イオントラップを用いた量子ゲート実験

大阪大学大学院基礎工学研究科
占部伸二
H22.8.27 量子情報処理サマースクール

The contents of this lecture

1.Introduction
2. Ion trap and ion qubit
3.Initialization and state detection
4.Coherence time
5.Quantum gate
6.Spin dependent force and its application

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1.Introduction

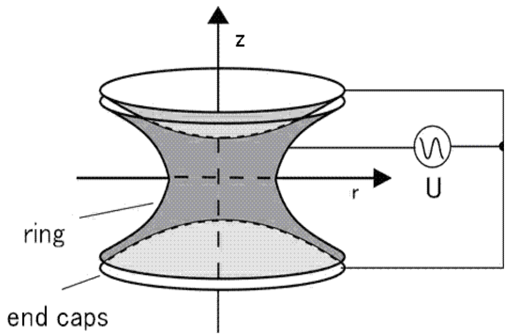
Ion trap: Trapping of charged particles with electromagnetic fields

Mass spectrometry (1950's),

Spectroscopy ← Laser cooling (1975)

Wineland & Dehmelt,

Hänsch & Schawlow



High resolution spectroscopy:

Isolation from the environment

→ Optical frequency standard with single ions($Q \sim 10^{15}$)

Mg^{+}ーAl^{+}: 8×10^{-18}: quantum logic spectroscopy(NIST, 2010)

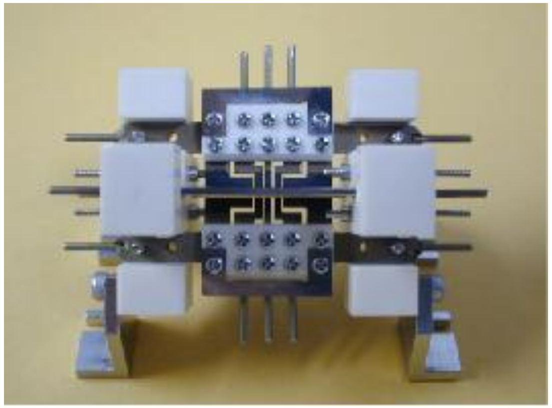
Quantum information processing

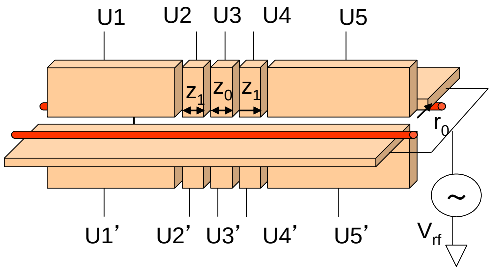
qubit: internal states of an ion in an ion string

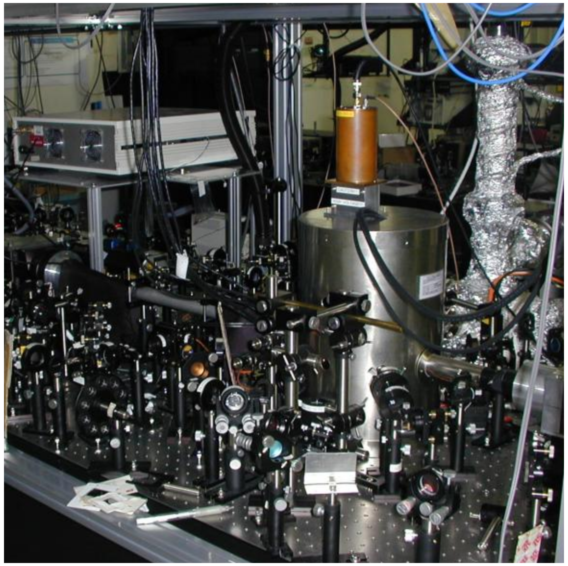
Cirac & Zoller (1995)

2. Ion traps and ion qubit

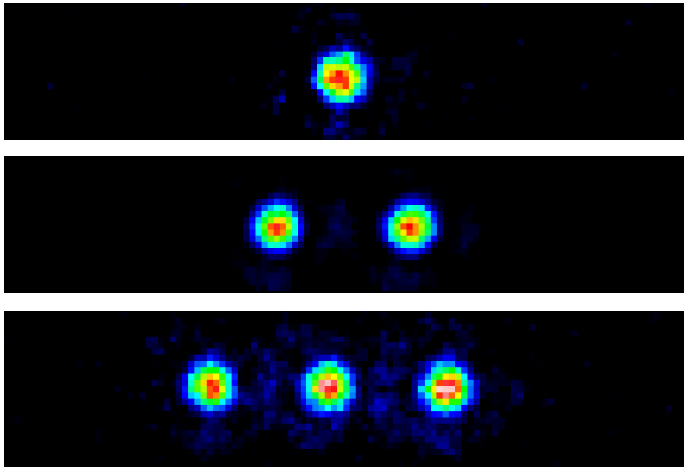
Linear rf traps







Typical trap operating parameters:
- ultra high vacuum: less than 10^{-8} Pa
- trap dimension (r_0) : 0.6 mm
- rf frequency (Ω) : 24 MHz
- effective potential depth (V_{eff}) : ∼10V
- collective motional frequency
  - z: 0.7MHz, x: 2.1MHz, y: 2.3 MHz
- distance between ions in strings: about 7μ



Images of 1,2,3 ions

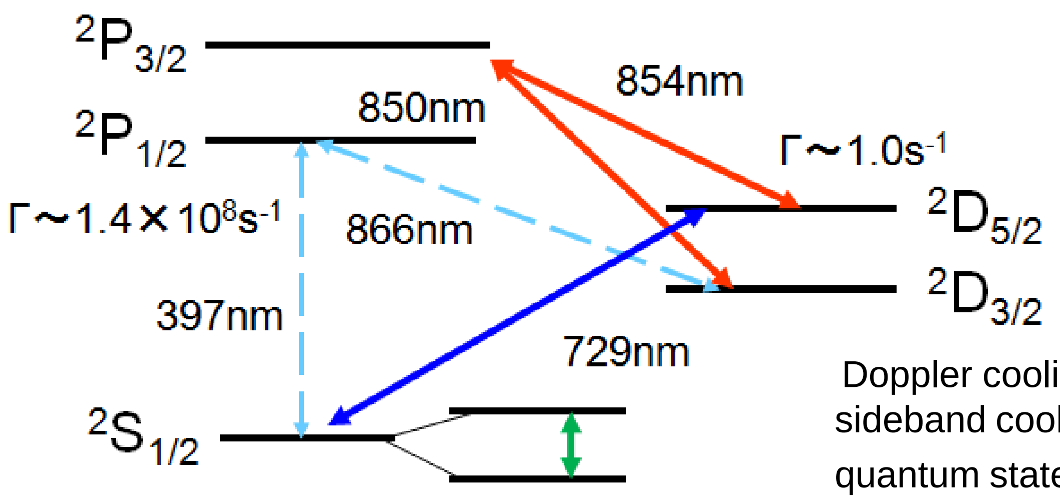
Ion qubit

Hyperfine levels, ground state - metastable state

Ions: Be^+, Mg^+, Zn^+, Cd^+ (hyperfine qubits)

Ca^+, Sr^+, Ba^+, Yb^+, Hg^+ (hyperfine or metastabe qubits)

$^{40}Ca^+$ ion



Doppler cooling : 397nm, 866nm

sideband cooling : 729nm, 854nm

quantum state control : 729nm etc.

Zeeman qubits: $^2S_{1/2}$,m=-1/2 - $^2S_{1/2}$,m=1/2 (~10MHz)

Optical-transition qubits: $^2S_{1/2}$ - $^2D_{5/2}$ (729nm)

Terahertz-separated qubits : $^2D_{3/2}$ - $^2D_{5/2}$ (1.82THz)

Terahertz-separated qubit:

Raman transitions driven by phase locked lasers bridged by a frequency comb

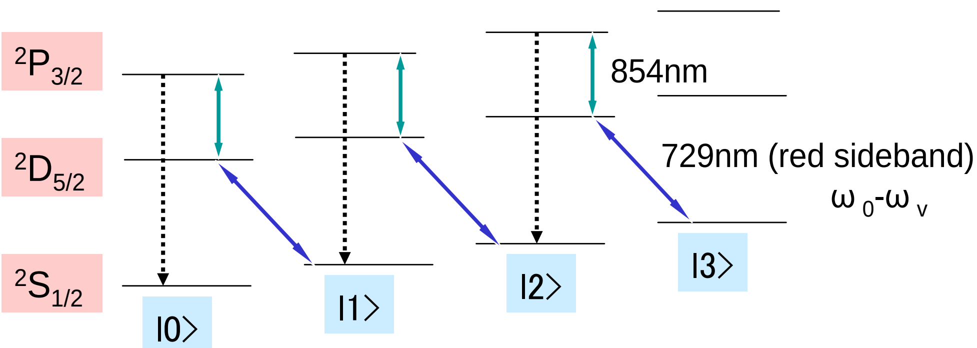
3.Initialization and state detection

Initialization

internal state: optical pumping ～100%

external state: Doppler cooling : from 10000 K to mK

sideband cooling : to the motional ground state

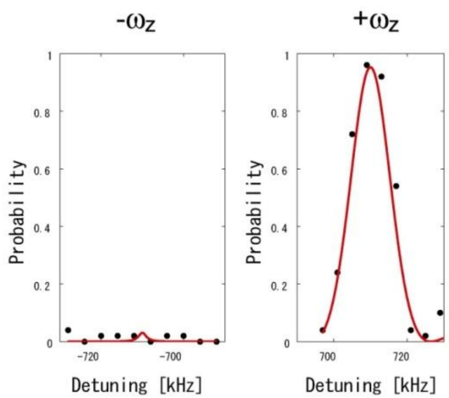


$S_- / S_+ = \langle n_z \rangle / (\langle n_z \rangle + 1)$

S_-: height of red sideband spectrum

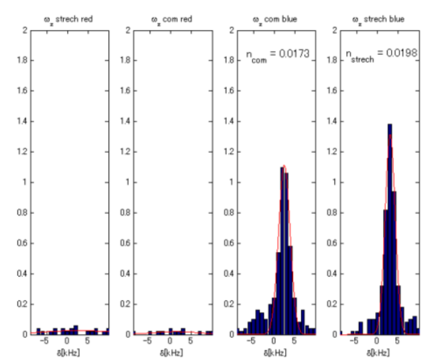
S_+: height of blue sideband spectrum

Red and blue sideband spectra of axial modes in S-D transitions after sideband cooling



$$\left(\overline{n_z}\right) \sim (0.01)$$

Single ions



$$\left(\overline{n_{COM}}, \overline{n_{st}}\right) \sim (0.017,\ 0.020)$$

Two ions

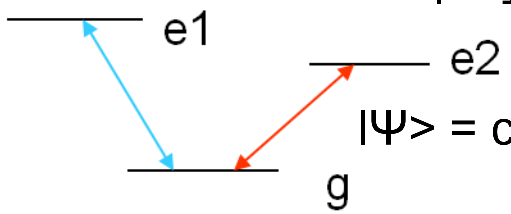
State detection

Electron shelving method: nearly 100% efficiency

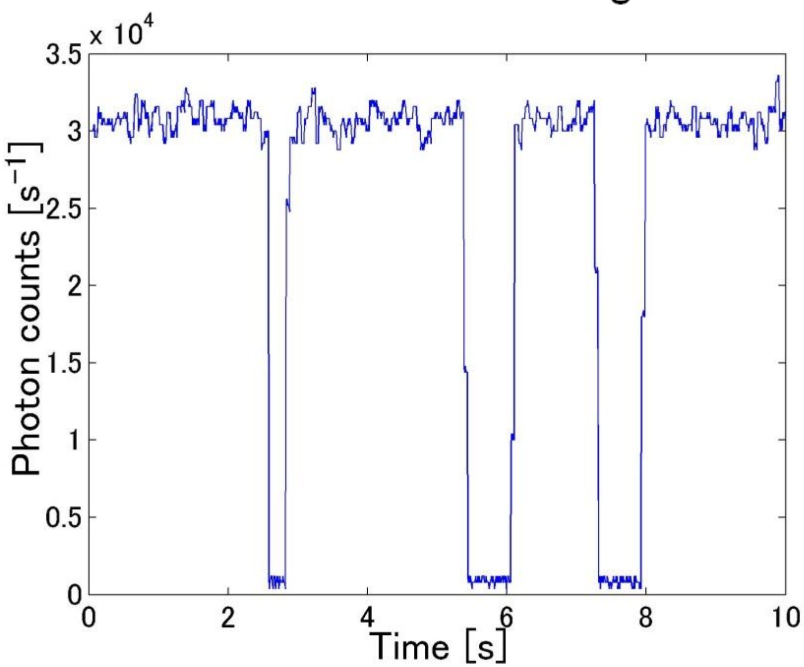
Cycling transitions･･･fluorescence signal ～3×10^4 photons/s/ion

$\Gamma \sim 1.4 \times 10^{-8}\ s^{-1}$

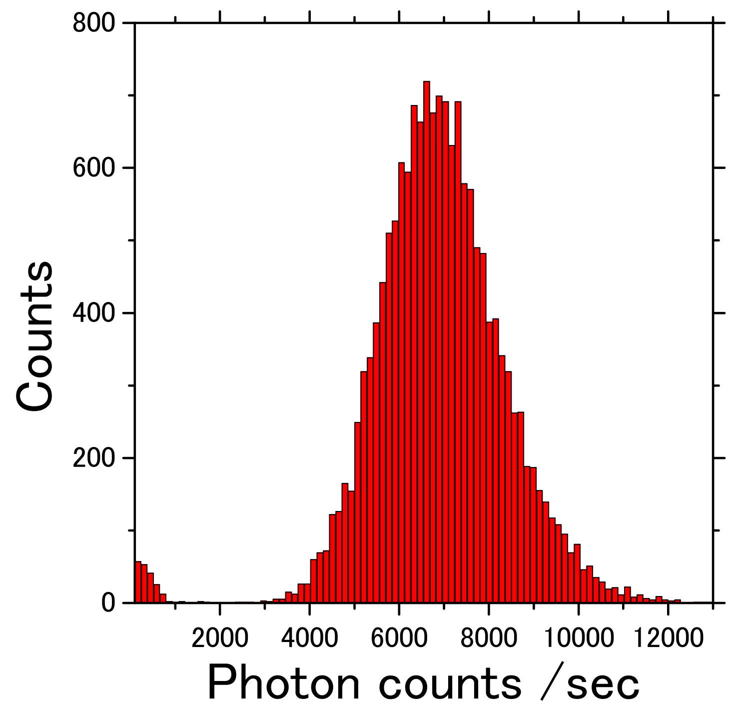
$\Gamma \sim 1\ s^{-1}$



$|\Psi\rangle = c_1|g\rangle + c_2|e2\rangle$



Quantum jump signal of single ions



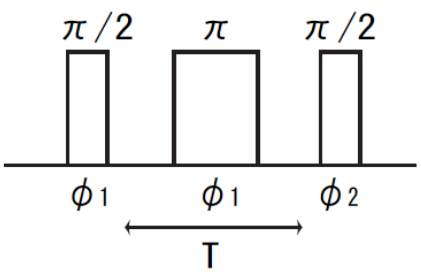
Histogram of photon counts

4.Coherence time

Coherence time: hyperfine ground state･･･several minutes
metastable state･･･ about 1.0 s ($^{40}Ca^+$)
External disturbance: magnetic field fluctuation, laser linewidth etc.

Coherence time of terahertz-separated ($D_{3/2}$-$D_{5/2}$) qubits

・Spin echo sequence

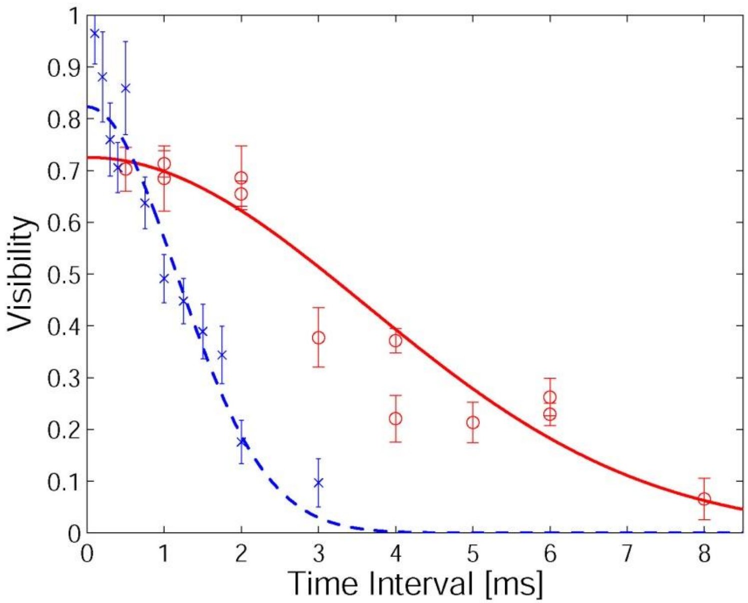


Ramsey spin echo pulse

Coherence Revival by Spin echo π pulse
(Effective against slow magnetic field fluctuation)

Coherence time of normal and spin echo sequence

	Spin echo sequence	Normal sequence
Coherence time (e^{-1} decay)	5.1[ms]	1.7[ms]



Fringe visibility of Ramsey signal

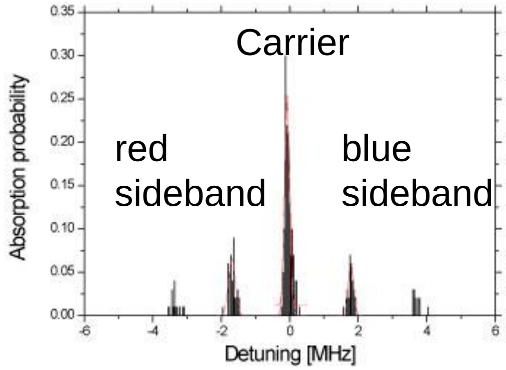
K.Toyoda, H.Shiibara, S.Haze, R.Yamazaki, S.Urabe, Phys. Rev. A 79, 023419, 2009

5.Quantum gate

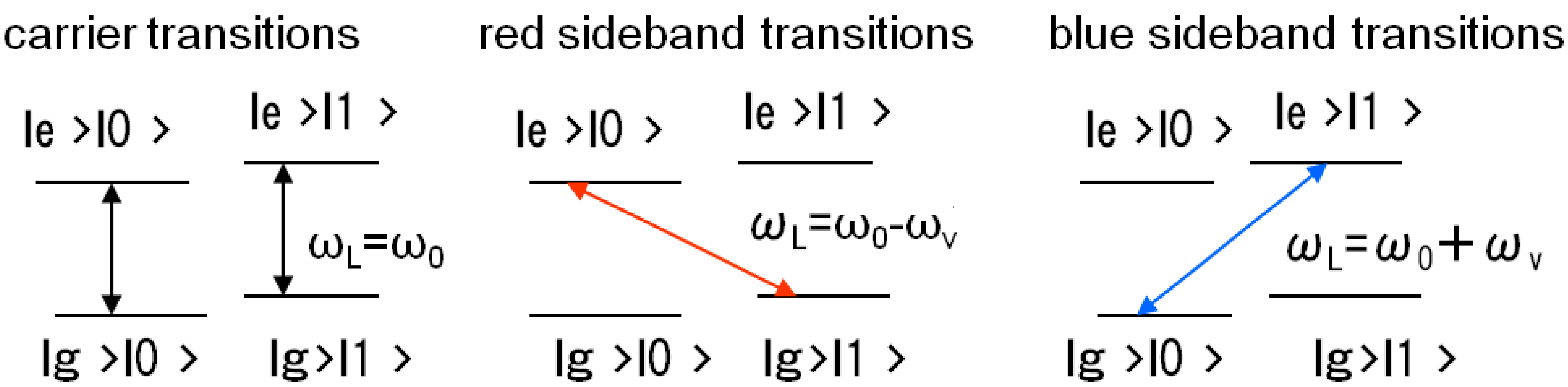
Entanglement between qubits ･･･ mediated by the collective motional states.

manipulation of qubits･･･ laser pulses
carrier pulse,
red sideband pulse,
blue sideband pulse

hyperfine qubit: Raman transitions,
metastable qubit: E2 transitions



Optical spectrum of single ions
(Electric quadrupole transitions)



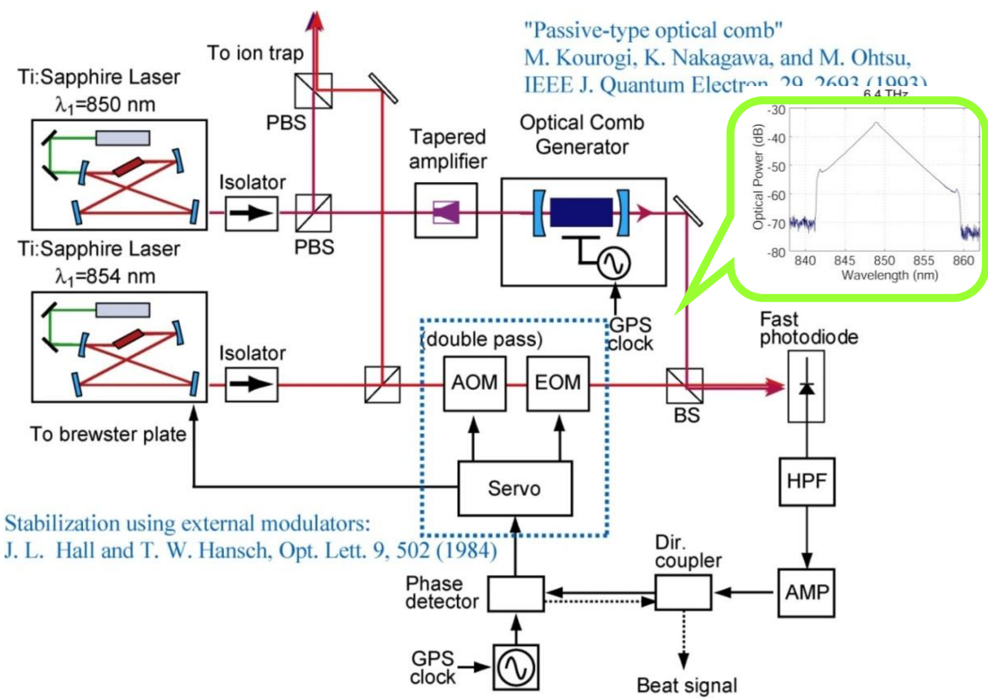
Qubit : internal states, |**g**>, |e>, Bus bit : motional states, |0>, |1>

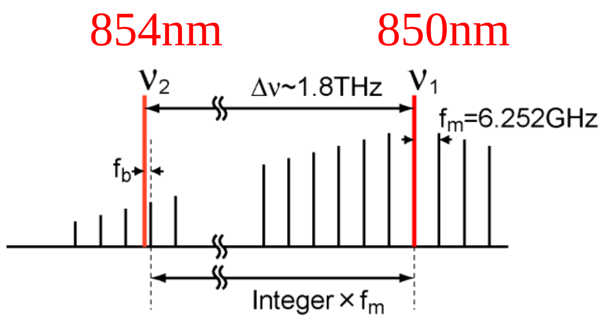
729nm Ti : sapphire laser for S-D qubits

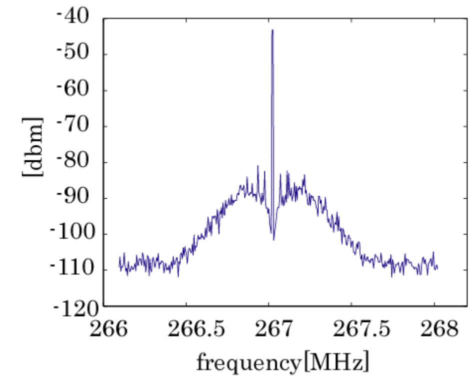
The frequency is locked to a ULE cavity by the Pound-Drever-Hall method.
line width : less than 1KHz,
frequency drift : less than 3kHz/h

Phase-locked laser system with a frequency comb for D-D qubits

1.8194･･ THz ~ 6.252 GHz × 291 lines + 267.･･ MHz







$\Delta\Phi_{rms}$=50 mrad

R.Yamazaki, T.Iwai, K.Toyoda, and S.Urabe, Opt. Lett. Vol.32,No.5,(2007)2085
S.Haze, Y.Senokuchi, R.Yamazaki, K.Toyoda, S.Urabe, Appl. Phys. B to be published

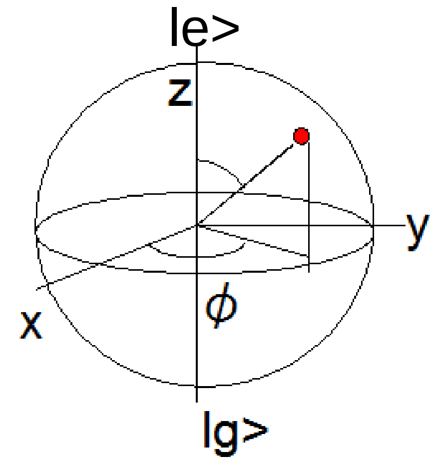
5.1 Single qubit rotation

carrier pulse, pulse area : $\Omega_0 t = \theta$, phase: φ

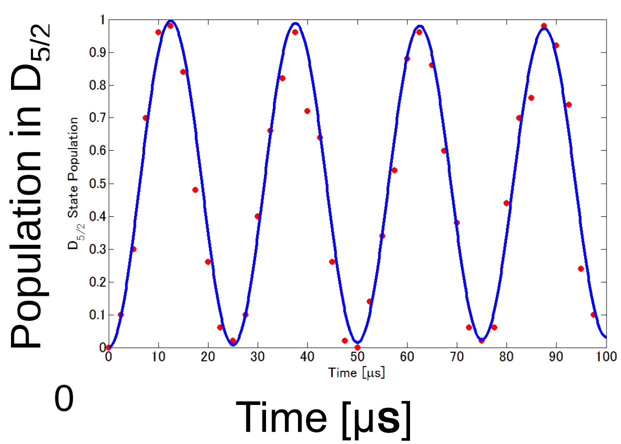
$$|\Psi(t)\rangle = \hat{R}(\theta,\varphi)|\Psi(0)\rangle$$

$$\hat{R}(\theta,\varphi) = \exp[i\frac{\theta}{2}(\hat{\sigma}_x \cos\varphi - \hat{\sigma}_y \sin\varphi)]$$

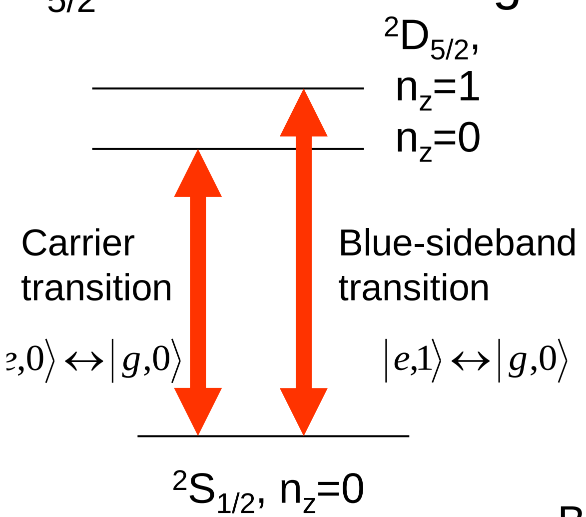
$$\Rightarrow \begin{pmatrix} \cos(\theta/2) & ie^{i\varphi}\sin(\theta/2) \\ ie^{-i\varphi}\sin(\theta/2) & \cos(\theta/2) \end{pmatrix}$$

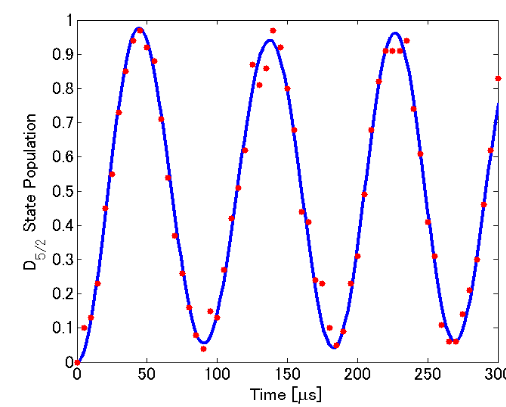


Rabi oscillations of $S_{1/2}$-$D_{5/2}$ transitions in single $^{40}Ca^{+}$ ions



Carrier Rabi oscillation

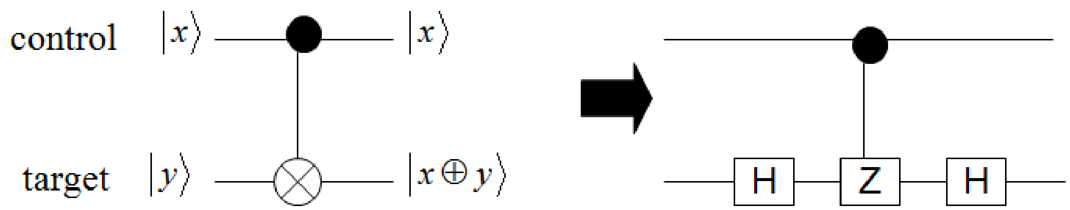


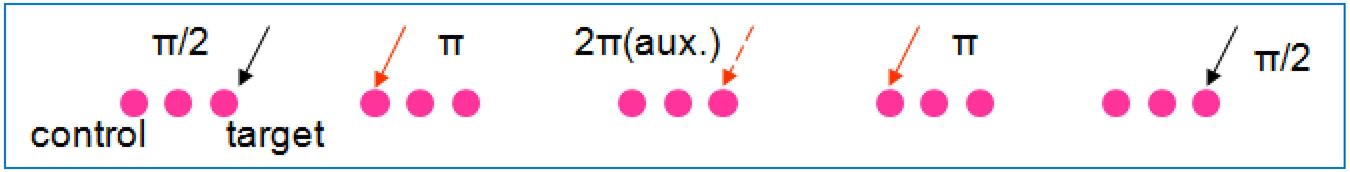


Blue-sideband Rabi oscillation

5.2 Two-qubit gate

Cirac-Zoller C-Not gate





carrier $\pi/2$ pulse: Hadamard gate $\quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix},$

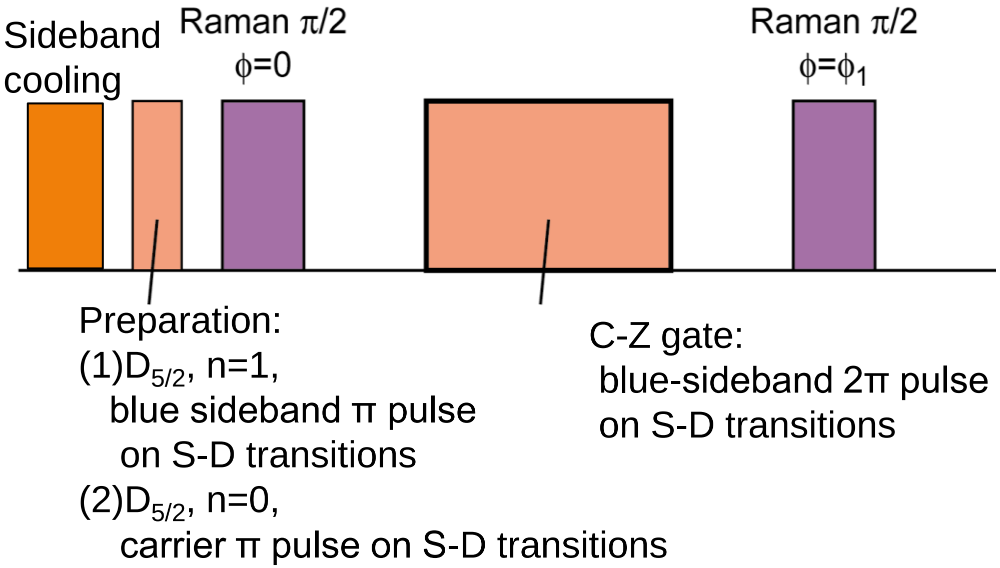
red sideband π pulse: swap operation

$$|0,g\rangle \rightarrow |0,g\rangle, \quad |0,e\rangle \rightarrow |1,g\rangle, \qquad |0\rangle\left(\alpha|g\rangle + \beta|e\rangle\right) \rightarrow \left(\alpha|0\rangle + \beta|1\rangle\right)|g\rangle$$

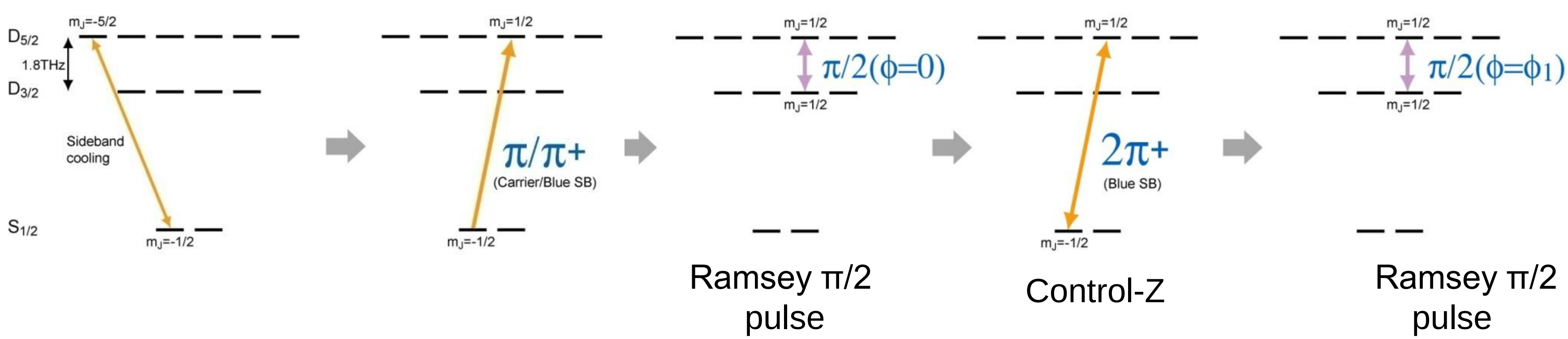
red sideband 2π pulse(aux) : control-σ_z : $\quad C\text{-}Z = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} \hat{1} & \hat{0} \\ \hat{0} & Z \end{pmatrix}$

Cirac-Zoller Gate experiment using terahertz-separated qubits

Single $^{40}Ca^+$,
Control bit : phonon states
|0>: n=0
|1>: n=1
Target bit: internal states
$|\uparrow\rangle$: $D_{5/2}(m=1/2)$
$|\downarrow\rangle$: $D_{3/2}(m=1/2)$



CZ gate excitation scheme



$|\psi\rangle = |\uparrow\rangle$ → $|\psi\rangle = (|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}$ →

(1) $n = 1, |\psi\rangle = (|\downarrow\rangle - |\uparrow\rangle)/\sqrt{2}$
(2) $n = 0, |\psi\rangle = (|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}$

→

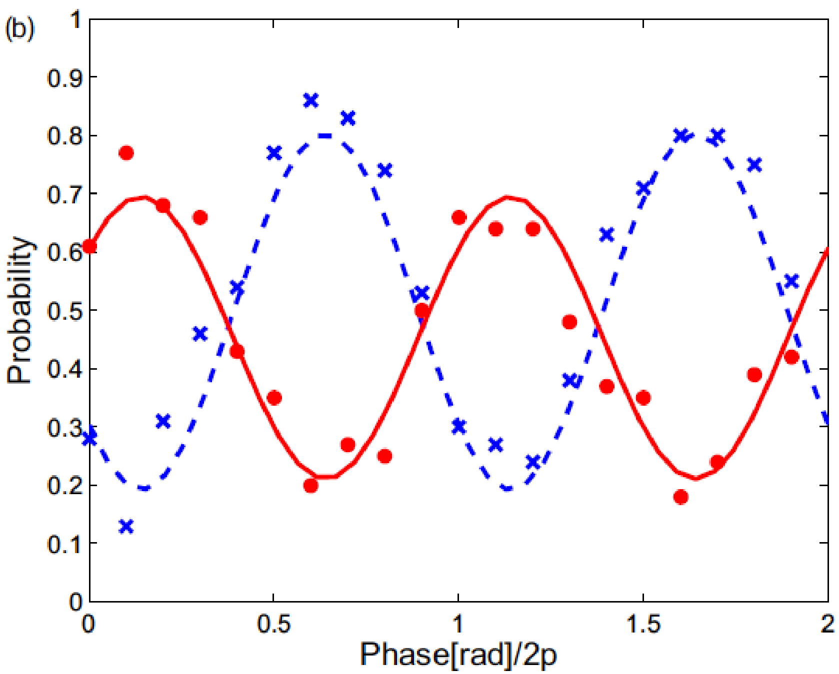
(1) $|\psi\rangle = |\uparrow\rangle$
(2) $|\psi\rangle = |\downarrow\rangle$

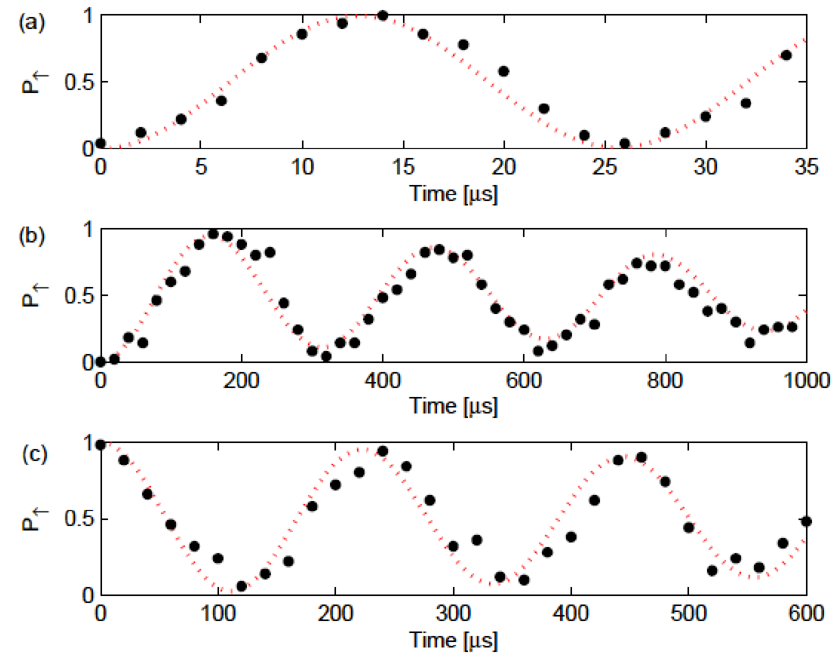
CZ gate result

Initial phonon state: |0>

Initial phonon state: |1>

Simulation results obtained by solving the density matrix equation





Fidelity～0.74

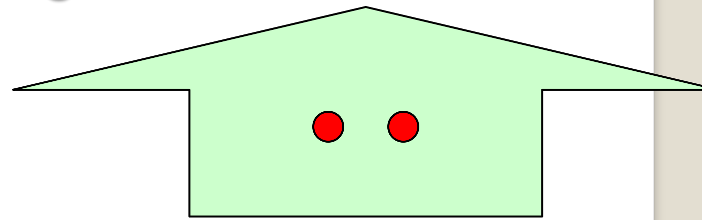
(a) Carrier Rabi oscillation in S-D transition

(b) BSB Rabi oscillation in S-D transition

(c) Carrier Rabi oscillation in D-D transition

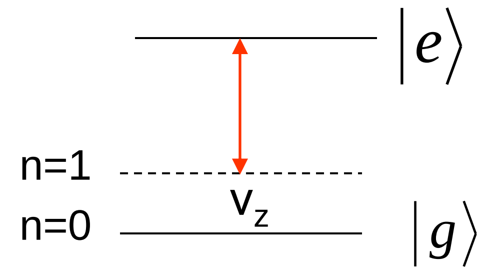
K.Toyoda, S.Haze, R.Yamazaki, S.Urabe, Phys. Rev. A, 81, 032322 , 2010

5.3 Creation of two-particle entanglement



2 two-level ions are irradiated equally with a laser pulse, whose frequency is tuned near the first red sideband of the COM mode.

The total number of excitation of quanta is conserved and the basis of one-quantum Hamiltonian is composed of : $\{|g,g\rangle|1\rangle,\ |e,g\rangle|0\rangle,\ |g,e\rangle|0\rangle\}$



I.E.Linington & N.V. Vitanov: Phys. Rev. A77,010302 (2008)

Interaction Hamiltonian (rotating frame)

$$\text{Basis}:\{|g,g\rangle|1\rangle,\ |e,g\rangle|0\rangle,\ |g,e\rangle|0\rangle\}$$

$$\hat{H}_I = \begin{bmatrix} \hbar\Delta_1 & \hbar\Omega/2 & \hbar\Omega/2 \\ \hbar\Omega/2 & \hbar\Delta_0 & 0 \\ \hbar\Omega/2 & 0 & \Delta_0 \end{bmatrix}$$

$$\Delta_0 = -\Delta_1 = \delta/2$$

$$\delta = \omega_0 - \nu - \omega_L,\quad \Omega = \eta\Omega'/\sqrt{N},$$

η : Lamb - Dicke parameter

$$\text{Basis}:\{|g,g\rangle|1\rangle,\ |\Psi_+\rangle|0\rangle,\ |\Psi_-\rangle|0\rangle\}$$

$$\hat{H}_I = \begin{bmatrix} \hbar\Delta_1 & \hbar\Omega/2 & 0 \\ \hbar\Omega/2 & \hbar\Delta_0 & 0 \\ 0 & 0 & \hbar\Delta_0 \end{bmatrix}$$

$$|\Psi_+\rangle = (|e,g\rangle + |g,e\rangle)/\sqrt{2},$$

$$|\Psi_-\rangle = (|e,g\rangle - |g,e\rangle)/\sqrt{2}$$

symmetric two-state subspace: $\{|g,g\rangle|1\rangle,\ |\Psi_+\rangle|0\rangle\}$

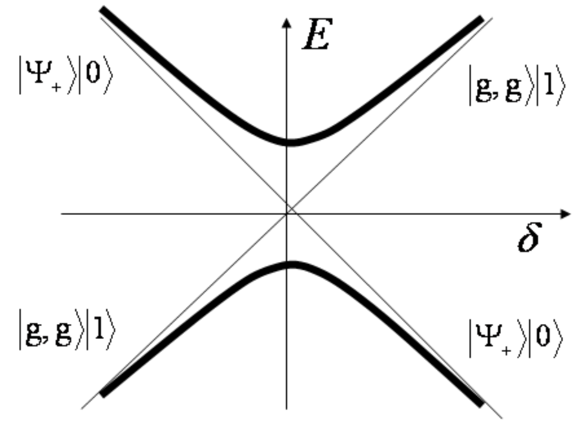
(1) Rapid adiabatic passage method

$$|g,g\rangle|1\rangle \Rightarrow \frac{1}{\sqrt{2}}(|g,e\rangle+|e,g\rangle)|0\rangle$$

Adiabatic condition

$$\frac{1}{2}\left|\dot{\Omega}\delta-\Omega\dot{\delta}\right| \ll (\Omega^2+\delta^2)^{3/2}$$

Energy of dressed states



N ions

$$|g,g,\cdots,g\rangle|m\rangle \Rightarrow |W_m^N\rangle|0\rangle,$$

RSB RAP pulse

$$\text{Dicke state}: |W_m^N\rangle = \frac{1}{\sqrt{C_m^N}}\sum_k P_k|e,e,\cdots e,g,\cdots g\rangle$$

I.E.Linington & N.V. Vitanov: Phys. Rev. A77,010302 (2008)

(2)Red sideband π pulse method (two-state system)

$$\Delta_0=-\Delta_1=0 \qquad |\Psi\rangle=\cos(\Omega t/2)|g,g\rangle|1\rangle-i\sin(\Omega t/2)|\Psi_+\rangle|0\rangle$$

$$|g,g\rangle|1\rangle,(t=0) \Rightarrow \frac{1}{\sqrt{2}}(|g,e\rangle+|e,g\rangle)|0\rangle,\ (t=\pi/\Omega)$$

D.B.Hume et al. PRA, 80, 052302,2009

Important process: initialization to $|g_1, g_2\rangle|1\rangle$

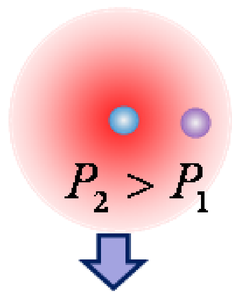
Individual addressing to one ion is necessary.

$$|\underline{g_1}, g_2\rangle|0\rangle \longrightarrow |\underline{e_1}, g_2\rangle|1\rangle \longrightarrow |\underline{g_1}, g_2\rangle|1\rangle$$

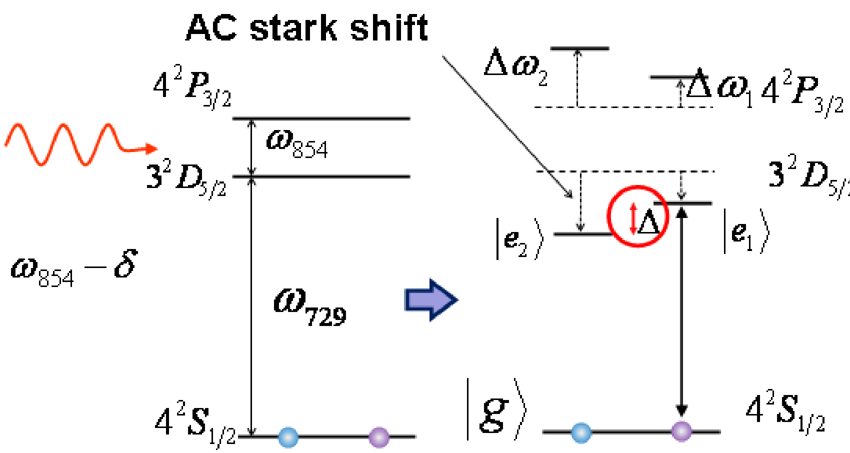
blue sideband π | carrier π

differential AC Stark shift methods

Off resonant 854nm laser (100GHz)

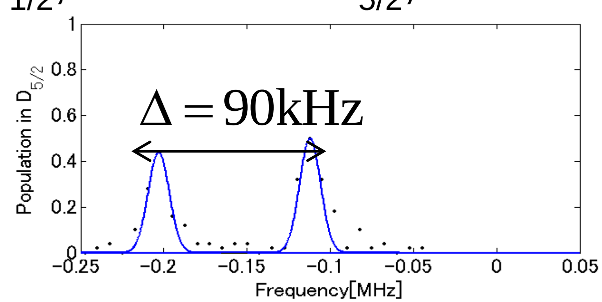


$$\Delta\omega_2 > \Delta\omega_1$$

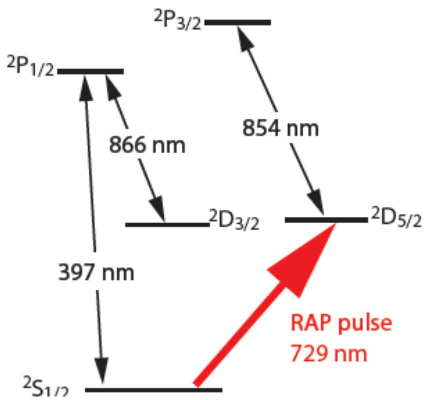


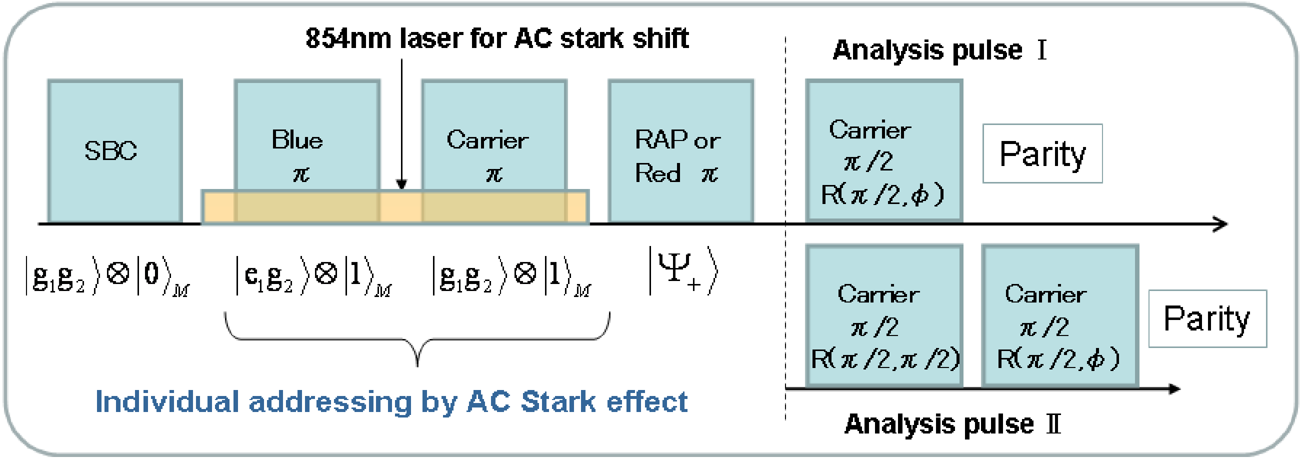
Qubit: $S_{1/2}$,m=-1/2 and $D_{5/2}$, m=-5/2

Carrier spectrum of two ions: AC Stark shift, on



Pulse sequence of generation of two-particle entangled states





RAP: rapid adiabatic passage pulse

Fidelity of the generated states

$$F \equiv \langle \Psi_+ | \rho | \Psi_+ \rangle = \frac{1}{2}\left(\rho_{ge,ge} + \rho_{eg,eg} + \rho_{eg,ge} + \rho_{ge,eg}\right)$$

Diagonal terms　　Off diagonal terms

Diagonal terms:　probability of single-ion fluorescing events after the state creation

Off diagonal terms:　parity signal after analysis pulse Ⅰ or Ⅱ

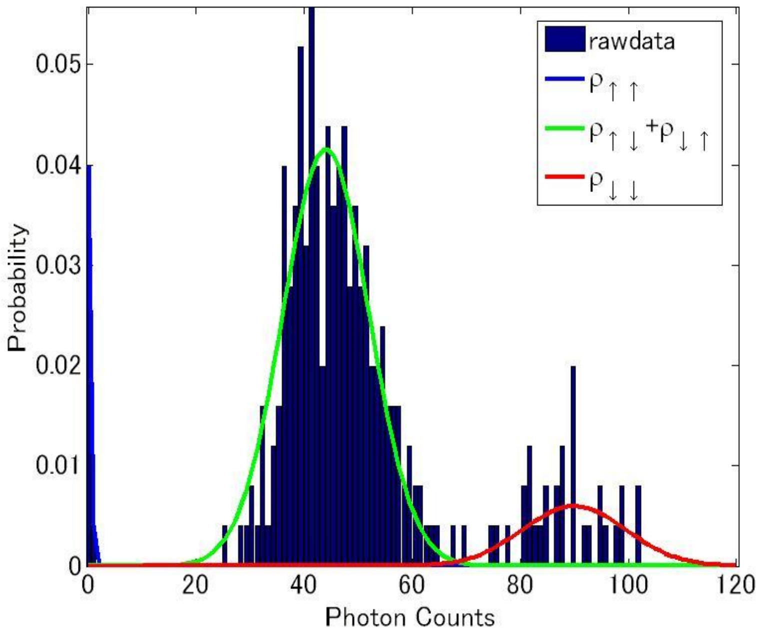
0 for Dicke states

Analysis Pulse Ⅰ：Parity　$P(\phi) \equiv \langle \sigma_{z1}\sigma_{z2} \rangle = 2|\rho_{gg,ee}|\cos(2\phi) + (\rho_{ge,eg} + \rho_{eg,ge})$

Analysis Pulse Ⅱ：Parity　$P(\phi) = \langle \sigma_{1z}\,\sigma_{2z} \rangle = \cos 2\phi,\quad \text{for } \rho = |\Psi_+\rangle\langle\Psi_+|$

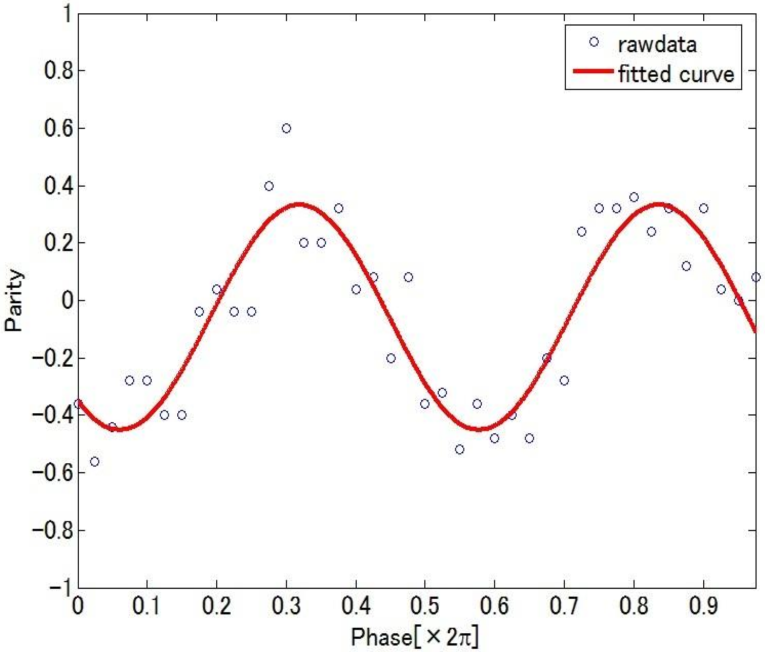
Result of the RAP method

Histogram of photon counts



$$\rho_{\uparrow\downarrow\uparrow\downarrow} + \rho_{\downarrow\uparrow\downarrow\uparrow} = 0.83 \pm 0.06 (\pm\sigma)$$

Parity signal after analysis pulse II



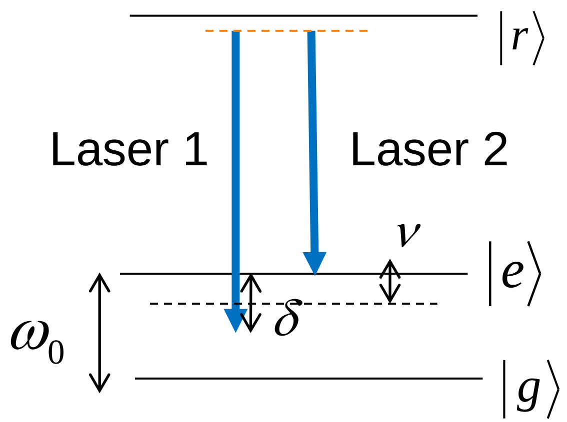
$$\rho_{\uparrow\downarrow\downarrow\uparrow} + \rho_{\downarrow\uparrow\uparrow\downarrow} \geq 0.40 \pm 0.03 (\pm\sigma)$$

$$F \geq 0.62 \pm 0.06$$

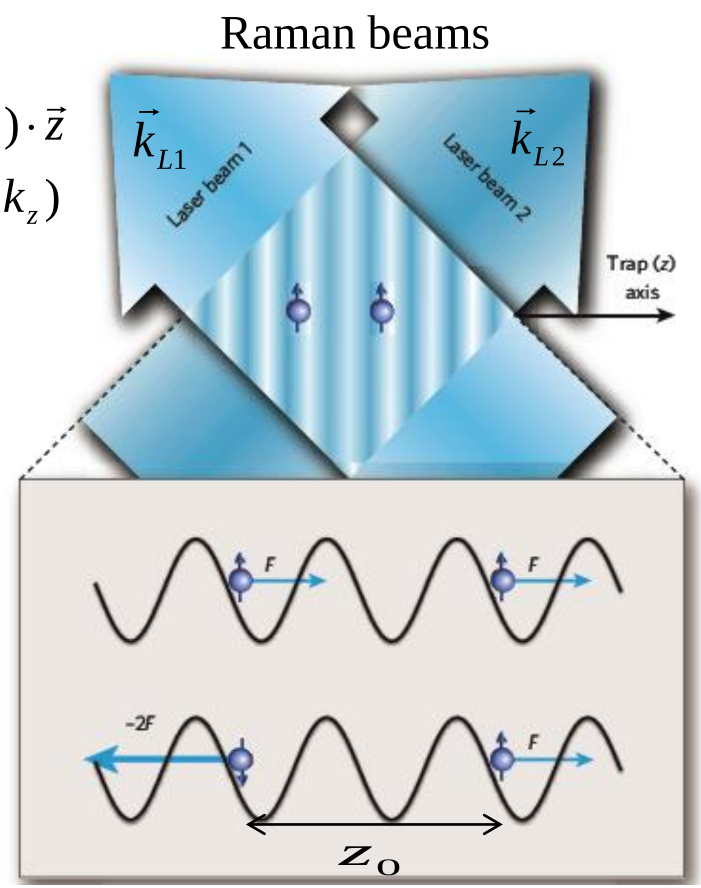
6.Spin dependent force and its applications

σ_z dependent force

D.Leibfried et al., Nature,422,412,2003
G.J.Milburn et al, Fortschr. Phys.,48,801,2000



$$k_z = (\vec{k}_{L1} - \vec{k}_{L2}) \cdot \vec{z}$$
$$z_0 = n(2\pi / k_z)$$



Optical dipole force (state dependent)

Spin dependent force Hamiltonian, $\Omega_j = \Omega$

$$\hat{H}_{\text{int}} = \hbar\Omega \sum_j k_z \hat{z}\, \sigma_{jz} \cos\delta\, t$$

COM mode : $k_z \hat{z}_j \to \eta(\hat{a} + \hat{a}^\dagger)$,

Interaction picture and rotating wave approximation

$$\hat{H}_{\text{int}} = (\hbar\Omega\eta)(\sum_j \hat{\sigma}_{j,z} / 2)(\hat{a}e^{-i(\nu-\delta)t} + \hat{a}^\dagger e^{i(\nu-\delta)t})$$

σ_φ dependent force
(Molmer & Sorensen gate)

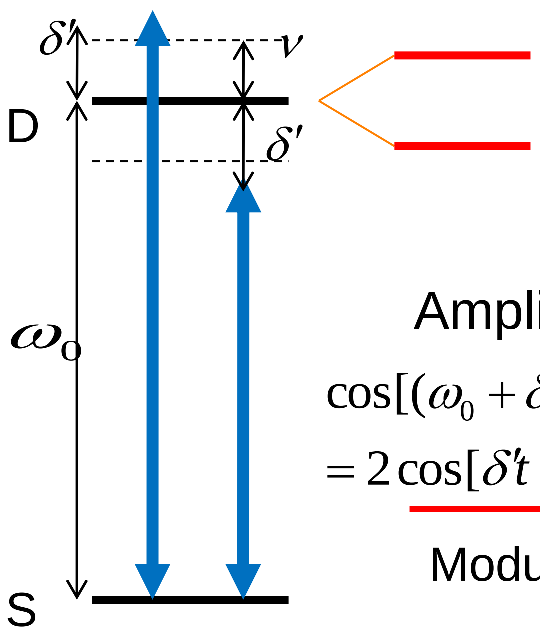
A.Sorensen & K.Molmer, PRA,62,022311, 2000
P.C.Haljan et al, PRA, 72,062316, 2005
C.F Roos, New J. Phys., 10, 013002, 2008

Two-color beams(Ω_1,Ω_2), 2 ions

collective addressing : $\Omega_1^j = \Omega_2^j = \Omega_0$

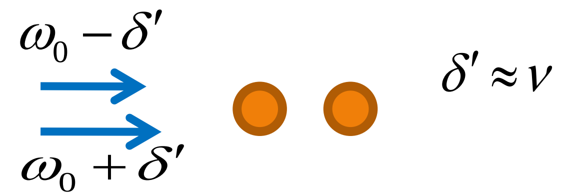
detuninng : $\omega_1 = \omega_0 + \delta', \ \omega_2 = \omega_0 - \delta'$

E2 transition   Dressed states

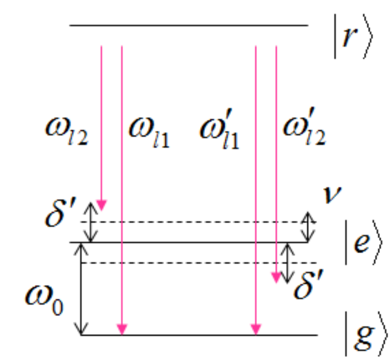


$$|+\rangle = \frac{1}{\sqrt{2}}(|e\rangle + |g\rangle)$$

$$|-\rangle = \frac{1}{\sqrt{2}}(|e\rangle - |g\rangle)$$



Two pairs of Raman beams



Amplitude-modulated beams

$$\cos[(\omega_0 + \delta')t + k_1 z] + \cos[(\omega_0 - \delta')t + k_2 z]$$
$$= 2\underbrace{\cos[\delta' t + (k_1 - k_2)z/2]}_{\text{Modulation signal}}\underbrace{\cos[\omega_0 t + (k_1 + k_2)z/2]}_{\text{Resonant carrier wave}}$$

Modulation signal   Resonant carrier wave

$$\hat{H}_{\text{int}} = \hbar\Omega_0 e^{-i\varphi} \sum_{i=1,2} \sigma_{+j}(e^{-i\delta' t + ik_1 z} + e^{i\delta' t + ik_2 z}) + h.c.$$

COM mode : $k_z \hat{z}_j \rightarrow \eta_c(\hat{a}_c + \hat{a}_c^\dagger), \ \ \eta_c = k_z\sqrt{\hbar/2M\nu N}$

stretch mode : $k_z \hat{z}_1 \rightarrow -\eta_s(\hat{a}_s + \hat{a}_s^\dagger), \ k_z \hat{z}_2 \rightarrow \eta_s(\hat{a}_s + \hat{a}_s^\dagger), \ \eta_s = k_z\sqrt{\hbar/2\mu\nu N}$

(1)General field coupling

$$\text{close to the sidebands}: \quad \nu - \delta' \ll \delta', \quad \text{and } \Omega_0 \ll \delta'$$

Interaction picture and rotating wave approximation

$$\hat{H}_{\rm int} = -\hbar\eta\Omega_0[\hat{J}_x \cos\varphi' + \hat{J}_y \sin\varphi'](\hat{a}^\dagger e^{i(\nu-\delta')t} + \hat{a}e^{-i(\nu-\delta')t})$$

σ_Φ dependence

$$\hat{J}_x = \frac{1}{2}\sum_j \hat{\sigma}_{xj}, \qquad \hat{J}_y = \frac{1}{2}\sum_j \hat{\sigma}_{yj}$$

Time evolution: $|\psi(\mathrm{t})\rangle = \hat{U}(t)|\psi(0)\rangle$

$$\hat{U}(t) = \exp[-\hat{J}_x\{\alpha(t)\hat{a}^\dagger - \alpha^*(t)\hat{a}\}] \cdot \exp(-i\Phi_g \hat{J}_x^2)$$

displacement operator

$$\alpha(t) = \alpha_0(1 - e^{i(\nu-\delta')t}),$$

$$\Phi(\mathrm{t}) = \alpha_0^2\{(\nu-\delta')t - \sin(\nu-\delta')t\}$$

Spin dependent circular motion in the phase space

$$\left|\uparrow_x\downarrow_x\right\rangle \Rightarrow \text{radius}: J_x\alpha_0,\ \text{center}: (-J_x\alpha_0, 0), \quad \left|\downarrow_x\uparrow_x\right\rangle \Rightarrow \text{radius}: J_x\alpha_0,\ \text{center}: (J_x\alpha_0, 0)$$

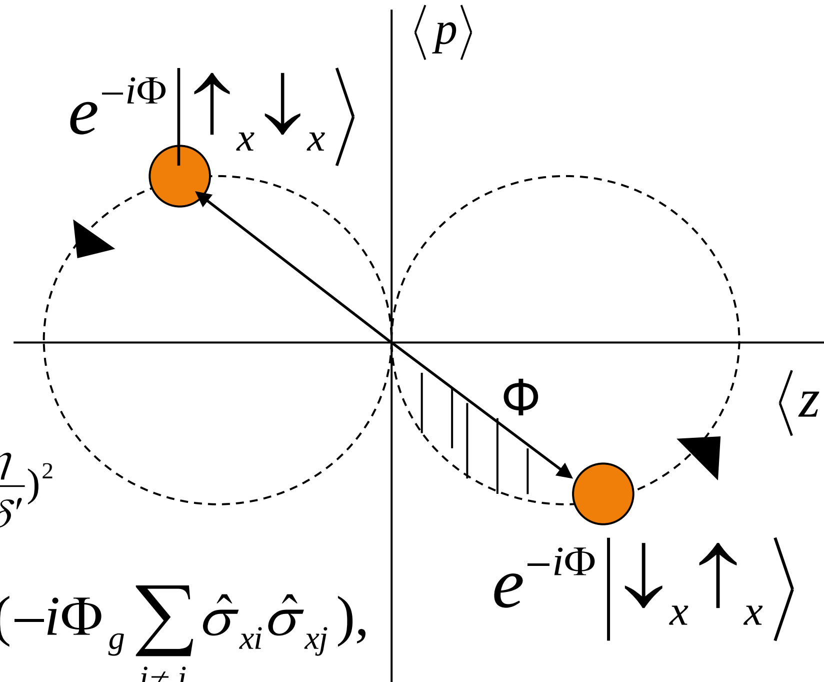
Disentangling condition

$\Rightarrow$ closed trajectory

$$(\nu - \delta')t = 2\pi n, \quad n : \text{integer}$$

$$\text{gained phase}: \Phi_g = 2\pi n\left(\frac{\Omega_0\eta}{\nu - \delta'}\right)^2$$

$$\text{ex}: \ n = 1 \rightarrow \tau_g = 2\pi/(\nu - \delta'), \quad \Phi_g = 2\pi\left(\frac{\Omega_0\eta}{\nu - \delta'}\right)^2$$



$$\hat{U} == \exp[-i\Phi_g J_x^2] = \exp(-i\Phi_g N/4)\exp(-i\Phi_g \sum_{i\neq j}\hat{\sigma}_{xi}\hat{\sigma}_{xj}),$$

$$\text{effective Hamiltonian}: \quad \hat{H}_{eff} = \hbar\Phi_g \sum_{i\neq j}\hat{\sigma}_{xi}\hat{\sigma}_{xj}$$ Spin-spin interaction

Φ_g: unconventional geometric phase

Φ_g=(geometric phase) +(dynamic phase),

(dynamic phase)=-2x(geometric phase)

S.Zhu, D.Z.Wang, PRL,91,187902,2003

Generation of entangled states

$$\Phi_g = \frac{\pi}{2}, \ (\text{or } \frac{\Omega_0 \eta}{\nu - \delta'} = \frac{1}{2}) \ \rightarrow \ \hat{U}_{\max} = \exp[-i\pi J_x^2 / 2]$$

Entangled of two ions:
(stretch mode)
P.C.Haljan et al, PRA, 72,062316, 2005

$$|ee\rangle \Rightarrow |\Psi_1\rangle = (1/\sqrt{2})(|ee\rangle + i|gg\rangle)$$
$$|gg\rangle \Rightarrow |\Psi_2\rangle = (1/\sqrt{2})(|ee\rangle - i|gg\rangle)$$
$$|eg\rangle \Rightarrow |\Psi_3\rangle = (1/\sqrt{2})(|eg\rangle + i|ge\rangle)$$
$$|ge\rangle \Rightarrow |\Psi_4\rangle = (1/\sqrt{2})(|eg\rangle - i|ge\rangle)$$

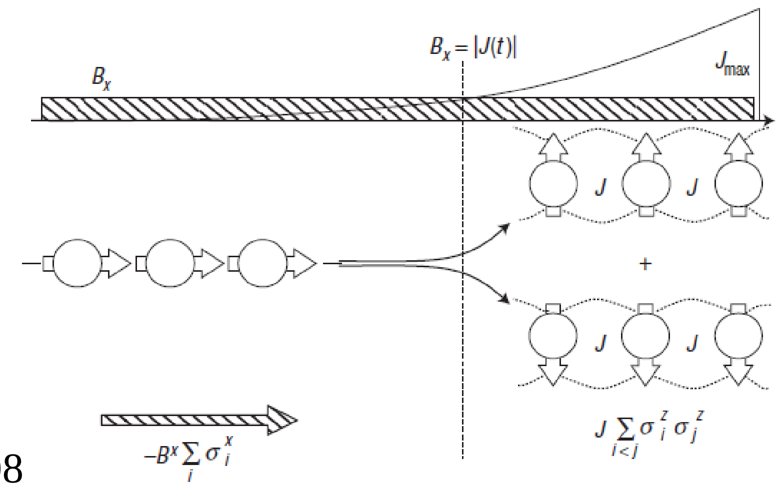
High fidelity Bell state generation: F=0.993,
J.Benheim et al, Nature phys. Vol.4,463,2008

Quantum simulation: Ising model

$$\hat{H}_{\text{Ising}} = \frac{1}{2}\sum_{i,j} J_{i,j}^x \sigma_{z,i}\sigma_{z,j} + \sum_i B_x \sigma_{x,i}$$

Phase transition: paramagnetc order
⇔ (anti-) ferromagnetic order

Two ions:A.Friedenauer et.al, Nature phys. 4,757,2008



(2)Weak-field coupling

A.Sorensen & K.Molmer, PRL,82,1971(1999)

$$\eta\Omega_0 \ll \nu - \delta' \to \alpha \ll 1$$

$$\hat{U}(t) = D(-\hat{J}_x\alpha)\exp(-i\Phi_g \hat{J}_x^2) \Rightarrow \hat{U}(t) = \exp(-i\tilde{\Omega}\hat{J}_x^2 t)$$

$$H_{eff} = \hbar\tilde{\Omega}\hat{J}_x^2 \approx (\hbar\tilde{\Omega}/4)\sum_{i\neq j}\hat{\sigma}_{xi}\hat{\sigma}_{xj}, \quad \tilde{\Omega} = (\eta\Omega_0)^2/(\nu - \delta')$$

Quantum simulation : frustrated Ising spins

Three ions, transverse mode

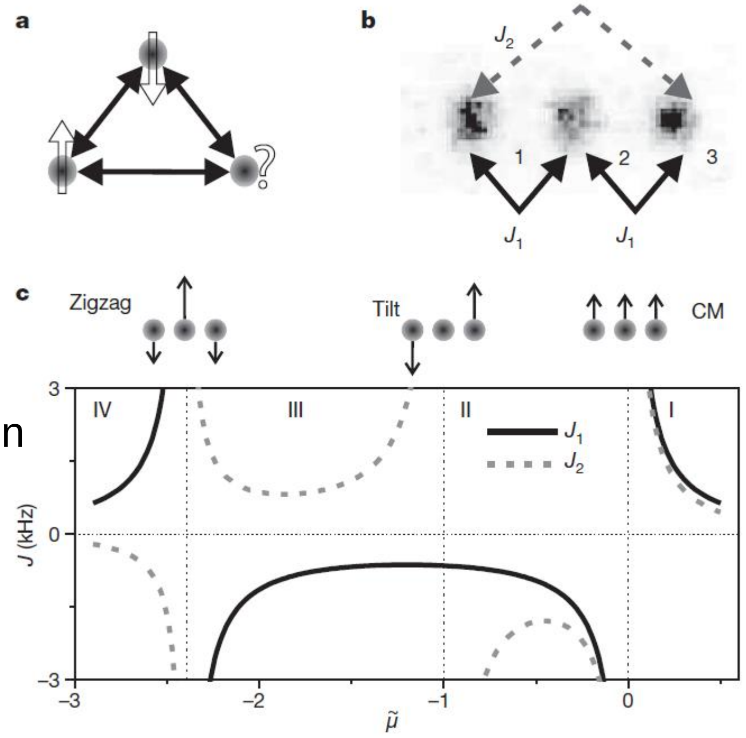
$$H_{eff} = \sum_{i<j} J_{ij}\hat{\sigma}_x^i\hat{\sigma}_x^j + B_y\sum_i \hat{\sigma}_y^i$$

$$J_{ij} = \Omega_i\Omega_j \frac{\hbar k_x^2}{2M}\sum_m \frac{b_{i,m}b_{j,m}}{\mu^2 - \nu_m^2},$$

$b_{i,m}$: normal mode transformation matrix

$J_1 \equiv J_{12} = J_{23}$ Nearest-neighbor interaction

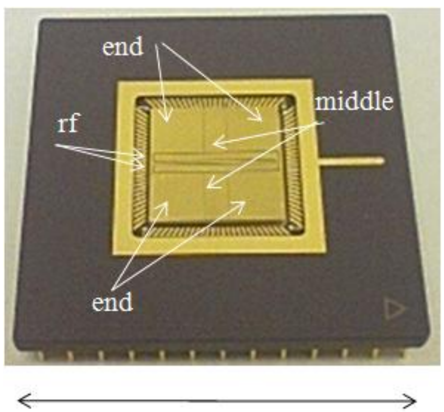
$J_2 \equiv J_{13}$ Next-nearest-neighbor interaction

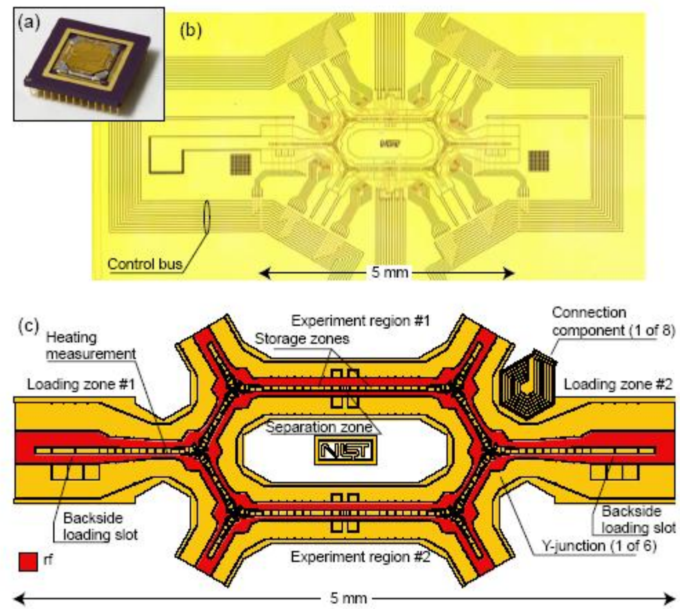


K.Kim et.al., PRL,103, 120502(2009)
K.Kim et .al., nature, 465,3(2010)

今後の方向

1. 大規模・集積化
   プレーナートラップ





2. 他の量子系との結合
3. 量子シミュレーション
4. 高速化