Robust quantum logic in neutral atoms via adiabatic Rydberg dressing

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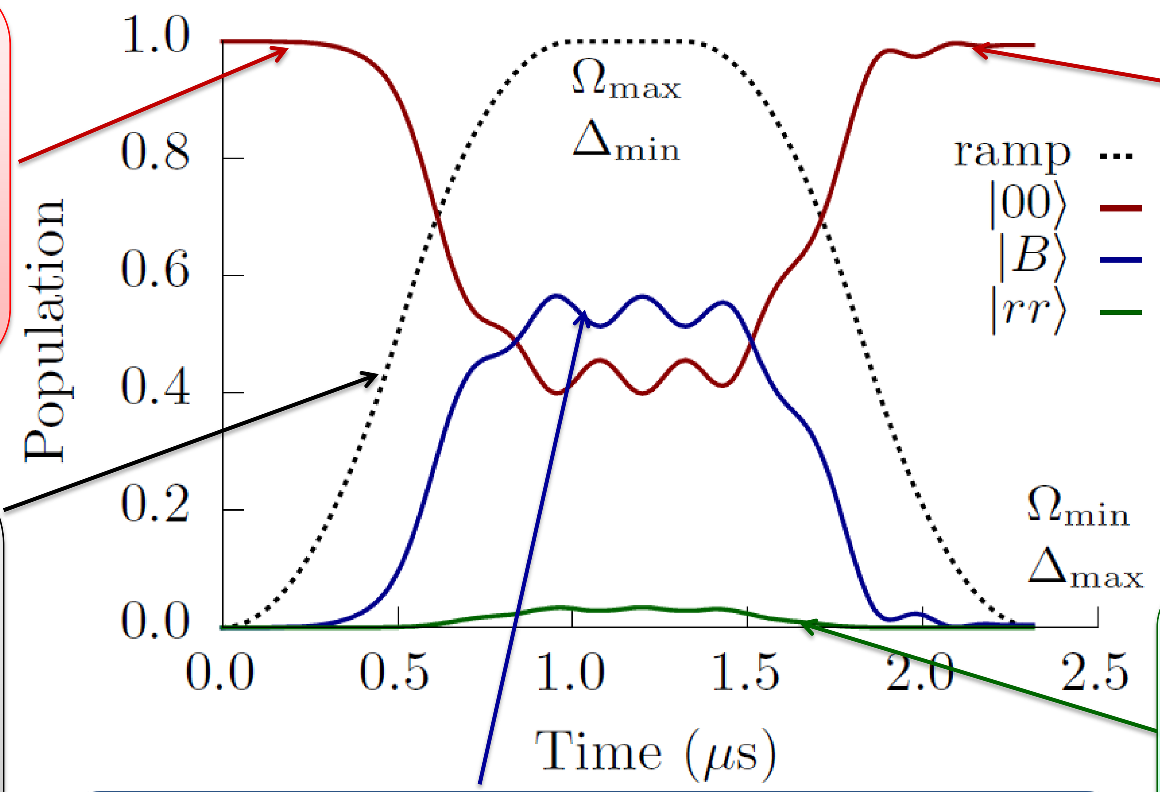
Motivation

- The Rydberg blockade effect is a promising tool for quantum logic gates in neutral atom qubits.
- In experimental efforts to produce such a gate, errors arising from the atoms' thermal motion have been primary limiting factors to the achievable fidelity.
- Adiabatic processes are known to be robust against some types of noise – might we be able to use adiabaticity to suppress these motional errors?

Gate Architecture

1. Both atoms start in electronic ground states. Specifically, the logical basis states $\{|0\rangle, |1\rangle\}$ are hyperfine states in the atomic ground manifold.

2. A 319 nm laser, couples the $|0\rangle$ state to a high-lying Rydberg state $|r\rangle$. The laser power is slowly, smoothly turned up to maximum, while its detuning is swept onto resonance.



3. The two atom ground state $|00\rangle$ is now "dressed" by significant admixture of the entangled bright state $|B\rangle$. This dressing causes it to accumulate an entangling phase over time.

4. The Rydberg dipole interaction "blockades" the $|rr\rangle$ state, strongly suppressing double-excitation.

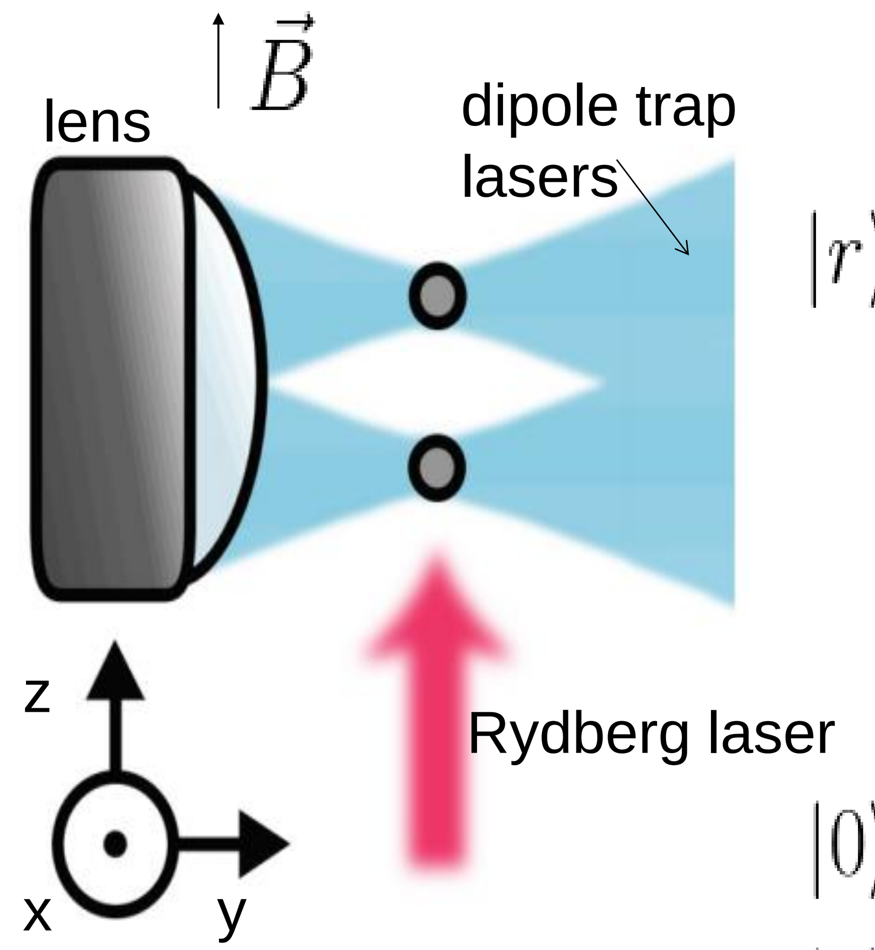
5. When the desired phase is accumulated, the laser is ramped back down and swept far off resonance. This returns the atoms to stable ground states while preserving entanglement.

Quantitatively, Rydberg-dressing a single atom imparts a light shift energy $E_{LS}^{(1)}$, while dressing two atoms at once imparts an energy $E_{LS}^{(2)}$. Because of the blockade interaction, the two-atom collective light shift will be less than the total shift for two atoms dressed separately. The "differential light shift" between these two cases can be used to generate entanglement:

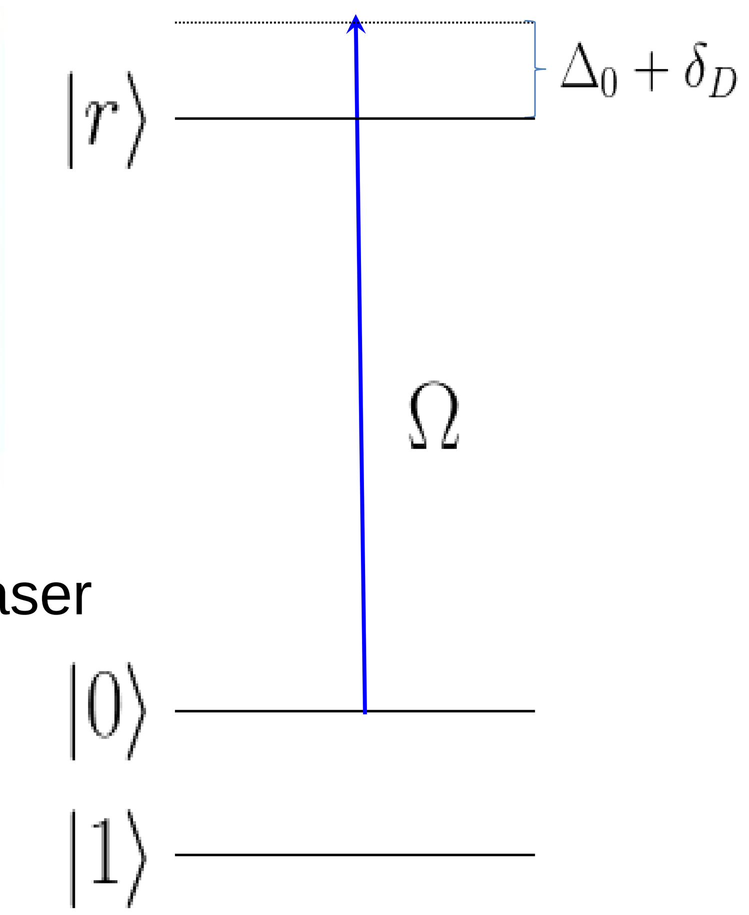
$$J = E_{LS}^{(2)} - 2E_{LS}^{(1)}$$

See Yuan-Yu Jau's talk in Session 7 for the latest on producing J experimentally!

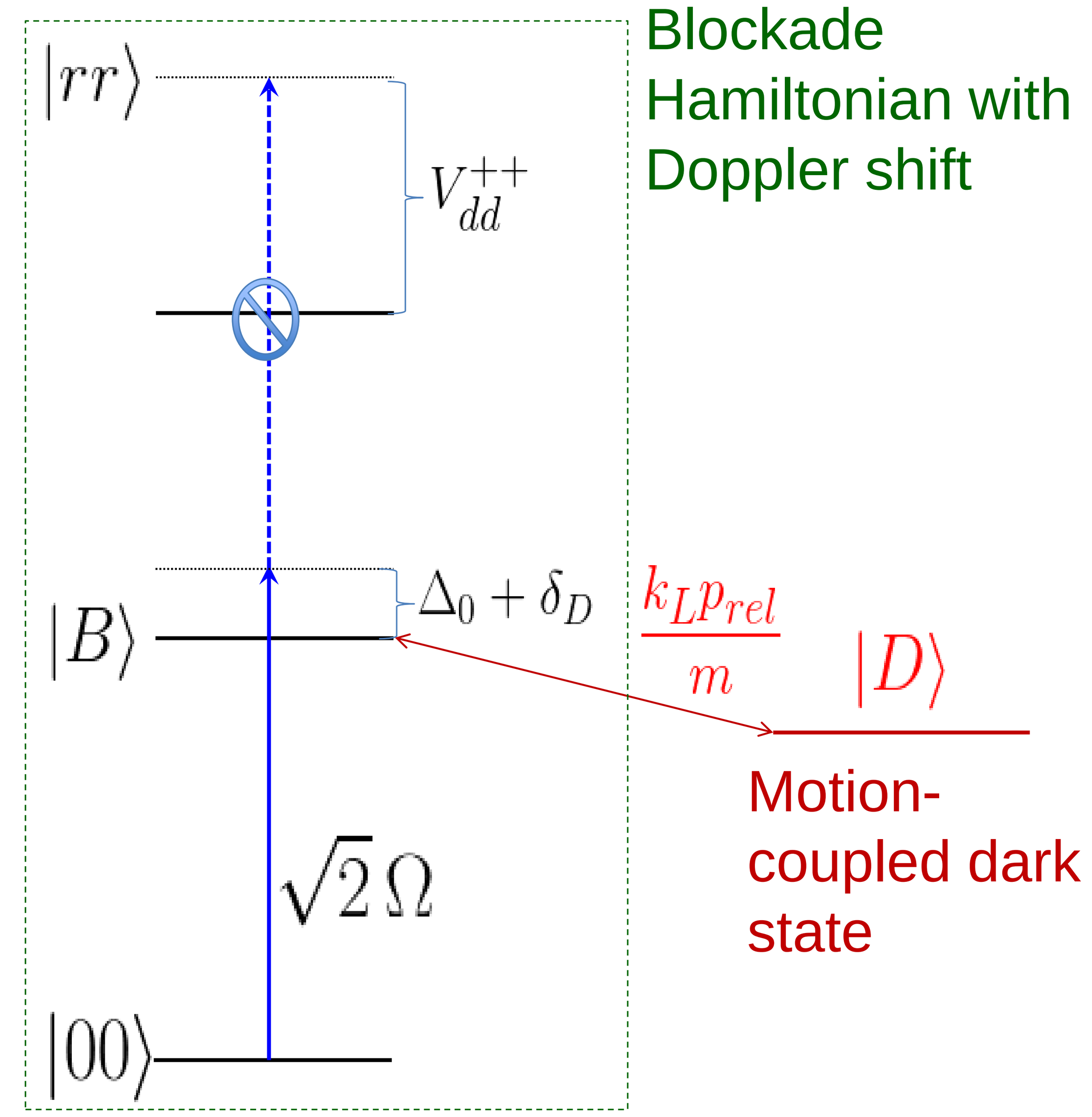
Single-beam design



The trapped atoms are illuminated by a single laser, with wavenumber k_L, to drive Rydberg excitations.



Each atom's logical $|0\rangle$ state is coupled to the Rydberg state, with a base detuning Δ_0 and a Doppler shift $\delta_D = k_L * p$.



In the 2-atom basis, $|00\rangle$ is light shifted off the entangled bright state:

$$|B\rangle = \frac{1}{\sqrt{2}}(|0r\rangle + |r0\rangle)$$

while the double-Rydberg state is blockaded. The atoms' *center-of-mass* motion leads to a Doppler shift, while their *relative* motion couples them to a dark state outside the ideal subspace.

Since the dark state lies outside the subspace of the ideal Hamiltonian, population transfer can be suppressed through adiabatic following. Residual errors from p_{rel} are small.

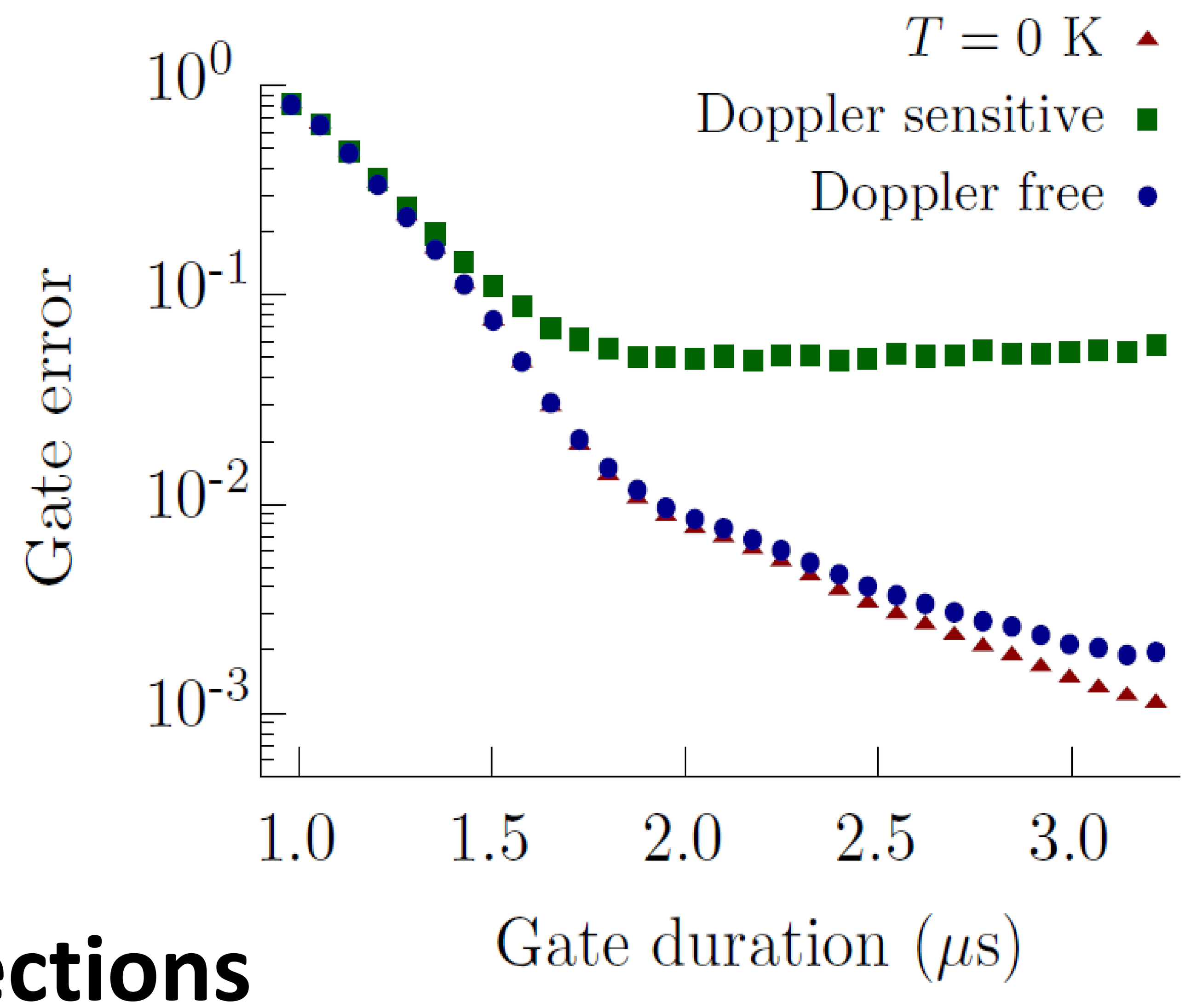
The Doppler shift modifies the Hamiltonian within the ideal subspace, so adiabatic following cannot protect against its effects. Fluctuations in the light shift strength due to center-of-mass motion are a primary error source, even at low temperatures.

In particular, by choosing parameters to generate a total phase of π, we can make a controlled-X gate, which can be turned into a controlled-NOT with only single-atom controls.

$$\int J(t)\, dt = \pi \;\rightarrow U_{gate} = |11\rangle\langle 11| + |10\rangle\langle 10| + |01\rangle\langle 01| - |00\rangle\langle 00|$$

Simulated Performance

- Simulated gate fidelities with Rabi rate $\frac{\Omega}{2\pi} = 3$ MHz and dipole interaction strength $\frac{V_{dd}}{2\pi} = 6.4$ MHz, at 16 μK.
- For gate durations less than ~2 μs, the ramp is too fast to be adiabatic, and both gate designs perform poorly.
- For longer durations, the single-beam design is limited by Doppler noise and bottoms out at ~96% fidelity.
- The Doppler-free design suppresses Doppler noise by more than an order of magnitude; fidelity is now at ~99.8%, limited mainly by finite blockade strength.
- These fidelities are close to those from photon scattering alone, which set a fundamental limit on this architecture independent of temperature.



Future Directions

This scheme exploits a two-body instance of the Rydberg blockade, but the blockade can be a many-body effect. With 3 atoms, for instance, the coupled bright state becomes:

$$|B^{(3)}\rangle = \frac{1}{\sqrt{3}}(|r,0,0\rangle + |0,r,0\rangle + |0,0,r\rangle)$$

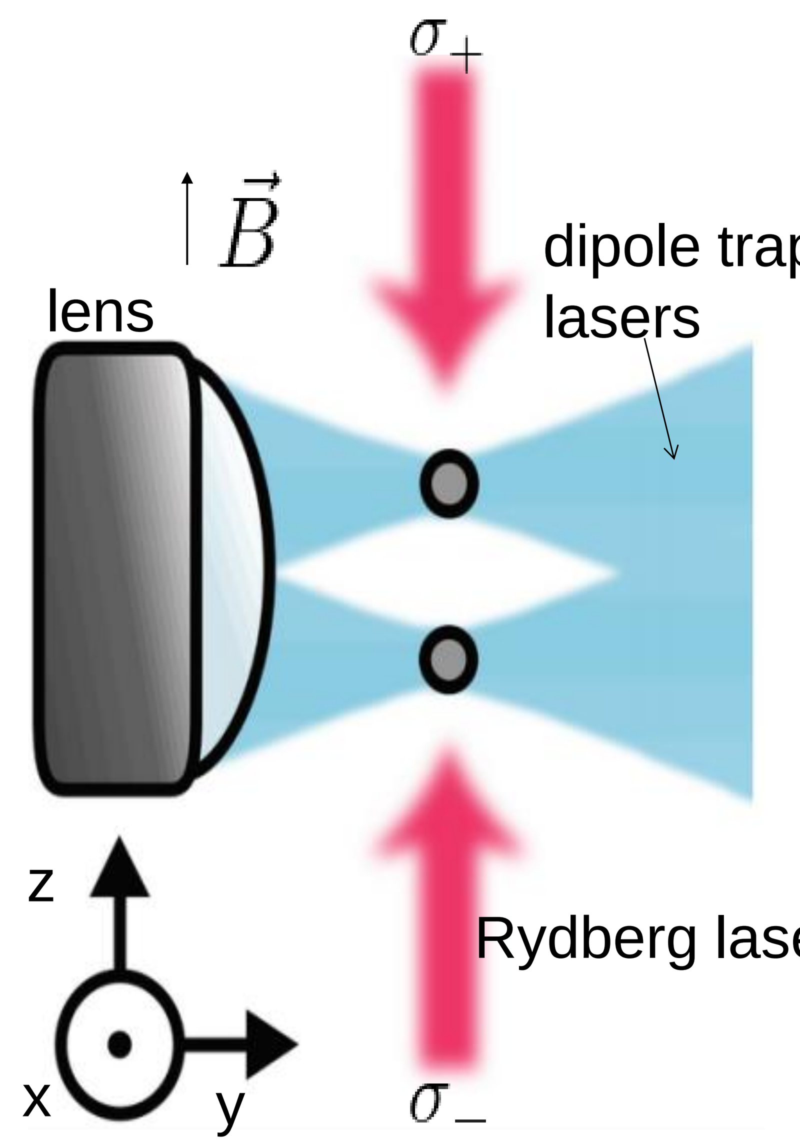
Just as dressing off the 2-atom $|B\rangle$ made something equivalent to a CNOT gate, dressing off $|B^{(3)}\rangle$ could produce a Toffoli gate, and it could do so in just one step.

If each trap site is allowed to hold a small ensemble of *N* atoms, the blockade will still only allow one Rydberg excitation per ensemble. This means each ensemble can act as a collective qubit, with enhanced coupling to the laser:

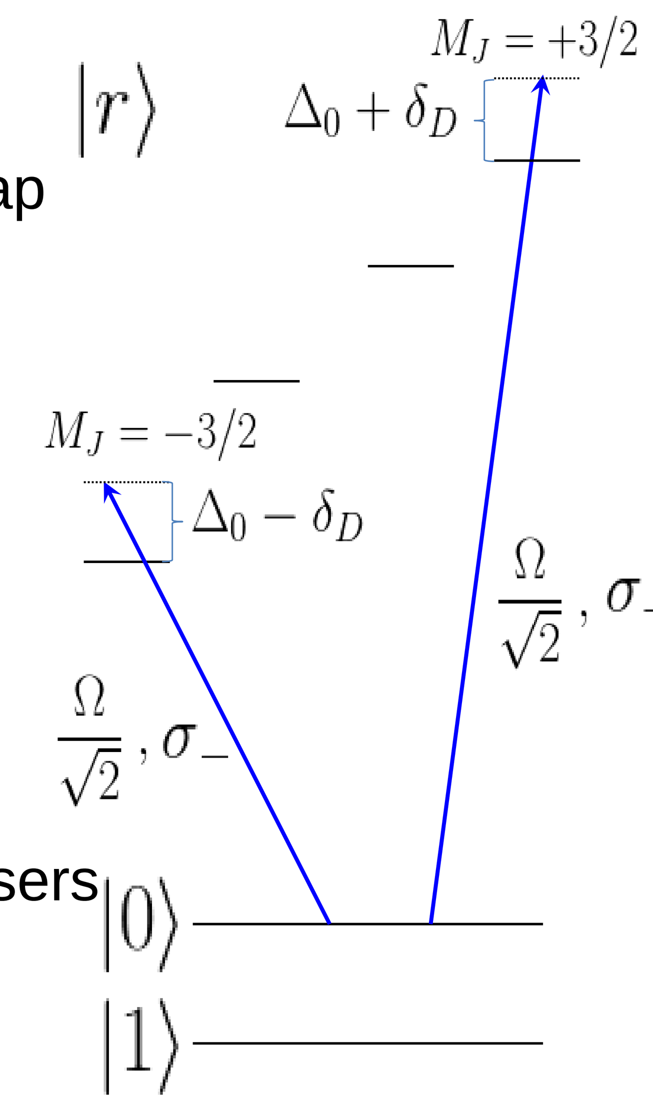
$$\Omega_{eff} = \sqrt{N}\Omega$$

A gate with ensemble qubits could be easier to set up and faster than its single-atom counterpart, but statistical variations in *N* mean the gate must be robust to variations in Ω.

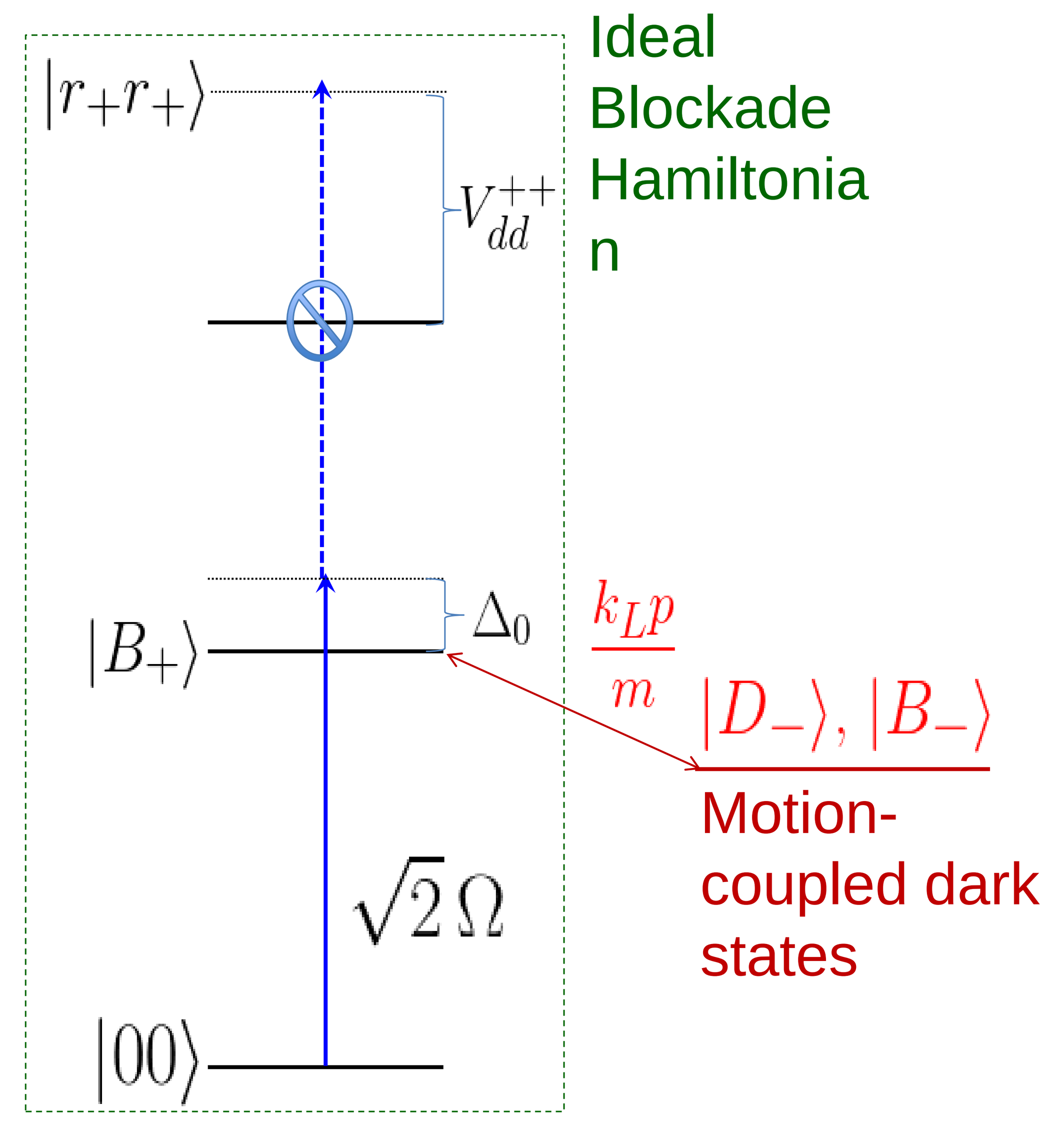
"Doppler-Free" Design



The trapped atoms are illuminated by two counter-propagating lasers, with equal frequencies but opposite circular polarizations.



Each laser couples the atom's $|0\rangle$ state to a different magnetic sublevel of $|r\rangle$. These transitions have equal base detunings but opposite Doppler shifts.



In the 2-atom basis, $|00\rangle$ is coupled to a more complicated bright state,

$$|B_+\rangle = \frac{1}{2}(|0r_1\rangle + |r_1 0\rangle + |0r_2\rangle + |r_2 0\rangle)$$

The opposite Doppler shifts cancel out for this collective state, and all motional error now takes the form of coupling to dark states.

Both relative and center-of-mass motion now couple to states outside the ideal subspace, so adiabatic evolution suppresses both of them. ✓

By evolving sufficiently slowly, motional errors can be reduced by more than an order of magnitude, to the point where photon scattering and imperfect blockade strength become more significant. ✓

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