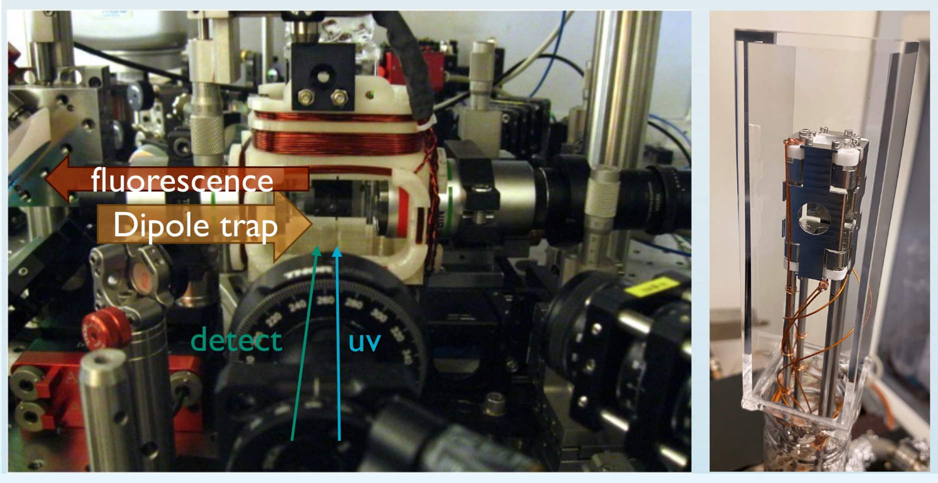
- Laser-cooled atoms are loaded into optical dipole traps
- Collisional blockade = 1 atom/site [4]
- Raman lasers control atomic state
- Fluorescence detection measures the atomic states
- $99.91^{+0.02}_{-0.02}\%$ detection fidelity and $0.9(2)\%$ detection-driven loss. See our recent paper [5]:
  Physical Review A 108.3 (2023): 032407.



Cesium atoms are confined in a dipole trap. An APD measures fluorescence.

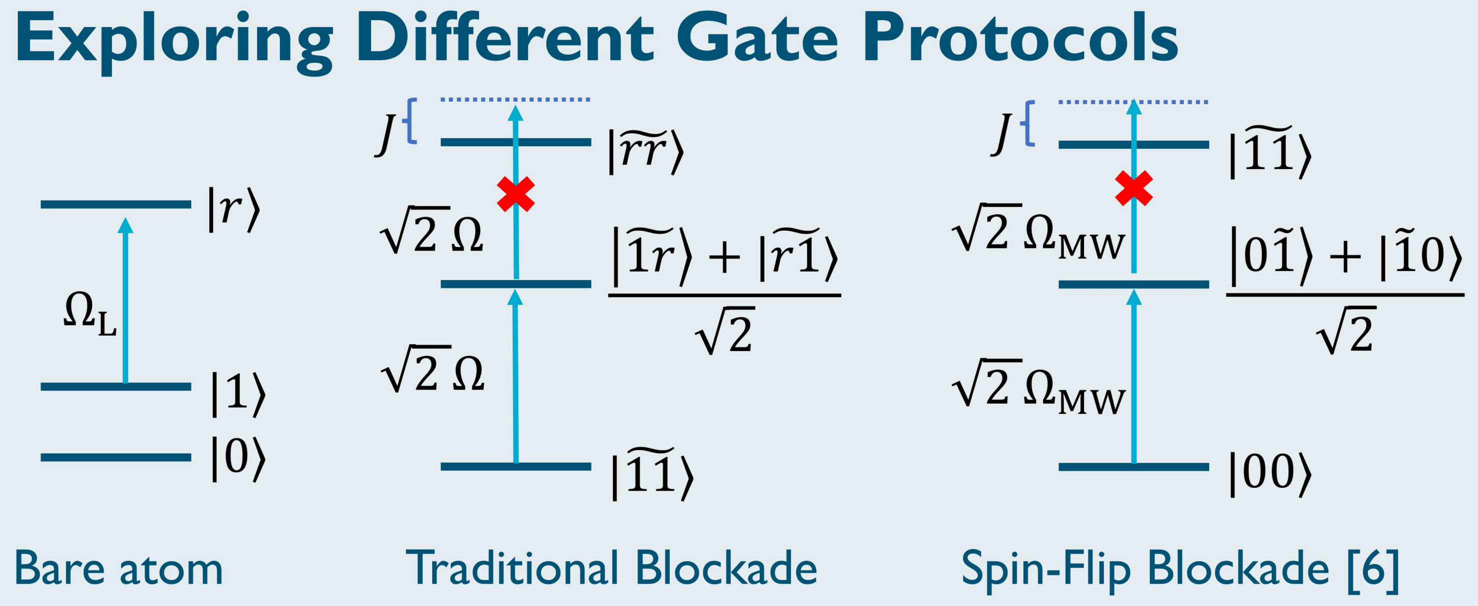
- For Rydberg excitation, we use a direct (single photon) approach:
  - Excited state: n=64
  - λ=319 nm
- A Faraday cage (in vacuum) shields the atoms from electric fields and allows control on all 3 axes.





Left: Experiment apparatus with vacuum chamber and objective lenses. Right: Faraday cage

Exploring Different Gate Protocols

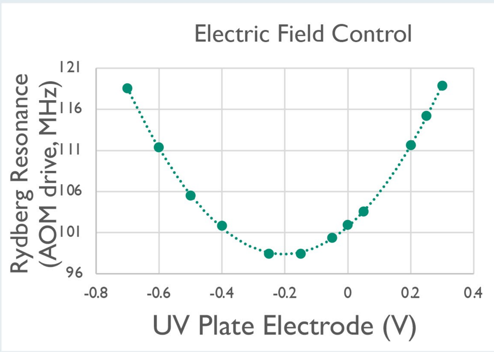


Protocols

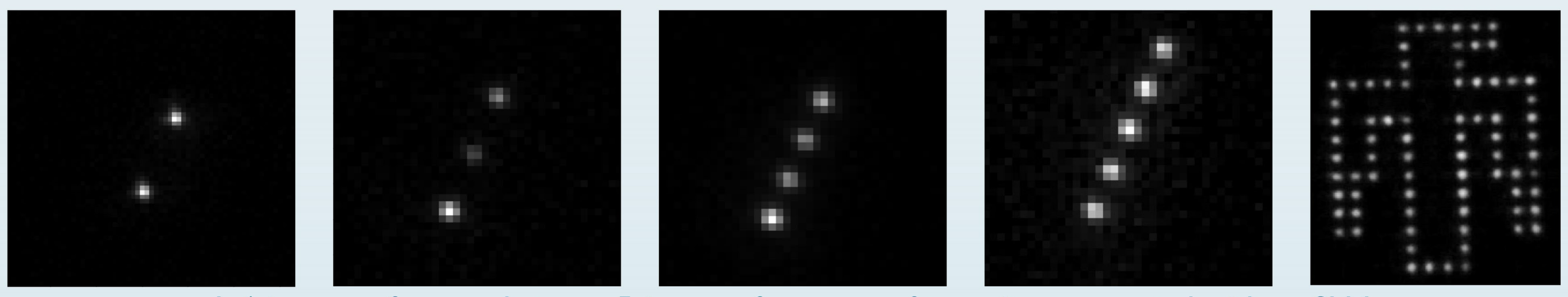
- Optical vs microwave
- Adiabatic vs dynamical
- Optimal control

Platform Challenges and opportunities

- Electric field stability
- Atom motion
- UV laser system
- Coherence of single and 2-qubit interactions



The Path Forward



1-4: images of trapped atoms; 5: image of an array of trap sites generated with an SLM

- Test the performance of various gates
- 2D array of atoms (crossed AODs)
- Gate Set Tomography and quantum benchmarking

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[1] Buchemmavari et al., arXiv:2307.16434 (2023)
[2] Mitra et al., PRA 101 (2020): 030301
[3] Evered et al., arXiv:2304:05420 (2023)
[4] Schlosser et al., PRL 89.2 (2002)
[5] Chow, Little, & Jau, PRA 108.3 (2023): 032407
[6] Y.-Y. Jau, et al., Nat Phys 12.1 (2016)