THE UNIVERSITY OF ARIZONA
Wyant College
of Optical Sciences

Trapped Ion Quantum Computing Gates

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Final Presentation
12/8/23

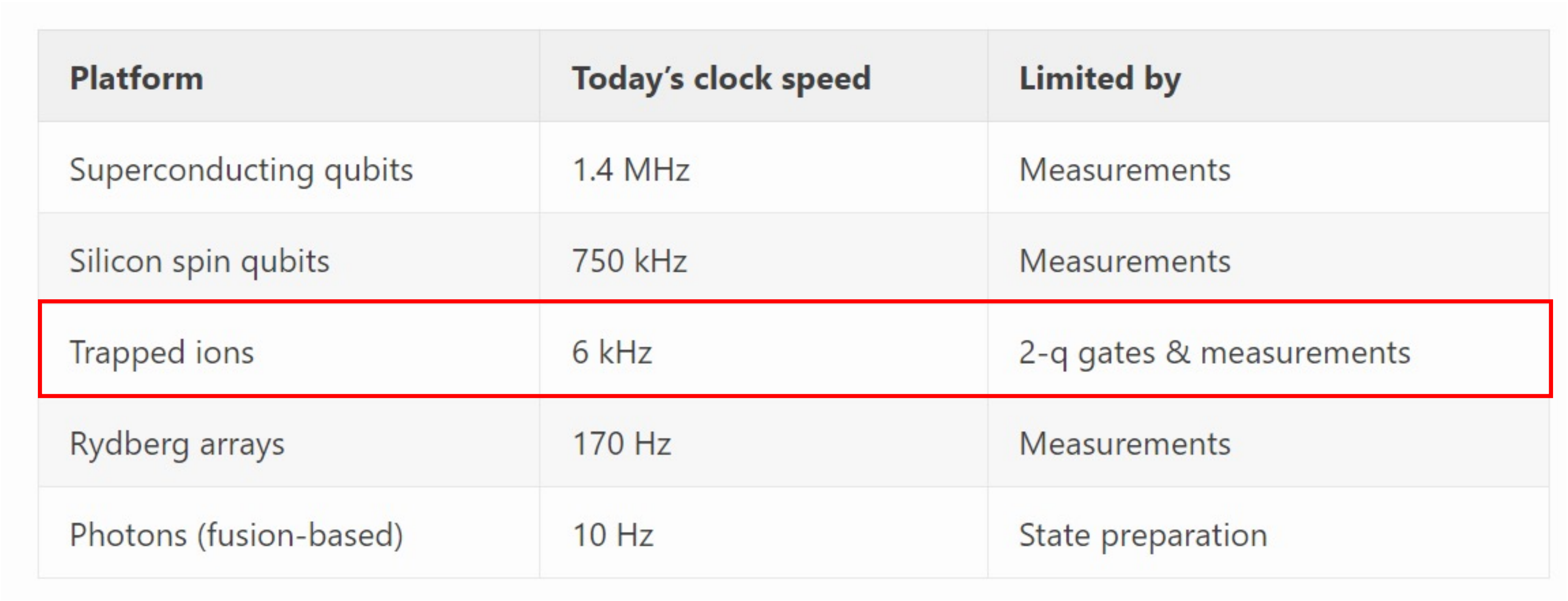
Outline

1. Review of Trapped Ion Quantum Computers
    a. What do we need and how do trapped ions give us this?
    b. Physical Implementation, etc.
2. Different Qubit Types in trapped ions
    a. Zeeman Qubits
    b. Hyperfine Qubits
    c. Optical Qubits
3. Laser based Gates in Trapped Ion Computing
    a. Mølmer-Sørensen Gate
    b. Light Shift Gate

DiVincenzo Criteria

1) A physical system containing well-defined two-level quantum systems, or qubit, which can be isolated from the environment.
2) The ability to initialize the system into a well-defined and determinate initial state.
3) Qubit decoherence times much longer than the gate times;
4) a set of universal quantum gates which can be applied to each qubit (or pair of qubits, in the case of two-qubit gates).
5) The ability to read out the qubit state with high accuracy.

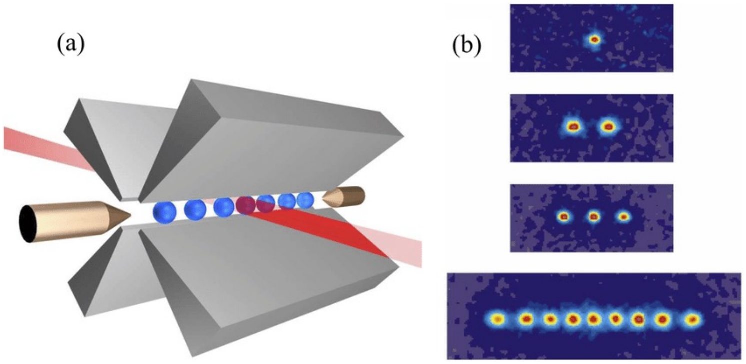
General Gate Speeds



Platform	Today's clock speed	Limited by
Superconducting qubits	1.4 MHz	Measurements
Silicon spin qubits	750 kHz	Measurements
Trapped ions	6 kHz	2-q gates & measurements
Rydberg arrays	170 Hz	Measurements
Photons (fusion-based)	10 Hz	State preparation

https://m-malinowski.github.io/2022/12/04/how-fast-are-quantum-computers-part-2.html

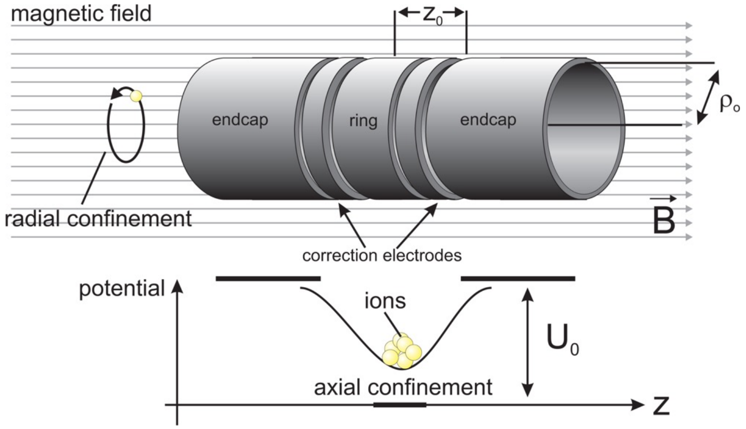
Review: Ion Traps



A linear Paul trap cartoon and pictures of trapped ions

- Uses quadrapole switchingelectric fields in 2 directions and a single static in one
- Used for ease of construction
- Most commonly used
- Approximately harmonic potential

Eltony, Amira & Gangloff, Dorian & Shi, Molu & Bylinskii, Alexei & Vuletic, Vladan & Chuang, Isaak. (2016). Technologies for trapped-ion quantum information systems. Quantum Information Processing. 15. 10.1007/s11128-016-1298-8.



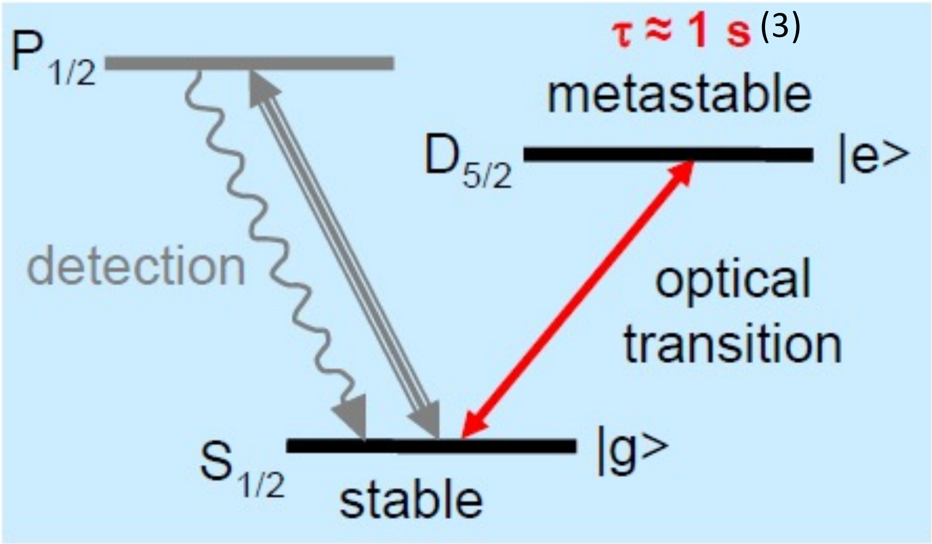
A Penning trap and of trapped ions cartoons

- Uses quadrapole electric fields in 2 directions and a single static in one
- Allows for much larger trap
- Not as common…yet?

Vogel, M.; Quint, W.; Nörtershäuser, W. Trapped Ion Oscillation Frequencies as Sensors for Spectroscopy. *Sensors* **2010**, *10*, 2169-2187. https://doi.org/10.3390/s100302169

Review: Trapped Ion Computers

- Load/Cool Ions in trap (1/2)
- Generate entanglement/initialize states (2/4)
- Perform additional qubit operations (4)
- Read-out of states (5)
  - Most common method is fluorescence via s → p transition (cycling transition)



Colin D. Bruzewicz, John Chiaverini, Robert McConnell, Jeremy M. Sage
Trapped-ion quantum computing: Progress and challenges, *Appl. Phys. Rev.* 6, 021314 (2019)
https://doi.org/10.1063/1.5088164

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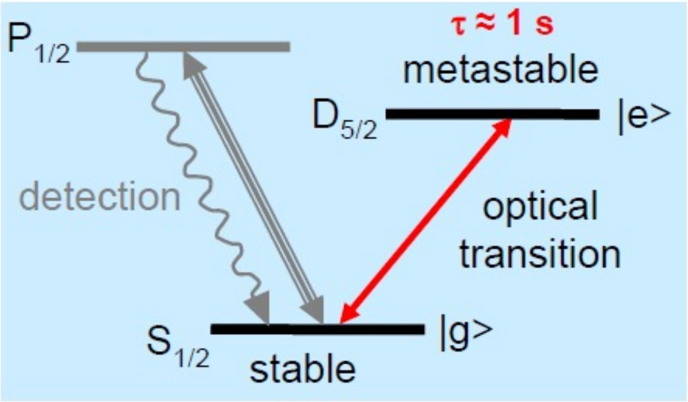
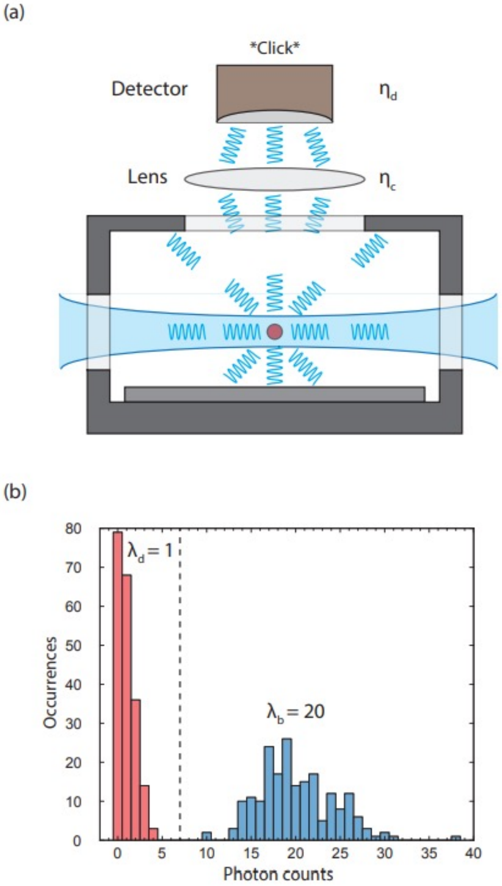
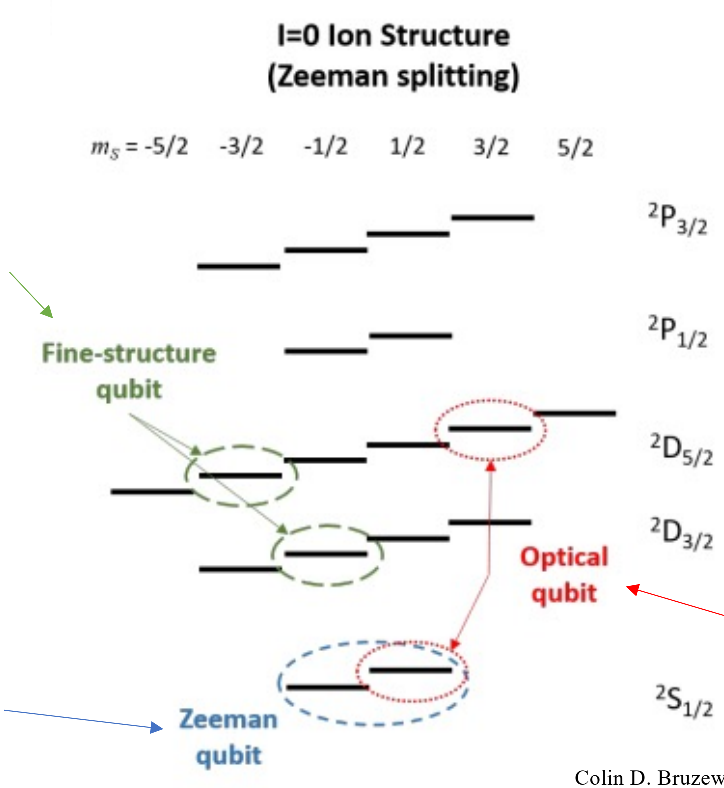




Poisson Distributions

Different Qubits for Trapped Ions



Fine-structure qubits – GHz Range

Optical qubits – Hundreds of THz Range

Zeeman qubits – MHz Range

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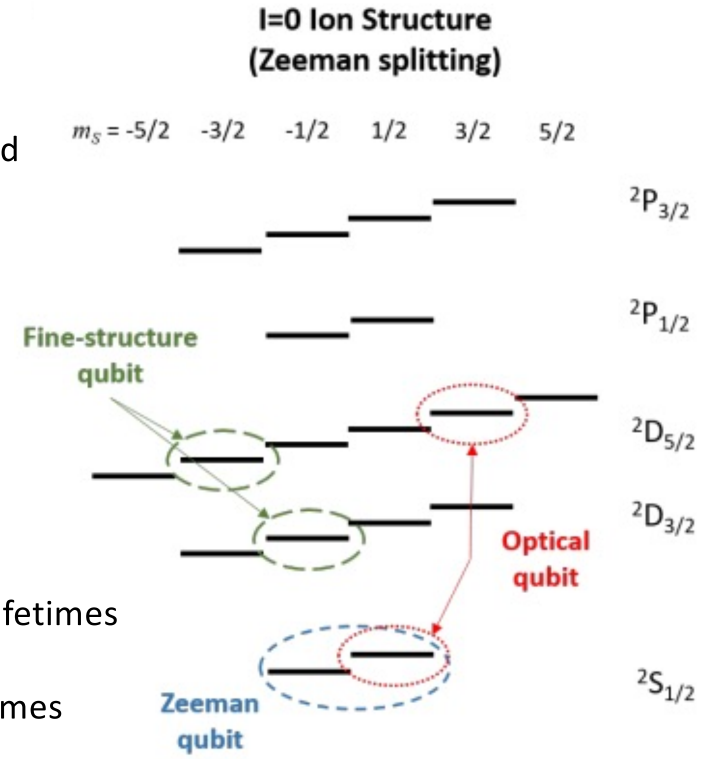
Different Qubits for Trapped Ions

- Zeeman qubits (MHz)
  - Extremely long coherence times
  - Gates typically through Optical Raman transitions
  - Need to split sublevels with magnetic field
    - Almost by definition these gates are sensitive to magnetic field
  - Need an ‘auxiliary’ step to readout
    - Optical readout can couple to either state
    - Typically use ‘shelving’, which requires access to D-states
- Hyperfine qubits (GHz)
  - Also have very long coherence times
  - Require ions with non-zero nuclear spin
  - Less sensitive to magnetic fields than Zeeman qubits
  - Can directly read out due to larger splitting of states
- Optical qubits (Hundreds of THz)
  - Need ultranarrow linewidth lasers to fully take advantage of long lifetimes
  - Extremely high readout fidelity due to optical separation of states
  - 10s of seconds coherence time limitations due to upper-state lifetimes
  - Wavelength sources are in VIS and NIR
  - Easier to address individual qubits (diffraction limit)



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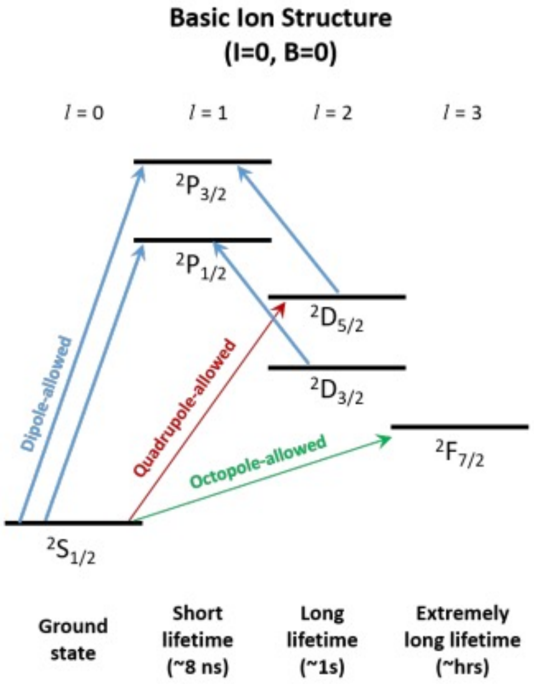
Laser-based Gates

- Usually, a first order magnetic field insensitive transition is desired ($m_f = 0, m'_f = 0$) (either for raman or optical transitions)
  - Often referred to as a “clock transition”
- $\eta = \frac{\Delta k q}{\sqrt{2}}$ is the Lamb-Dicke Parameter
  - If $\eta^2 \left(n + \frac{1}{2}\right) \ll 1$, we only change motional quantum number by ± 1
- Common gates (two-qubit)
  - Cirac and Zoller
  - Mølmer-Sørensen Gates
  - Leibfried’s geometric-phase gate / Light Shift Gates



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Mølmer-Sørensen Gates

First proposed by Klaus Mølmer and Anders Sørensen in 1999, as an alternative to the Cirac-Zoller Gate.

- This gate is insensitive to the vibrational states of the two qubits (no need to cool completely to motional ground state)
- Uses red and blue sidebands to create interference of pathways, leading to lack of photon interaction

Hamiltonian

$$H_{ms} = H_{rsb} + H_{bsb} + H_c + H_{HO} \xrightarrow[\text{RWA}]{2^{\text{nd}}\text{ order PT}}$$

Maximally entangled with $\frac{\pi}{2}$ pulse (Bell States)

e.g.

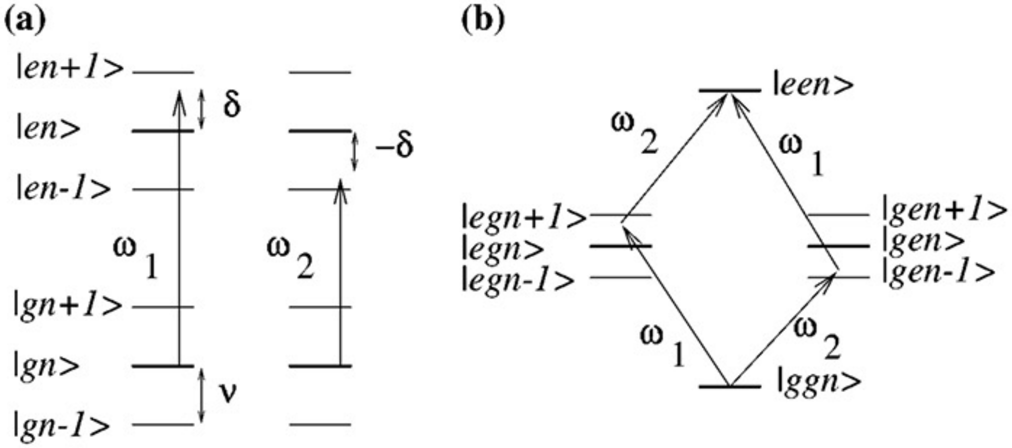
$$|gg\rangle \rightarrow \cos\left(\frac{\Omega t}{2}\right)|gg\rangle + i\sin\left(\frac{\Omega t}{2}\right)|ee\rangle$$

Phonon Independent!

Sørensen, Anders; Mølmer, Klaus (March 1, 1999). "Quantum Computation with Ions in Thermal Motion". *Physical Review Letters*. **82** (9): 1971–1974. arXiv:quant-ph/9810039

Mølmer-Sørensen Gates

- These gates can be directly applied to clock transitions, which allow for long lived states.
- Phase of driving fields are extremely important
  - Any phase/frequency difference on sidebands will cause partial loss of destructive interference. This will allow "leakage" of motional modes into the two-qubit gate (noise).



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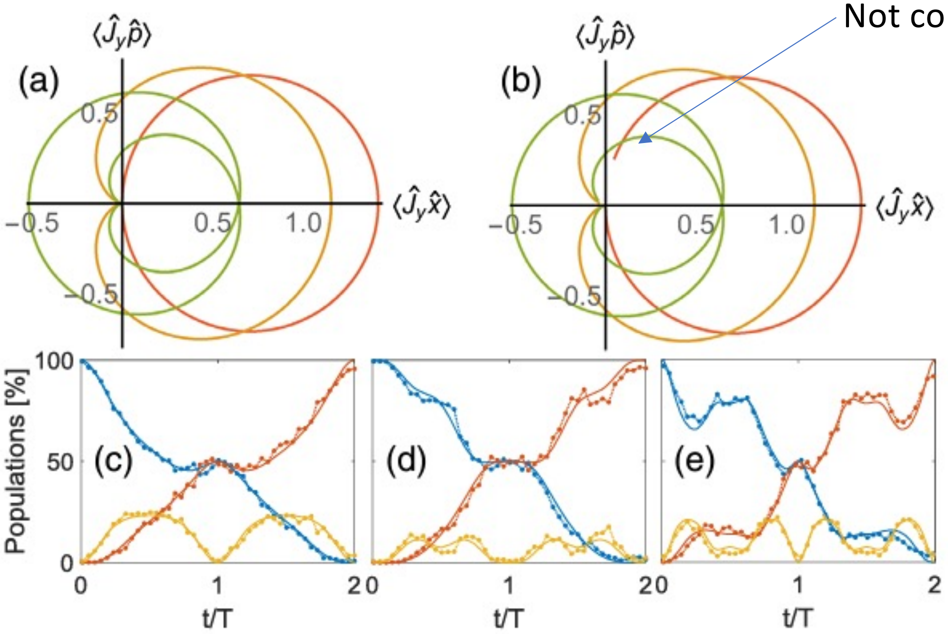
Multi-Sideband Mølmer-Sørensen Gates

Driven at 313 nm! UV is difficult!

Yotam Shapira,*Ravid Shaniv, Tom Manovitz, Nitzan Akerman, and Roee Ozeri, Robust Entanglement Gates for Trapped-Ion Qubits, PRL 2018, DOI:10.1103/PhysRevLett.121.180502



Not completed

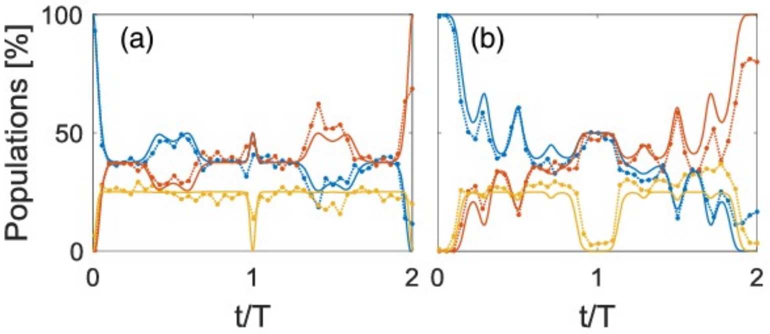


FIG. 2. Finite-temperature gates. Here ions are Doppler cooled to $\bar{n} \approx 9.8$. Color coding is identical to that of Fig. 1(c). (a) Antioid(2,3) gate population evolution. A narrow change around $t = T$ marks ion entanglement. Gate fidelity is very sensitive to timing errors. (b) Cardioid(2,3,7,8) gate population evolution. Using four tones increases the robustness, resulting in a wide feature around gate time.

- ‘Cardioid’ gates are generalized MS gates, using multiple sidebands
- Gates are much more robust against timing errors

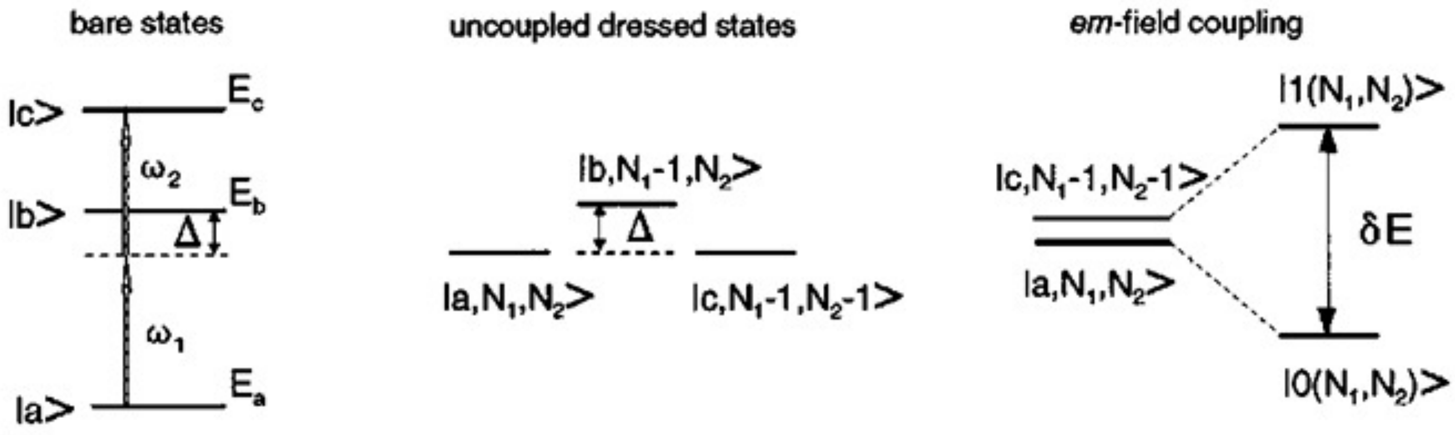
Multi-Sideband Mølmer-Sørensen Gates

- These gates along with single qubit gates form a universal gate set!
- Many of these demonstrations were in the UV which is difficult.
  - Scalability and different platforms (waveguides, etc.) are not currently feasible
- High frequency (GHz) sidebands can be hard to control
- Complexity helps solve timing/phase noise problems, but is it worth?

- Light shift gates solve some of these issues…

Light Shift Gates/ Geometric Phase Gates

- A light shift is also called an AC Stark Shift
- The interaction with the driving field and the atom causes an electronic resonance shift.



Two photon transition.
Enhancement of virtual state due to proximity to $|b\rangle$

A. F. Linskens, I. Holleman, N. Dam, and J. Reuss, Two-photon Rabi oscillations Phys. Rev. A **54**, 4854 – Published 1 December 1996

Light Shift Gates/ Geometric Phase Gates

- This can also be thought of a force acting on the atomic dipole.
- When driving two-ions qubits in harmonic potentials, the motional states acquire phase, which with other single qubit gates can be used for entanglement
- “Spin Dependent Force”

$D(\alpha) = \exp(\alpha a^{\dagger} - \alpha^{*} a)$ Single displacement in phase space of motion

$D(\alpha)D(\beta) = \mathrm{D}(\alpha + \beta)\exp(iIm[\alpha\beta^{*}])$ Consecutive displacements

- Use two lasers detuned by roughly motional mode frequency
- $\Delta k = k_1 - k_2$ parallel to trap axis (exciting modes along trap axis)
- Only if ions are in opposite spin states is the stretch mode excited, and ions entangled

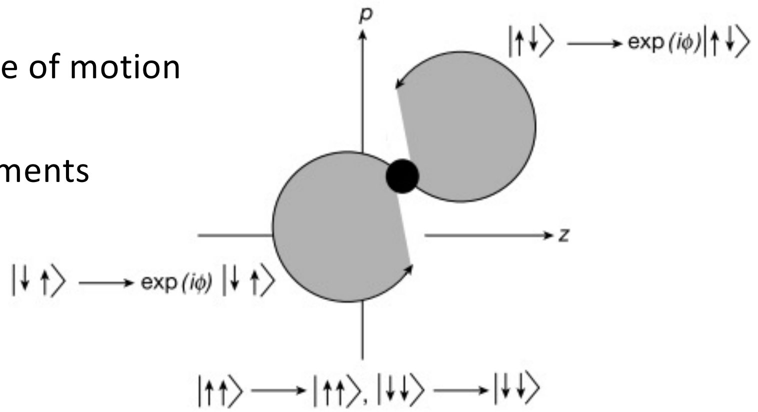


Figure 1 Phase space representation of the stretch-mode amplitude of two trapped ions. The displacement drive moves the motional state components associated with the $|\downarrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$ internal states around circular trajectories in phase space as indicated. Both components acquire the same phase because the enclosed area and sense of rotation are equal.

Leibfried, D., DeMarco, B., Meyer, V. *et al.* Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. *Nature* **422**, 412–415 (2003). https://doi.org/10.1038/nature01492

Light Shift Gates/ Geometric Phase Gates

- Spin echo technique used to measure state entanglement
- By tuning $t < T_s$ the entangled state will vary, and the fluorescent level will drop after spin echo pulses ($\pi, \frac{\pi}{2}$)

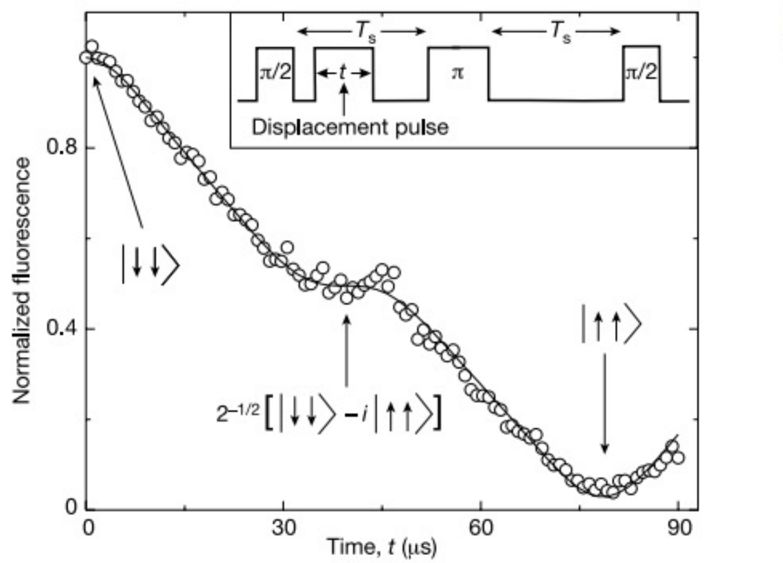


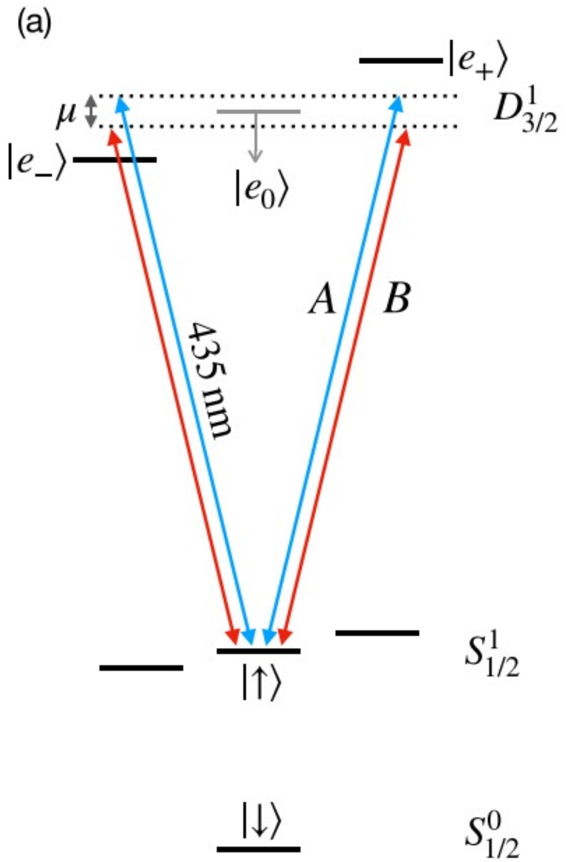
Figure 2 State evolution upon displacement. Normalized fluorescence signal (see Methods) after inserting a displacement pulse of variable duration into a spin-echo experiment that is applied to the $|\downarrow\downarrow\rangle|0\rangle$ state (see inset). The motional state returns to its point of origin after every 39 μs, leading to an approximate state $2^{-1/2}(|\downarrow\downarrow\rangle - i|\uparrow\uparrow\rangle)|0\rangle$ after 39 μs and to the approximate state $|\uparrow\uparrow\rangle|0\rangle$ after 78 μs. The

Leibfried, D., DeMarco, B., Meyer, V. *et al.* Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. *Nature* **422**, 412–415 (2003). https://doi.org/10.1038/nature01492

Light Shift Gates/ Geometric Phase Gates

Implementation from Honeywell (~20 years later)

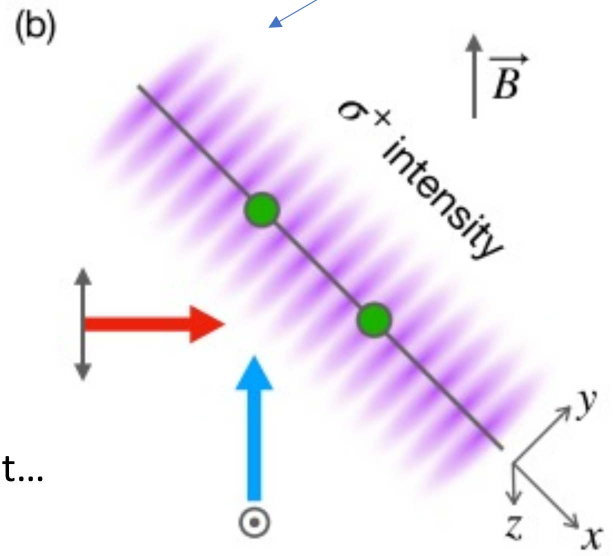
- First demonstration on clock transition
- Wanted longer lifetimes, so using s→d transition (quadrapole transition)
- Two beams used, oppositely detuned from $|e_0\rangle$
  - Average zero-stark shift (otherwise, would lead to decoherence)
  - This also means less sensitivity to laser intensity



Baldwin, C. H., et al. "A high fidelitylight-shift gate for clock-state qubits."arXiv preprint arXiv:2003.01102(2020)

Light Shift Gates/ Geometric Phase Gates

- Again, coupling to the stretch mode
  - Ions spaced by integer number of Δk
- The polarizations are chosen to ensure $\Delta m_f = \pm 1$
  - Ensure no coupling to $|e_0\rangle$
- Detuning between two lasers is close to stretch mode frequency ω_s



"Polarization gradient"

- Final note: this has not been established as a universal gate set…

Baldwin, C. H., et al. "A high fidelitylight-shift gate for clock-state qubits."arXiv preprint arXiv:2003.01102(2020)

Summary

- Trapped Ions meet the DiVincenzo Criteria
- There are trade-offs depending on the qubits used
  - Lifetimes/ease of use
  - Control and noise
- Universal gate sets are the biggest hurdle for small scale computing
- Scaling of trapped ions also presents problem for large scale computing

Questions?