

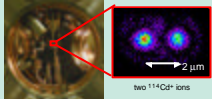
Strong Field Control of Trapped Ions: *Quantum Surfing* and Fast Quantum Logic

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Trapped Ions in Strong Fields

Ion trap fundamentals

- Trap individual ions; store quantum information in spin-states of the trapped ions
- RF (Paul) trap: ions confined in parabolic potential:

$$V = U_0 \cos(\omega_{\text{trap}} t) \left(\frac{x^2 + y^2 - 2z^2}{d^2} \right)$$


two $^{114}\text{Cd}^+$ ions

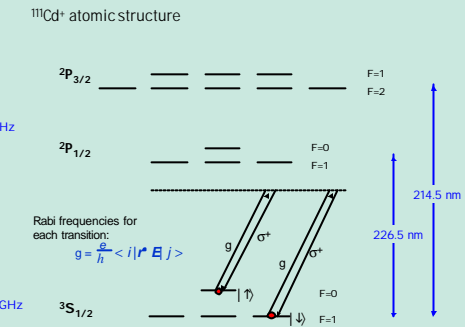
- Quantum logic gates via exchange of phonons: $\Omega_{\text{Rabi}} < \omega_{\text{trap}} \sim 1 \text{ MHz}$ (slow)

New regime: $W_{\text{Rabi}} \gg W_{\text{trap}}$

Strong Field Coupling – Spin-Dependent Force

- faster gates \Rightarrow less decoherence

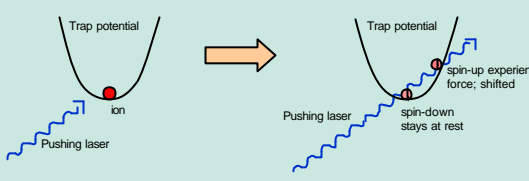
$^{111}\text{Cd}^+$ atomic structure



Rabi frequencies for each transition:
 $g = \frac{e}{h} \langle i | \mu^x | j \rangle E_j$

- Spin-up state experiences larger AC Stark shift, thus stronger force

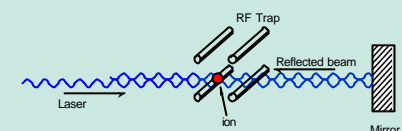
Using spatially-dependent Stark shift to produce spin-dependent force



(Large) Schrödinger-cat states of motion

Quantum Surfing on a Standing Wave

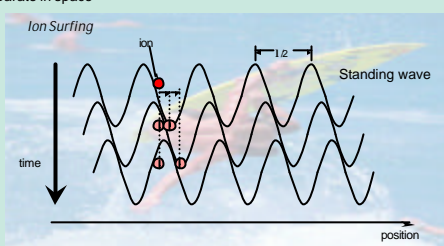
Using a standing wave to create high E-field gradient



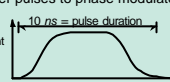
- Problem:** maximum ion displacement limited to $\lambda/2$
- Solution:** phase-modulate the standing wave to shift the pattern in space. Ion "surfs" on the wave!

- If a spin-dependent force is applied by the standing wave, spin states separate in space

Ion Surfing



- Chirping laser pulses to phase-modulate the standing wave:



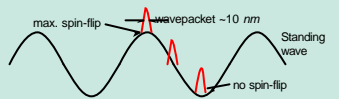
- Self-phase modulation or
- Fast EO phase modulator

Example: 228.5 nm (Positive Light's *Indigo DUV* tunable $\text{Ti:Al}_2\text{O}_3$)
 $10 \mu\text{J}$ in 10 ns pulse = 1 kW average power, focused to $5 \mu\text{m}$

Rabi frequency: $\Omega_{\text{Rabi}}/2\pi \sim 150 \text{ GHz}$
 Max. displacement: $k\delta \sim \eta^2 \Omega_{\text{Rabi}}^2 / \omega_{\text{trap}}^2 \sim 6 = 1.37 \mu\text{m}$

Stabilizing an atom to a standing wave:

- fundamental limit of optical atomic control
- nanometer-scale imaging (Heisenberg microscope)



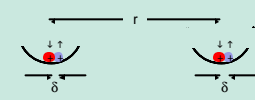
- important in precision measurements:
 - optical frequency standards Th. Udem *et al.*, Phys. Rev. Lett. **86** 4996 (2001)
 - parity non-conservation N. Fortson, Phys. Rev. Lett. **70** 2383 (1993)
- improved trapped ion quantum logic

J.I. Cirac and P. Zoller Phys. Rev. Lett. **74**, 4091 (1995)
 C. Monroe *et al.*, Phys. Rev. Lett. **75** 4714 (1995)

Fast Scalable Quantum Computer via Dipole-Dipole Interaction

Engineering Dipoles

- Apply surfing standing wave to two ions *simultaneously*



$$U_{\text{dd}} = \mu_1 \mu_2 / r^3 = (\epsilon \delta)^2 / r^3$$

- Quantum phase gate (a universal 2-qubit quantum logic gate):

$ \downarrow\downarrow\rangle \rightarrow \downarrow\downarrow\rangle = \downarrow\downarrow\rangle$	$\kappa = \text{linear shift}$ $\phi = \text{nonlinear shift} = 2U_{\text{dd}}t/\hbar$
$ \downarrow\uparrow\rangle \rightarrow e^{+i\kappa-i\phi/2} \downarrow\uparrow\rangle = \downarrow\uparrow\rangle$	
$ \uparrow\downarrow\rangle \rightarrow e^{-i\kappa-i\phi/2} \uparrow\downarrow\rangle = \uparrow\downarrow\rangle$	
$ \uparrow\uparrow\rangle \rightarrow e^{i\phi} \uparrow\uparrow\rangle = \uparrow\uparrow\rangle$	

- Entanglement via a phase gate:
 $(|\downarrow\rangle + |\uparrow\rangle)(|\downarrow\rangle + |\uparrow\rangle) \xrightarrow{\pi \text{ phase gate}} |\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle + |\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle$ - maximally entangled state
- π -phase gate speed: $\chi = 2U_{\text{dd}}/h - \frac{2(\eta\Omega_{\text{Rabi}})^2 (f_{\text{osc}})^3}{\omega_{\text{trap}}} = (k\delta\Omega_{\text{Rabi}}) \left(\frac{f_{\text{osc}}}{\Gamma}\right)^3$ Standing wave force
 $[r_0 = \text{ion-ion separation if in same trap} = (2e^2/m\omega_{\text{trap}}^2)^{1/3}]$
- Stark shift: $\Delta E_{\text{Stk}}/\hbar \sim \Omega_{\text{Rabi}}$
 spontaneous emission rate: $\Gamma_{\text{sp}} \sim \Omega_{\text{Rabi}}^2/\Delta$

Example: $P = 1 \text{ kW}$ standing wave, focused to $5 \mu\text{m}$
 $\Delta = 10 \text{ THz}$
 $k\delta = 1$
 $r = 10 r_0$

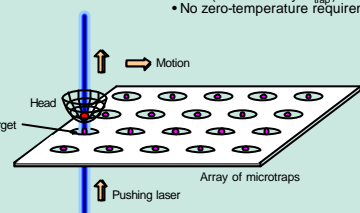
Stark shift $\sim \Omega_{\text{Rabi}}/2\pi \sim 150 \text{ GHz}$
 spontaneous emission rate $\Gamma_{\text{sp}}/2\pi \sim 1 \text{ MHz}$
 π -phase gate speed $2\pi/\gamma \sim 7 \text{ ns}$

Scalable, Fast Quantum Computer

- Quantum logic gates via dipole-dipole interaction of ions in different wells (array of microtraps)

Cirac and Zoller, *Nature* **404**, 579 (2000)

- Scalable
- Fast (not limited by ω_{trap})
- No zero-temperature requirement



- 2-qubit operations between the *Target* and the *Head* ions
- Head* moves across the plane of ion traps thus allowing entanglement between distant ions