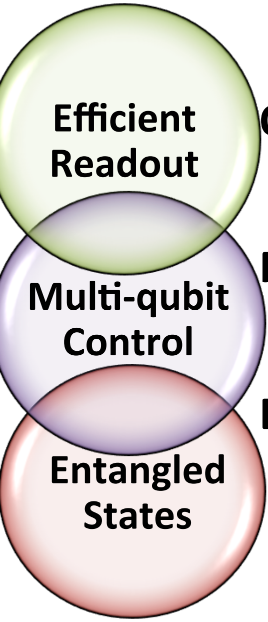
Trapped-ion metrology experiments at NIST

Ion Storage
Group
March 23, 2011

Jim Bergquist
Brad Blakestad (now JQI)
John Bollinger
Ryan Bowler
Joe Britton
Kenton Brown
James Chou
Yves Colombe
John Gaebler
David Hanneke (now at Amherst)
Dustin Hite
David Hume (now OFM)
Wayne Itano
Robert Jördens
John Jost
Dietrich Leibfried
Yiheng Lin
Christian Ospelkaus (now U Hannover)
Till Rosenband
Brian Sawyer
Ting-Rei Tan
Mike Thorpe
Ulrich Warring
Andrew Wilson
David Wineland



Quantum Measurement (Ancilla-assisted readout):
- Readout of the Al^+ clock state

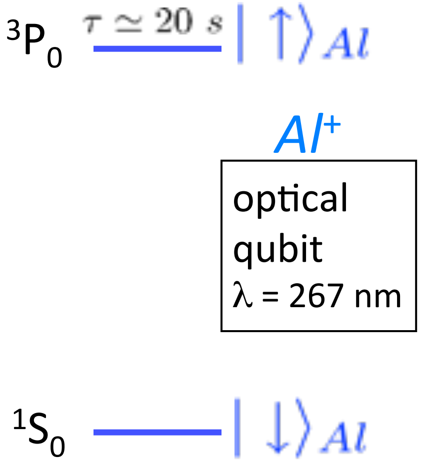
Multi-qubit control:
- Entanglement and control with many ions in Penning traps

Entangled States:
- Generation of entangled states with microwave field gradients (novel schemes)
- Coupled ion trap spectroscopy (novel systems and applications)

Theme – Shared ion motion due to strong Coulomb interaction used to generate entanglement and read out quantum states

Readout of the Al$^+$ clock state/ ancilla-assisted readout

Hume, Chou, Leibrandt, Thorpe, Wineland, and Rosenband, arXiv:11085922v2



$^3P_0$ $\tau \simeq 20\ s$ $|\uparrow\rangle_{Al}$

Al^+

optical
qubit
λ = 267 nm

$^1S_0$ $|\downarrow\rangle_{Al}$

$$\Psi = \alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}$$

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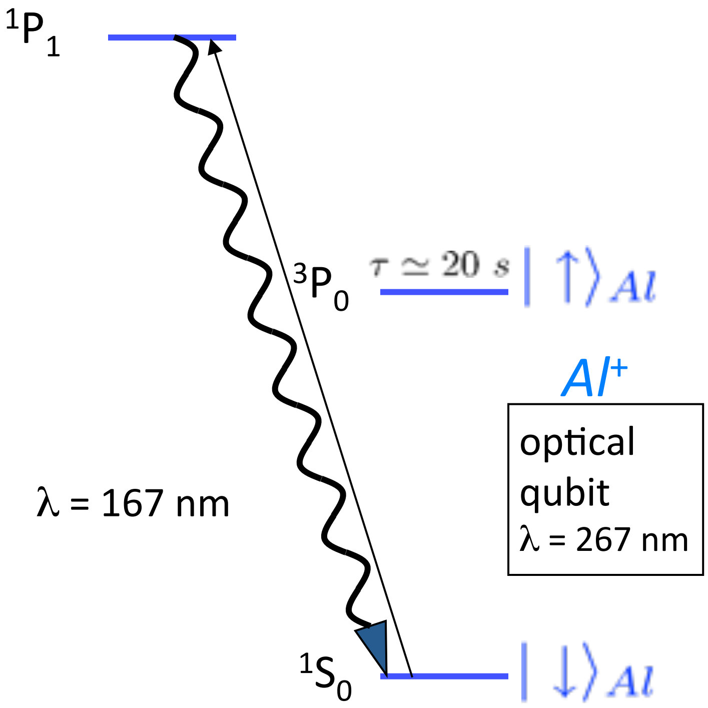


$^1P_1$

$^3P_0$ $\tau \simeq 20\ s$ $|\uparrow\rangle_{Al}$

Al^+

optical
qubit
λ = 267 nm

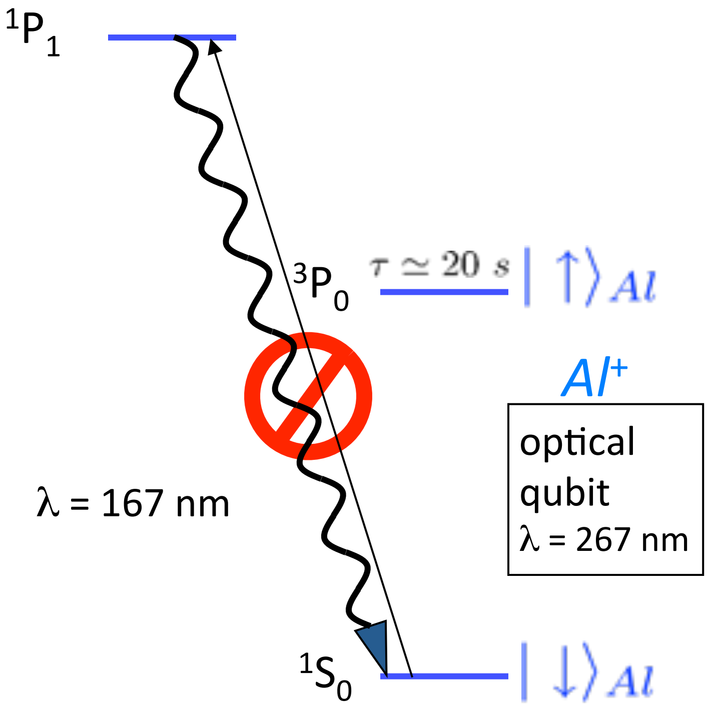
λ = 167 nm

$^1S_0$ $|\downarrow\rangle_{Al}$

$$\Psi = \alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}$$

Readout of the Al⁺ clock state/ ancilla-assisted readout

Hume, Chou, Leibrandt, Thorpe, Wineland, and Rosenband, arXiv:11085922v2

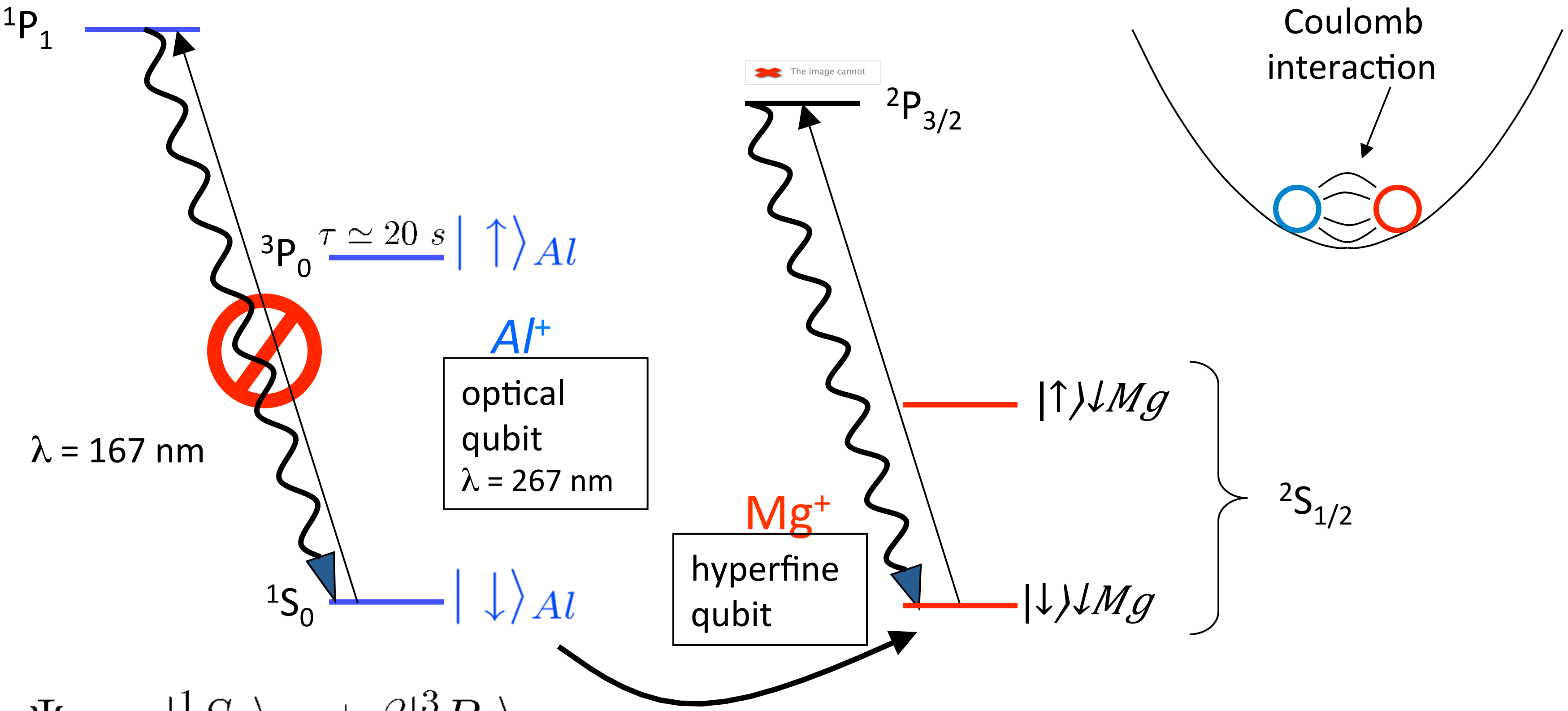


optical
qubit
λ = 267 nm

$$\Psi = \alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}$$

Readout of the Al$^+$ clock state/ ancilla-assisted readout

Hume, Chou, Leibrandt, Thorpe, Wineland, and Rosenband, arXiv:11085922v2



$$\Psi = \alpha|^1S_0\rangle_{Al} + \beta|^3P_0\rangle_{Al}$$

transfer information to ^{25}Mg$^+$

Readout of the Al$^+$ clock state/ ancilla-assisted readout

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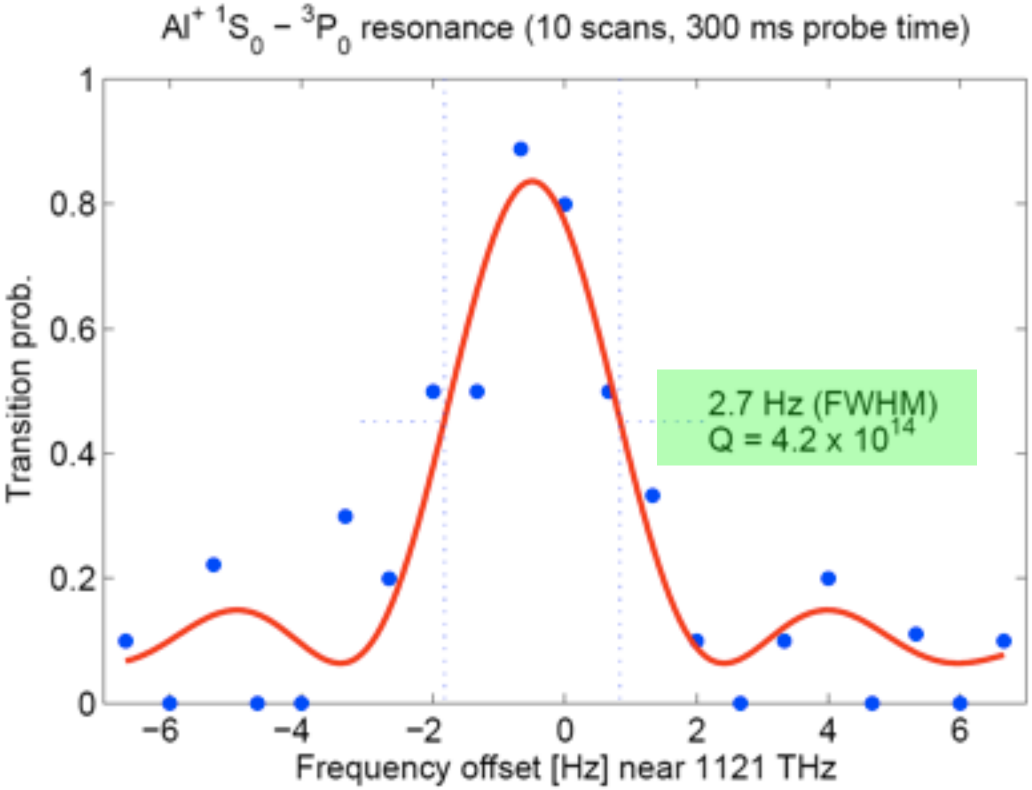

- Insensitive to external fields
- Smallest known temperature sensitivity (10^{-19} / Kelvin)
- current evaluated inaccuracy 0.9 $\times 10^{-17}$
- Hg$^+$/Al$^+$ comparison places limit $\frac{\dot{\alpha}}{\alpha} < 3 \times 10^{-17}$/yr
- Measure time dilation due to 1 m change in height
- Potential applications in geodesy/geophysics

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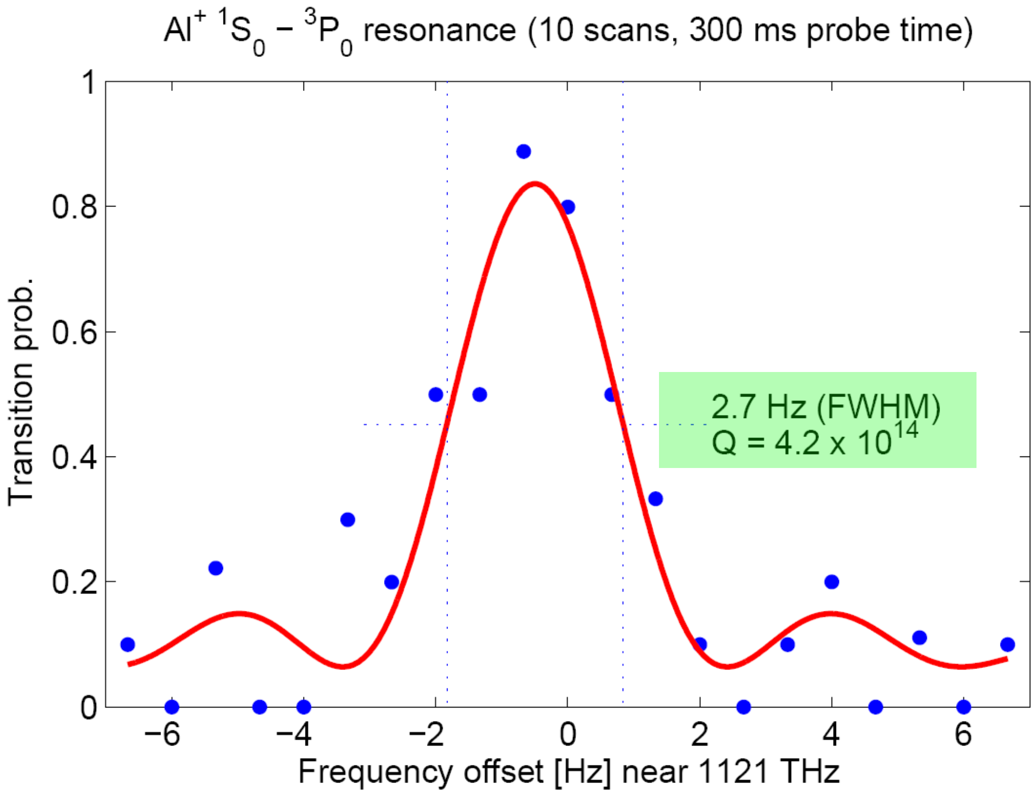


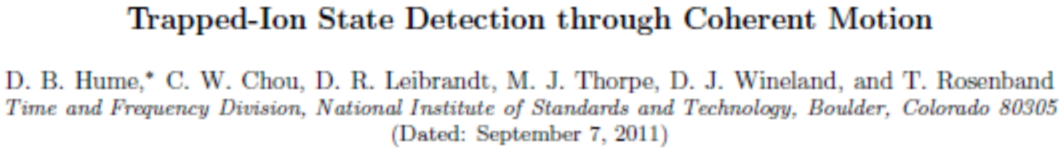
Al^+ $^1S_0$ – $^3P_0$ resonance (10 scans, 300 ms probe time)

2.7 Hz (FWHM)
Q = 4.2 x 10^{14}

- Insensitive to external fields
- Smallest known temperature sensitivity (10^{-19} / Kelvin)
- current evaluated inaccuracy 0.9×10^{-17}
- Hg^+/Al^+ comparison places limit $\dot{\alpha}/\alpha < 3\times10^{-17}$/yr
- Measure time dilation due to 1 m change in height
- Potential applications in geodesy/ geophysics

Current effort: move the Al^+ clock out of the lab

Simplified readout:

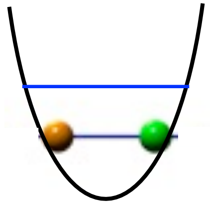


Trapped-Ion State Detection through Coherent Motion

D. B. Hume,* C. W. Chou, D. R. Leibrandt, M. J. Thorpe, D. J. Wineland, and T. Rosenband
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305
(Dated: September 7, 2011)

arXiv:1108.5922v2
To appear in PRL

Al^+ quantum-logic spectroscopy



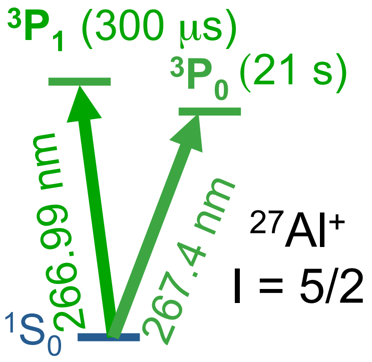
1. Cool to motional ground-state with Mg^+ (Raman cooling)
2. Depending on Al^+ clock state, add one vibrational quantum via $^1S_0$-$^3P_1$
3. Detect vibrational quantum with Mg^+

$^{27}Al^+$ $^1S_0$

Mean = 1.3

$^{27}Al^+$ $^3P_0$

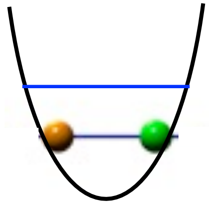
Mean = 6.9

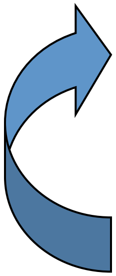


Probability

Mg^+ photon counts

Al$^+$ quantum-logic spectroscopy





QND

1. Cool to motional ground-state with Mg$^+$ (Raman cooling)
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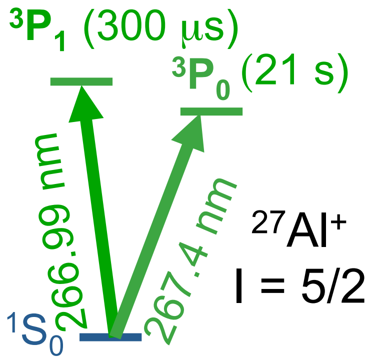


Probability

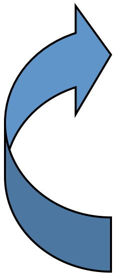
99.94% Detection fidelity

Mg$^+$ photon counts

P.O. Schmidt, *et al.*
Science **309**, 749 (2005)

D. B. Hume, *et al.*
PRL **99**, 120502 (2007)

Al$^+$ ~~quantum-logic~~ spectroscopy



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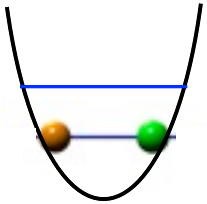
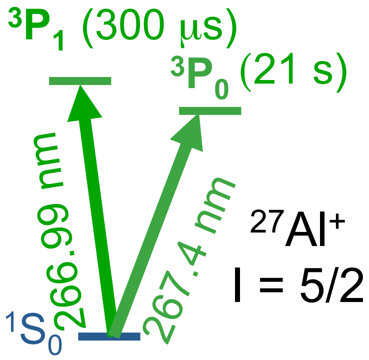


D. B. Hume, *et al.*
PRL (accepted)



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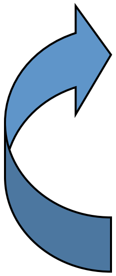
Al$^+$ ~~quantum-logic s~~ coherent-drive spectroscopy



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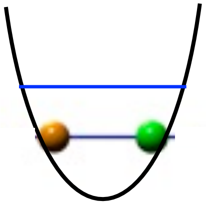

D. B. Hume, *et al.*
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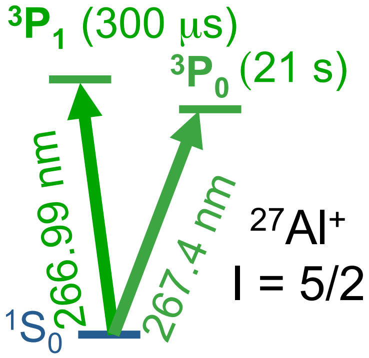

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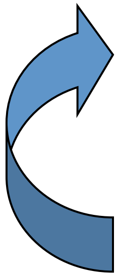

Mg$^+$ Doppler

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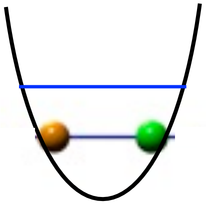

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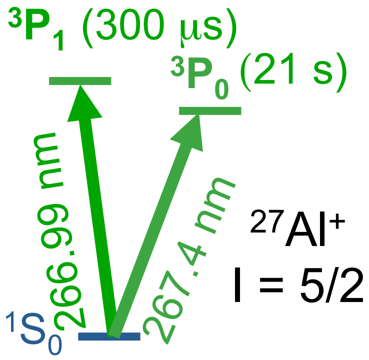

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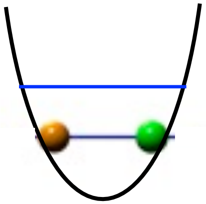

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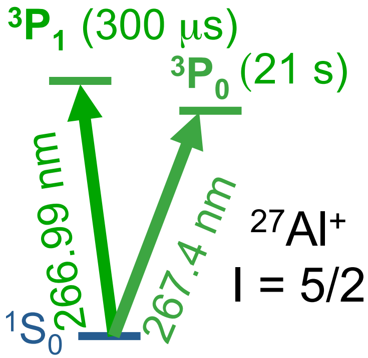

Al$^+$ ~~quantum-logic~~ coherent-drive spectroscopy

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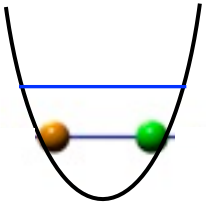

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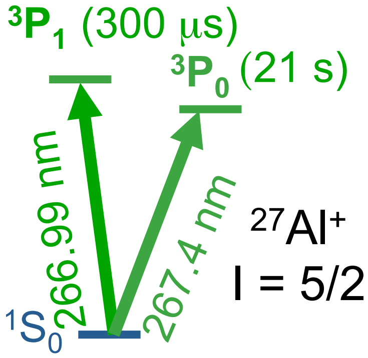

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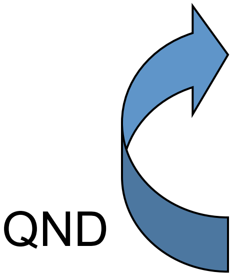

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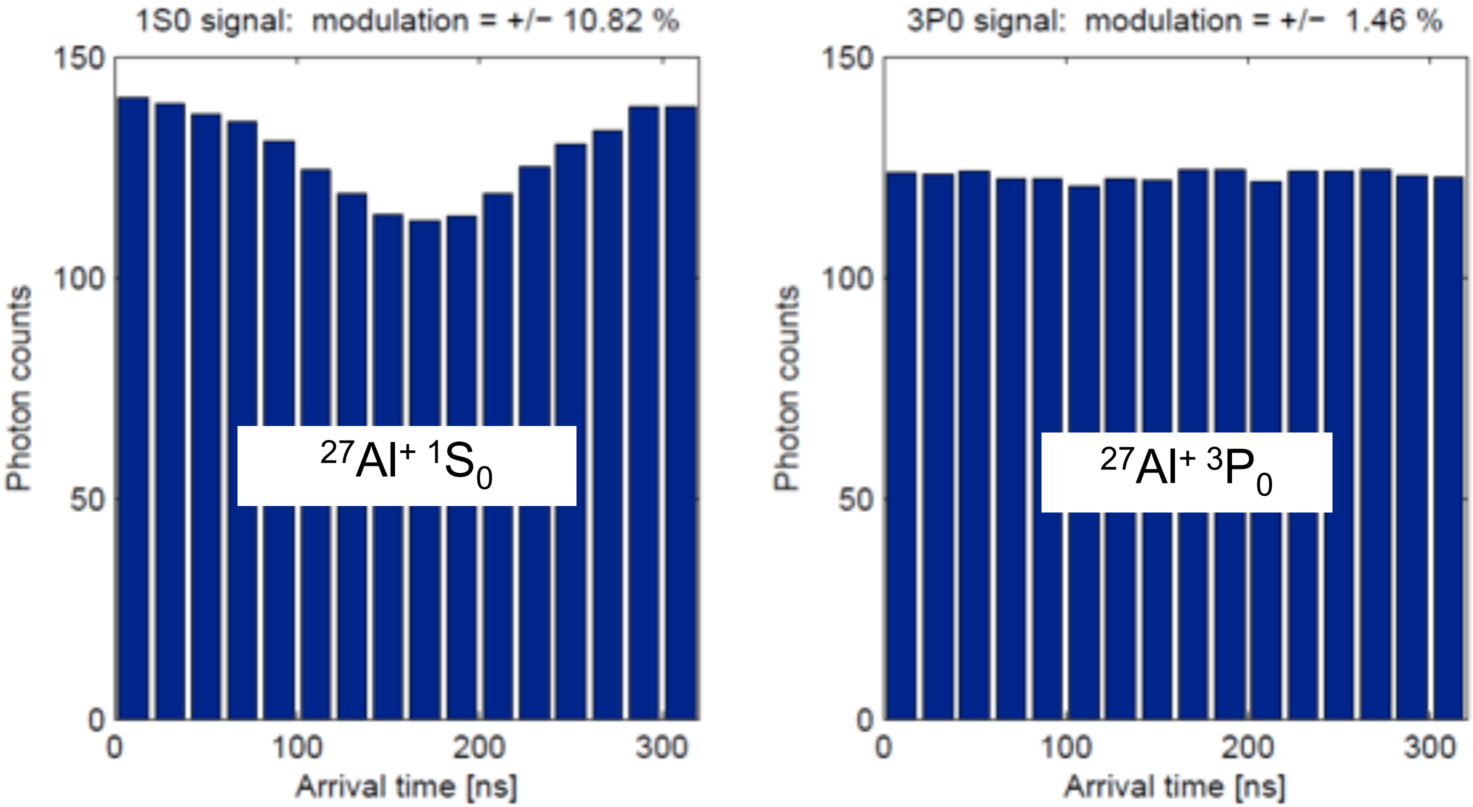

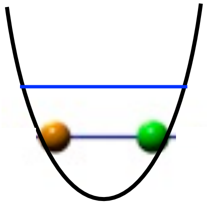

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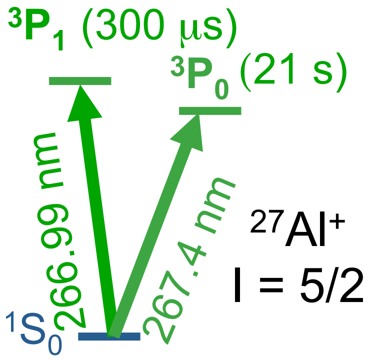
PRL (accepted)



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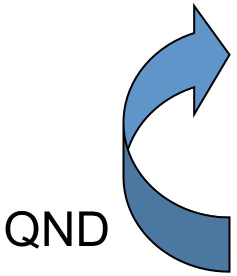

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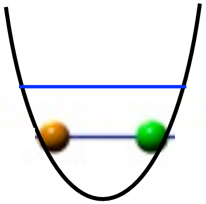

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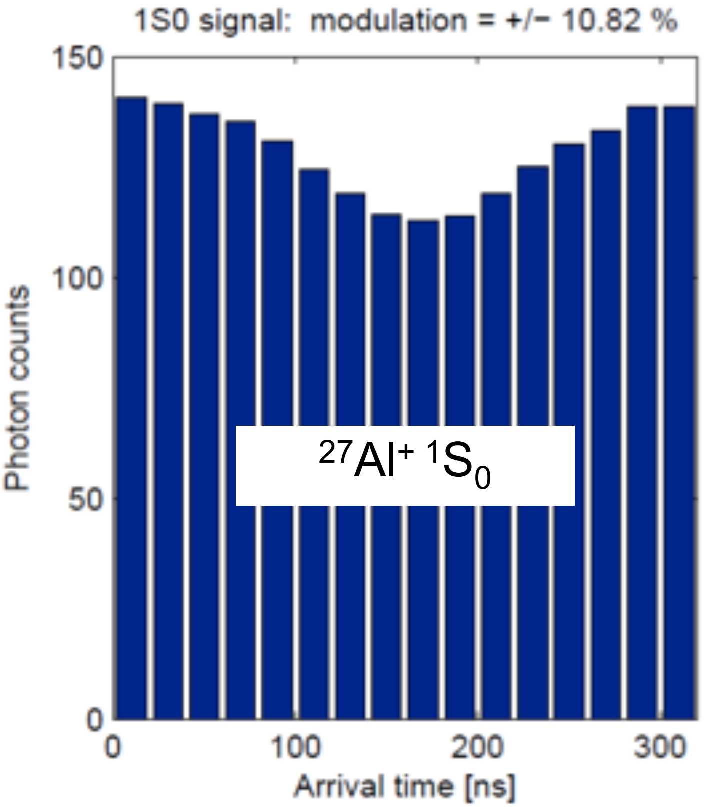
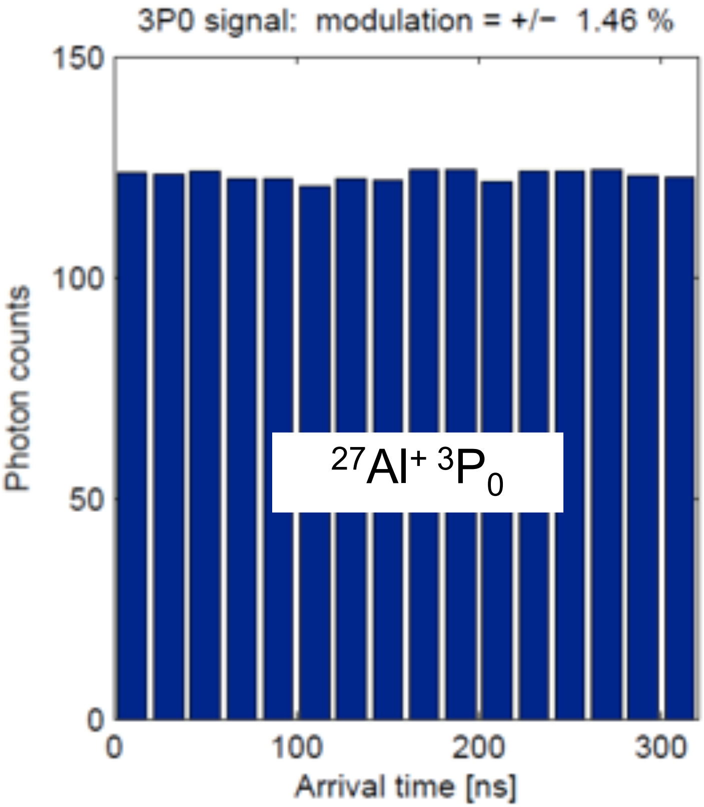




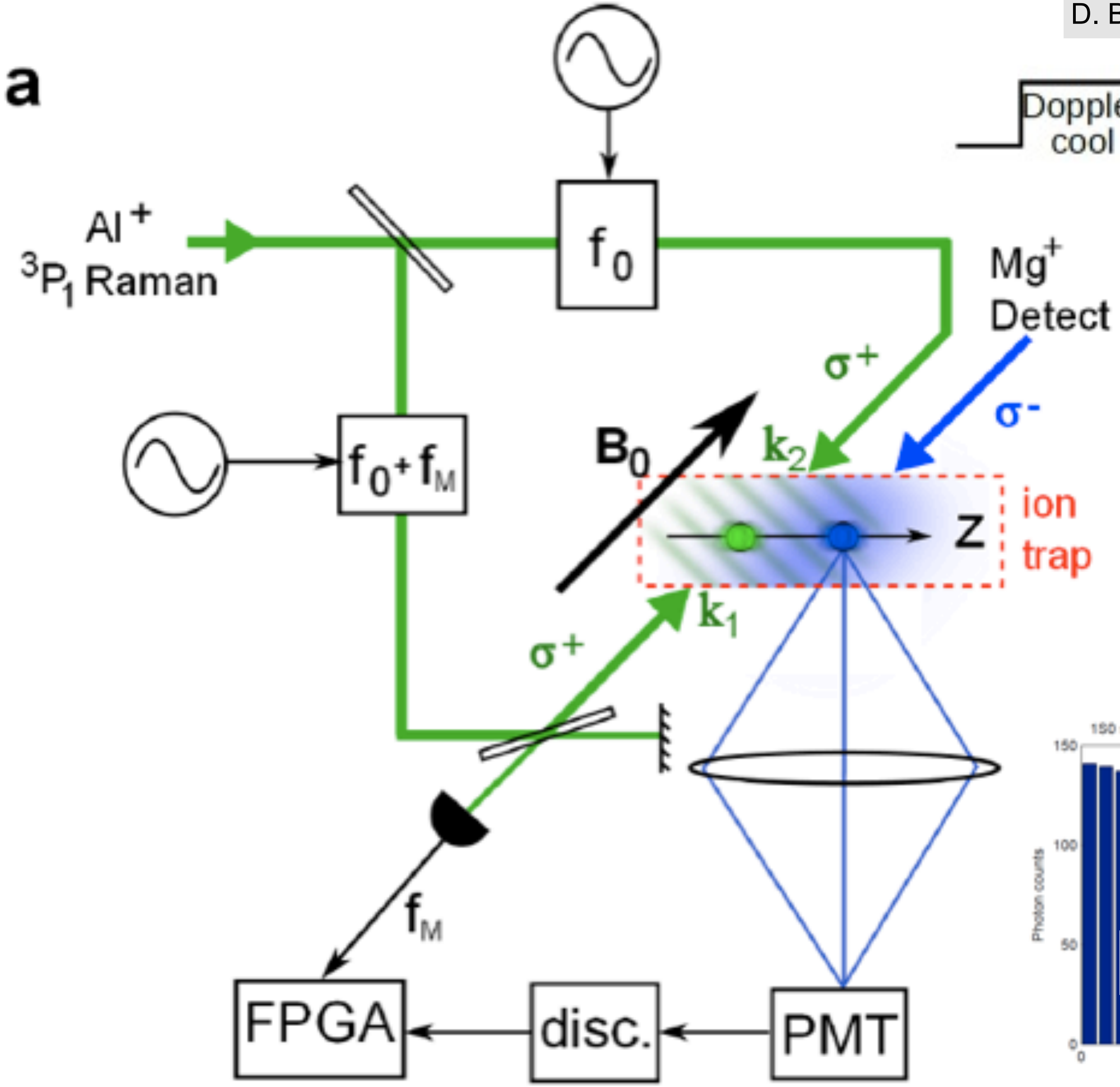
Measure quantum state w/o scattering photons

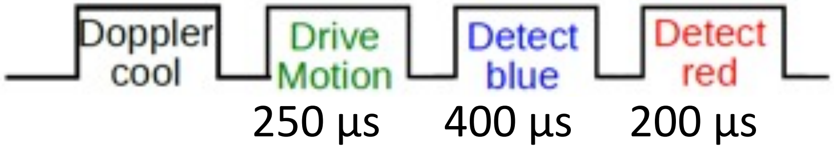
Simplified lasers (no ground-state cooling)

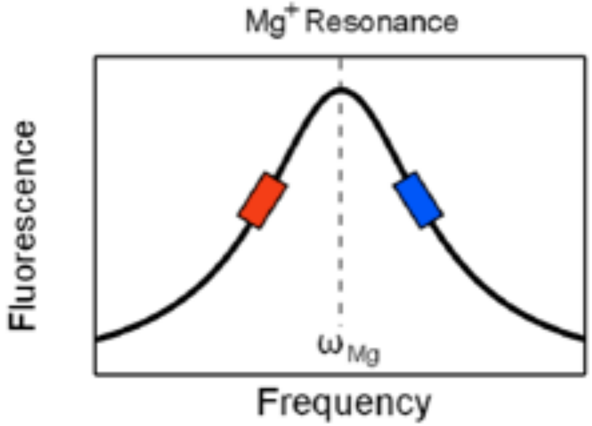
Slower

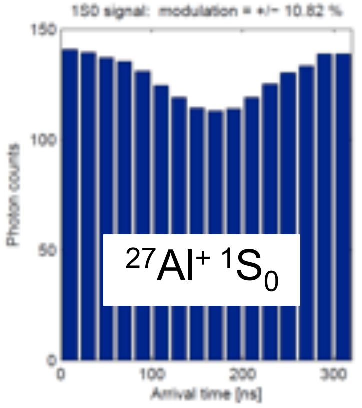
Al^+ coherent-drive spectroscopy

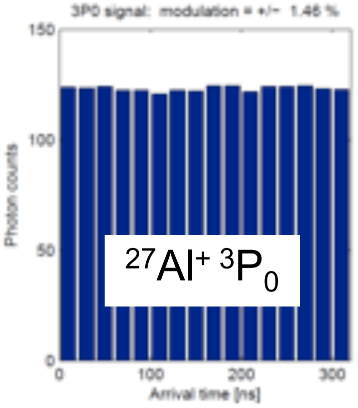
D. B. Hume, et al., PRL (Accepted)



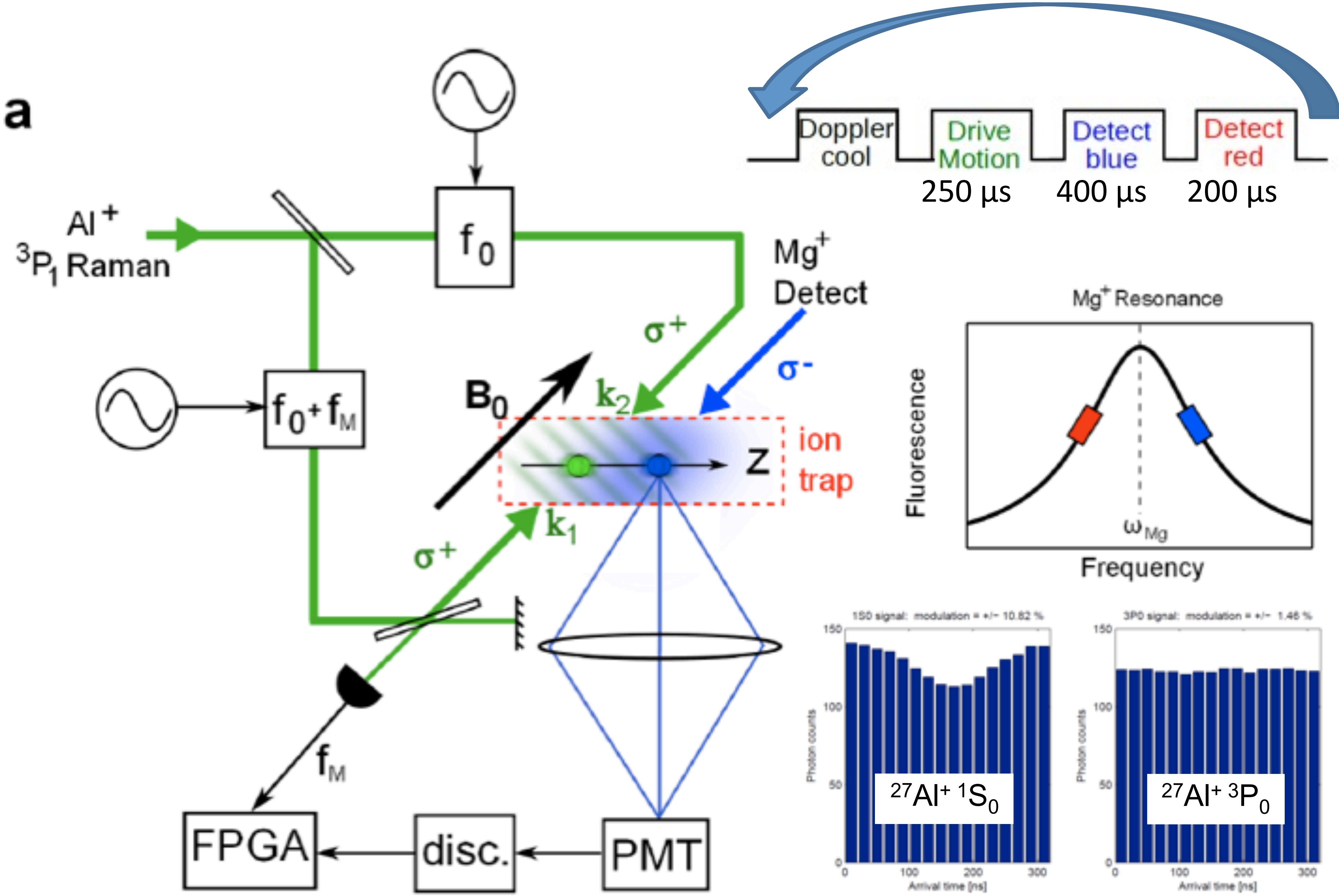








Al^+ coherent-drive spectroscopy

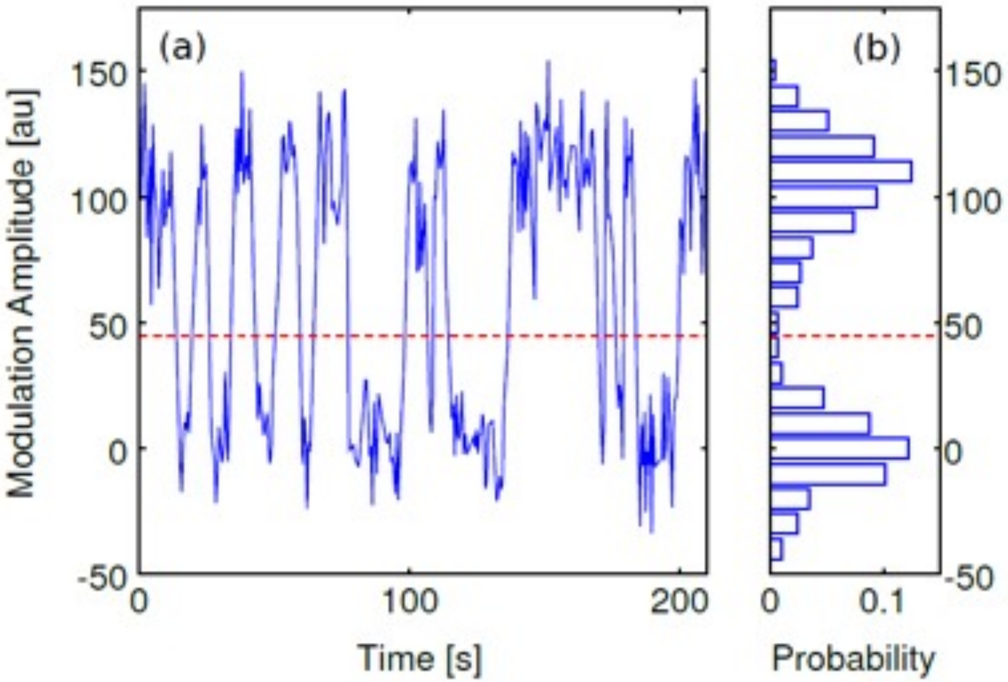


Readout of the Al$^+$ clock state/ ancilla-assisted readout

Hume, Chou, Leibrandt, Thorpe, Wineland, and Rosenband, arXiv:11085922v2

Quantum jumps between clock states ($^1S_0$ and $^3P_0$)

0.53 s average



$^1S_0$

$^3P_0$

93% state-detection fidelity within 80 ms

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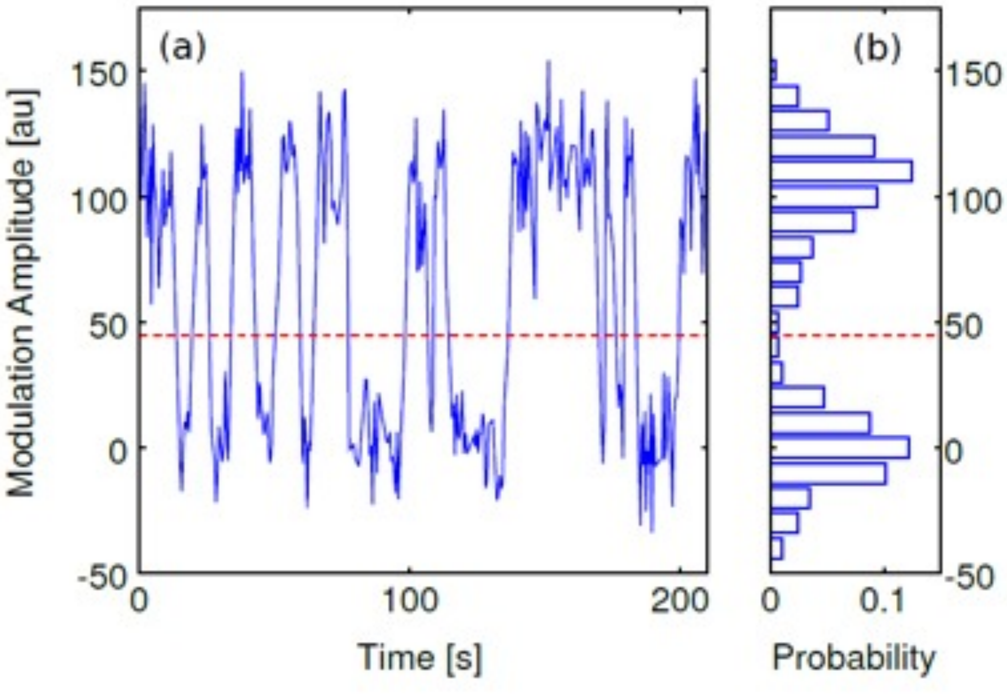

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93% state-detection fidelity within 80 ms

with quantum logic:
99% within 10 ms

Readout of the Al⁺ clock state/ ancilla-assisted readout

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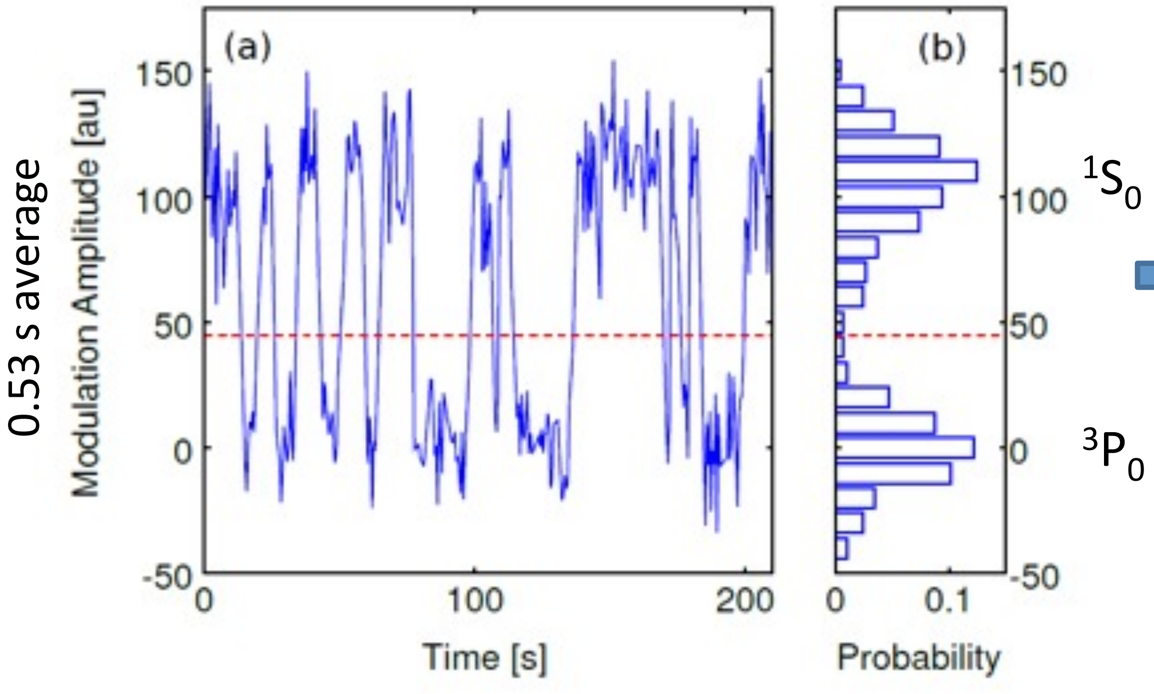

93% state-detection fidelity within 80 ms

with quantum logic:
99% within 10 ms

- coherent drive detection rate could be improved by higher modulation amplitude or photon collection efficiency
- can be generalized for more than one Al⁺ ion

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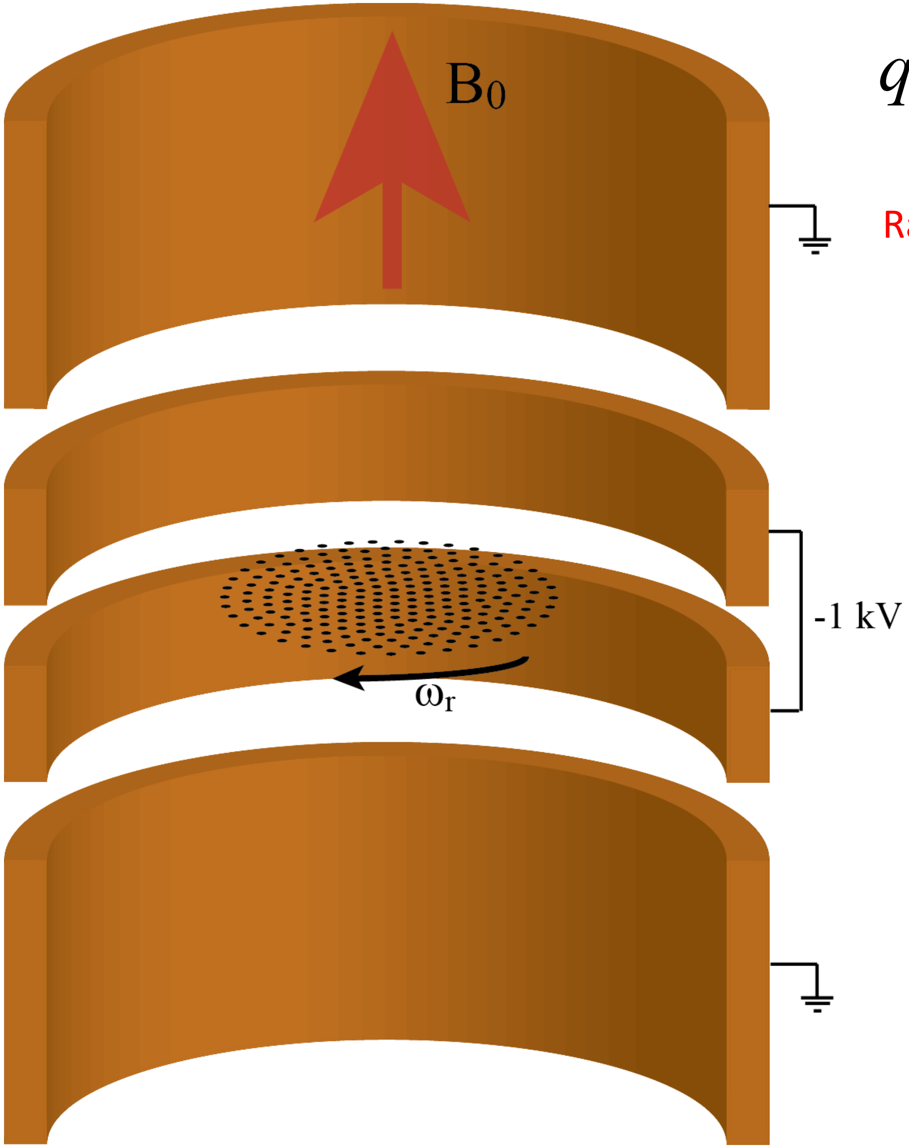
DARPA ONR IARPA NIST

Multi-qubit control - Entanglement and control with many ions in Penning traps

Britton, Sawyer, Bollinger/work supported by DARPA OLE



trap axial frequency

$$q\Phi_{trap}(r,z) = \frac{1}{2} m\omega_z^2\left(z^2 + \beta(\omega_r) r^2\right)$$

cyclotron frequency

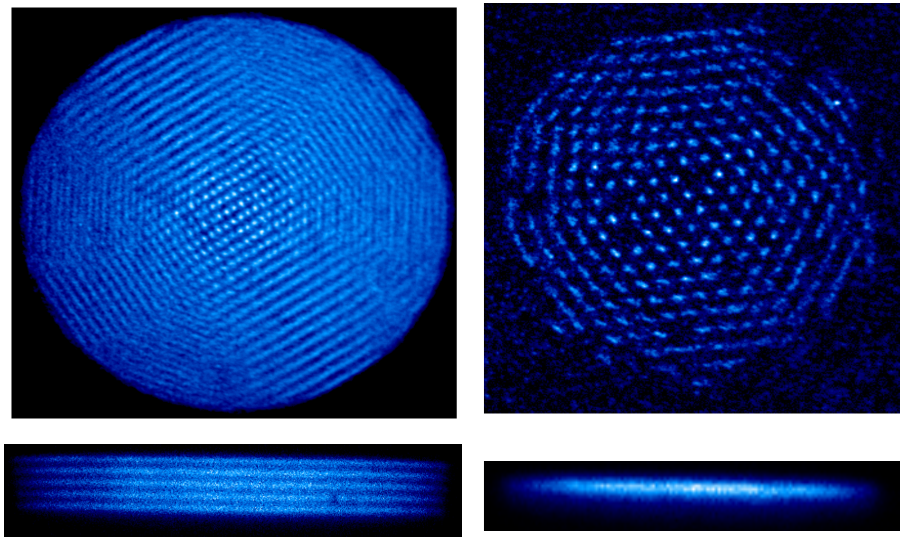
Radial confinement by rotation through the B_0 field

$$\beta \equiv \frac{\omega_r(\Omega_c - \omega_r)}{\omega_z^2} - \frac{1}{2}$$

$\omega_r \simeq 2\pi \times 45\ kHz$

$\omega_z \simeq 2\pi \times 800$ kHz

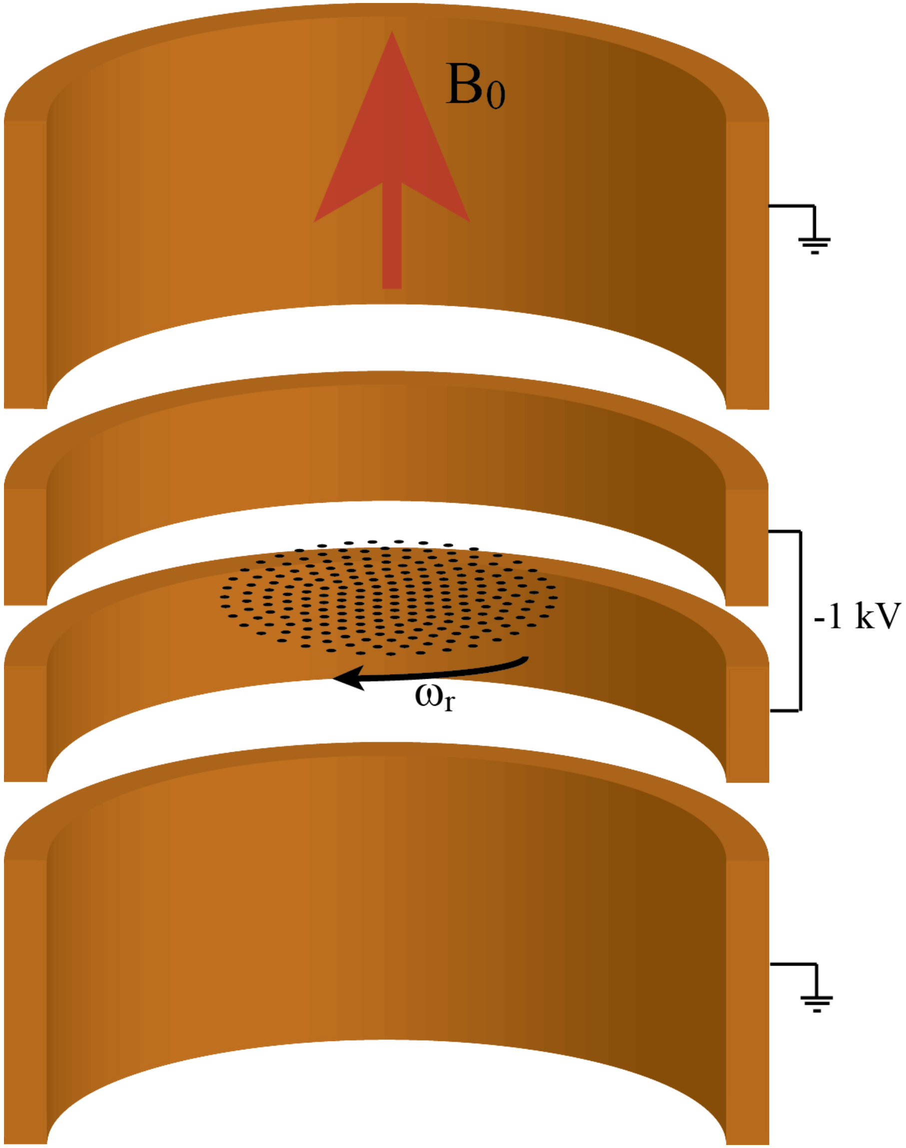
$\Omega_c \simeq 2\pi \times 7.6\ MHz$

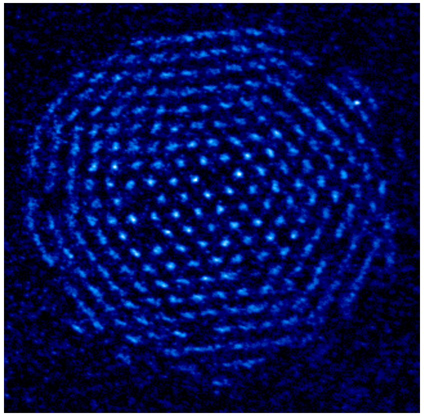


T≲1 mK

Multi-qubit control - Entanglement and control with many ions in Penning traps

Britton, Sawyer, Bollinger/work supported by DARPA OLE





$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z$$

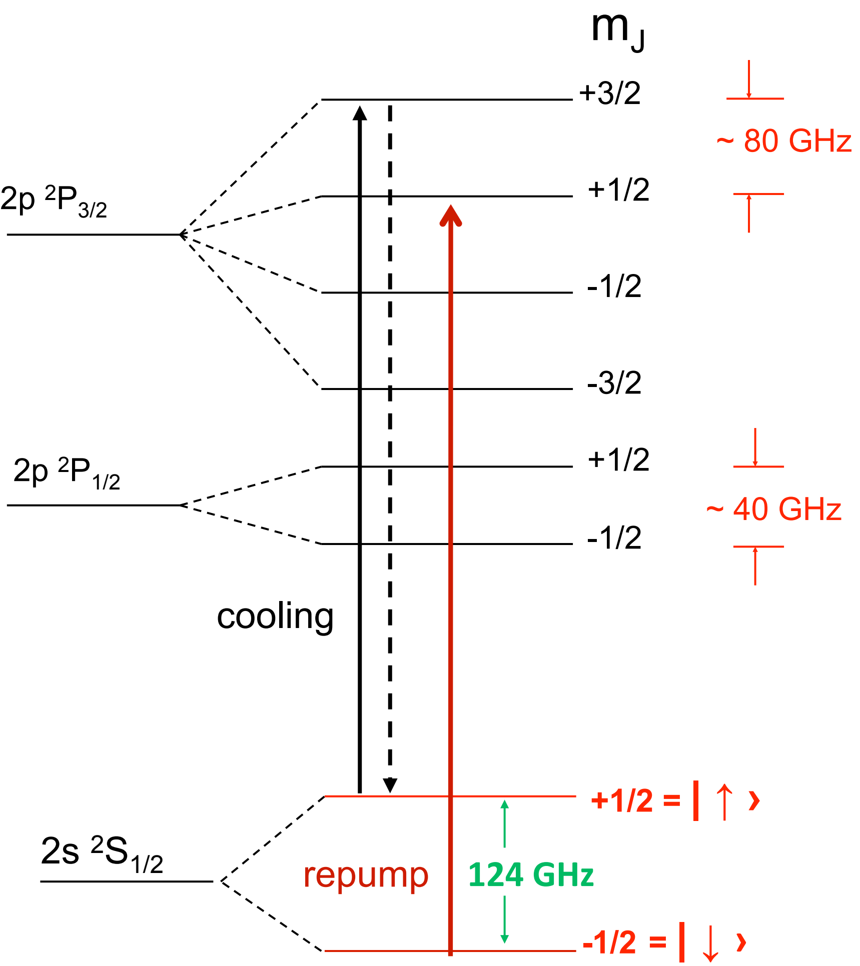
current effort: engineer spin-spin interactions for simulation of quantum magnetism

potential QuISM MURI interest: engineered spin-spin interactions should generate entanglement

Penning trap provides well controlled environment for measuring entanglement and studying techniques such as DD for extending the entanglement lifetime.

High magnetic field Be$^+$ qubit

^{9}Be$^+$, B~4.6 T, $\omega_o /2\pi$ ~124.1 GHz



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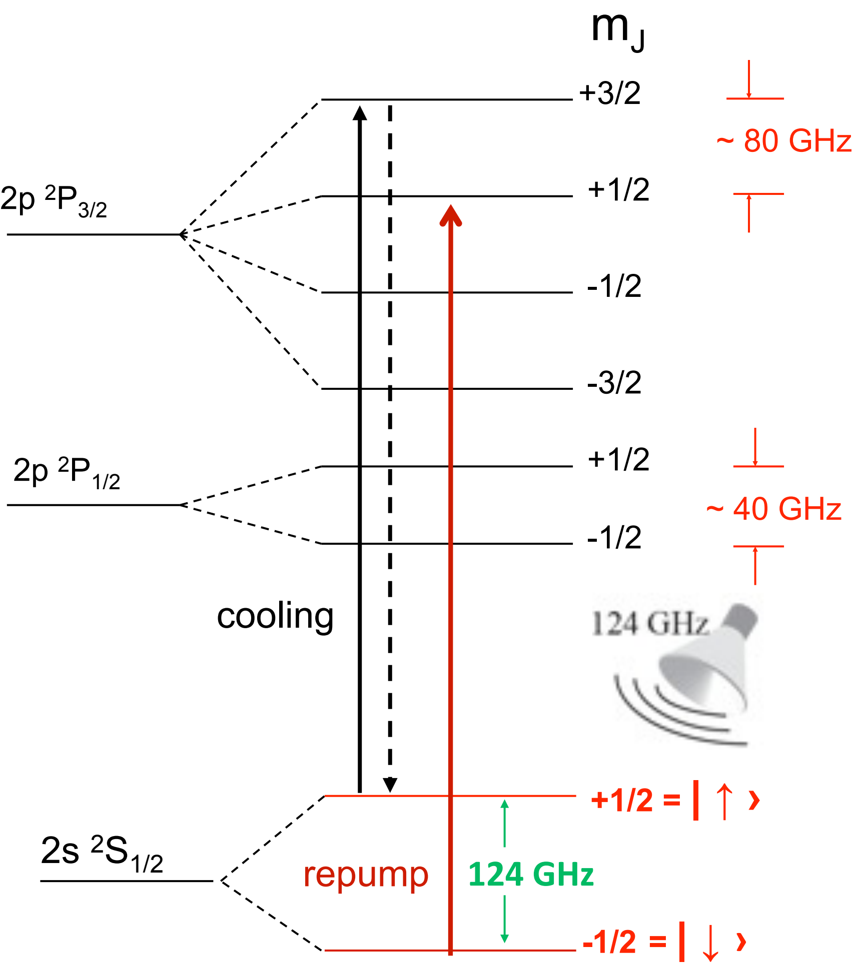

Rabi flopping with 150 mW, 124 GHz μW source

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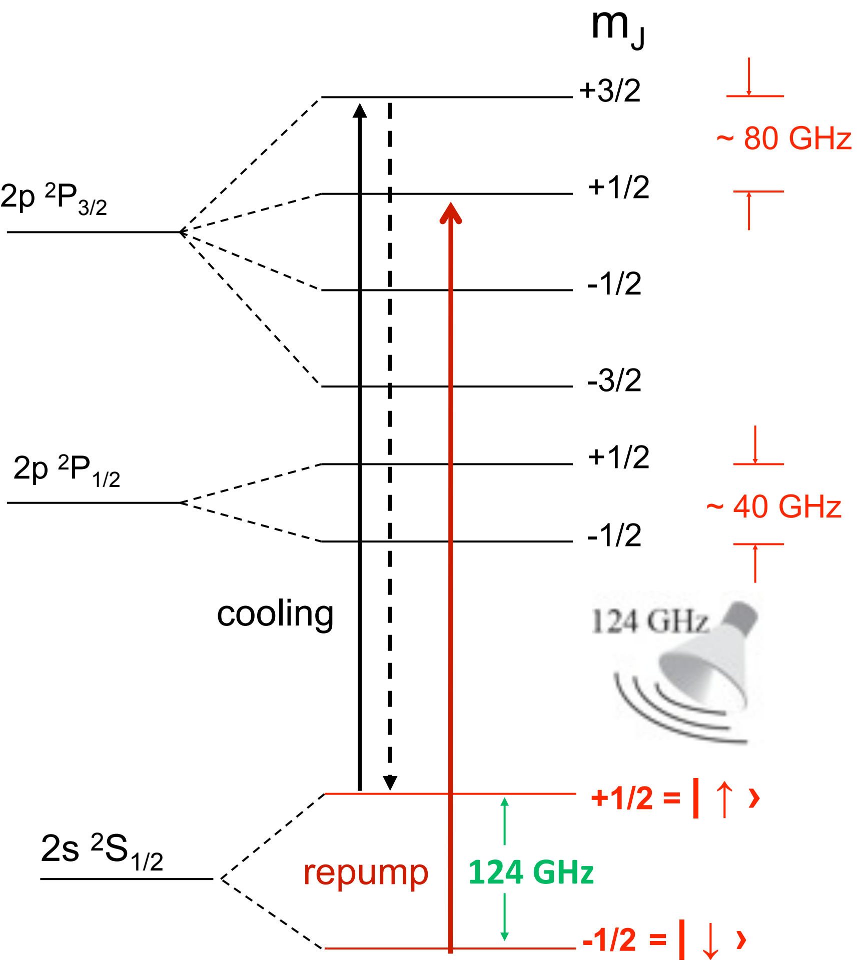

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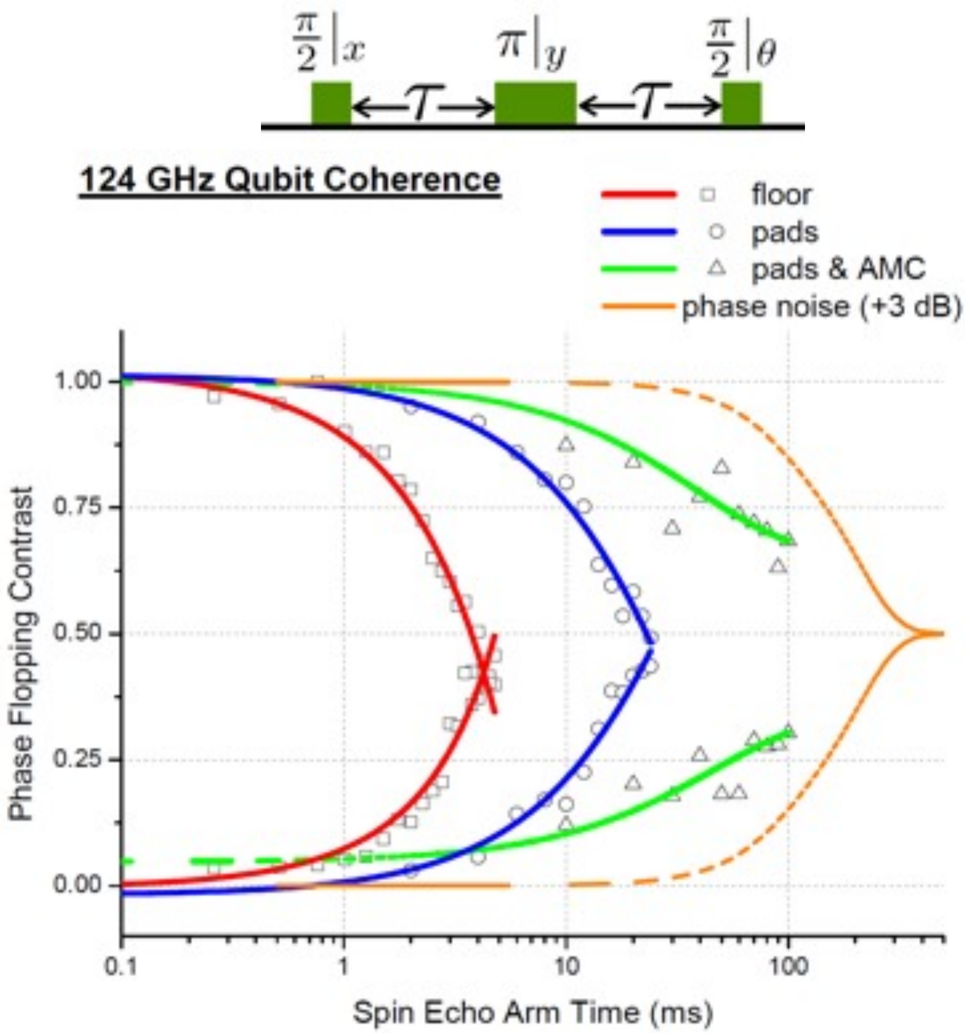
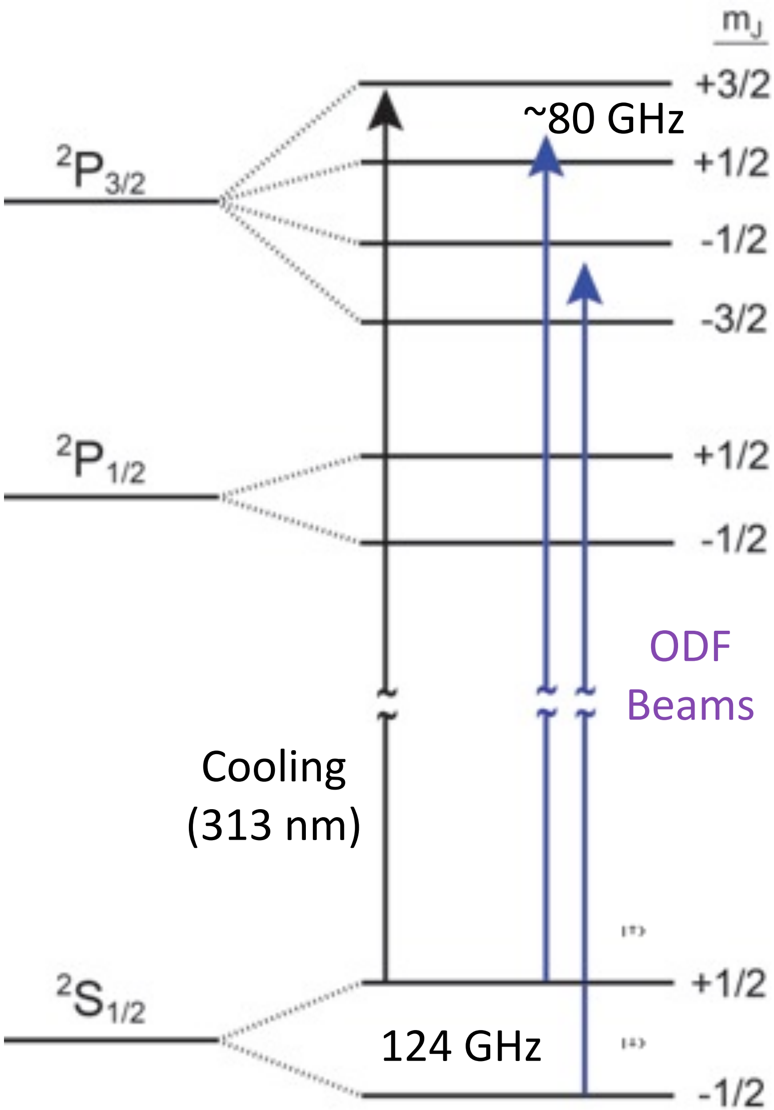
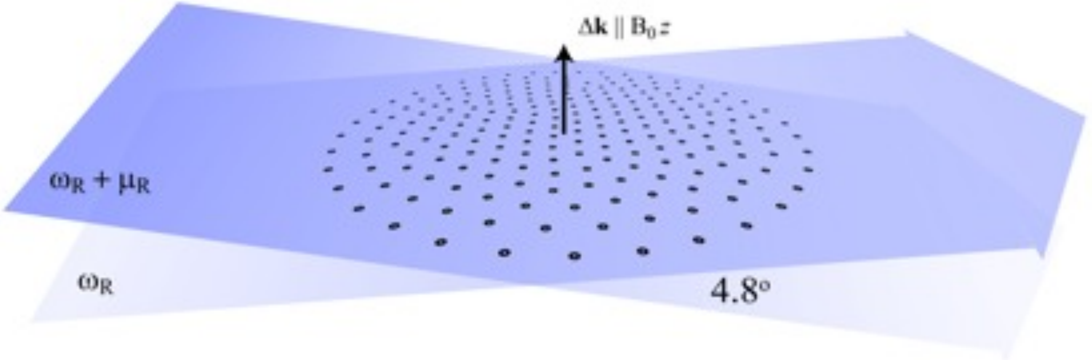


Engineer spin-spin interaction with spin-dependent optical dipole force

Leibfried et al., Nature **422**, 412-415 (2003)





beam waists ~ 2000 μm x 200 μm

intensity ~ 1 W/cm² per beam

Engineer spin-spin interaction with spin-dependent optical dipole force

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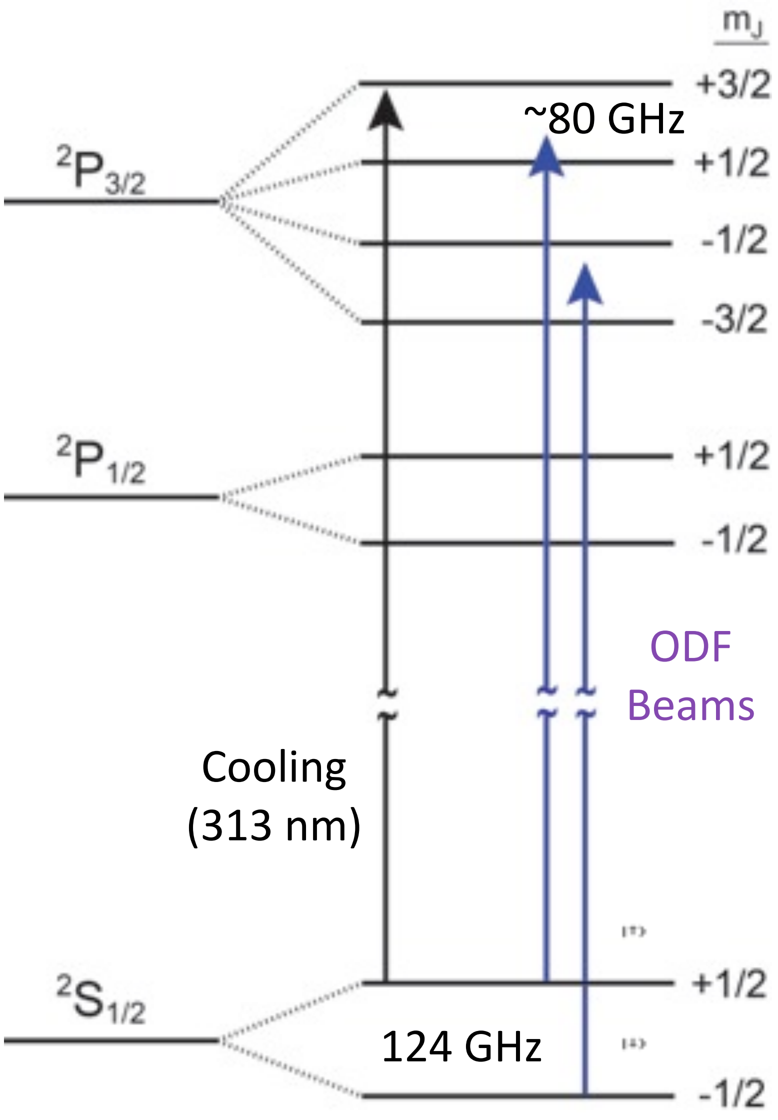
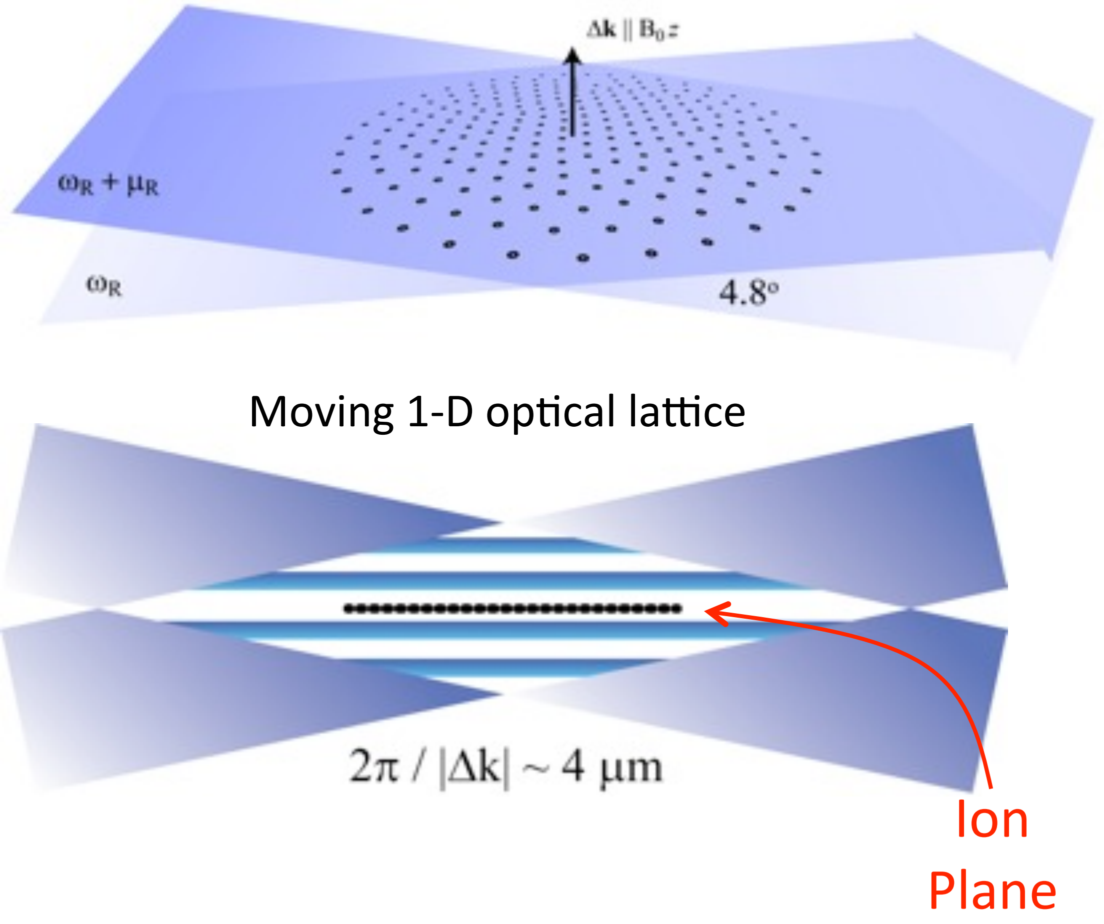
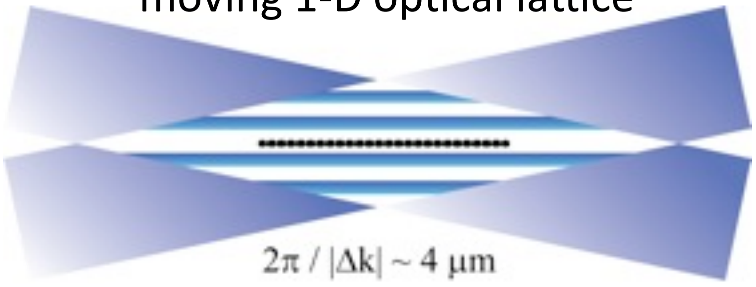




- alignment of 1D lattice and ion plane crucial

Engineer spin-spin interaction with spin-dependent optical dipole force

moving 1-D optical lattice



- $F_\uparrow(t) = -F_\downarrow(t)$
  $F_\uparrow(t) = F_0 \cos(\mu_R t)$

$$\hat{H}_{ODF} = -F_0 \cos(\mu_R t)\sum_{j=1}^{N} \hat{z}_j \times \hat{\sigma}_j^z =$$

$$-F_0 \cos(\mu_R t)\sum_{j=1}^{N}\sum_{m=1}^{N} b_{jm}\sqrt{\frac{\hbar}{2M\omega_m}}\left(\hat{a}_m^\dagger e^{i\omega_m t} + \hat{a}_m e^{-i\omega_m t}\right)\hat{\sigma}_j^z$$

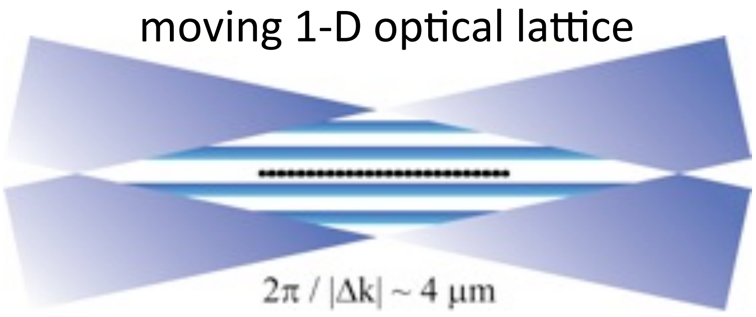
N transverse eigenmodes $\omega_m, \vec{b}_m$; eigenmodes calculated with code from Freericks group, Georgetown Univ.

$$U(\tau) = \exp\left(\sum_i \hat{\phi}_i \hat{\sigma}_i^z + i\sum_{i,j} \phi_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z\right)$$

$$\boxed{\hat{\phi}_i = \sum_m \alpha_{im}(\tau)\hat{a}_m^\dagger - \alpha_{im}^*(\tau)\hat{a}_{im}}$$

$$\boxed{\phi_{ij} \approx \frac{F_0^2}{2\hbar M}\sum_m \frac{b_{im} b_{jm}}{\mu_R^2 - \omega_m^2} \times \tau}$$

Engineer spin-spin interaction with spin-dependent optical dipole force



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Displacement

$$\boxed{\hat{\phi}_i = \sum_m \alpha_{im}(\tau) \hat{a}_m^\dagger - \alpha_{im}^*(\tau) \hat{a}_{im}}$$

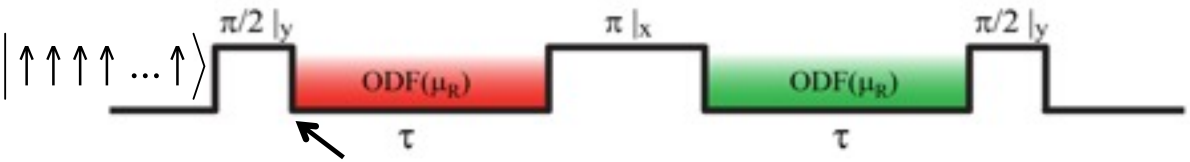
spin-motion entanglement→ decoherence in in spin Bloch vector

spin-spin coupling

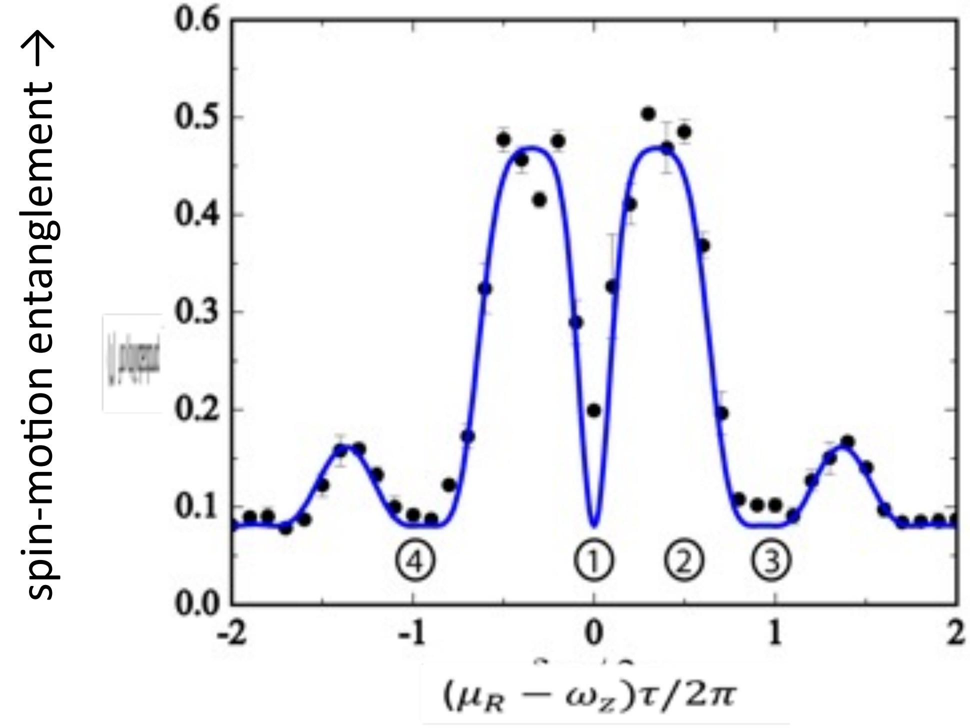
$$\boxed{\phi_{ij} \approx \frac{F_0^2}{2\hbar M} \sum_m \frac{b_{im} b_{jm}}{\mu_R^2 - \omega_m^2} \times \tau}$$

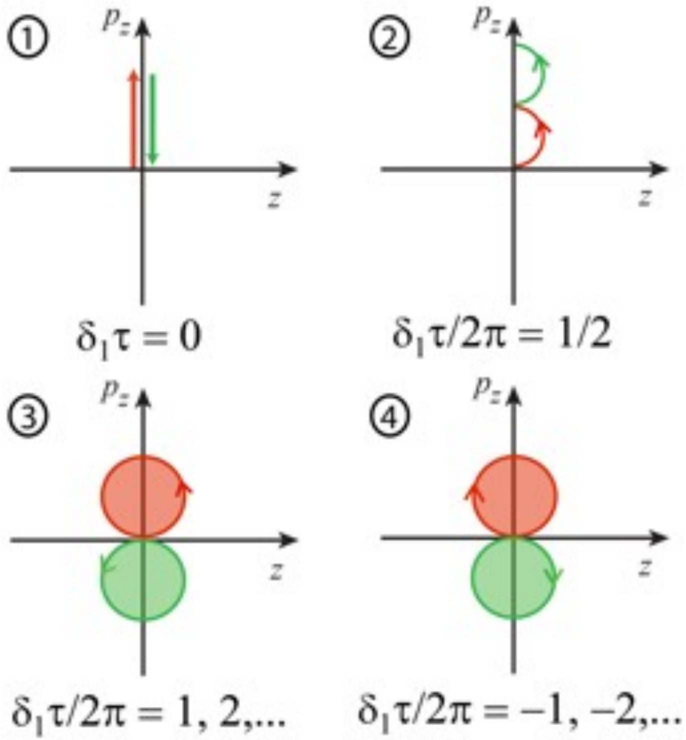
Porras and Cirac, PRL 2004 and 2006; Kim, Chang, Korenblit, Duan, Monroe PRL 2009

Spin-motion entanglement →spectroscopy and <u>thermometry</u> of transverse modes

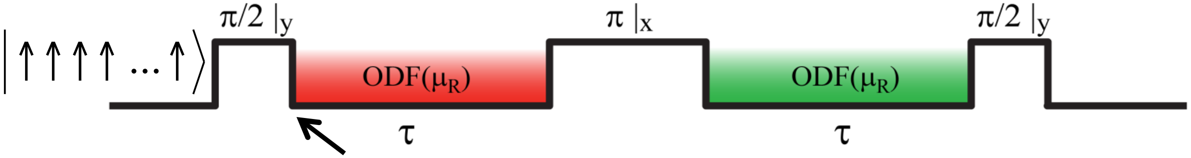


$$\prod_i \left(\frac{|\uparrow\rangle_i + |\downarrow\rangle_i}{\sqrt{2}} \right)$$





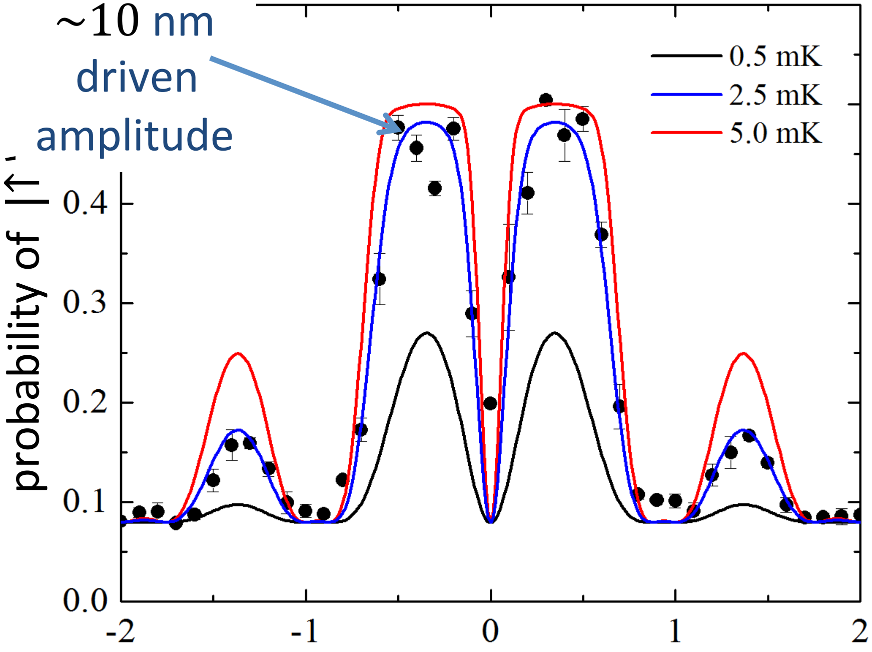
Spin-motion entanglement →spectroscopy and thermometry of transverse modes



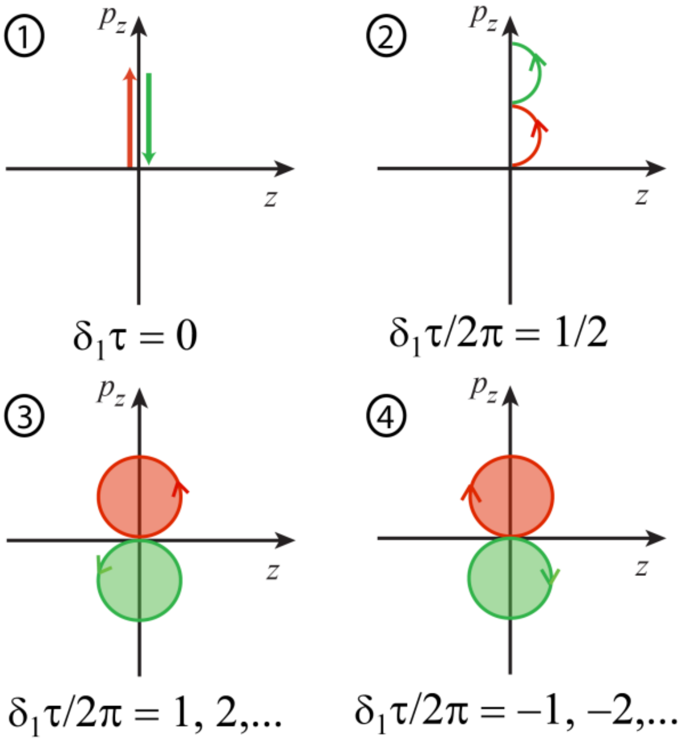
$$\prod_i \left(\frac{|\uparrow\rangle_i + |\downarrow\rangle_i}{\sqrt{2}}\right)$$

spin-motion entanglement →

~10 nm driven amplitude



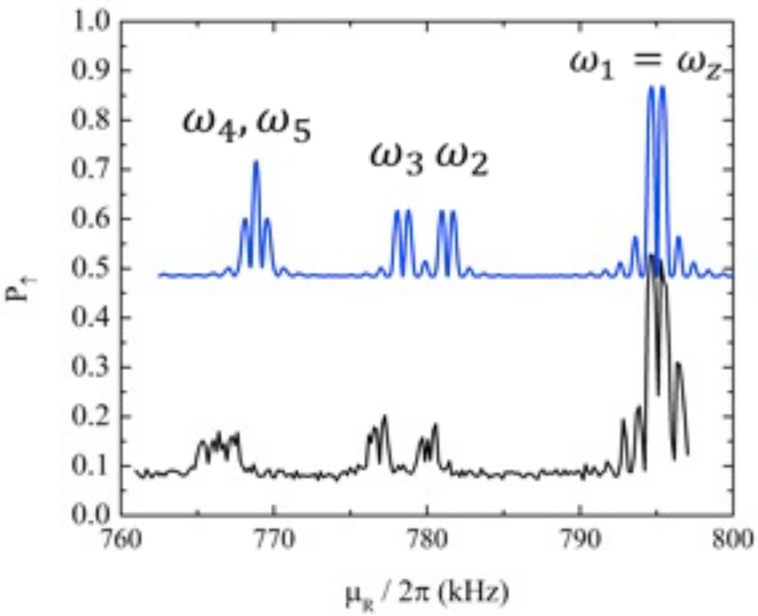
(μ↓R − ω↓z)τ/2π

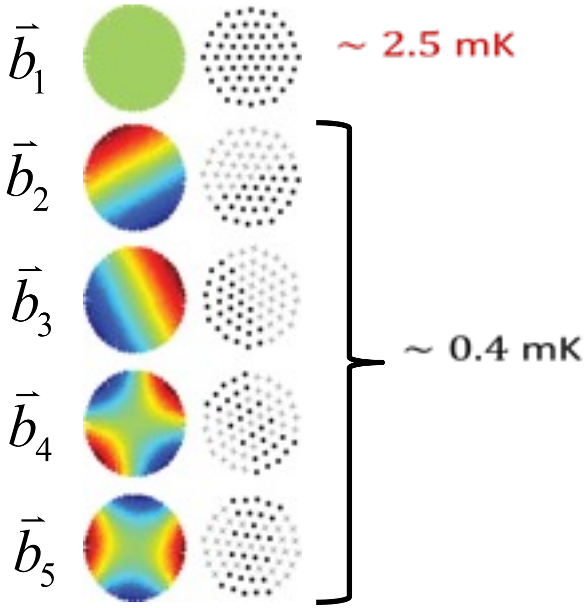


$$P_\uparrow = \frac{1}{2}\left(1 - e^{-2|\alpha|^2(2\bar{n}+1)}\right)$$

$\alpha(t) = \langle z(t) + ip_z(t)\rangle$ is the coherently driven amplitude

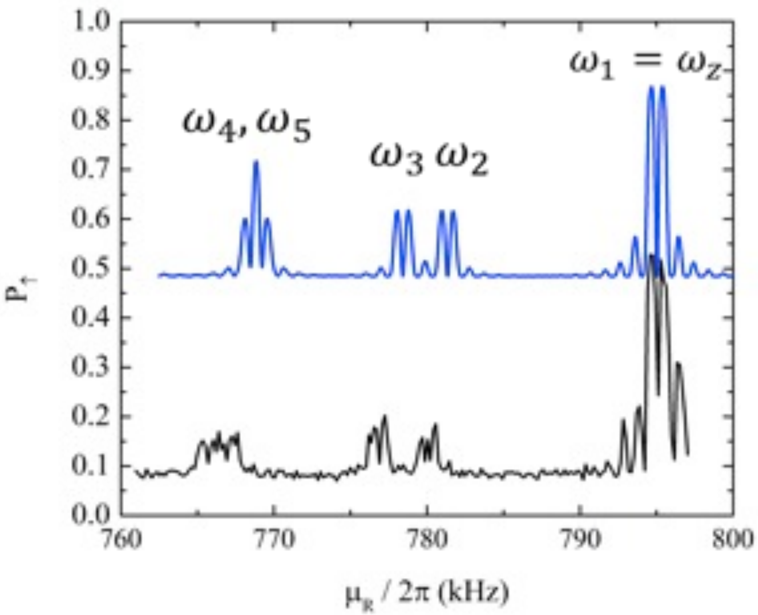
Spin-motion entanglement →spectroscopy and thermometry of transverse modes

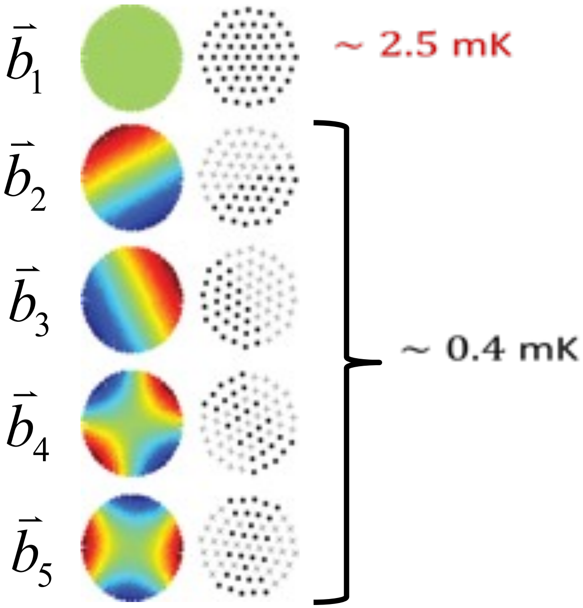




Doppler cooling limit

Spin-motion entanglement →spectroscopy and thermometry of transverse modes

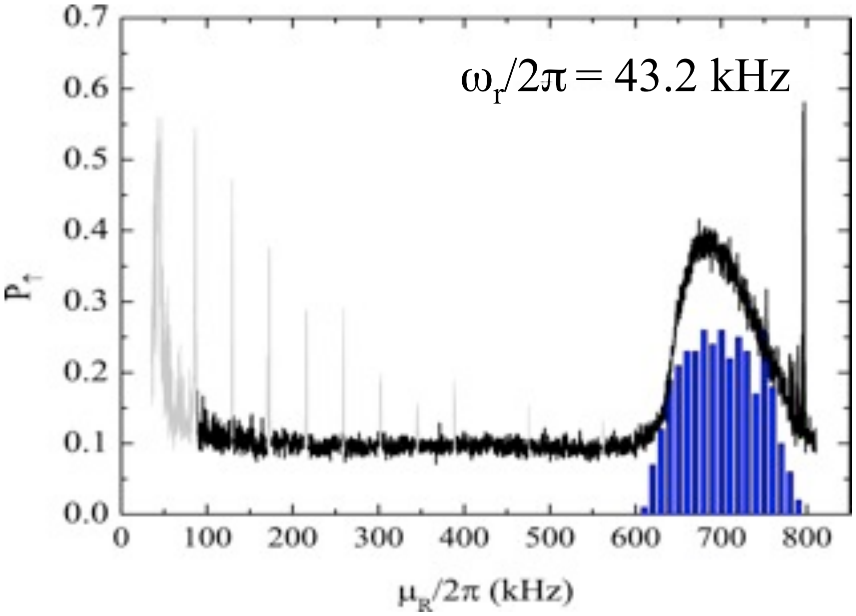


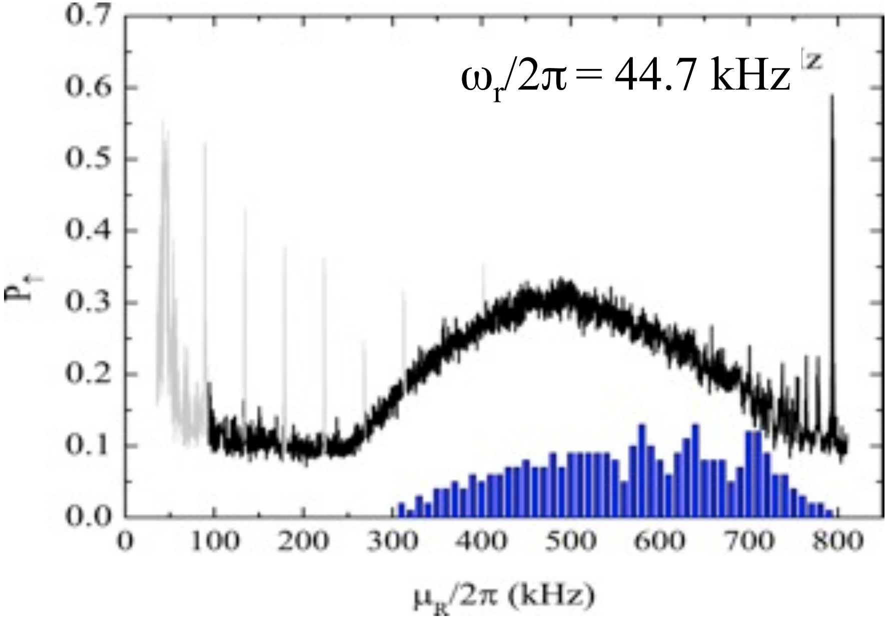


Doppler cooling limit

Broad sweep over all (N>300) transverse modes

$$q\Phi_{trap}(r,z) = \frac{1}{2} m\omega_z^2 \left(z^2 + \beta(\omega_r) r^2\right) \quad \beta \equiv \frac{\omega_r(\Omega_c - \omega_r)}{\omega_z^2} - \frac{1}{2}$$

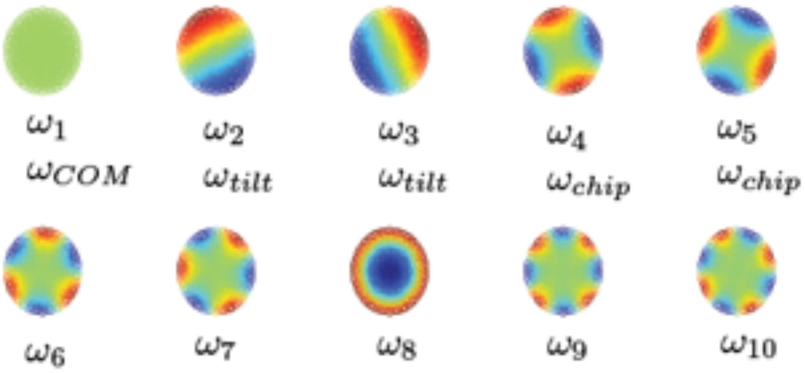




spin-spin coupling with spin-dependent optical dipole force

$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z, J_{i,j} = \frac{F_0^2 N}{\hbar \times 2M}\sum_{m=1}^{N}\frac{b_{i,m}b_{j,m}}{\mu_R^2-\omega_m^2}$$

Theory – Freericks Georgetown group



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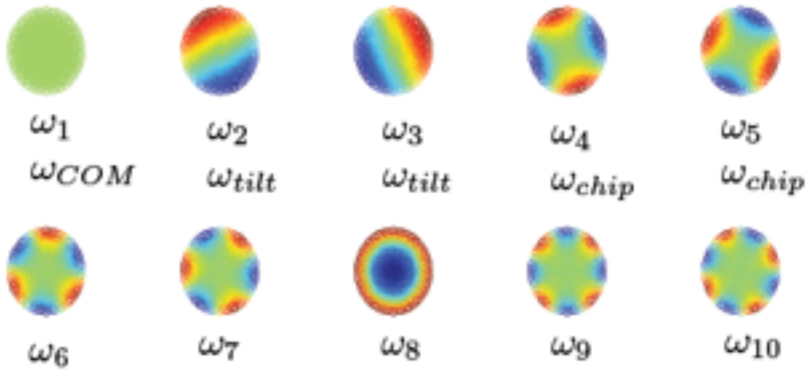
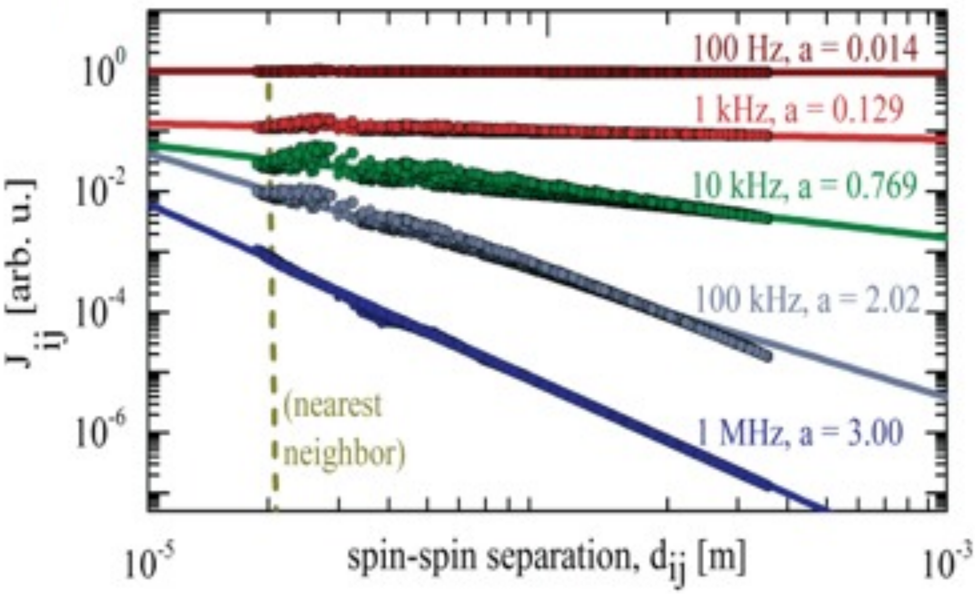


power-law interaction range $J_{i,j} \propto d_{i,j}^{-a}$



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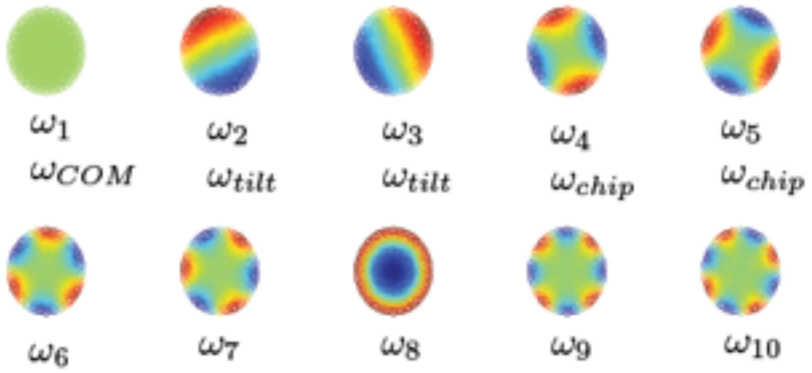

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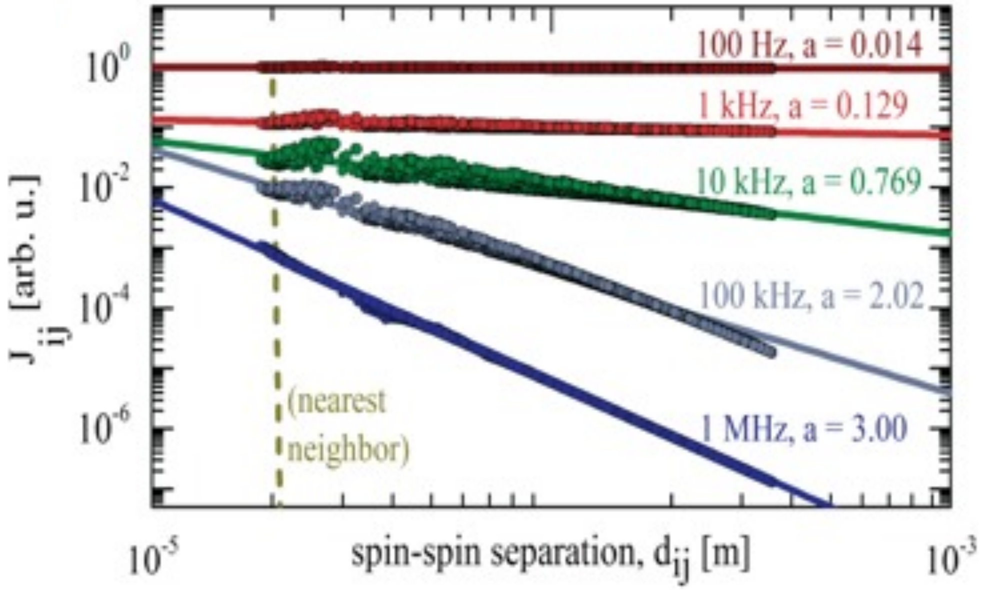
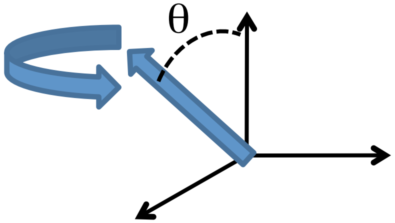


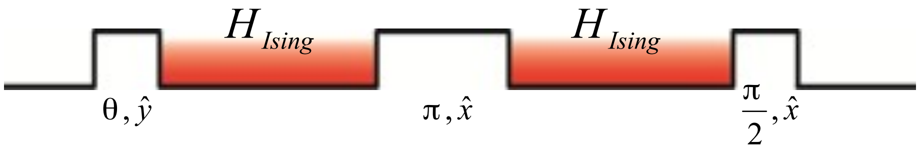
Benchmarking for $\omega_z<\mu_R<\omega_z+(2\pi)35$ kHz

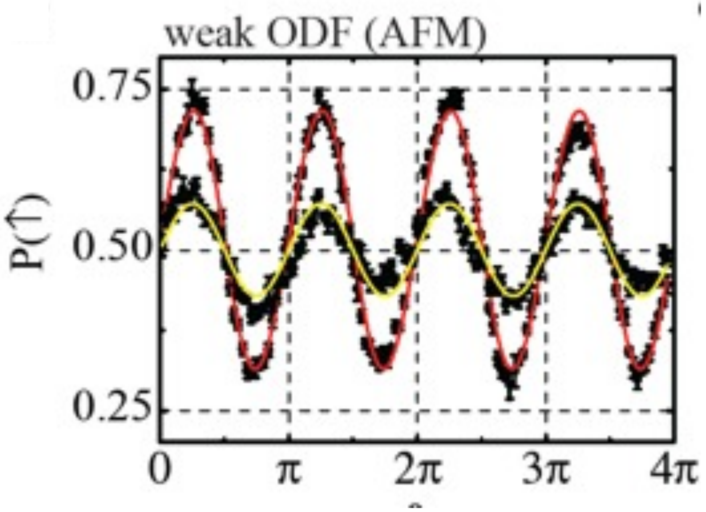
- measure mean-field spin precession

$$\omega_{precession} \sim \bar{J} \times \cos(\theta),$$

$$\bar{J} = \frac{1}{N^2}\sum_{i\neq j} J_{i,j}$$







$$P(\uparrow) = \frac{1}{2}\left[1 + e^{-\Gamma \times 2\tau_{arm}} \sin(\theta)\sin\left(2\bar{J}\cos(\theta)\times 2\tau_{arm}\right)\right]$$

single parameter fit → $\bar{J}$

spin-spin coupling with spin-dependent optical dipole force

$$H_{\text{Ising}} = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z, \quad J_{i,j} = \frac{F_0^2 N}{\hbar\cdot 2M}\sum_{m=1}^{N}\frac{b_{i,m}b_{j,m}}{\mu_R^2-\omega_m^2}$$

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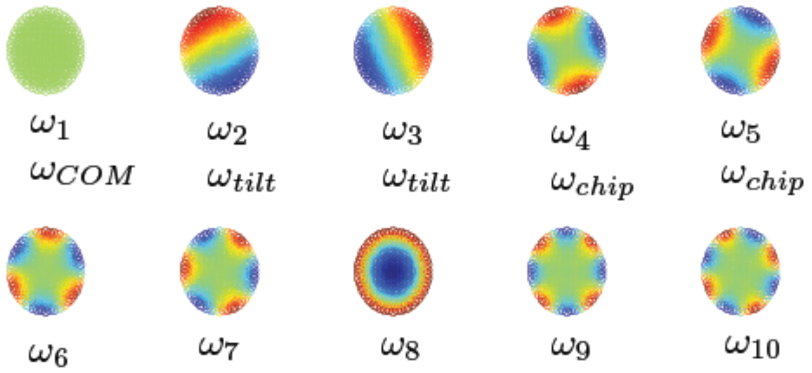

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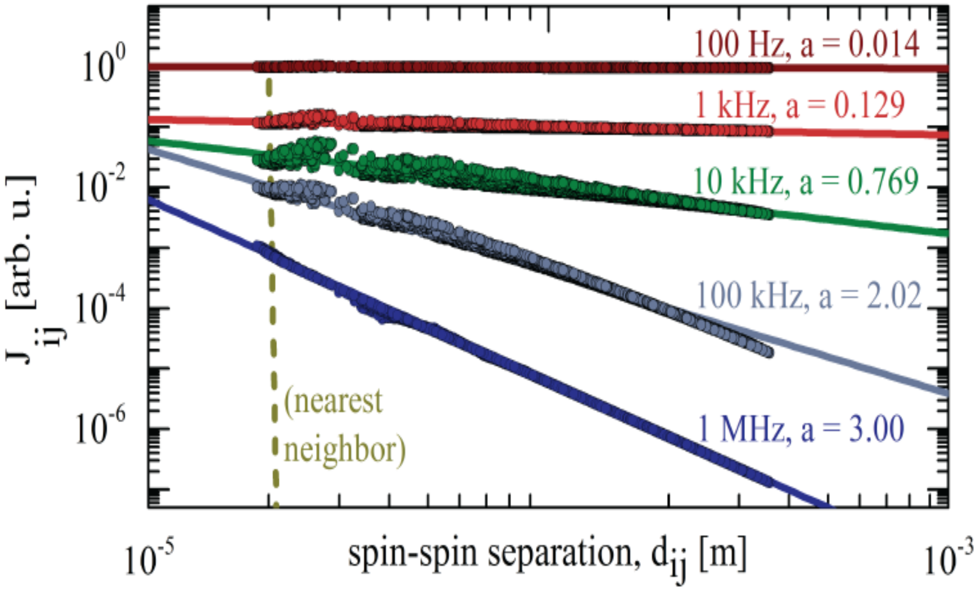

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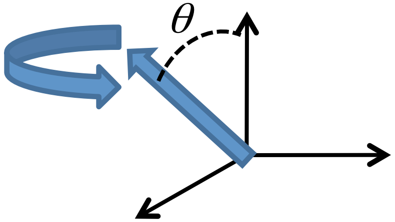
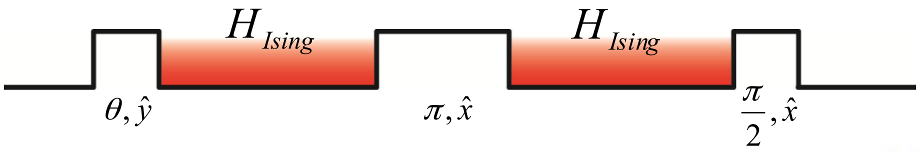
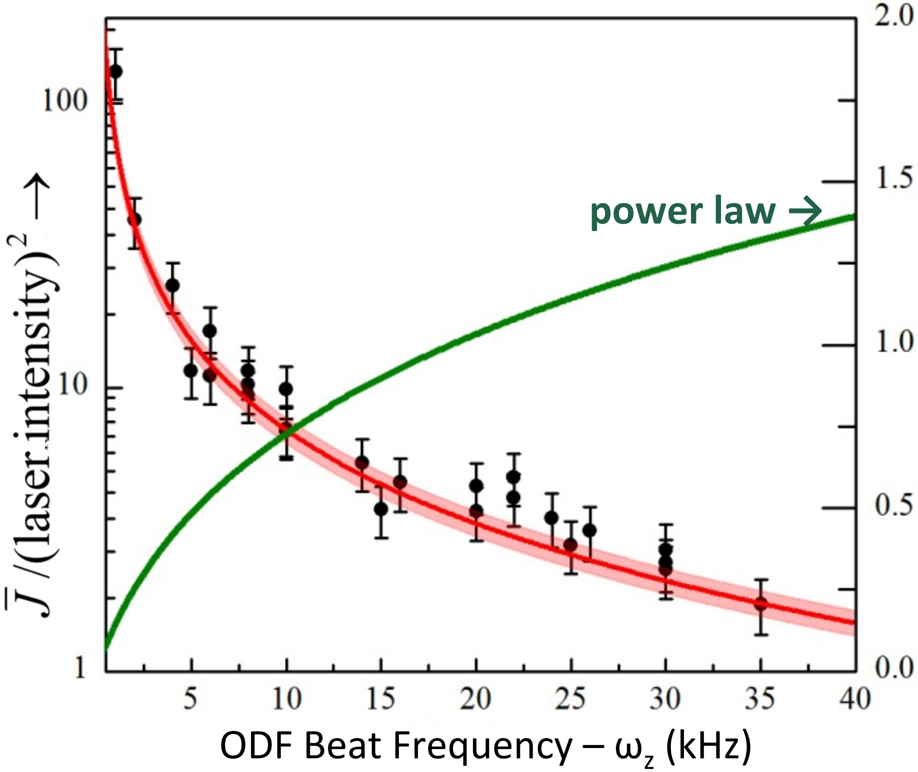




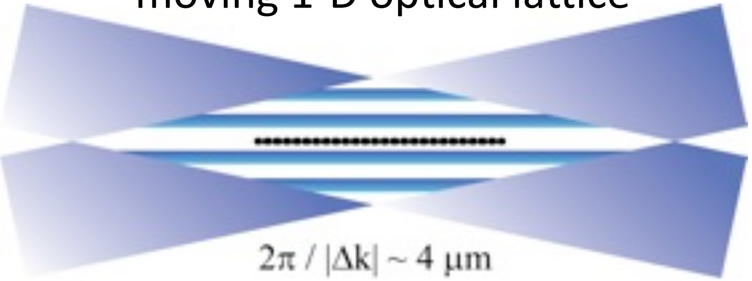


Multi-qubit control - Entanglement and control with many ions in Penning traps

Britton, Sawyer, Bollinger

- mean field analysis and spin precession measurement benchmark Ising interaction strength

moving 1-D optical lattice



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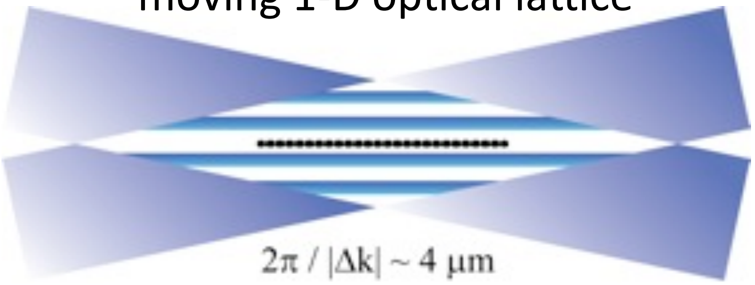

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- H_{Ising} should generate entanglement

$$\text{For } \mu_R \approx \omega_z, J_{i,j} \approx \frac{F_0^2}{\hbar \times 2M} \times \frac{1}{\mu_R^2-\omega_m^2} \equiv \chi$$

$$H_{\text{Ising}} \approx \frac{2\chi}{N} \times J_z^2,\ J_z = \sum_i \sigma_i^z/2$$

spin squeezing

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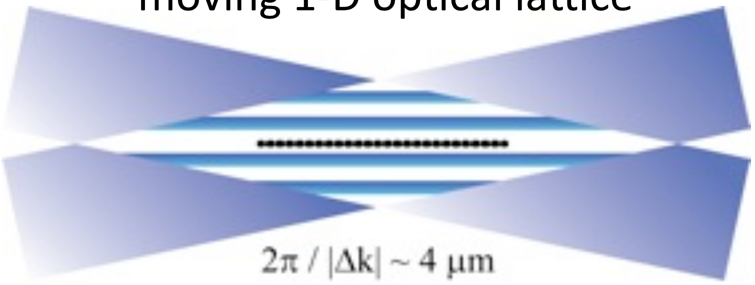

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~~spin squeezing~~

not yet
observed

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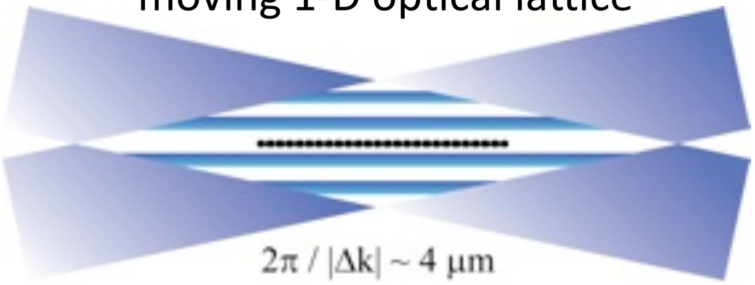

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~~spin squeezing~~ not yet observed

- planned improvements:
  - individual spin detection in the rotating frame → direct measurement of $\langle \sigma_i^z \sigma_j^z \rangle$
  - increase angle between ODF beams (+/- 20°) → minimize decoherence due to spontaneous emission

Trapped-ion metrology experiments at NIST

Ion Storage
Group
March 23, 2011

Jim Bergquist
Brad Blakestad (now JQI)
John Bollinger
Ryan Bowler
Joe Britton
Kenton Brown
James Chou
Yves Colombe
John Gaebler
David Hanneke (now at Amherst)
Dustin Hite
David Hume (now OFM)
Wayne Itano
Robert Jördens
John Jost
Dietrich Leibfried
Yiheng Lin
Christian Ospelkaus (now U Hannover)
Till Rosenband
Brian Sawyer
Ting-Rei Tan
Mike Thorpe
Ulrich Warring
Andrew Wilson
David Wineland

Quantum Measurement (Ancilla-assisted readout):
- Readout of the Al^+ clock state

Multi-qubit control:
- Entanglement and control with many ions in Penning traps

Entangled States:
- Generation of entangled states with microwave field gradients (novel schemes)
- Coupled ion trap spectroscopy (novel systems and applications)

Theme – Shared ion motion due to strong Coulomb interaction used to generate entanglement and read out quantum states

DARPA ONR *Revolutionary Research . . . Relevant Results* IARPA NIST

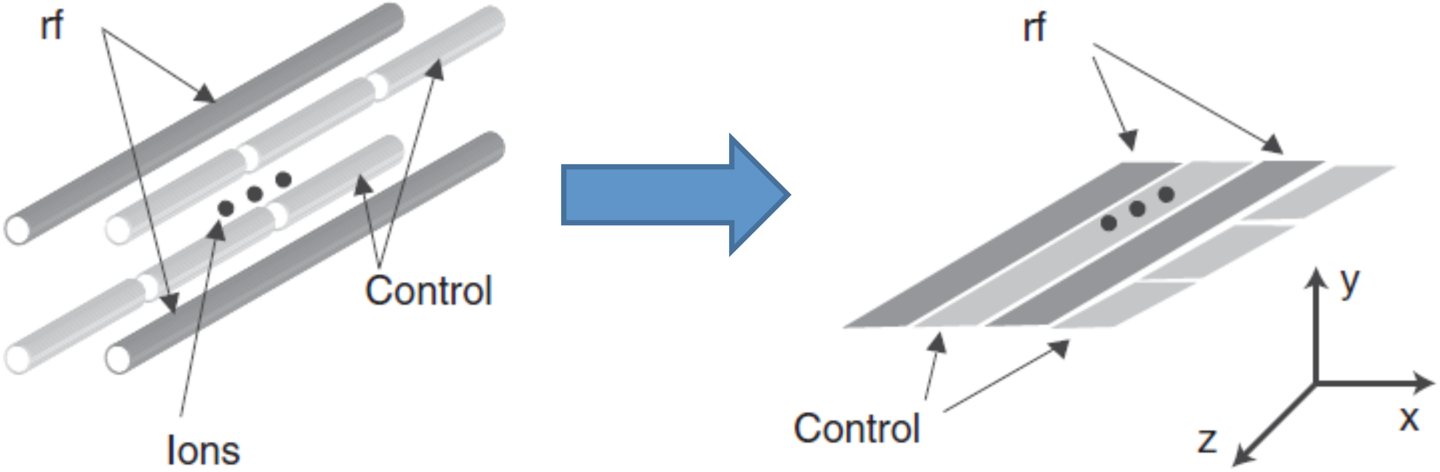
Generation of entangled states with microwave field gradients

Ospelkaus, Warring, Colombe, Brown, Amini, Leibfried, Wineland, Nature 476, 181 (2011)

Potential benefits of microwave gradients vs laser intensity gradients:

- better control with RF/microwaves
- no spontaneous emission
- ground state cooling not necessary (small Lamb-Dicke parameter)
- laser overhead vastly reduced

Requirement of strong microwave field gradient → use near field from microwave currents in surface electrode ion traps



Generation of entangled states with microwave field gradients

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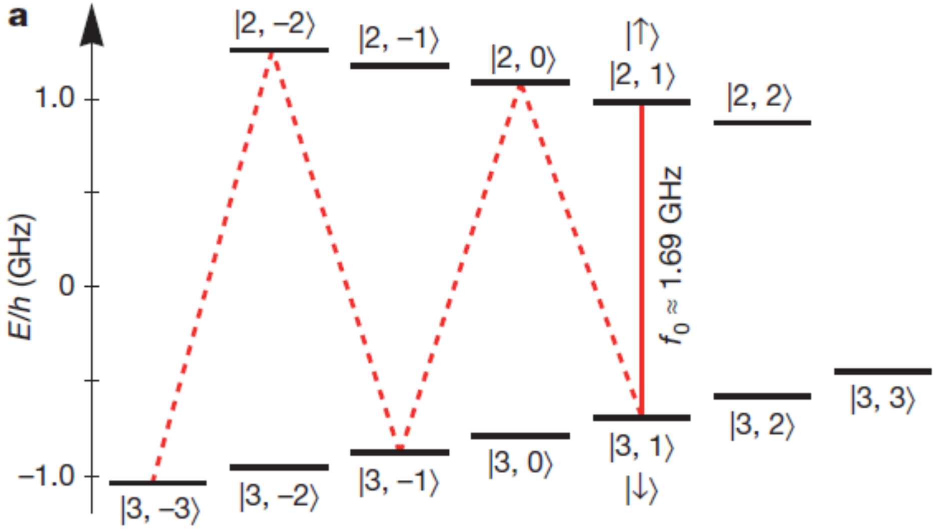
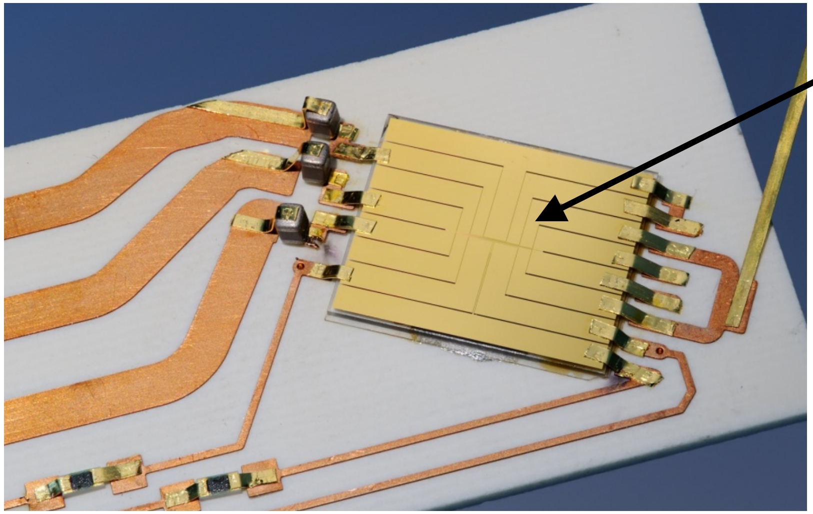


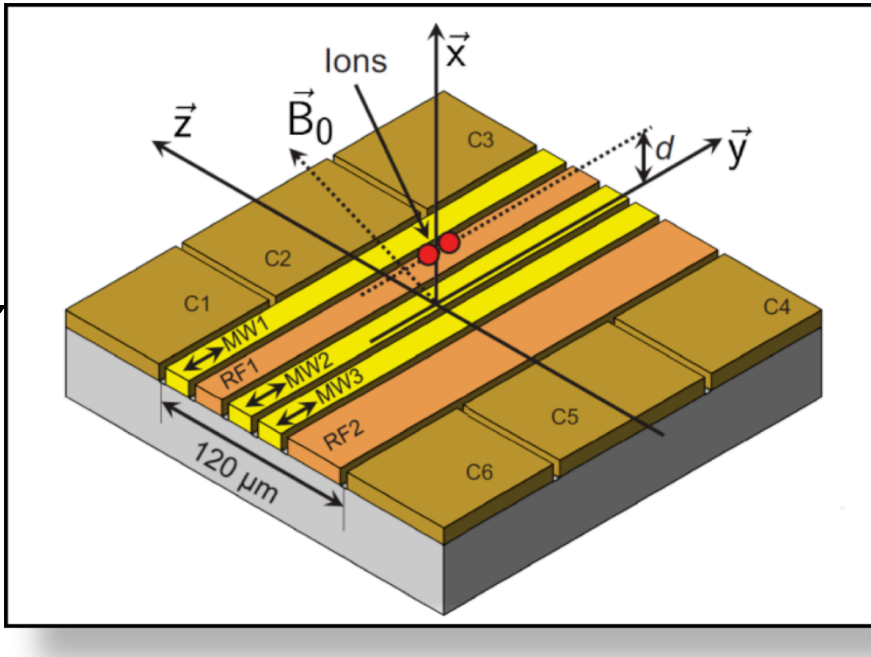
^{25}Mg^{+}, radial trap frequency ≈ 5 MHz,

B_0= 21.3 mT

ion – electrode distance = 30 μm

$dB_{uW}/dz \approx 35$ T/m

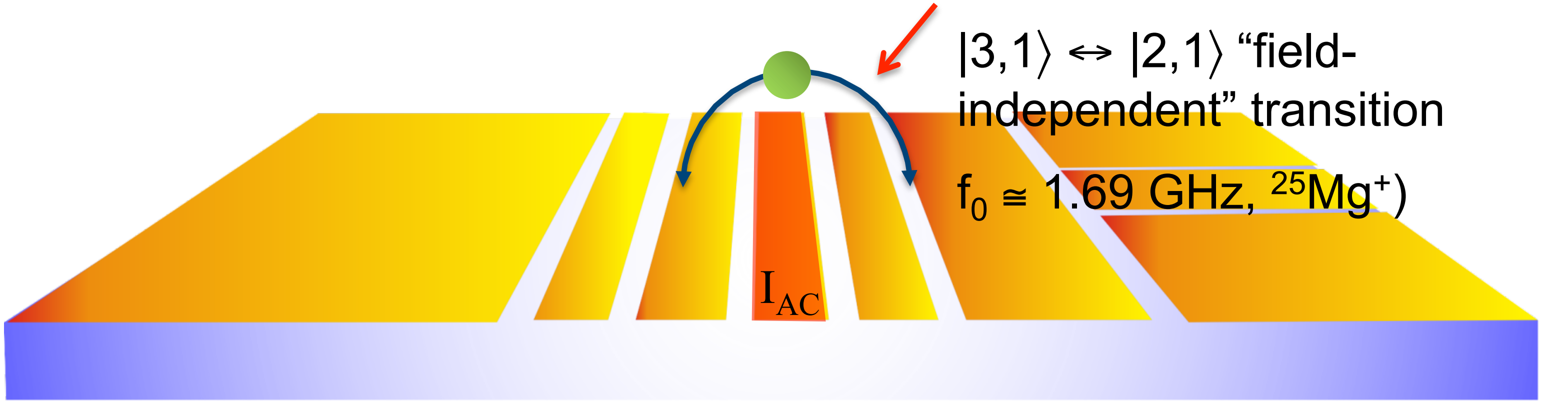




C. Ospelkaus *et al.*, PRL **101**, 090502 (2008)

C. Ospelkaus *et al.*, *Nature,* **476**, 181 (2011)

Single-qubit gates (Rabi flopping)

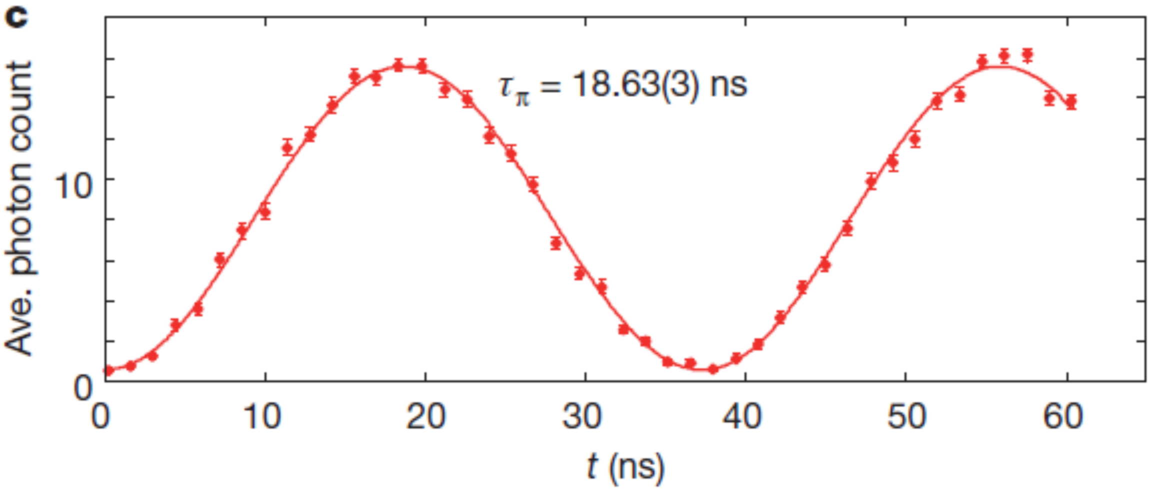


$B = B_1 \cos(2\pi f_0 t)$

$|3,1\rangle \leftrightarrow |2,1\rangle$ “field-independent” transition

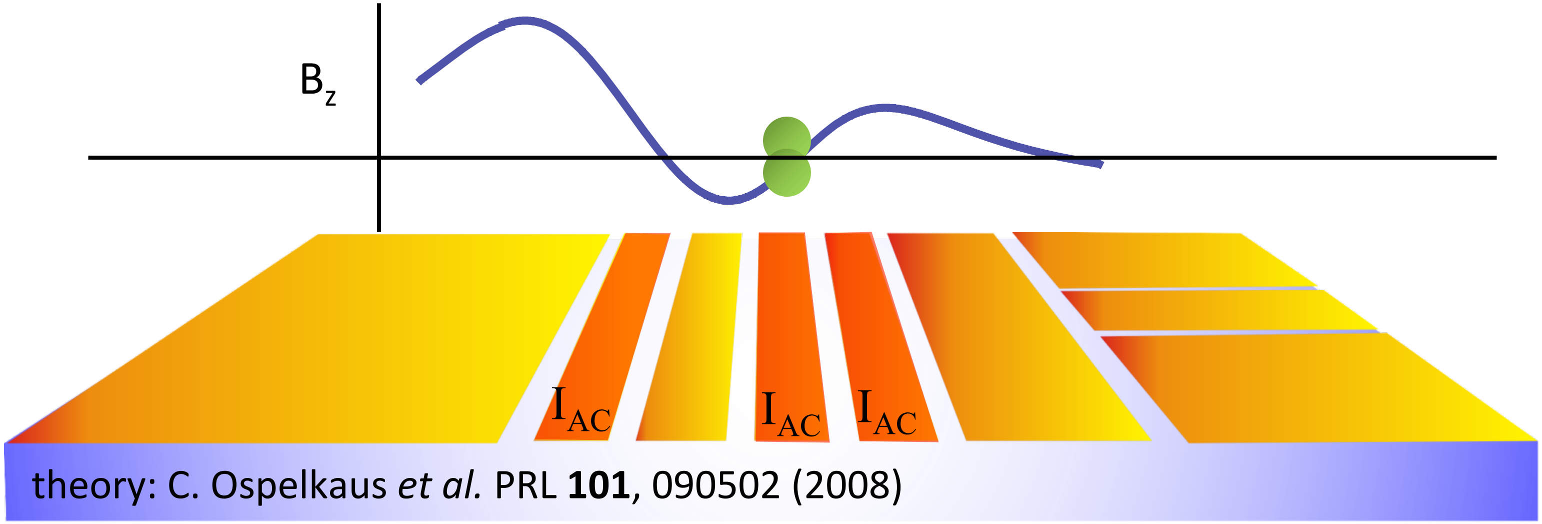
$f_0 \cong 1.69$ GHz, $^{25}Mg^+$)

Rabi flopping

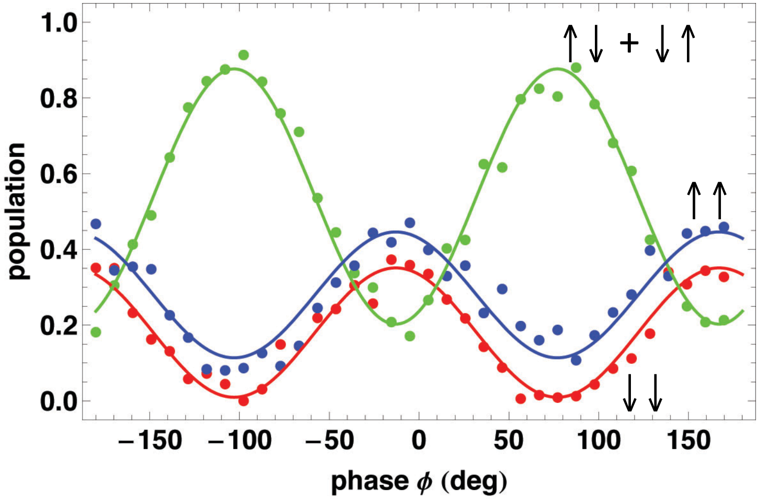


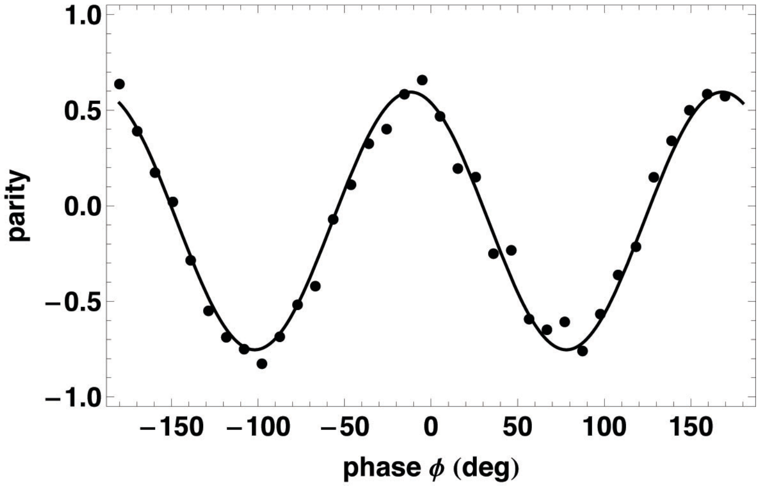
2-qubit (Mølmer-Sørensen) gate ($^{25}Mg^{+}$ hyperfine transition)

- $|\downarrow\downarrow\rangle \Rightarrow |\psi\rangle = \left(1/\sqrt{2}\right)\left(|\downarrow\downarrow\rangle - i|\uparrow\uparrow\rangle\right)$
- Generated through application of 2 μW field gradients at $f_0 \pm (f_r + \delta)$



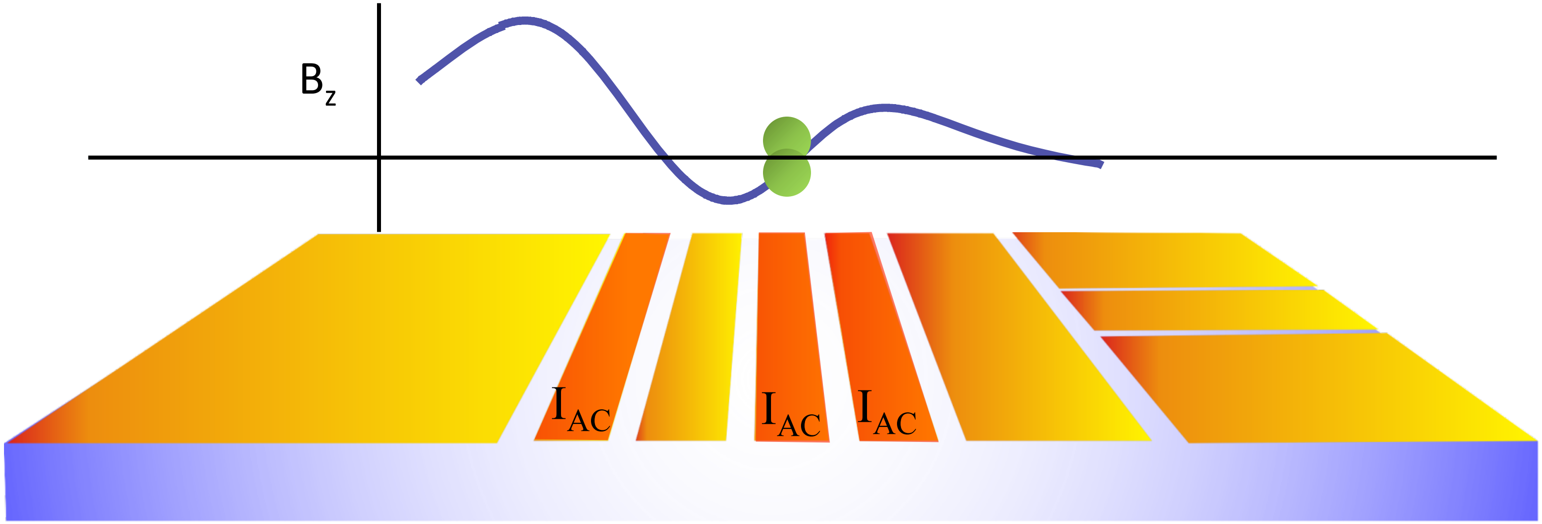
theory: C. Ospelkaus *et al.* PRL **101**, 090502 (2008)





$\Psi \simeq 1/\sqrt{2}\left(|\uparrow\uparrow\rangle + e^{i\phi}|\downarrow\downarrow\rangle\right)$ F = 0.76(3), T_{gate} = 200 μs

Limits to microwave gate fidelity:



- trap motional frequency stability

  ≈1 kHz fluctuation during gate, gate detuning δ=4.9 kHz

  causes: charge fluctuations on trap surface, RF pseudopotential fluctuations

  ⇒ cleaner trap surface, employ low-temperature trap
- $B_{osc} \neq 0$ due to μ-wave pulse shape differences between wires

  ⇒ AC-Zeeman shift ~1 kHz.

  ⇒ better pulse shaping, better amplitude stability
- anomalous heating and motional decoherence

  heating rate for 2-ion rocking mode < 0.2 quanta/ms, COM ~ 5 quanta/ms

  ⇒ low-temperature trap, smaller trap?
- crosstalk !? (single-qubit gates)

  ⇒ multizone test trap

Trapped-ion metrology experiments at NIST

Ion Storage
Group
March 23, 2011

Jim Bergquist
Brad Blakestad (now JQI)
John Bollinger
Ryan Bowler
Joe Britton
Kenton Brown
James Chou
Yves Colombe
John Gaebler
David Hanneke (now at Amherst)
Dustin Hite
David Hume (now OFM)
Wayne Itano
Robert Jördens
John Jost
Dietrich Leibfried
Yiheng Lin
Christian Ospelkaus (now U Hannover)
Till Rosenband
Brian Sawyer
Ting-Rei Tan
Mike Thorpe
Ulrich Warring
Andrew Wilson
David Wineland

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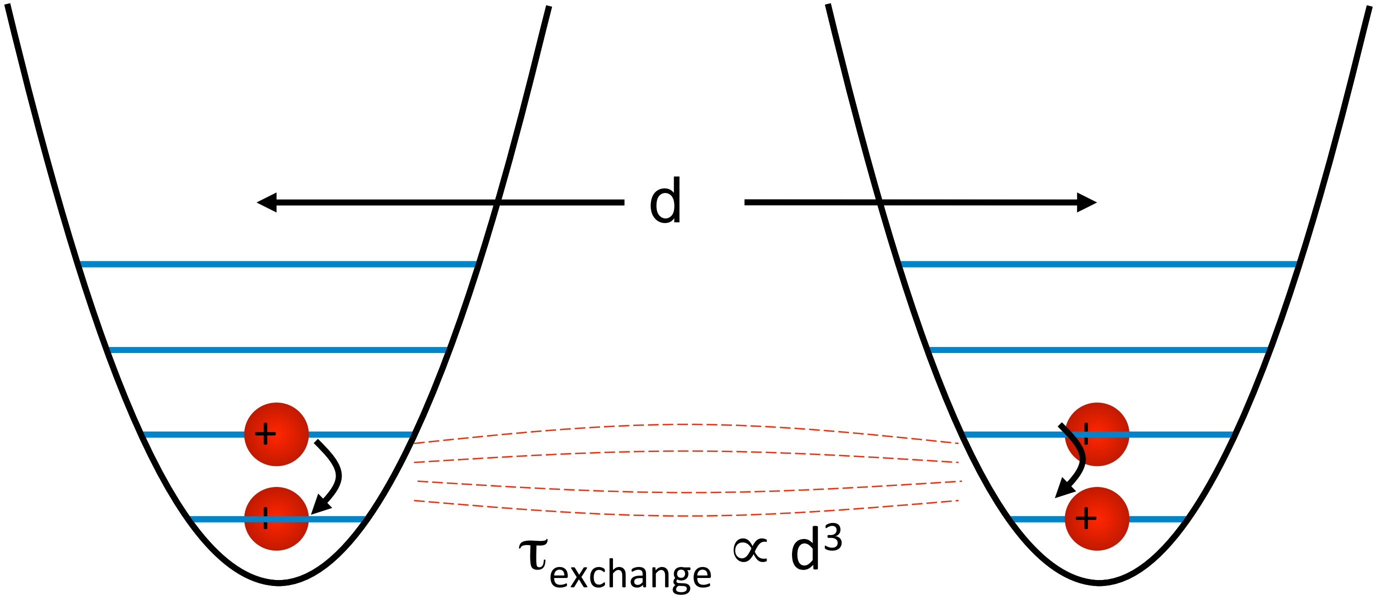
Coupled ion trap spectroscopy

Brown, Ospelkaus, Colombe, Wilson, Leibfried, Wineland, Nature **471**, 196 (2011)

see also M. Harlander *et al.*, *Nature*, **471**, 200 (2011)

Can we observe the Coulomb-mediated transfer of a single quantum of motion between ions in separate potential wells?



$\tau_{\text{exchange}} \propto d^3$

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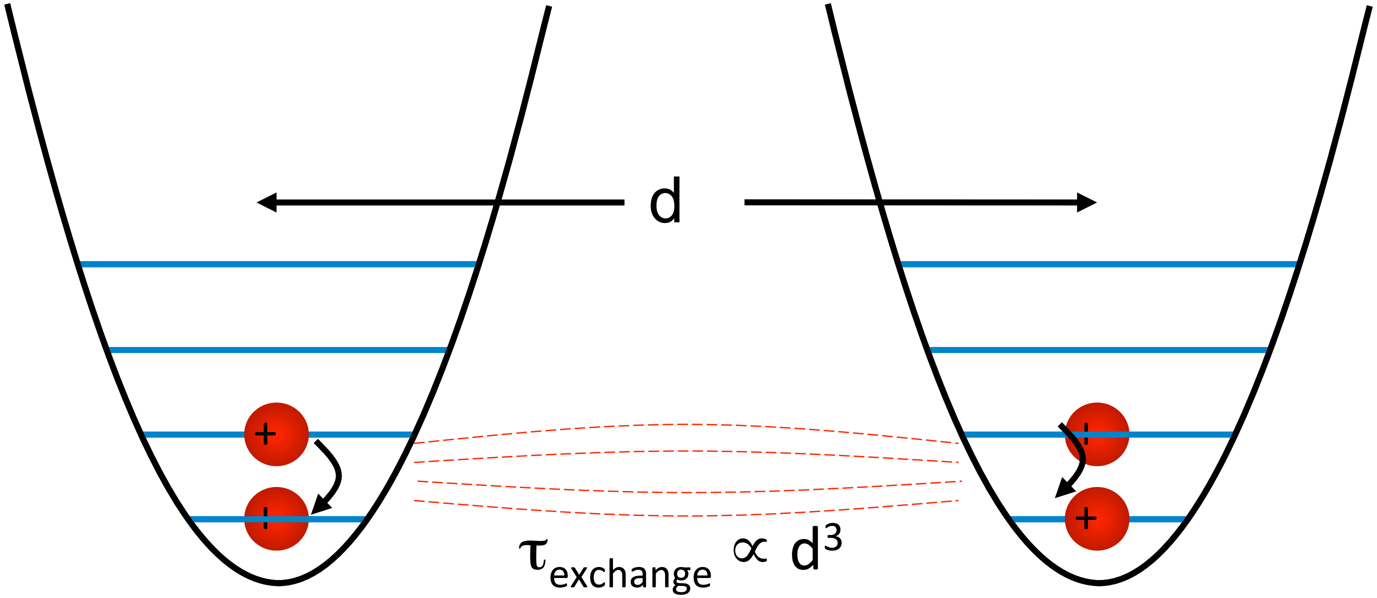


$$\tau_{exchange} \propto d^3$$

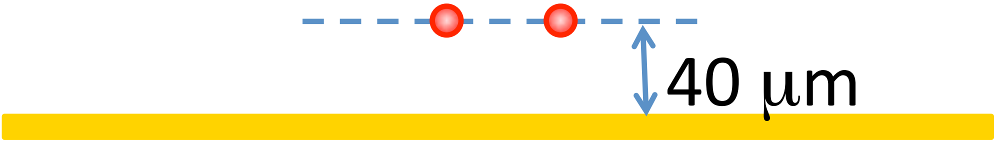
Motivations:

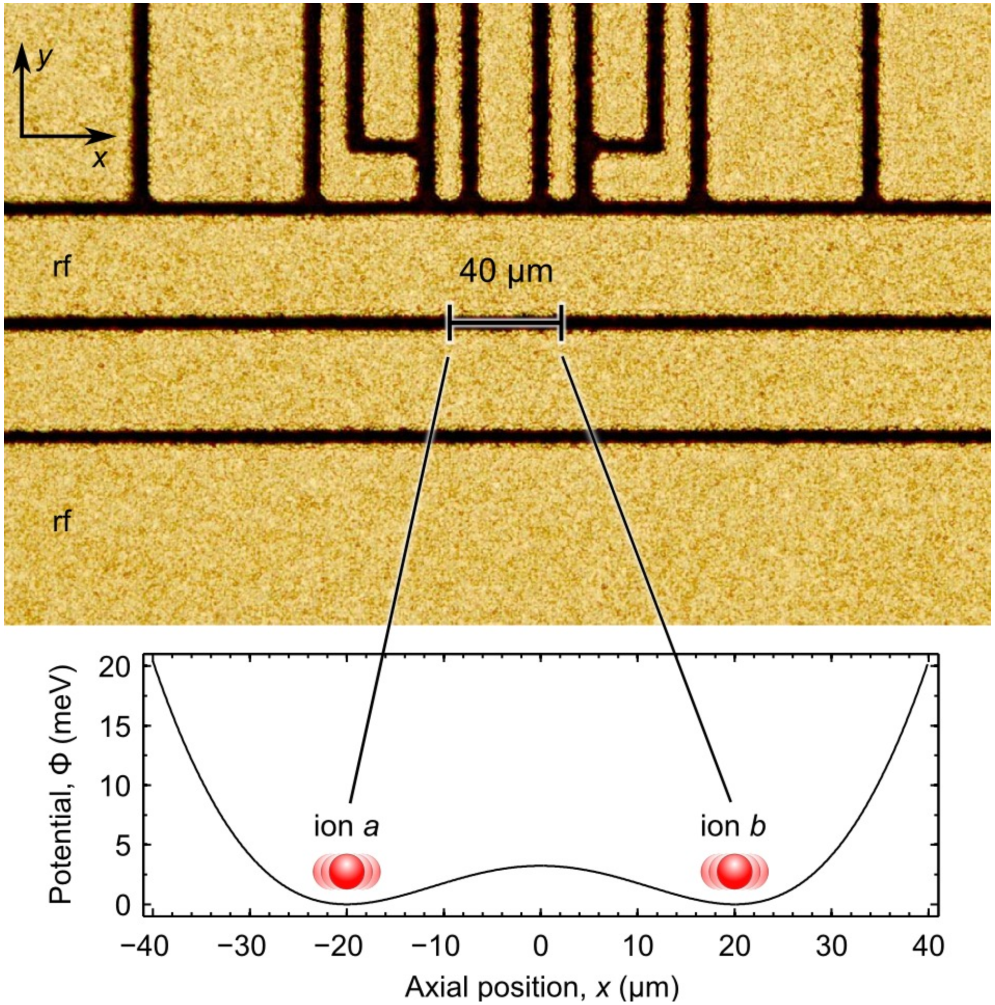
1. extend capabilities of quantum logic spectroscopy (for example between oppositely charged particles or even antimatter particles)
2. potential speed-up of quantum logic operations in a multi-zone quantum information processor
3. first step towards using trapped ions in a hybrid quantum system (i.e. coupling a trapped ion to a quantized mechanical or electrical oscillator)

Coupled ion trap spectroscopy

Brown, Ospelkaus, Colombe, Wilson, Leibfried, Wineland, Nature 471, 196 (2011)

Trap parameters:





- $^9Be^+$ ions

- 8 µm gold thickness
- 5 µm gaps
- T≈ 4 mK

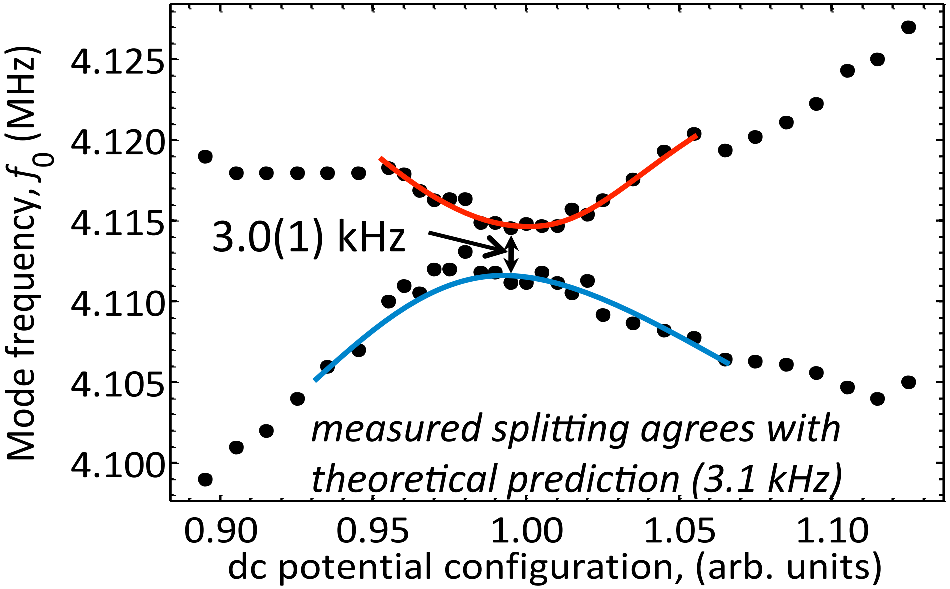
- 40 µm ion height
- 40 µm ion separation
- 4 MHz axial frequency

- Individual control of potentials in both trapping sites

Coupled ion trap spectroscopy

Brown, Ospelkaus, Colombe, Wilson, Leibfried, Wineland, Nature 471, 196 (2011)

Avoided crossing of eigenmode frequencies



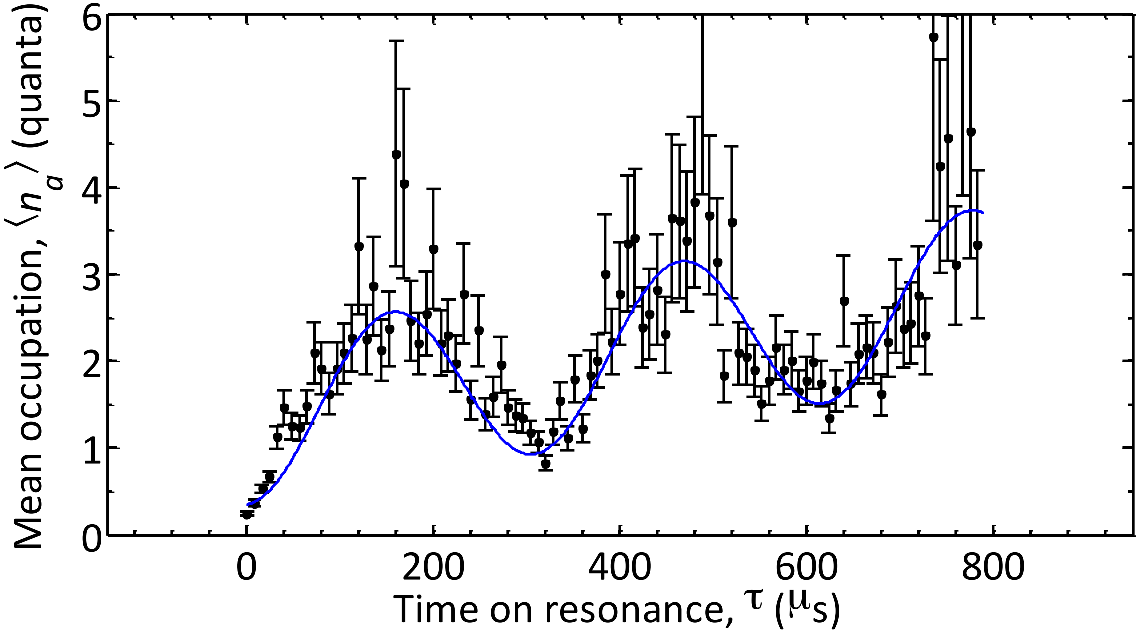
3.0(1) kHz

measured splitting agrees with theoretical prediction (3.1 kHz)

Coulomb exchange of a thermal state

τ_{ex} = 155 μs (162 μs predicted)

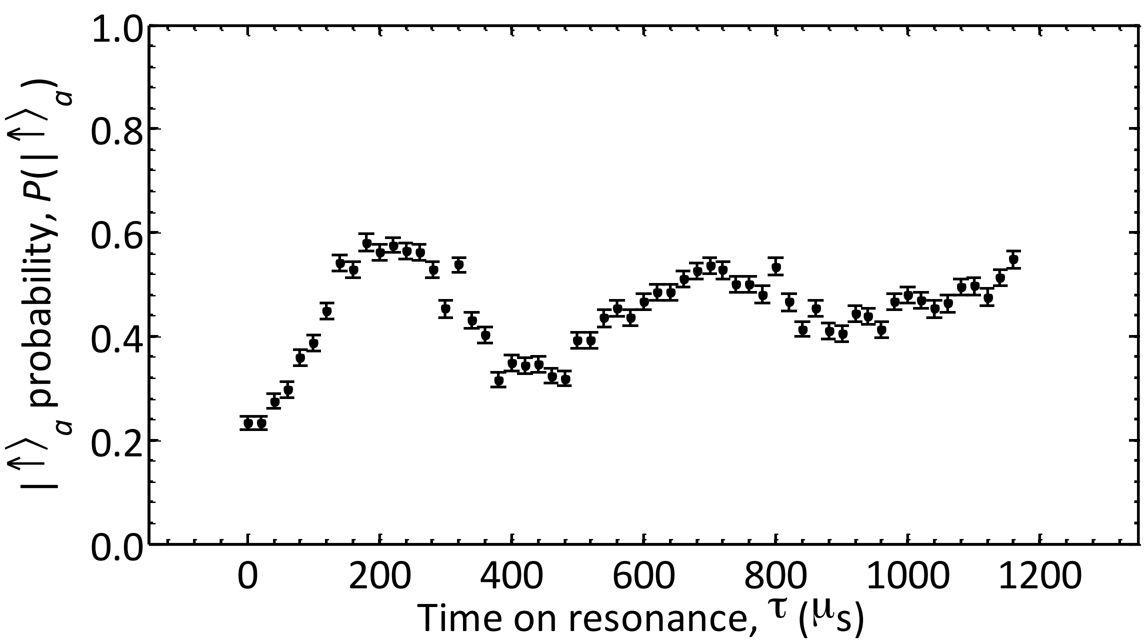
d‹n›/dt = 1,885 quanta/s (heating rate)



Coupled ion trap spectroscopy

Brown, Ospelkaus, Colombe, Wilson, Leibfried, Wineland, Nature 471, 196 (2011)

Coulomb exchange of a single quantum



- Initial contrast limited by imperfect state preparation
  - set-up can be improved through better laser polarization, reduced cryostat vibrations, improved laser beam pointing instability, actively control laser
- Decay in contrast is due to motional decoherence
  - heating → try a new, cleaner trap
  - trap frequency instability → try a new, cleaner trap

Trapped-ion metrology experiments at NIST

Efficient Readout

Ancilla-assisted readout):

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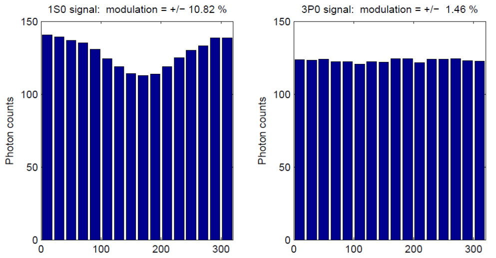

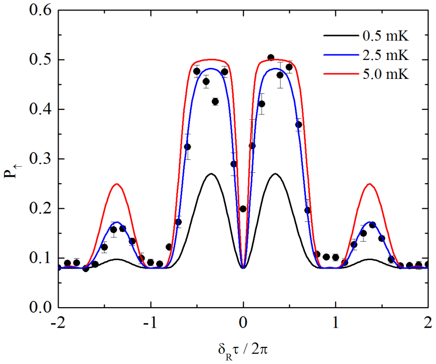

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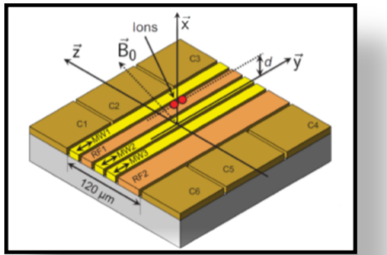

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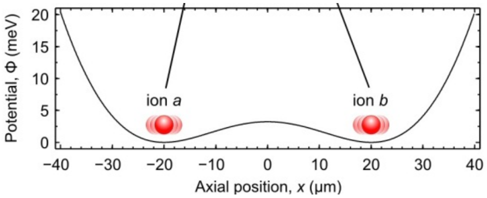

Entangled States:

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