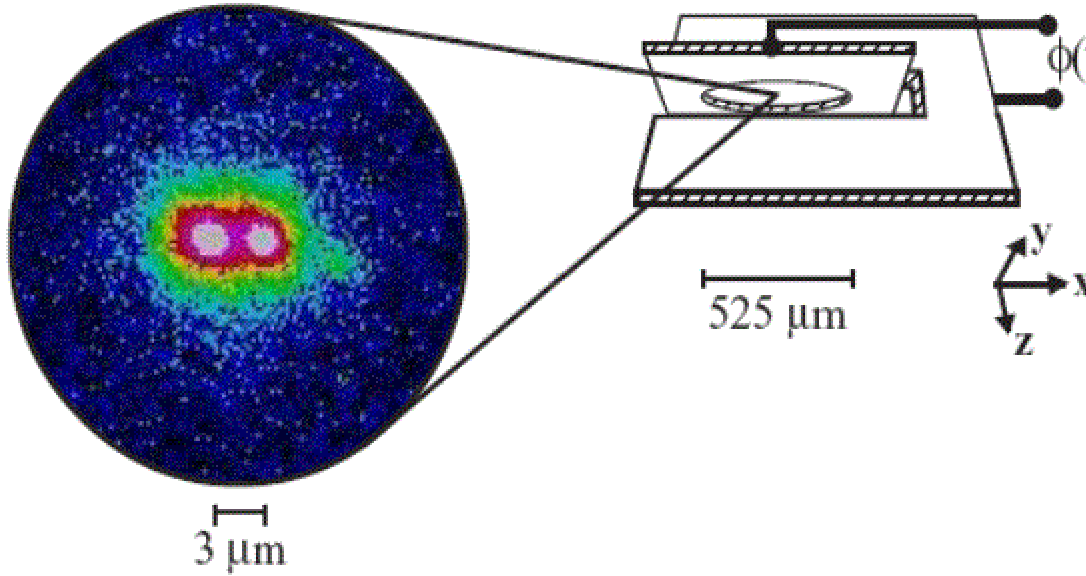
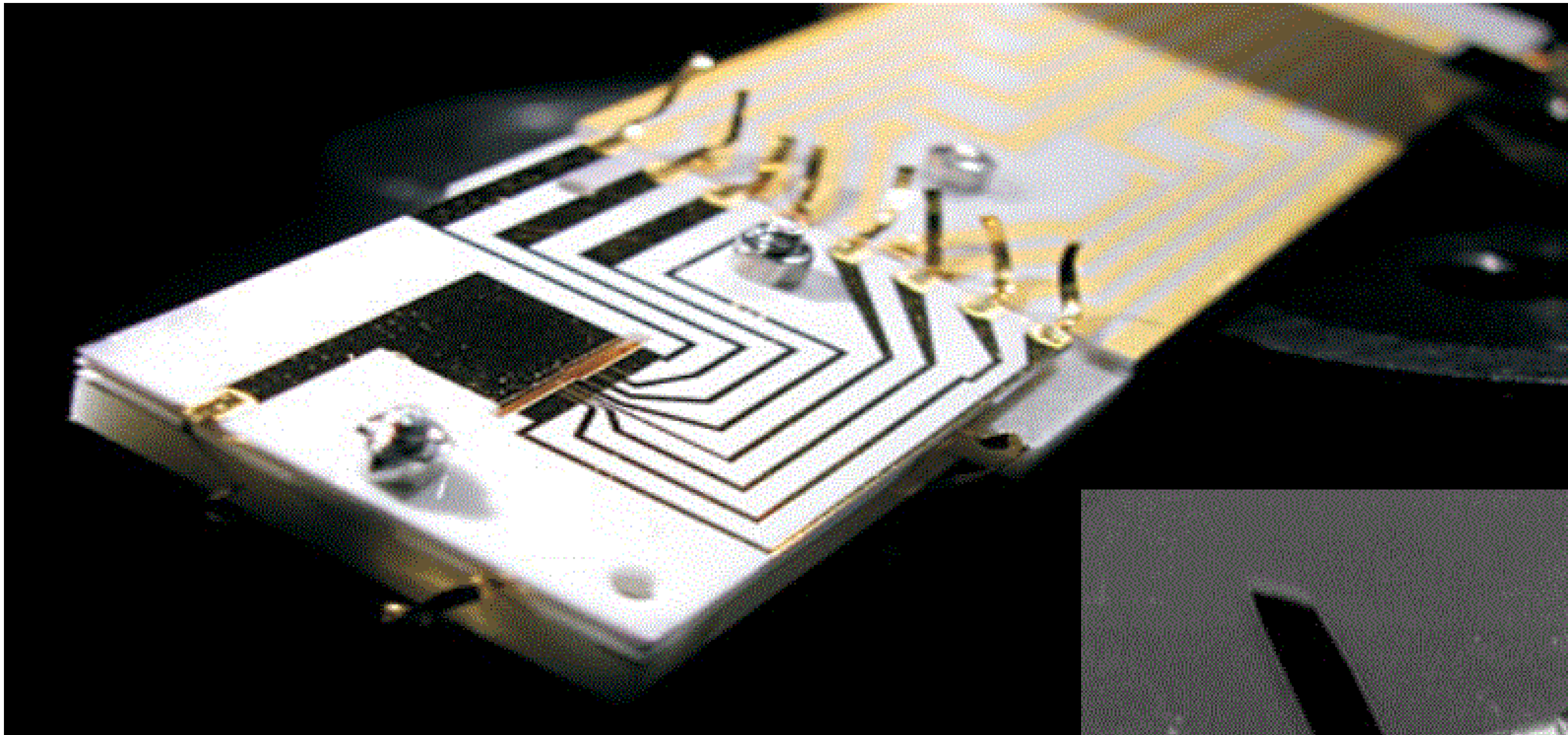
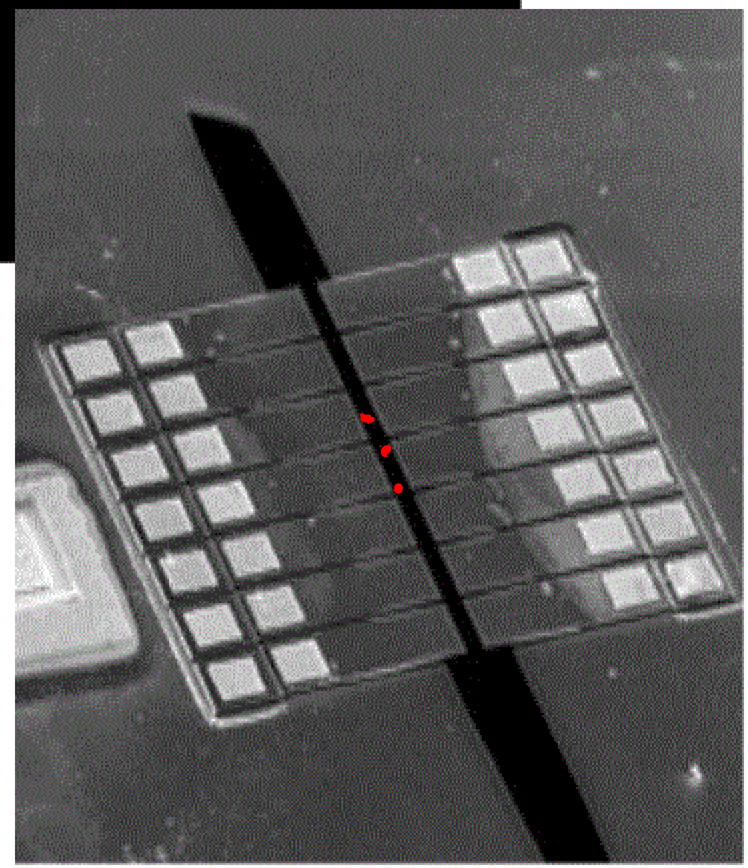
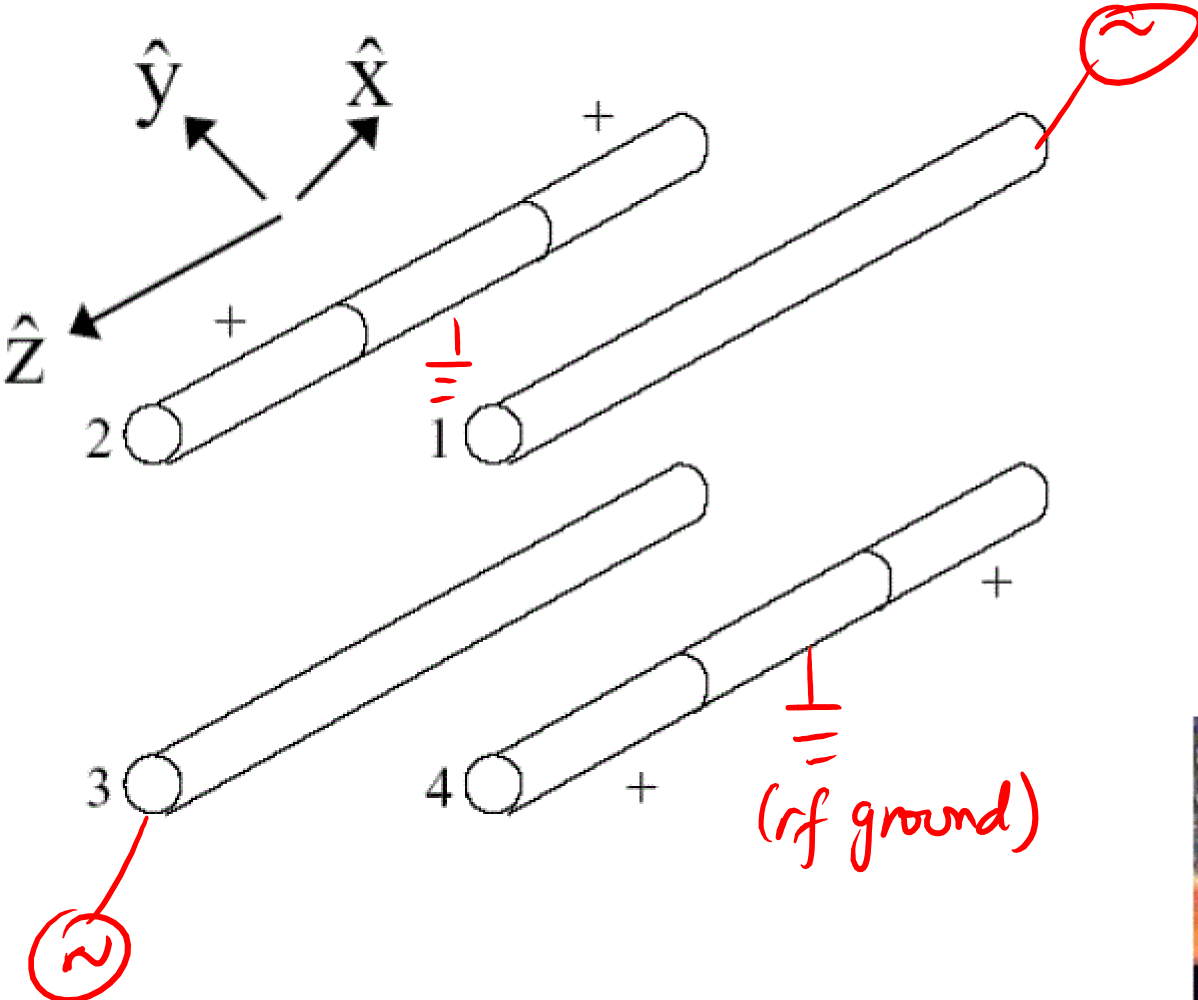
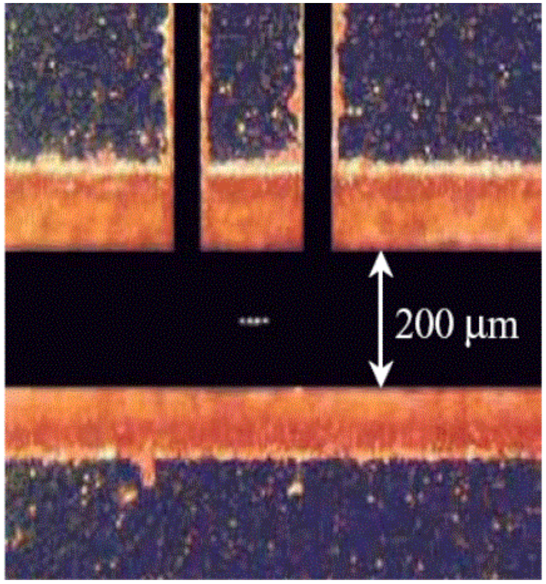

φ(t)
y
x
z
525 µm
3 µm





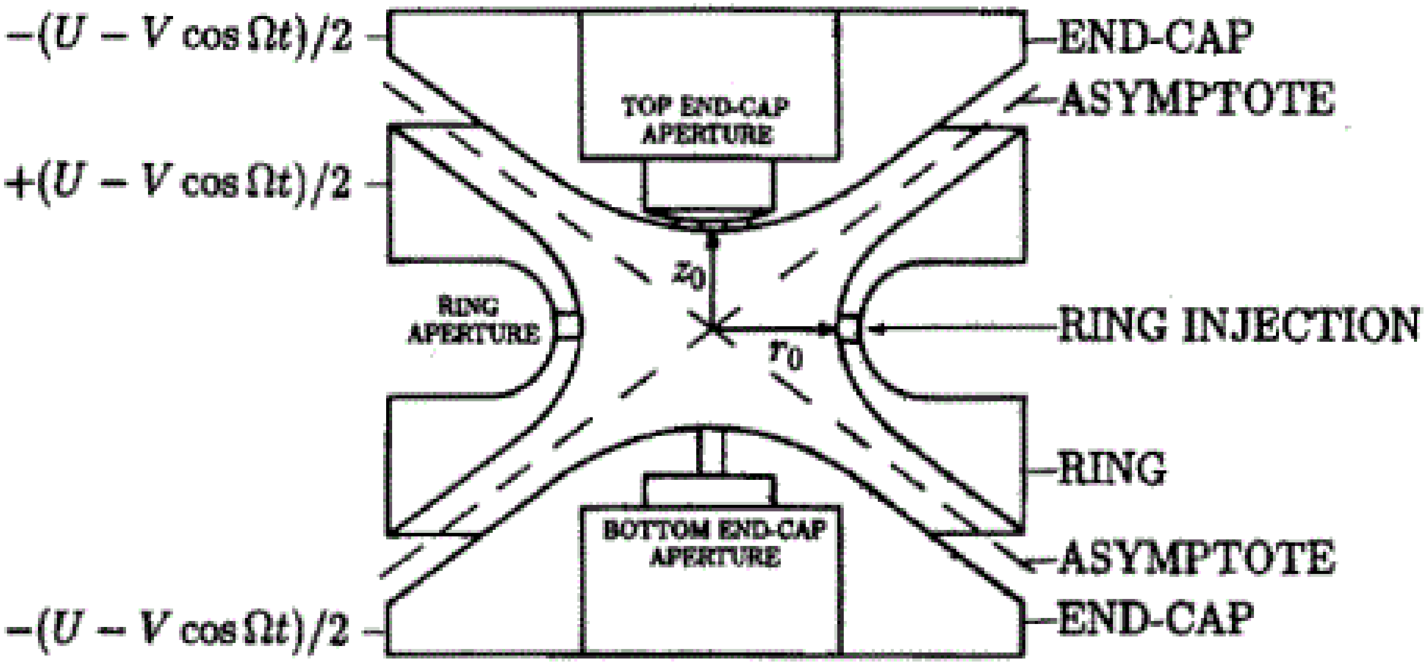
linear Paul trap


ŷ
x̂
ẑ
+
+
2
1
3
4
+
+
(rf ground)


200 μm

http://www.youtube.com/watch?v=bkYXNeJ8IP0

http://www.youtube.com/watch?v=PYpbKSmOnNc



$$\Phi = \Phi_0 \frac{(x^2 + y^2 - 2z^2)}{2\, r_0^2} \cos(\Omega t)$$

$$\Phi = \Phi_0 \frac{(x^2 + y^2 - 2z^2)}{2\, r_0^2} \cos(\Omega t)$$

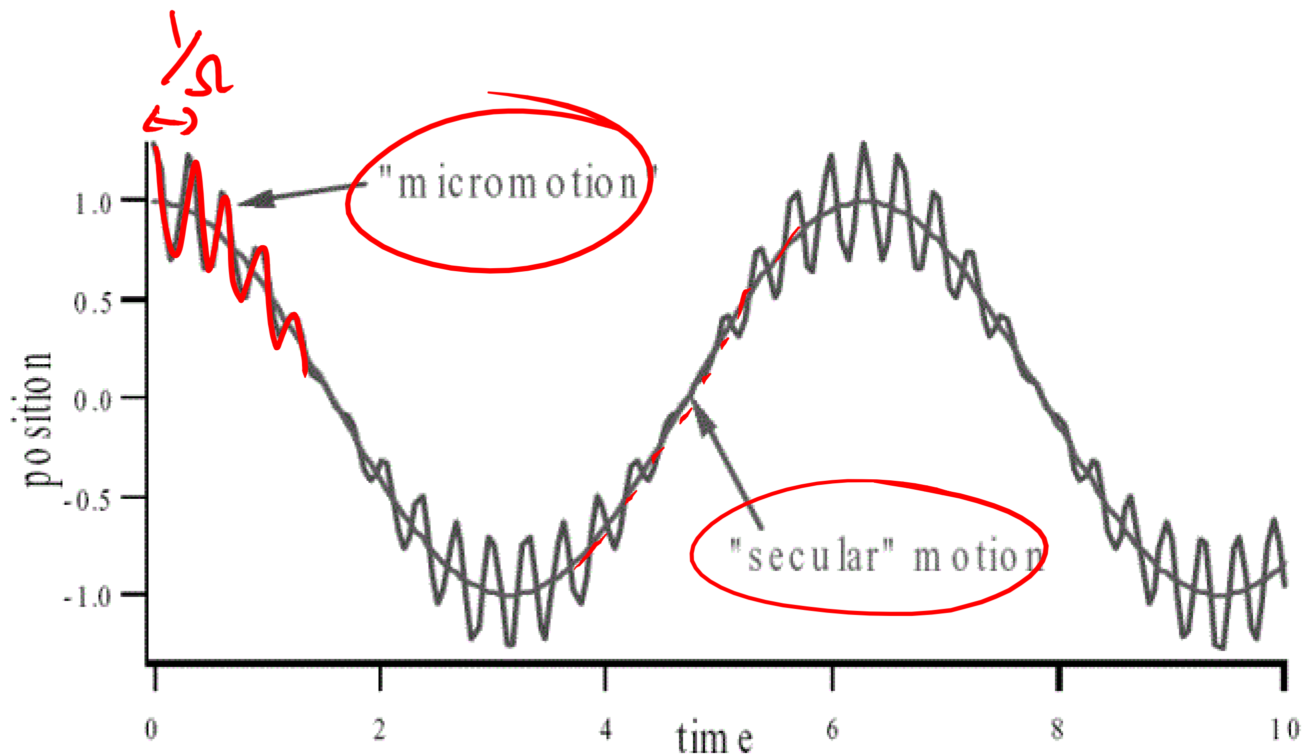
DC RF

$$\ddot{r} + \frac{e}{m r_0^2}[U - V cos(\Omega t)] = 0 \qquad \ddot{z} - \frac{2e}{m r_0^2}[U - V cos(\Omega t)] = 0$$

$$a_z = -2a_r = -\frac{8eU}{m r_0^2 \Omega^2} \qquad q_z = -2q_r = -\frac{4eV}{m z_0^2 \Omega^2} \qquad \zeta = \frac{\Omega t}{2}$$

Mathieu equations

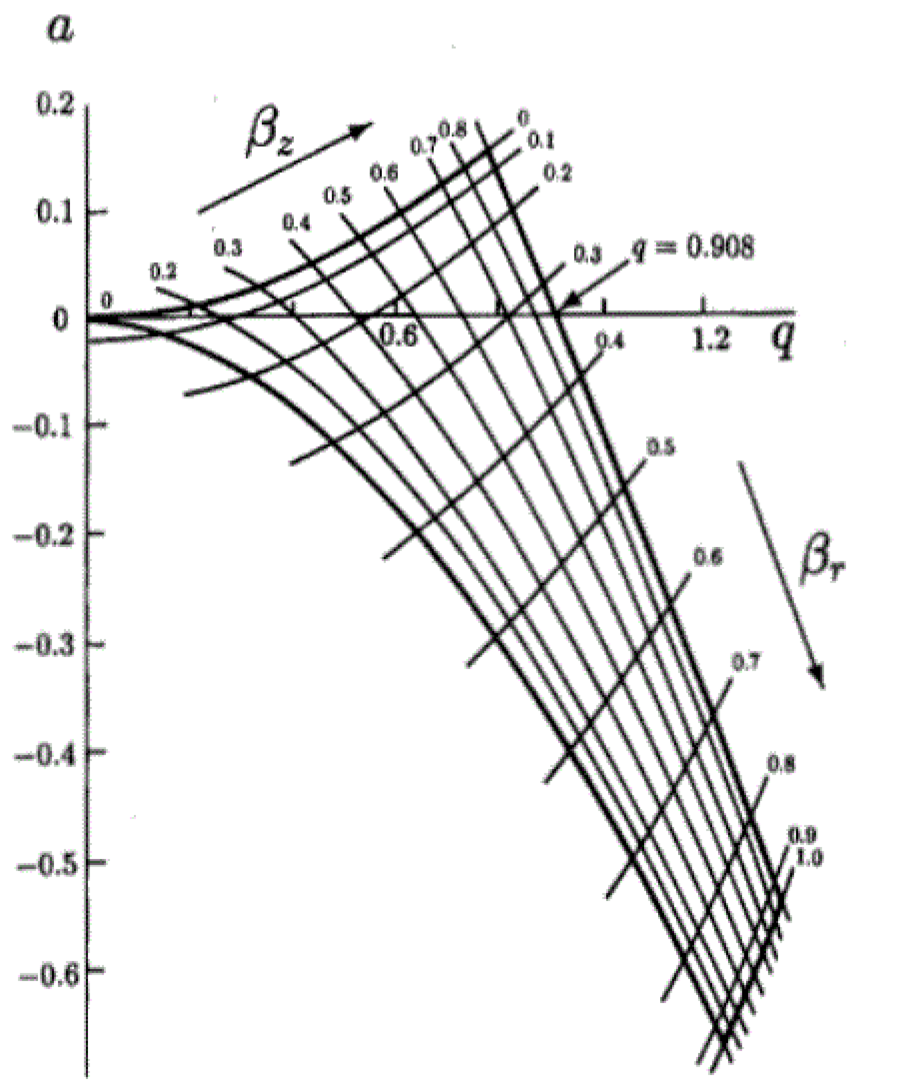
$$\frac{\partial^2 r}{\partial \zeta^2} + [a_r - 2q_r \cos(2\zeta)]r = 0 \qquad \frac{\partial^2 z}{\partial \zeta^2} + [a_z - 2q_z \cos(2\zeta)]z = 0$$



1/Ω
"micromotion"
"secular" motion
position
1.0
0.5
0.0
-0.5
-1.0
time
0
2
4
6
8
10

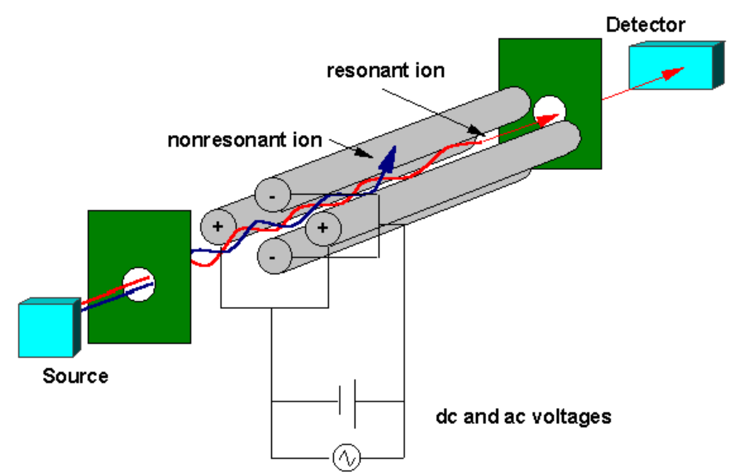
$$a_z = -2a_r = -\frac{8eU}{mr_0^2\Omega^2}$$

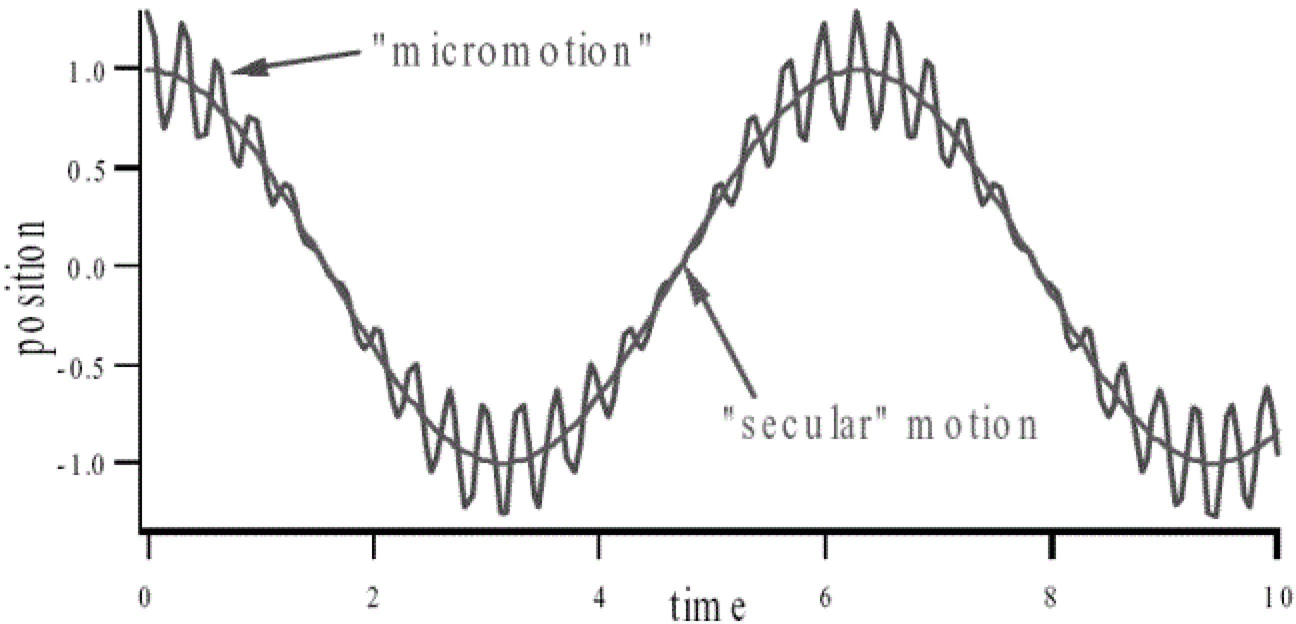
$$q_z = -2q_r = -\frac{4eV}{mr_0^2\Omega^2}$$



$$\beta_z = \sqrt{a_z^2 + \frac{q_z^2}{2}}$$

$$\beta_r = \sqrt{a_r^2 + \frac{q_r^2}{2}}$$



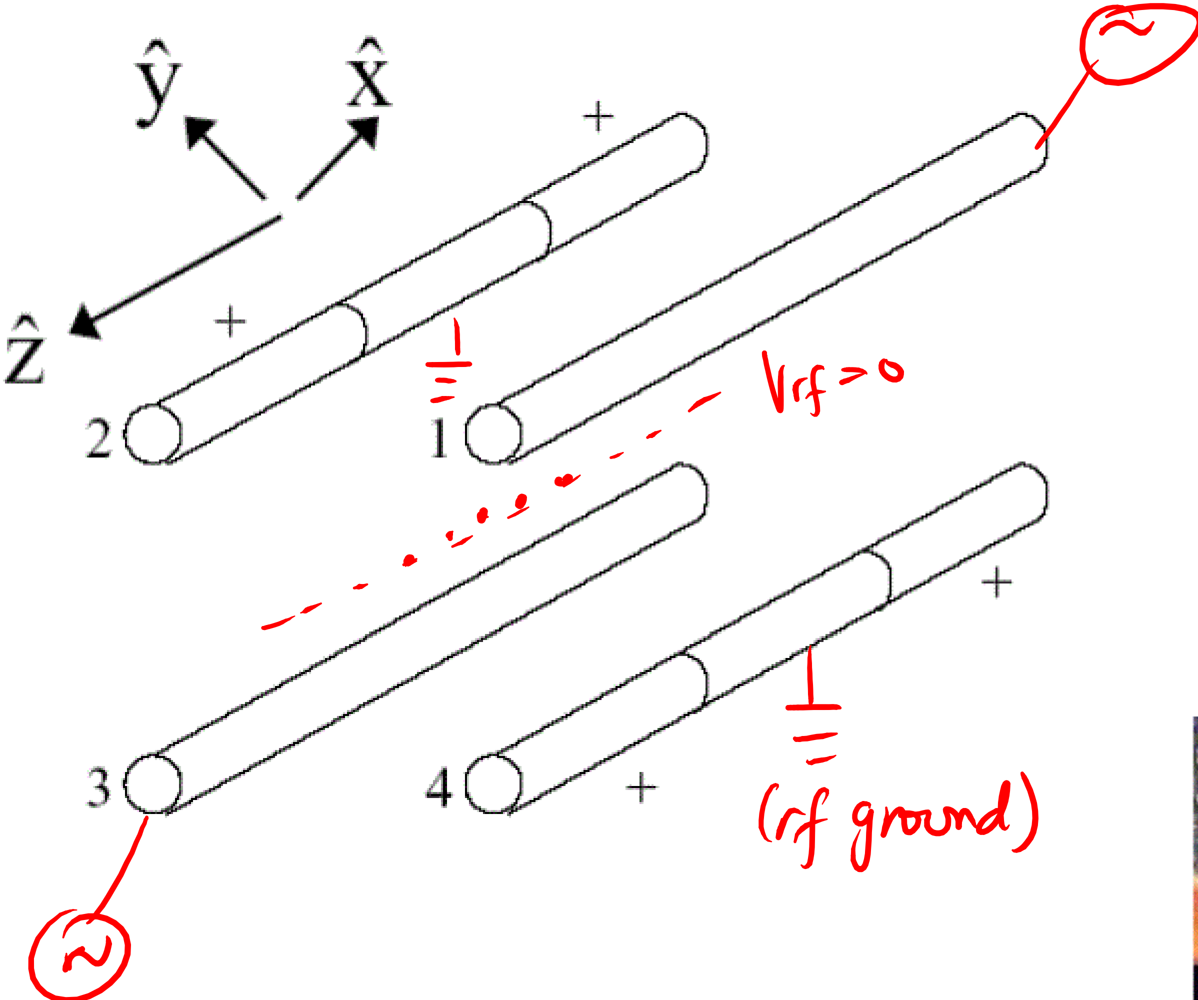


$$z = Z + \delta \qquad \dot{\delta} \gg \dot{Z}$$

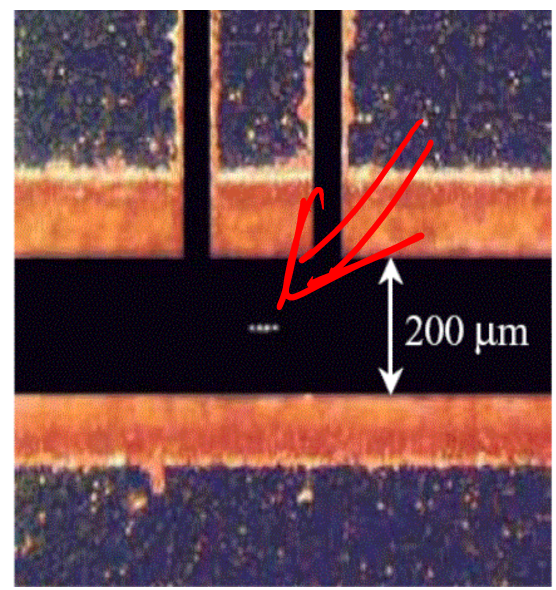
ω^2

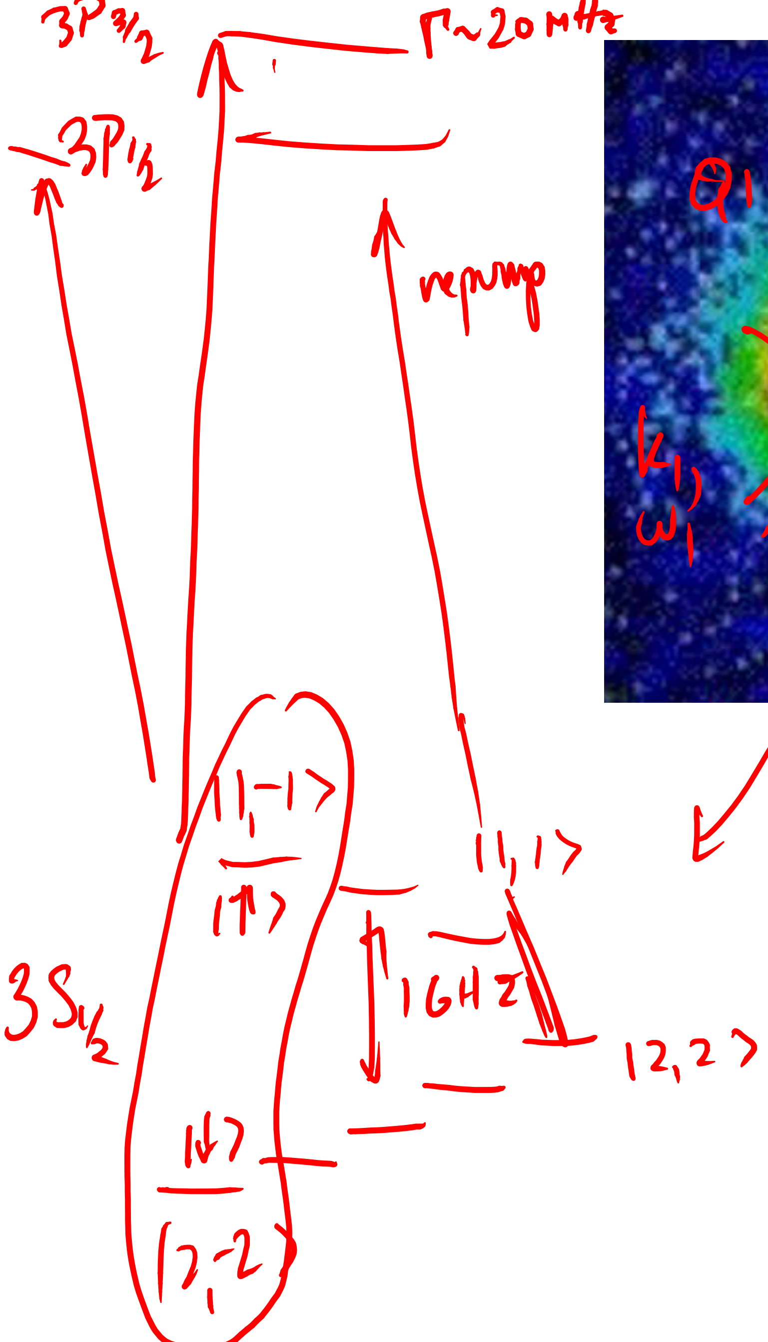
$$\delta \approx -\frac{q_z Z}{2}\cos(2\zeta) \qquad \langle\frac{d^2 Z}{dt^2}\rangle_\Omega \approx -\frac{\beta_z^2\Omega^2}{4} Z$$

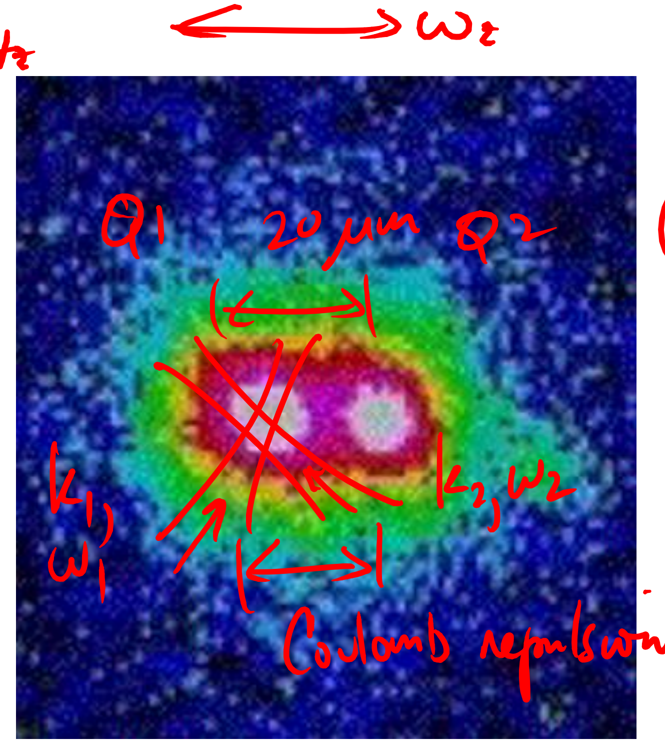
$\omega \sim 2\pi$ (few MHz)



linear Paul trap



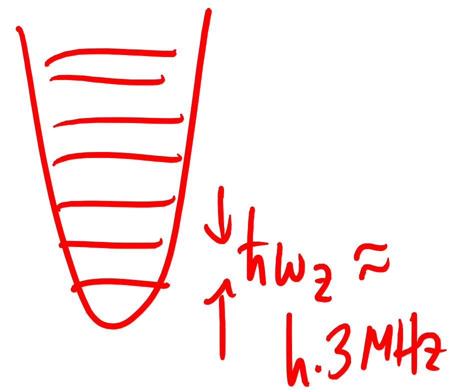




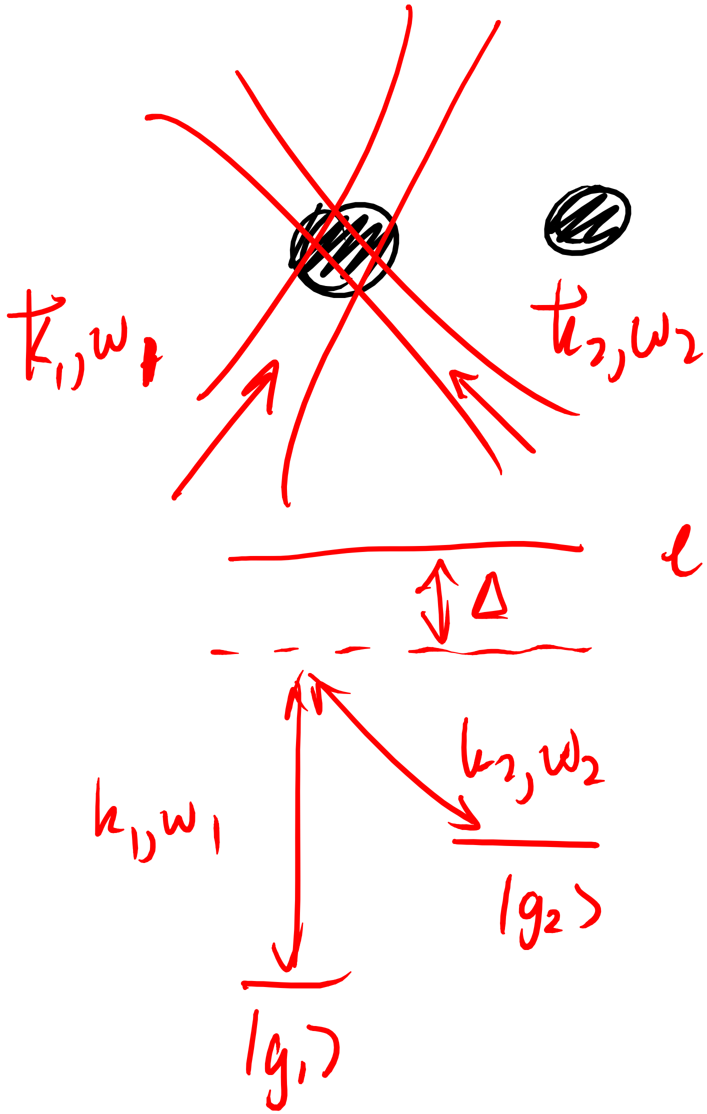
① single qubit rotations

② 2 qubit gate

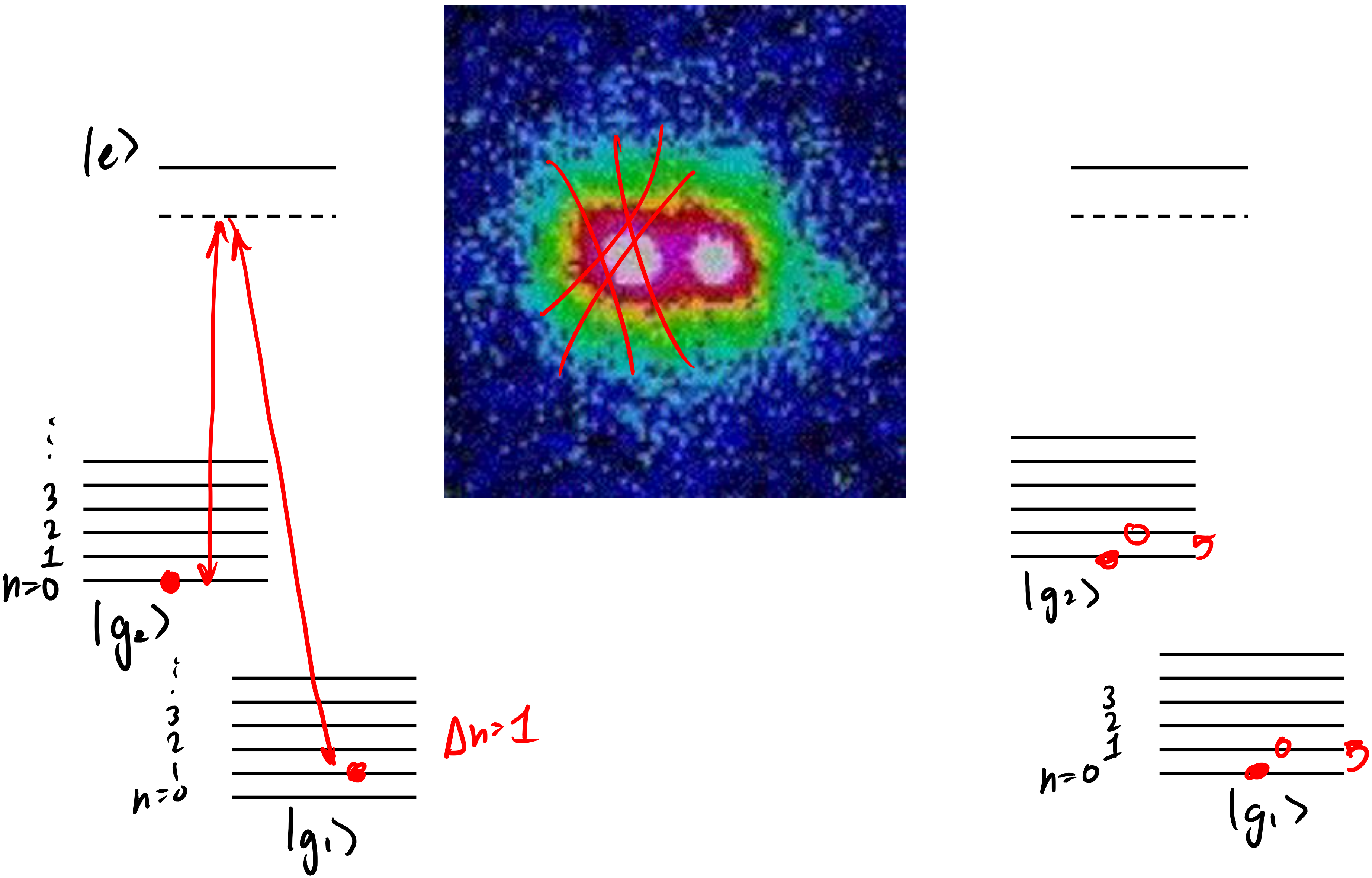
$^9Be^+$



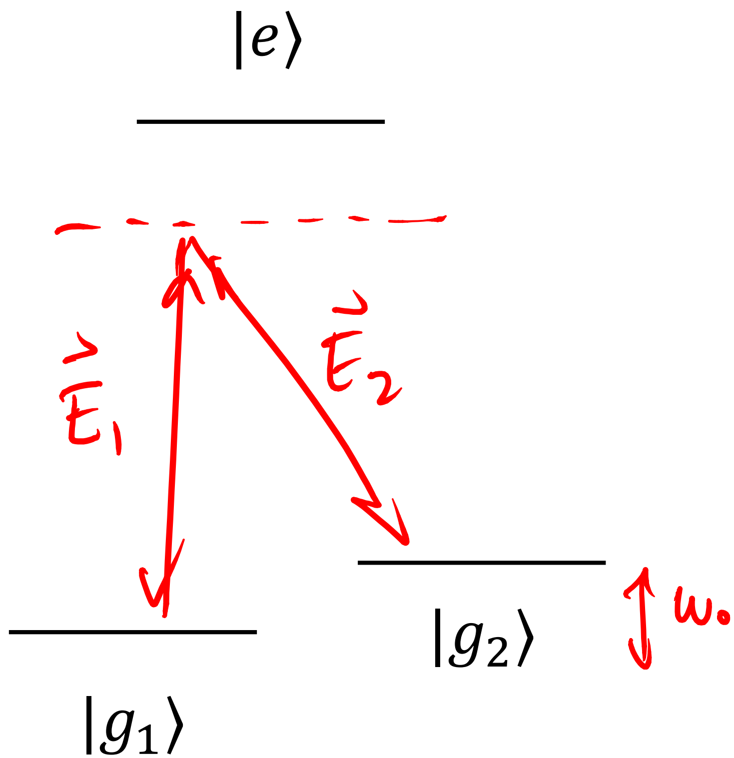
coherent
detection
initialization



stimulated Raman transition



|e⟩
3
2
1
n=0
|g₂⟩
3
2
1
n=0
|g₁⟩
Δn=1
|g₂⟩
3
2
1
n=0
|g₁⟩



$$\vec{E}_1 = E_1 e^{i\,k_1 z} e^{-i\omega_1 t}\hat{x}$$

$$\vec{E}_2 = E_2 e^{i\,k_2 z} e^{-i\omega_2 t}\hat{x}$$

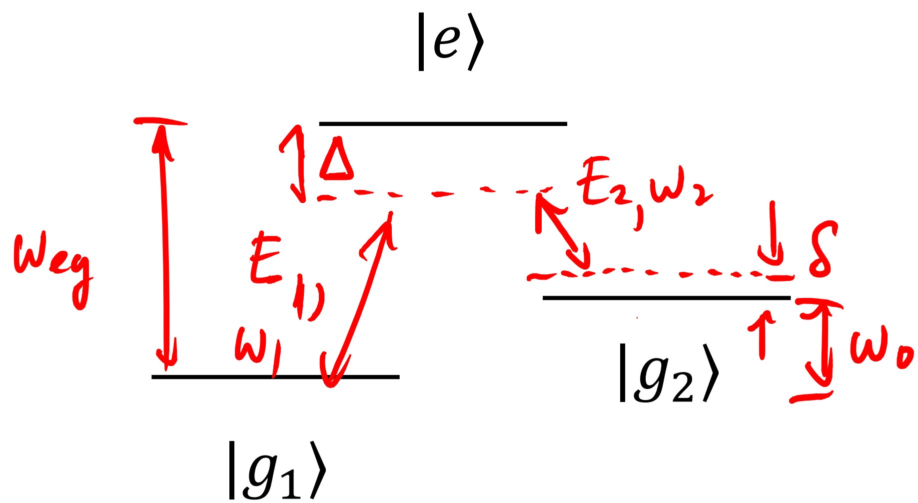
$$\vec{E} = \vec{E}_1 + \vec{E}_2 = e^{ikz} E\left(e^{i\omega_1 t} + e^{i\omega_2 t}\right)\hat{x}$$

$$\left|\vec{E}\right|^2 = 2E^2 + 2E^2 \cos[(\omega_1 - \omega_2)t]$$

$$\omega_1 - \omega_2 \approx \omega_0$$

$e^{ikx} \approx 1$

$$\vec{E}_1 = E_1\left(e^{-i\omega_1 t} + e^{i\omega_1 t}\right)\hat{\epsilon}_1$$
$$\vec{E}_2 = E_1\left(e^{-i\omega_2 t} + e^{i\omega_2 t}\right)\hat{\epsilon}_2$$



$$H_I' = -\frac{e}{2}\{\langle e|\hat{\epsilon}_1 \cdot \vec{r}|g_1\rangle\, |e\rangle\langle g_1|e^{i\omega_{eg}t}e^{-i\omega_1 t}E_1$$

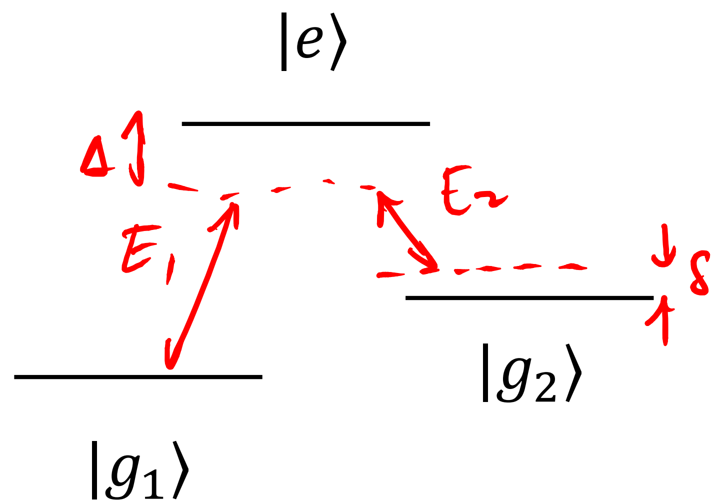
$$+\{\langle e|\hat{\epsilon}_2 \cdot \vec{r}|g_2\rangle\, |e\rangle\langle g_2|e^{i\omega_{eg}t}e^{-i\omega_2 t}e^{-i\omega_0 t}E_2\} + hc$$

$$\Delta = \omega_{eg} - \omega_1$$

$$\Delta \gg \delta$$

$$\Delta + \delta = \omega_{eg} - \omega_2 - \omega_0$$

$$|\psi\rangle = c_1|g_1\rangle + c_2|g_2\rangle + c_e|e\rangle$$



$$i\hbar\frac{\partial}{\partial t}|\psi\rangle = H_I'|\psi\rangle$$

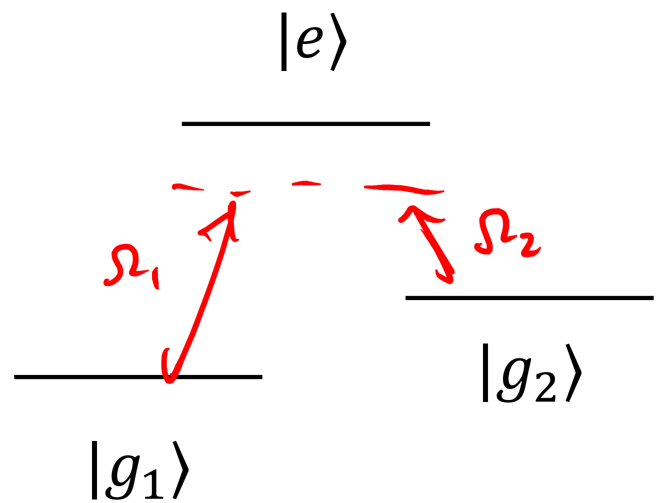
$$\Big\downarrow \text{RWA}$$

$$\dot{c}_1 = i\frac{eE_1^*}{2\hbar}e^{-i\Delta t}\langle g_1|\hat{\epsilon}_1\cdot\vec{r}|e\rangle c_e$$

$$\dot{c}_2 = i\frac{eE_2^*}{2\hbar}e^{-i(\Delta+\delta)t}\langle g_1|\hat{\epsilon}_2\cdot\vec{r}|e\rangle c_e$$

$$\dot{c}_e = i\frac{e}{2\hbar}\left[e^{i\Delta t}\langle e|\hat{\epsilon}_1\cdot\vec{r}|g_1\rangle E_1 c_1 + e^{i(\Delta+\delta)t}\langle e|\hat{\epsilon}_2\cdot\vec{r}|g_1\rangle E_2 c_2\right]$$

$$\dot{c}_1 = i\frac{eE_1^*}{2\hbar}e^{-i\Delta t}\underbrace{\langle g_1|\hat{\epsilon}_1\cdot\vec{r}|e\rangle}_{\Omega_1} c_e$$



$$\dot{c}_2 = i\frac{eE_2^*}{2\hbar}e^{-i(\Delta+\delta)t}\underbrace{\langle g_1|\hat{\epsilon}_2\cdot\vec{r}|e\rangle}_{\Omega_2} c_e$$

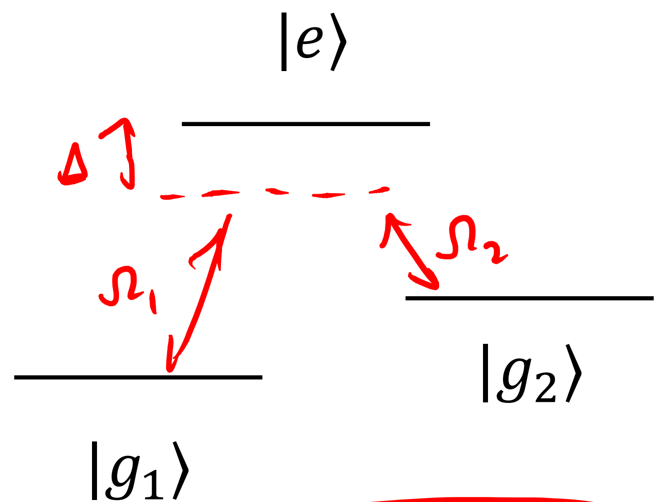
$$\dot{c}_e = i\frac{e}{2\hbar}\left[e^{i\Delta t}\underbrace{\langle e|\hat{\epsilon}_1\cdot\vec{r}|g_1\rangle}_{\Omega_1} E_1 c_1 + e^{i(\Delta+\delta)t}\underbrace{\langle e|\hat{\epsilon}_2\cdot\vec{r}|g_2\rangle}_{\Omega_2} E_2 c_2\right]$$

$$\Omega_1 = \frac{eE_1}{2\,\hbar}\langle e|\hat{\epsilon}_1\cdot\vec{r}|g_1\rangle \qquad \Omega_2 = \frac{eE_2}{2\,\hbar}\langle e|\hat{\epsilon}_2\cdot\vec{r}|g_2\rangle$$

$$c_e' = e^{-i\Delta t}c_e \qquad c_1' = c_1 \qquad c_2' = c_2$$

$$\dot{c}_e = e^{i\Delta t}\dot{c}_e' + i\Delta e^{\mathrm{i\Delta t}}c_e'$$

$$\dot{c}_1' = i\frac{eE_1^*}{2\hbar}\langle g_1|\hat{\epsilon}_1\cdot\vec{r}|e\rangle c_e'$$



$$\dot{c}_2' = i\frac{eE_2^*}{2\hbar}e^{-i\delta t}\langle g_1|\hat{\epsilon}_2\cdot\vec{r}|e\rangle c_e'$$

adiabatic elimination

$$\cancel{\dot{c}_e'} + i\Delta c_e' = i\frac{e}{2\hbar}\left[\langle e|\hat{\epsilon}_1\cdot\vec{r}|g_1\rangle E_1 c_1' + e^{i\delta t}\langle e|\hat{\epsilon}_2\cdot\vec{r}|g_2\rangle E_2 c_2'\right]$$

$\Delta \gg \Omega_1, \Omega_2, \delta$

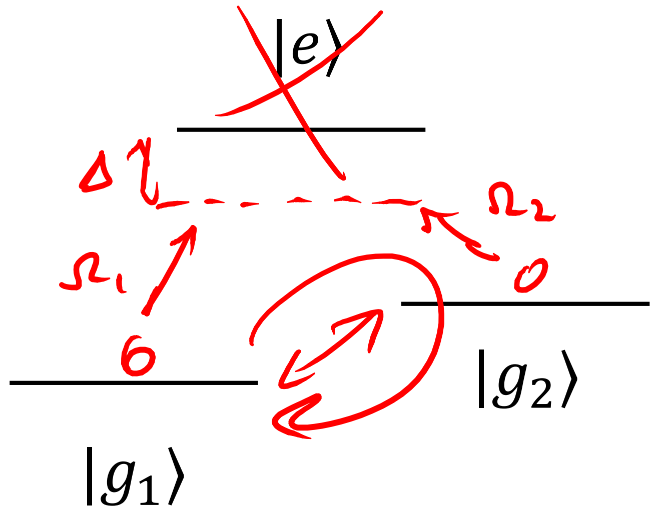
$$c_e' = \frac{1}{\Delta}\left(\Omega_1 c_1 + \Omega_2 e^{-i\delta t} c_2\right)$$

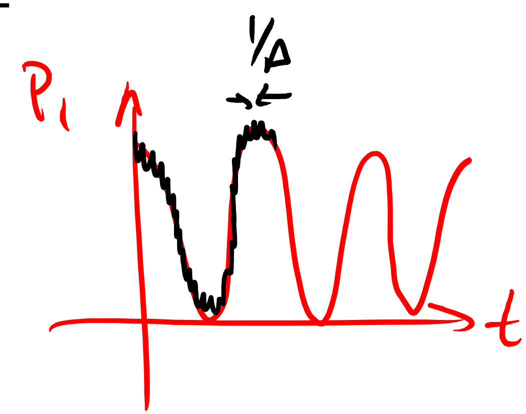
$$\dot{c}_1 = \frac{i|\Omega_1|^2}{\Delta}c_1 + i\frac{\Omega_1^*\Omega_2}{\Delta}c_2 e^{i\delta t} \qquad \dot{c}_2 = \frac{i|\Omega_2|^2}{\Delta}c_2 + i\frac{\Omega_1^*\Omega_2}{\Delta}c_1 e^{-i\delta t}$$

$$\boxed{\dot{c}_1 = \frac{i|\Omega_1|^2}{\Delta} c_1 + i\frac{\Omega_1^*\Omega_2}{\Delta} c_2 e^{i\delta t} \qquad \dot{c}_2 = \frac{i|\Omega_2|^2}{\Delta} c_2 + i\frac{\Omega_1^*\Omega_2}{\Delta} c_1 e^{-i\delta t}}$$

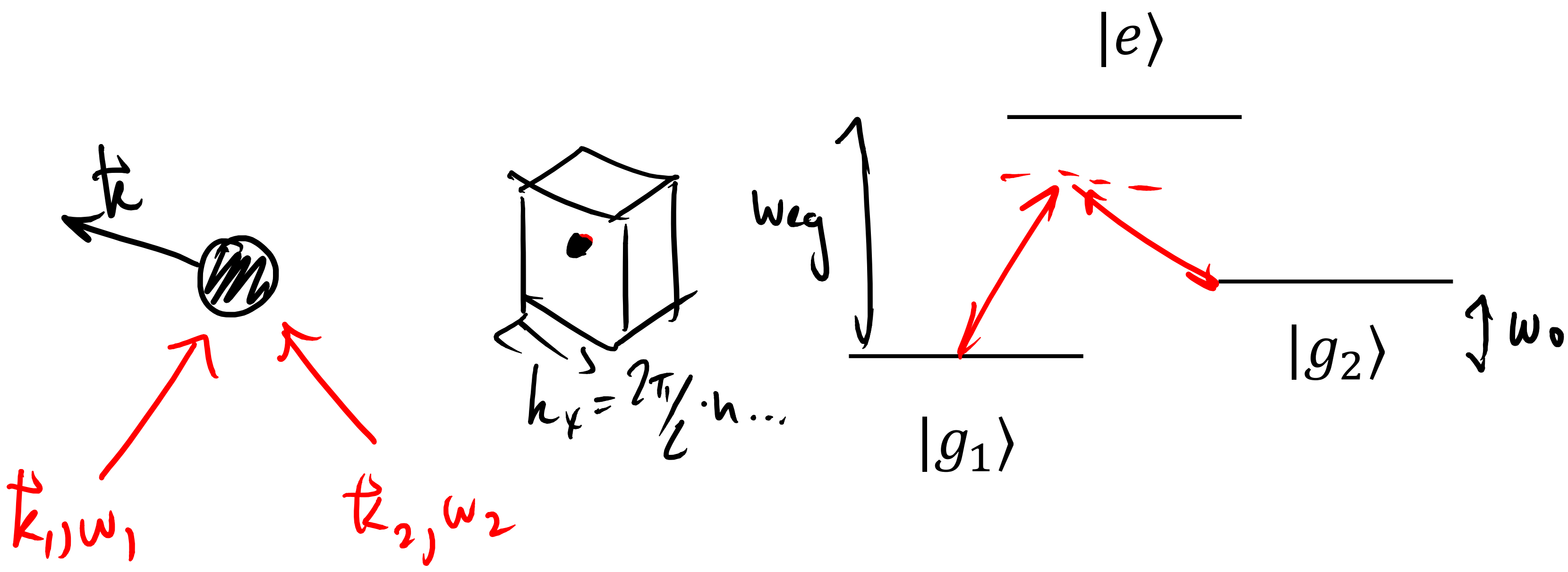
Ac Stark shift

Ac Stark shift





$$\boxed{\Omega = \frac{\Omega_1\Omega_2^*}{\Delta}}$$



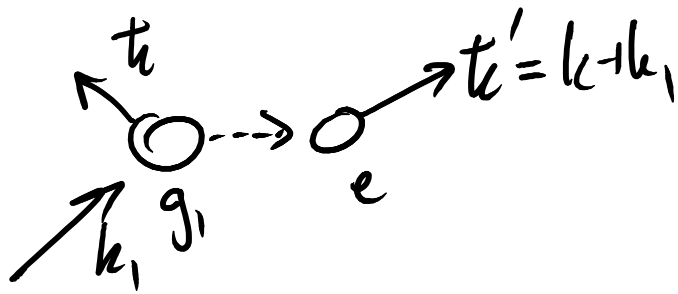
$$H_0 = \frac{\hbar^2 k^2}{2m} + \hbar\omega_0 |g_2\rangle\langle g_2| + \hbar\omega_{eg} |e\rangle\langle e|$$

$$|\psi\rangle = \sum_{\vec{k}} \left\{ \left\{ c_{1\vec{k}} |g_1\rangle + c_{2\vec{k}} |g_2\rangle + c_{e\vec{k}} |e\rangle \right\} \; |\vec{k}\rangle \right.$$

$$\dot{c}_{1\vec{k}} = i\,\frac{eE_1^*}{2\hbar}\,e^{-i\Delta t}\sum_{\vec{k}} e^{\frac{i(E_k - E_k')}{\hbar}t}\,\left\langle g_1\vec{k}\,\middle|\hat{\epsilon}_1\cdot\vec{r}e^{-i\vec{k}_1\cdot\vec{r}}\middle|\,e\vec{k}'\right\rangle c_{e\vec{k}'}$$

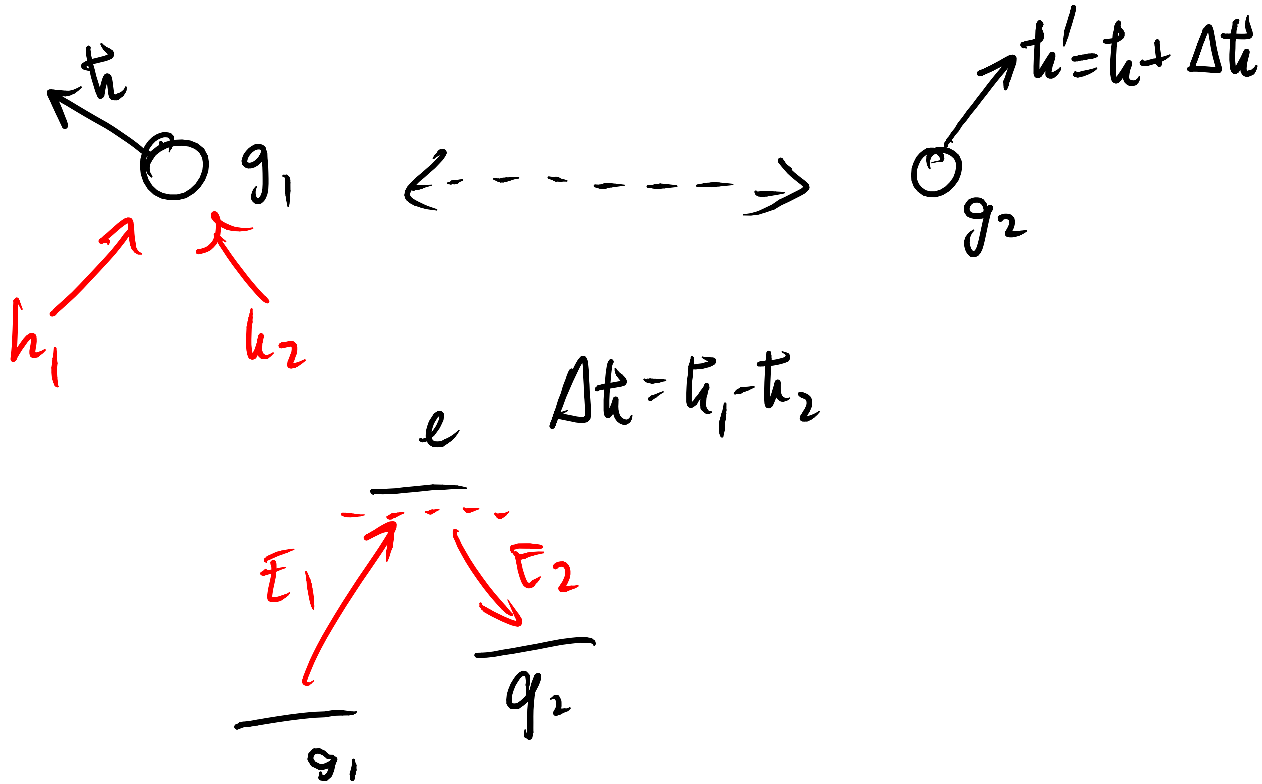
$$\langle g_1|\hat{\epsilon}_1\cdot\vec{r}|e\rangle\,\underbrace{\left\langle\vec{k}\,\middle|e^{-i\vec{k}_1\cdot\vec{r}}\middle|\,\vec{k}'\right\rangle}_{\delta_{k',k+k_1}}$$

$$\dot{c}_{1\vec{k}} = i\,\frac{eE_1^*}{2\hbar}\,e^{-i\Delta t}e^{-\frac{i\hbar^2k_1^2}{2m}}\langle g_1|\hat{\epsilon}_1\cdot\vec{r}|e\rangle c_{e,\vec{k}+\vec{k}_1}$$



$$\dot{c}_{1,\vec{k}} = \frac{i|\Omega_1|^2}{\Delta} c_{1,\vec{k}} + i\frac{\Omega_1^*\Omega_2}{\Delta} e^{i\delta t} e^{\frac{i\hbar}{2m}(k_2^2-k_1^2)t} c_{2,\vec{k}+\vec{k}_1-\vec{k}_2}$$

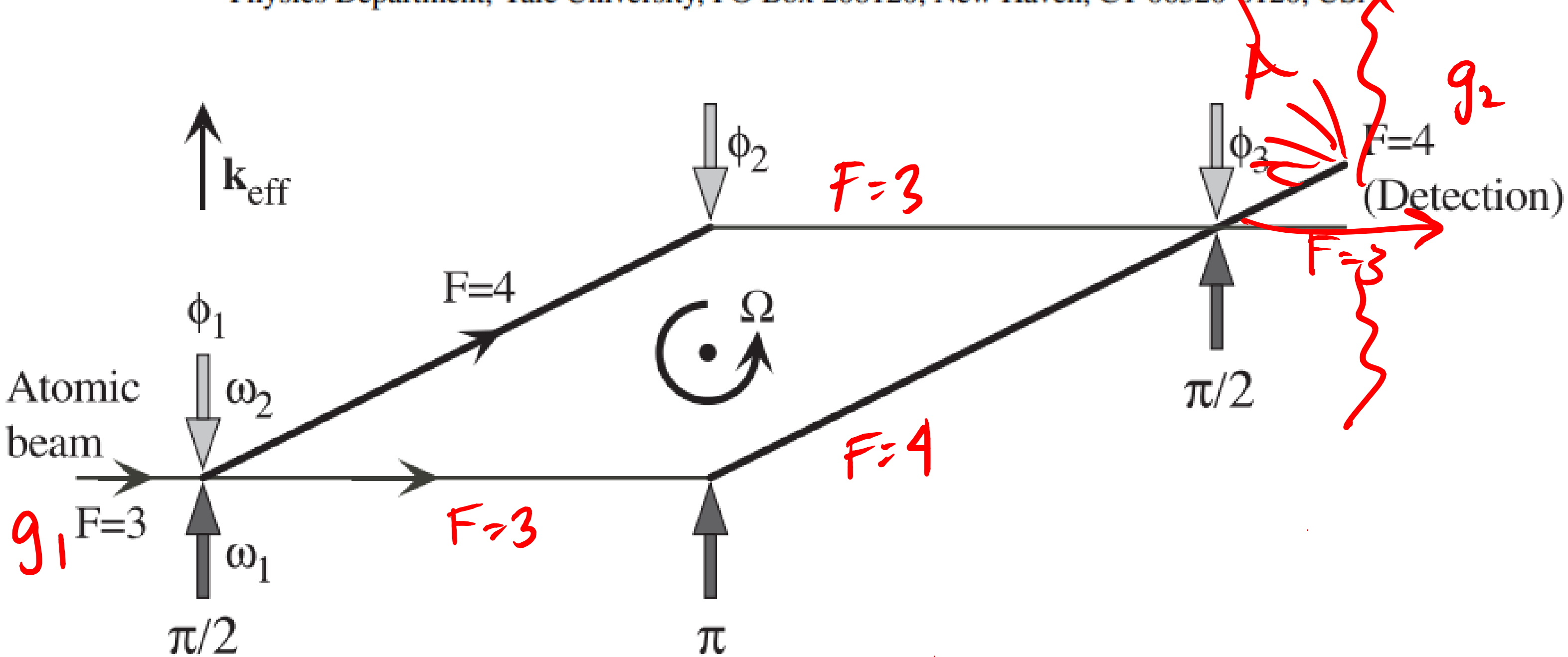
$$\dot{c}_{2,\vec{k}+\vec{k}_1-\vec{k}_2} = \frac{i|\Omega_2|^2}{\Delta} c_{2,\vec{k}+\vec{k}_1-\vec{k}_2} + i\frac{\Omega_1\Omega_2^*}{\Delta} e^{i\delta t} e^{-\frac{i\hbar}{2m}(k_2^2-k_1^2)t} c_{1,\vec{k}}$$

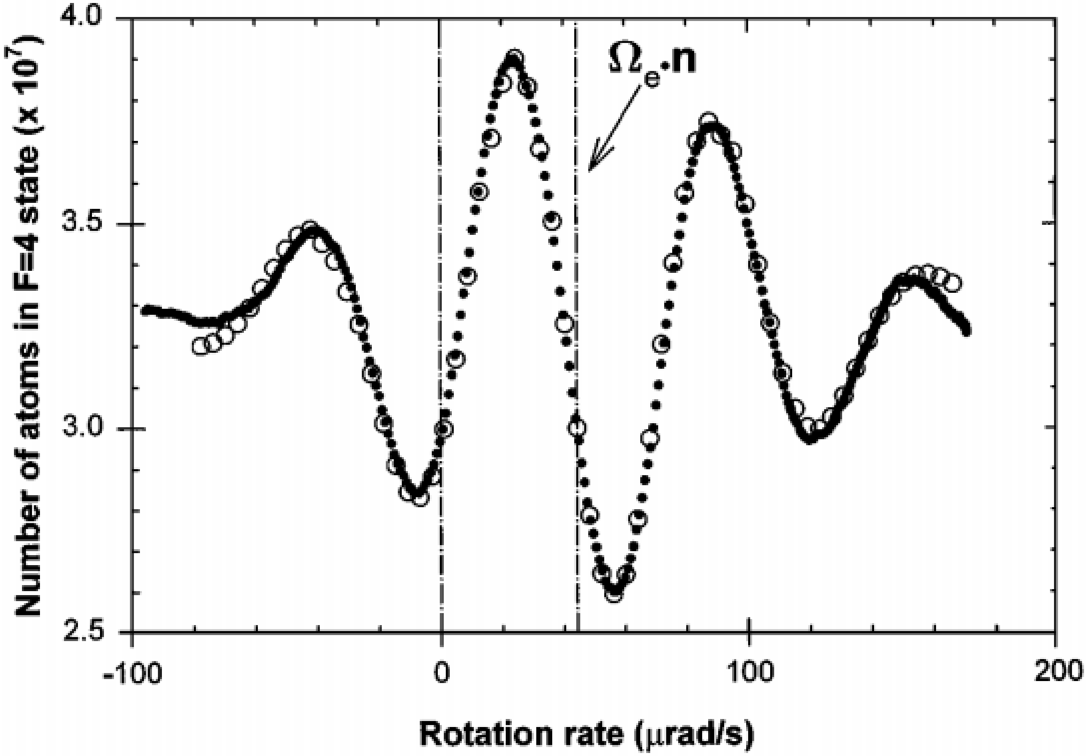


Class. Quantum Grav. **17** (2000) 2385–2398. Printed in the UK PII: S0264-9381(00)50380-3

Rotation sensing with a dual atom-interferometer Sagnac gyroscope

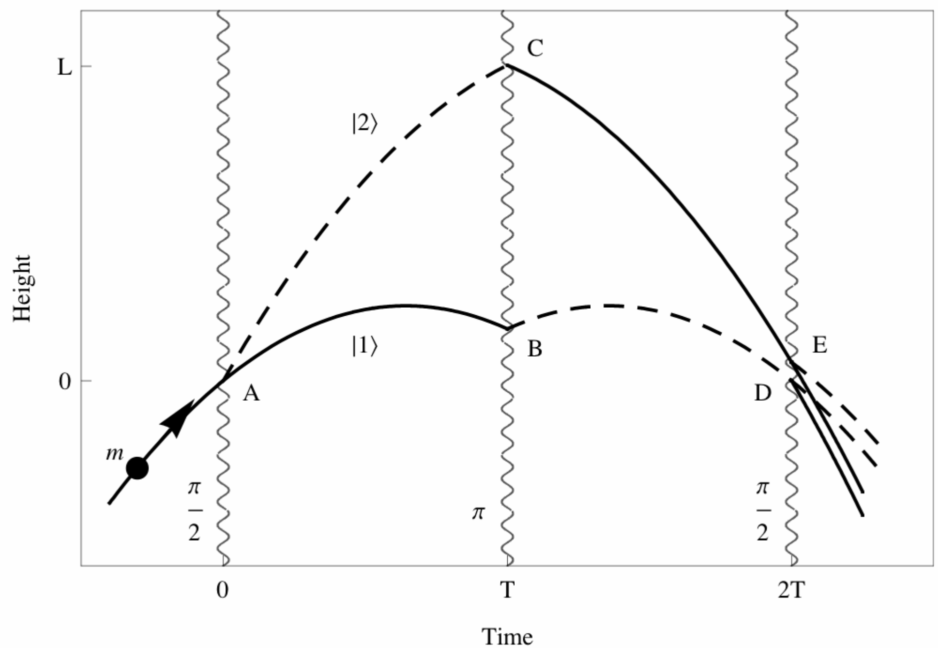
T L Gustavson†, A Landragin‡ and M A Kasevich
Physics Department, Yale University, PO Box 208120, New Haven, CT 06520-8120, USA

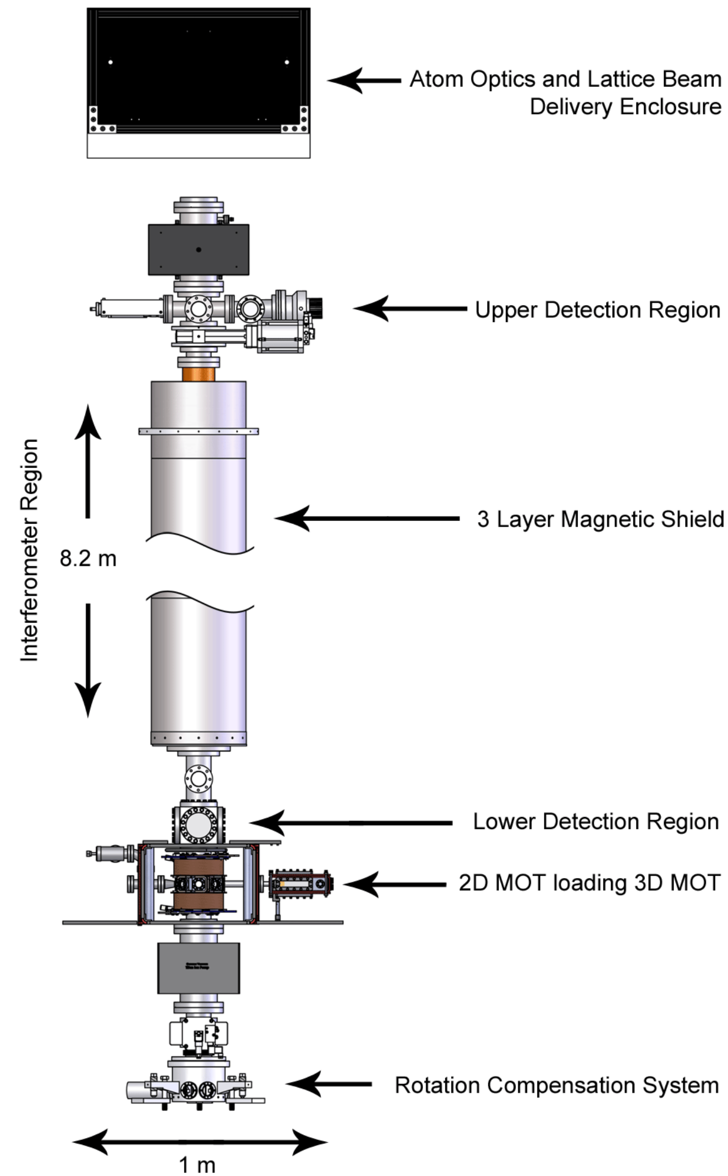




$\Omega \sim 8 \times 10^{-6}\, \Omega_E$


DANGER
HARD HAT AREA





These lead to a sensitivity to the differential acceleration between ^{87}Rb and ^{85}Rb of

$$(g_{87} - g_{85})/g \sim \delta\varphi/\Delta\varphi \sim 10^{-15}$$

To use a physical comparison, this corresponds to detecting the gravitational attraction of a can of soda about 1 meter away.

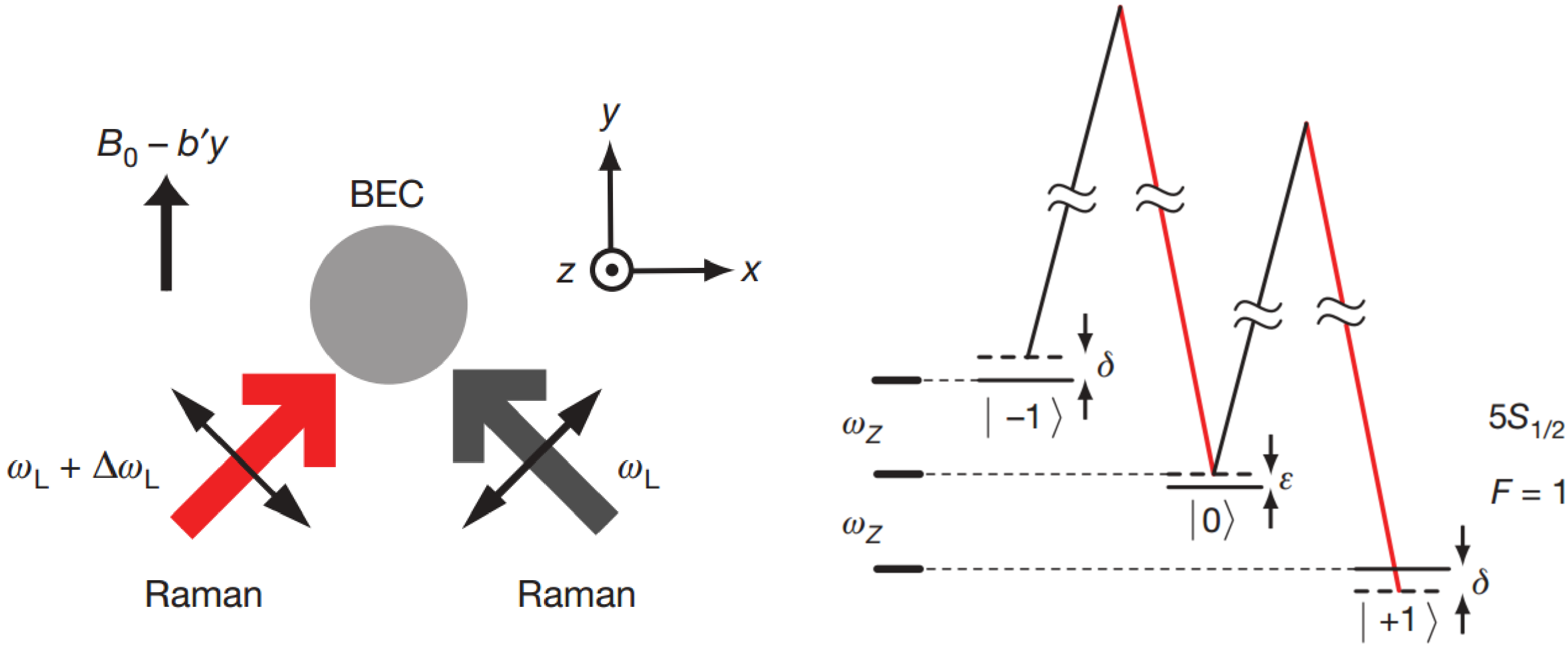
nature
Vol 462|3 December 2009|doi:10.1038/nature08609

LETTERS

Synthetic magnetic fields for ultracold neutral atoms

Y.-J. Lin[1], R. L. Compton[1], K. Jiménez-García[1,2], J. V. Porto[1] & I. B. Spielman[1]

$$H = \frac{\hbar^2}{2m}\left(\vec{k} - \frac{q\vec{A}}{\hbar}\right)^2$$



$$\dot{c}_{1,\vec{k}} = \frac{i|\Omega_1|^2}{\Delta} c_{1,\vec{k}} + i\frac{\Omega_1^*\Omega_2}{\Delta} e^{i\delta t} e^{\frac{i\hbar}{2m}(k_2^2 - k_1^2)t} c_{2,\vec{k}+\vec{k}_1-\vec{k}_2}$$

$$\dot{c}_{1,\vec{k}} \approx i\frac{\Omega_1^*\Omega_2}{\Delta} e^{i\delta t} c_{2,\vec{k}+\vec{k}_1-\vec{k}_2}$$

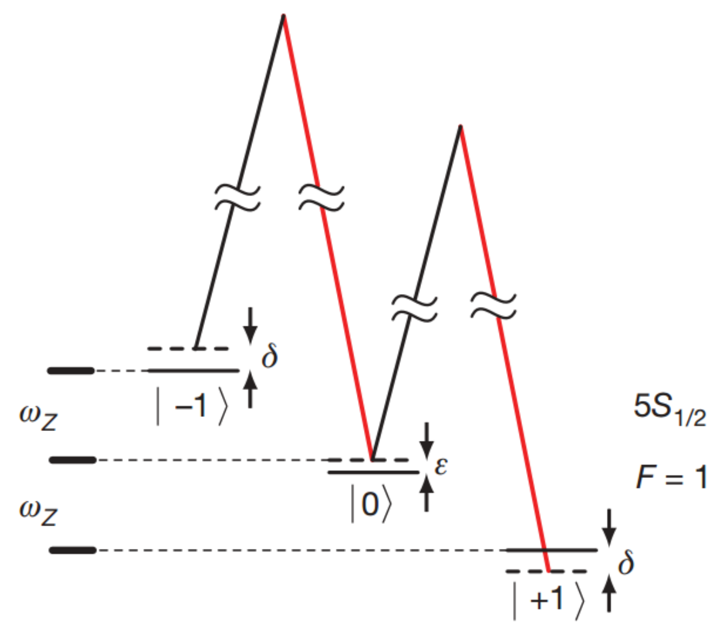
$$\dot{c}_{1,\vec{k}} \approx i\frac{\Omega_1^*\Omega_2}{\Delta}e^{i\delta t}c_{2,\vec{k}+\vec{k}_1-\vec{k}_2}$$

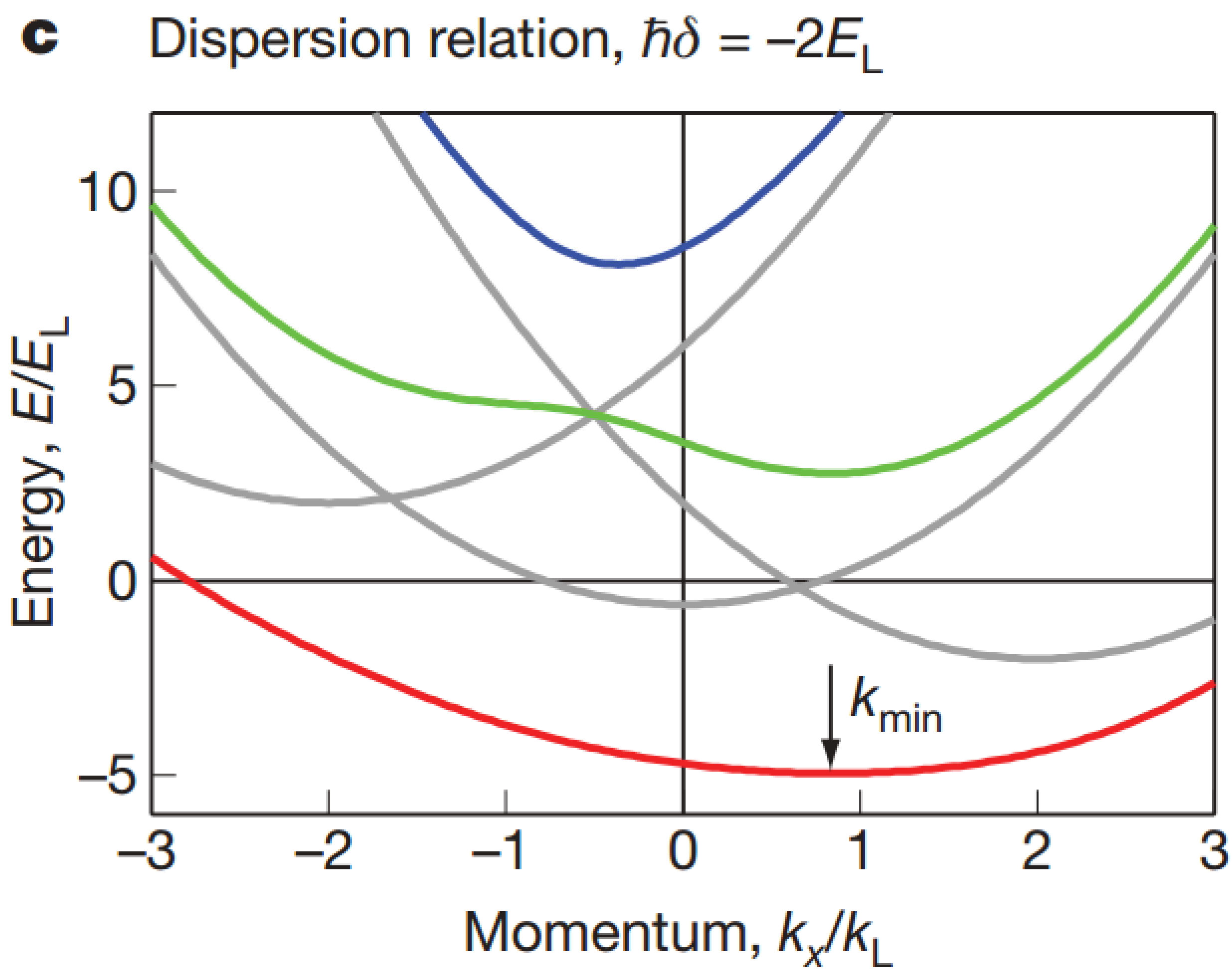
$$\dot{c}_{2,\vec{k}+\vec{k}_1-\vec{k}_2} \approx i\frac{\Omega_2^*\Omega_1}{\Delta}e^{-i\delta t}c_{1,\vec{k}}$$

$$c_{1,\vec{k}} = e^{\frac{i\delta}{2}t}c'_{1,\vec{k}} \qquad c_{2,\vec{k}} = e^{-\frac{i\delta}{2}t}c'_{2,\vec{k}}$$

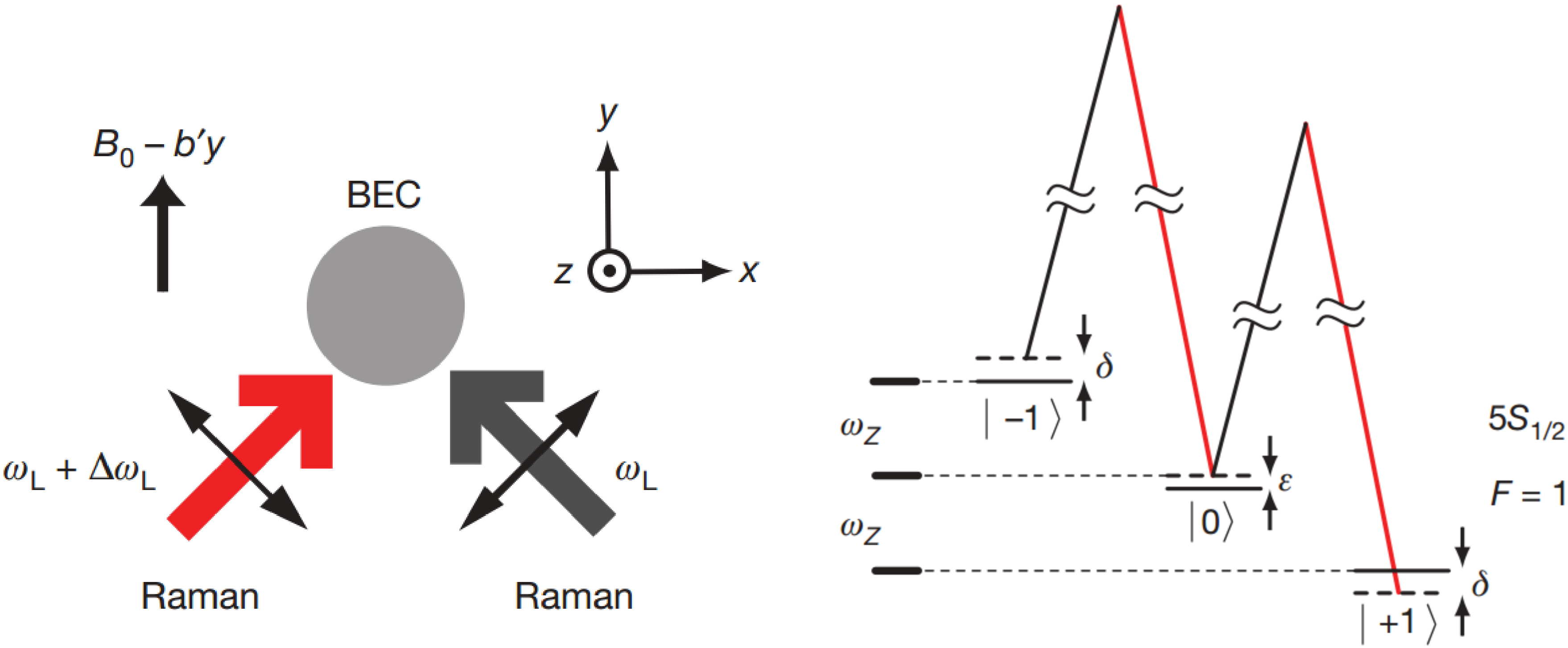
$$\dot{c}'_{1,\vec{k}} \approx -\frac{i\delta}{2}c_{1,\vec{k}} + i\frac{\Omega_1^*\Omega_2}{\Delta}c'_{2,\vec{k}+\vec{k}_1-\vec{k}_2}$$

$$\dot{c}'_{2,\vec{k}+\vec{k}_1-\vec{k}_2} \approx \frac{i\delta}{2}c_{2,\vec{k}} + i\frac{\Omega_2^*\Omega_1}{\Delta}c'_{1,\vec{k}}$$



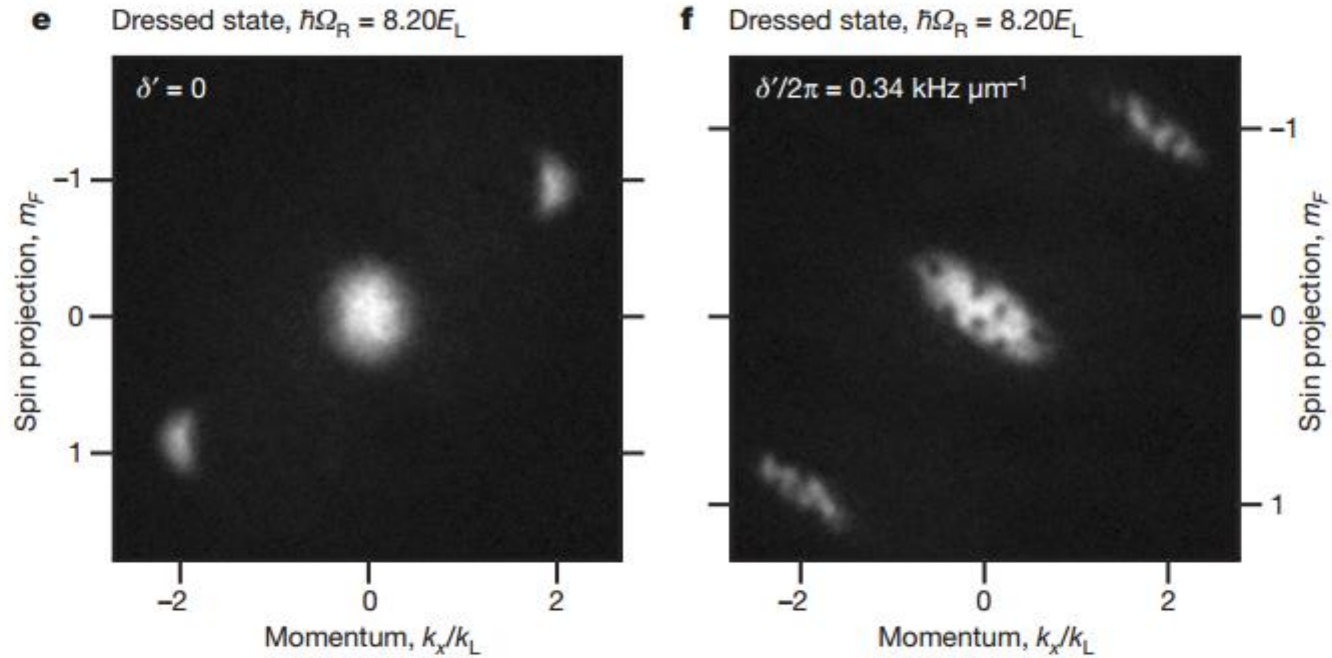


$$H = \frac{\hbar^2}{2m}(k_x - k_{min})^2 \rightarrow \frac{\hbar^2}{2m^*}\left(k_x - \frac{q^* A^*}{\hbar}\right)^2$$

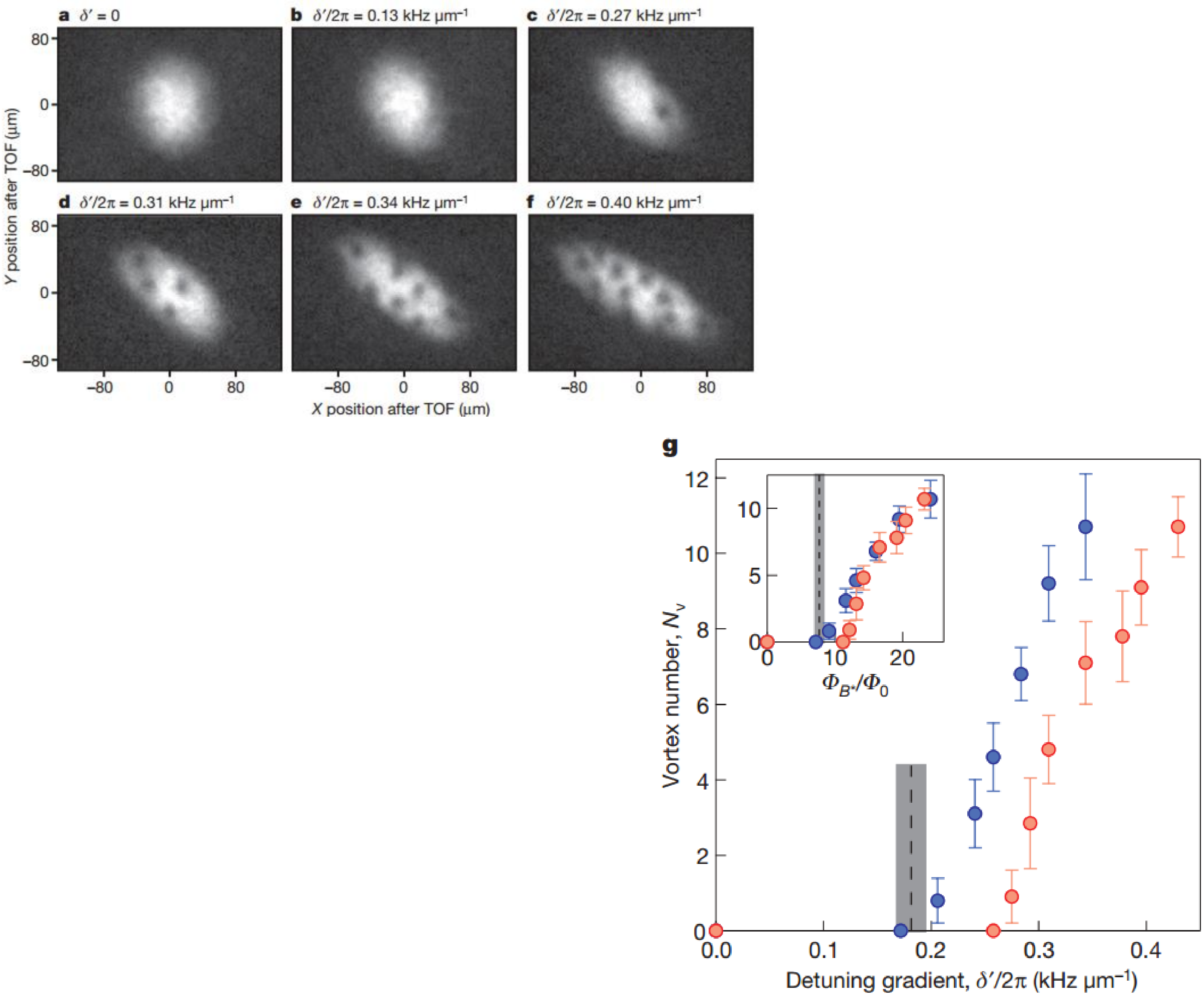


$$-B^* \hat{z} = \vec{\nabla} \times \vec{A}^*$$

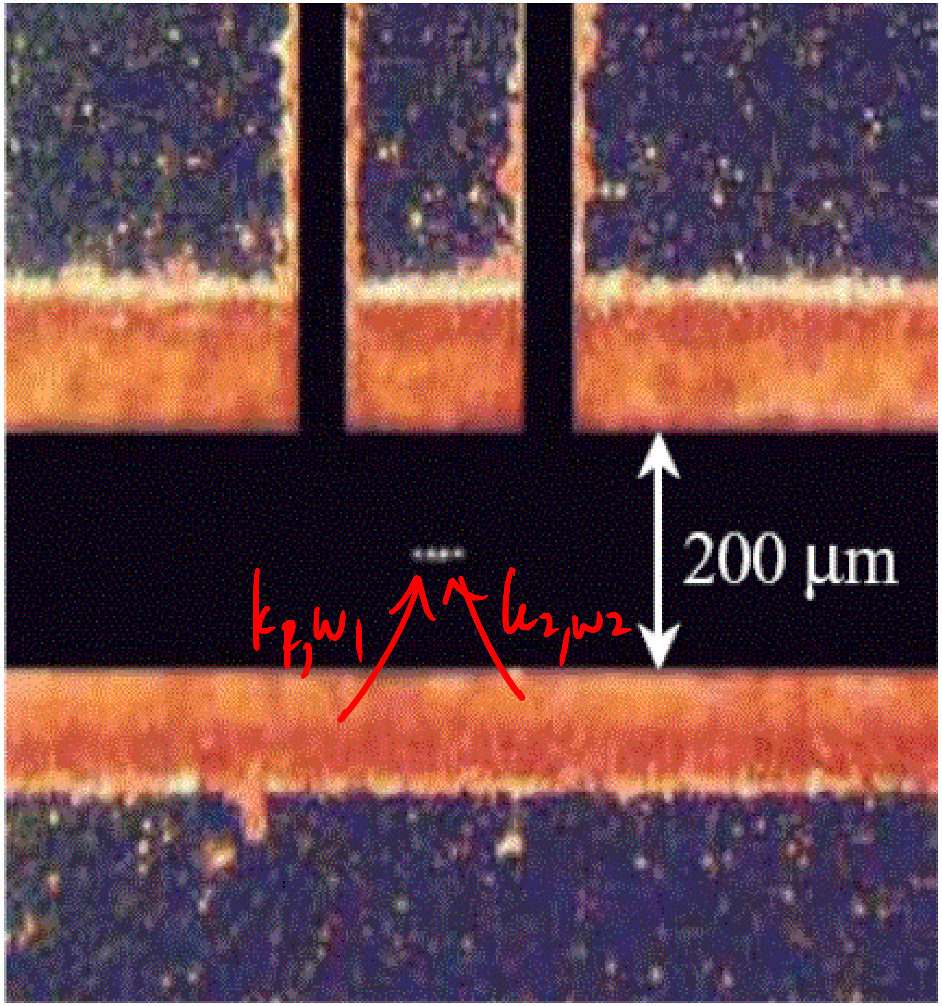
$$B_z^* = \frac{\partial A_x^*}{\partial y}$$



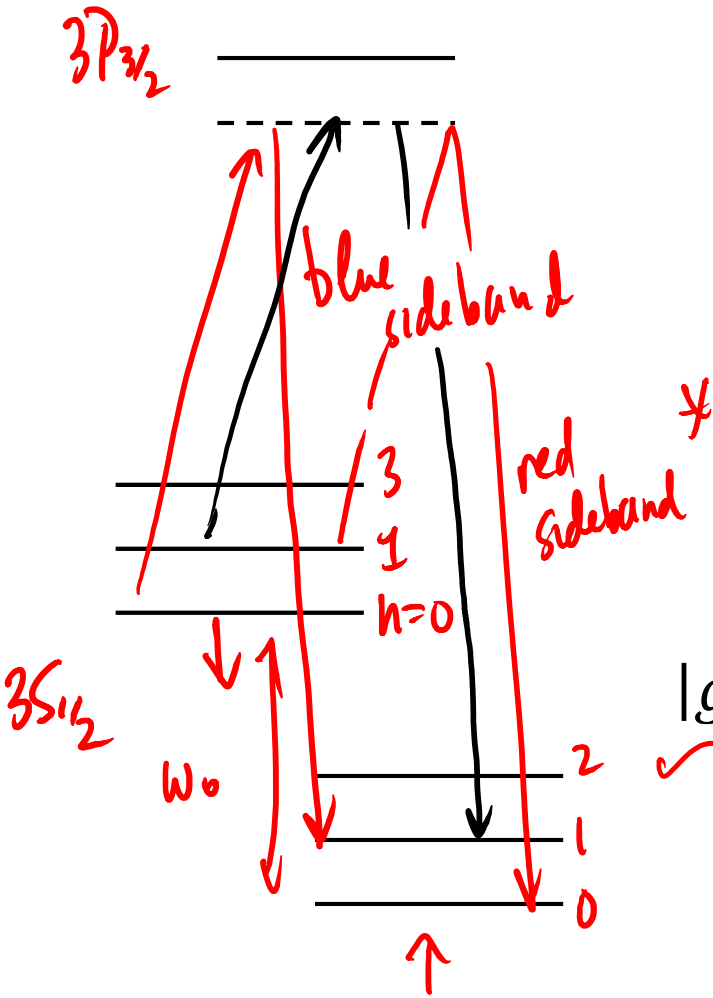
e
Dressed state, $\hbar\Omega_R = 8.20E_L$
$\delta' = 0$
Spin projection, m_F
−1
0
1
−2
0
2
Momentum, k_x/k_L
f
Dressed state, $\hbar\Omega_R = 8.20E_L$
$\delta'/2\pi = 0.34$ kHz μm^{-1}
Spin projection, m_F
−1
0
1
−2
0
2
Momentum, k_x/k_L



a $\delta' = 0$
b $\delta'/2\pi = 0.13$ kHz μm^{-1}
c $\delta'/2\pi = 0.27$ kHz μm^{-1}
d $\delta'/2\pi = 0.31$ kHz μm^{-1}
e $\delta'/2\pi = 0.34$ kHz μm^{-1}
f $\delta'/2\pi = 0.40$ kHz μm^{-1}
Y position after TOF (μm)
X position after TOF (μm)
80
0
–80
g
Vortex number, N_v
Detuning gradient, $\delta'/2\pi$ (kHz μm^{-1})
0.0
0.1
0.2
0.3
0.4
0
2
4
6
8
10
12
Φ_{B^*}/Φ_0
5
20


200 µm
k_1, ω_1
k_2, ω_2

$^9Be^+$



$$H = \hbar\omega|n\rangle\langle n| + \hbar\omega_0|g_2\rangle\langle g_2| + \hbar\omega_{eg}|e\rangle\langle e|$$

$$|\psi\rangle = \sum_n \left(c_{1n}|g_1\rangle + c_{2n}|g_2\rangle + c_{en}|e\rangle\right)|n\rangle$$

$$|g_1 n\rangle \leftrightarrow |g_2 n'\rangle \qquad \Omega = \frac{\Omega_1\Omega_2}{\Delta}\left\langle n'\left|e^{i\Delta\vec{k}\cdot\vec{x}}\right|n\right\rangle = \frac{\Omega_1\Omega_2}{\Delta}\left\langle n'\left|e^{i\eta(\hat{a}+\hat{a}^\dagger)}\right|n\right\rangle$$

$$\eta = \Delta k_z\, z_0 \qquad z_0 = \sqrt{\hbar/2m\omega_z}$$

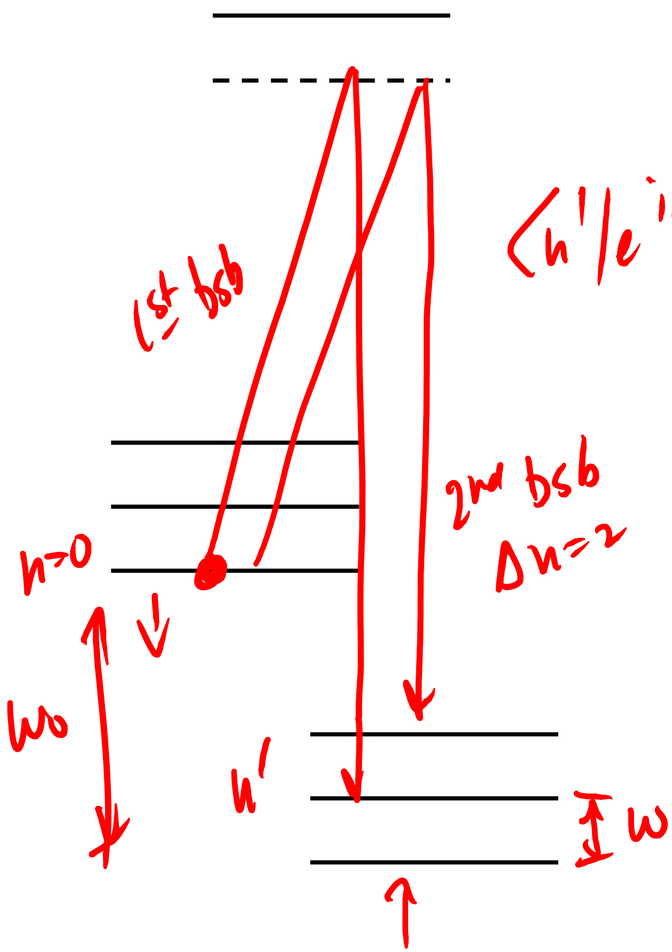
Lamb-Dicke parameter

carrier: $\Delta n = 0$

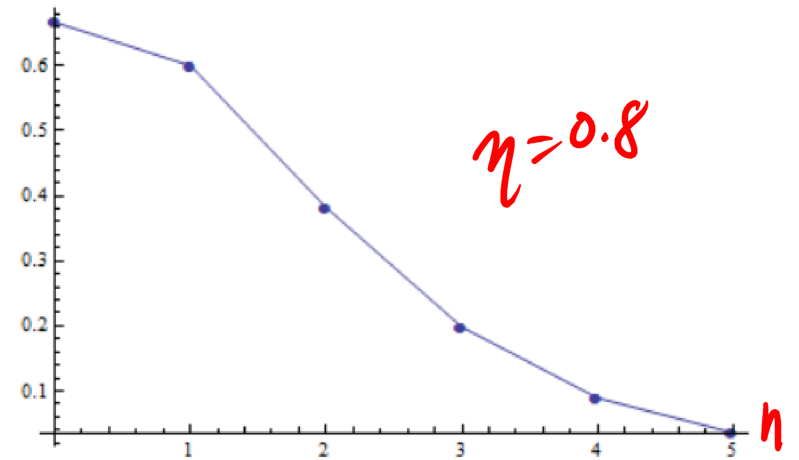
bsb : $\Delta n > 0$

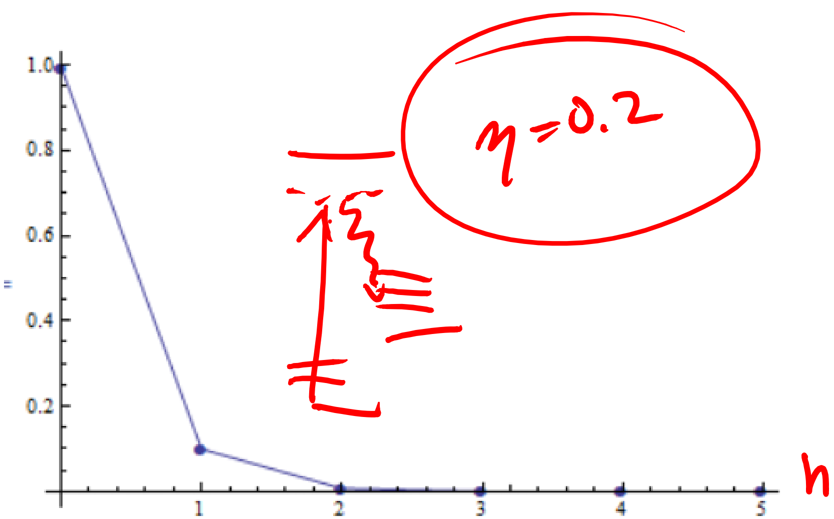
rsb : $\Delta n < 0$

$$\langle n' \left| e^{i\eta(\hat{a}+\hat{a}^\dagger)} \right| n\rangle = \mathrm{e}^{-\frac{\eta^2}{2}} \sqrt{\frac{n_<!}{n_>!}}\, \eta^{|n'-n|} L_{n_<}^{|n'-n|}(\eta^2)$$

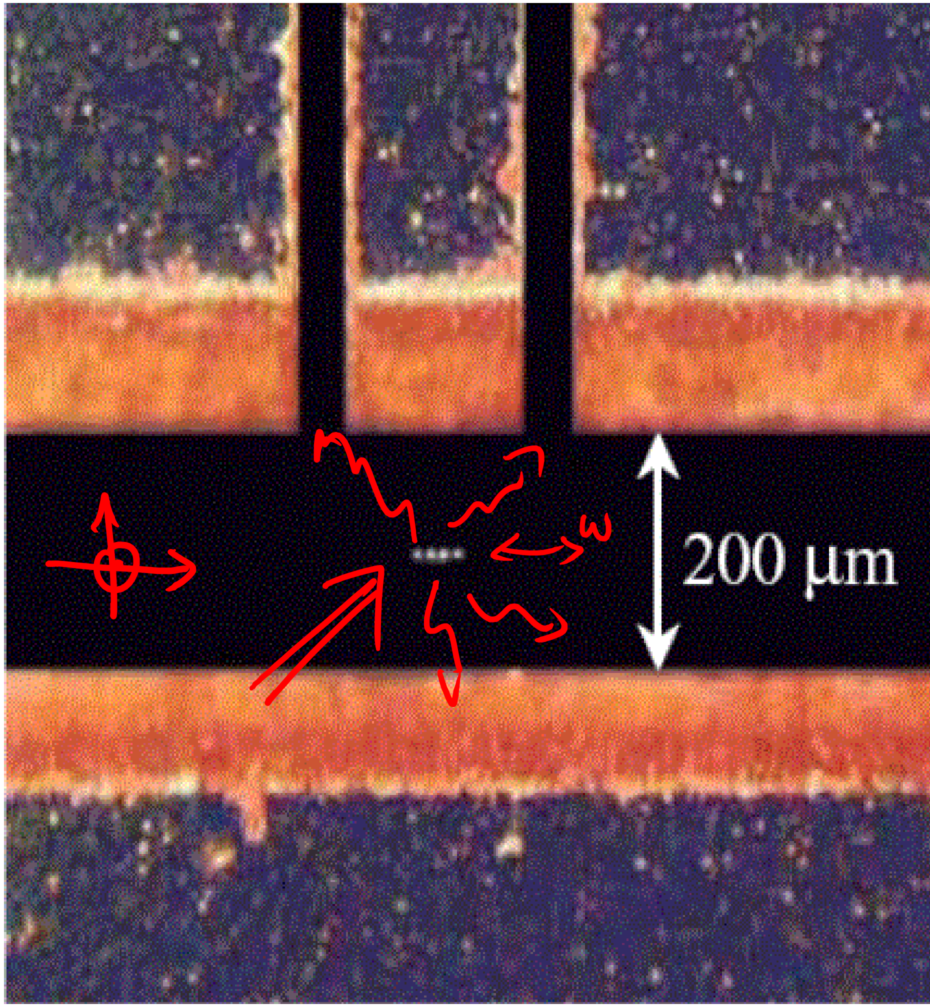


$\langle n' | e^{i\Delta k x} | n\rangle$





Doppler cooling



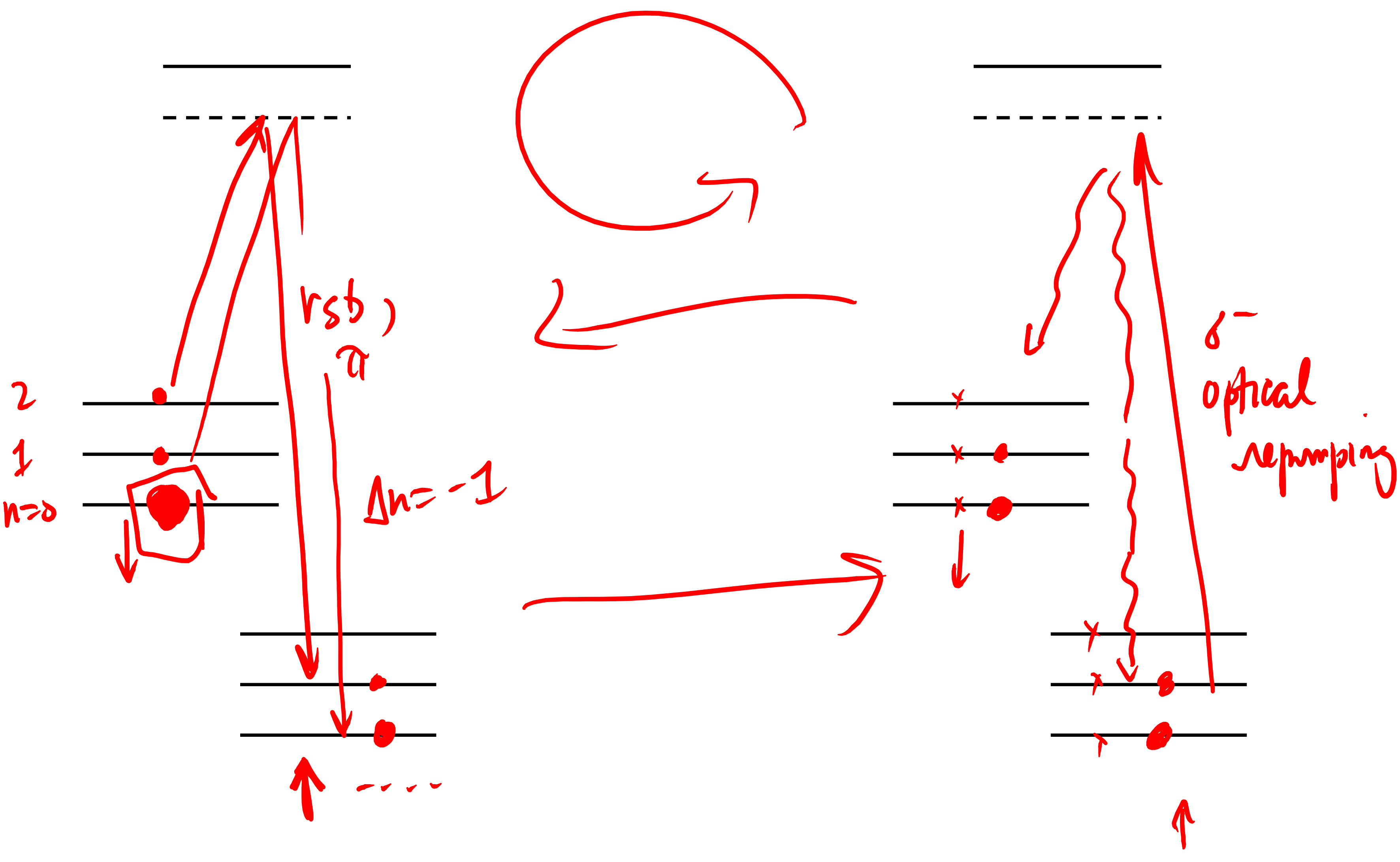
$$T_D = \frac{h\Gamma}{2\, k_B}$$ $\Gamma = 2\pi\, 20$ MHz

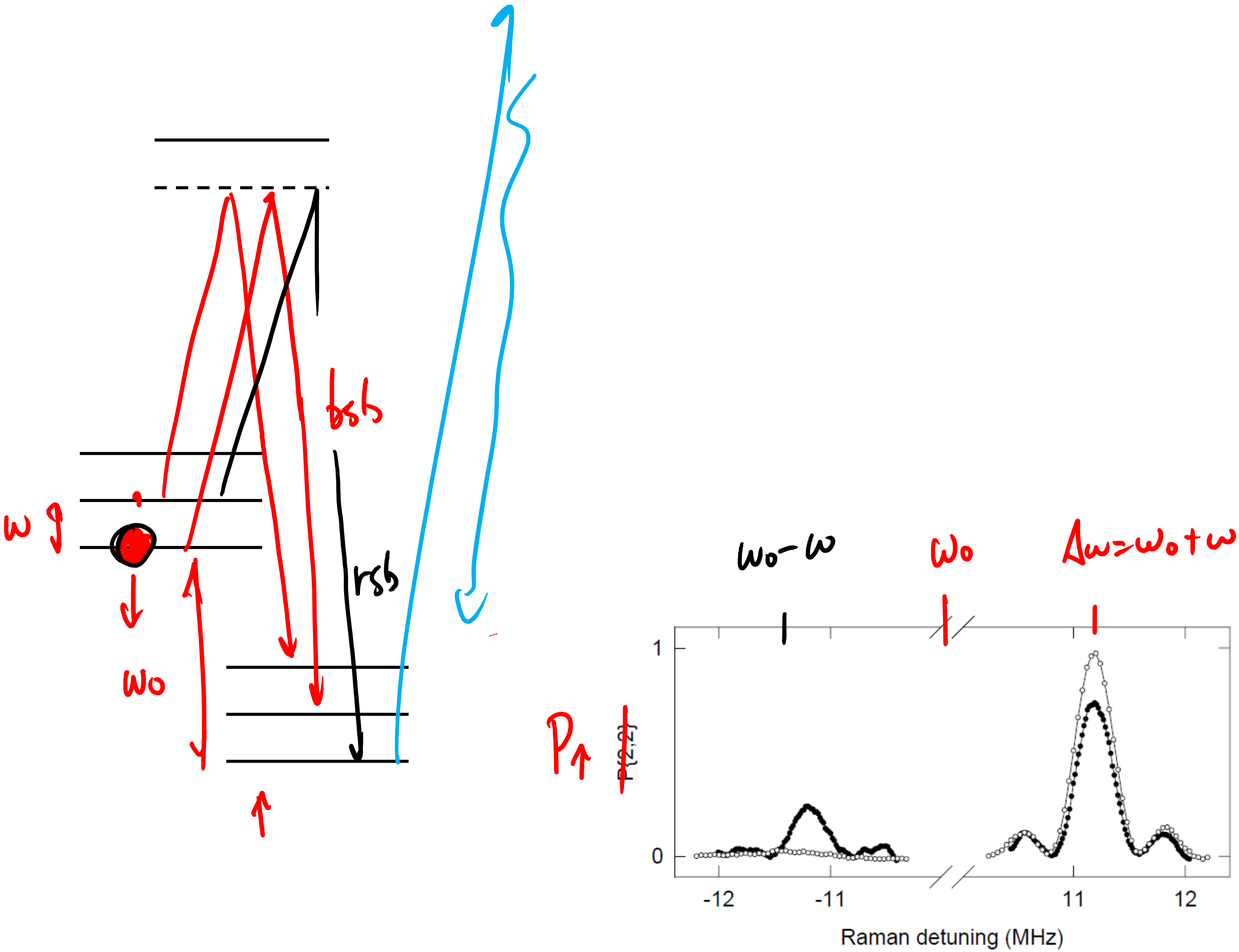
T_D =3 mK

$\omega = 2\pi\, 10$ MHz $\quad \langle n \rangle = \dfrac{\sum e^{-\frac{\hbar\omega}{kT} \cdot n}}{\sum e^{-\hbar\omega/kT}}$

$\langle n \rangle = 6$

resolved sideband cooling – Lamb-Dicke limit, $\eta \ll 1$





wo
bsb
rsb
wo-w
wo
Δw=wo+w
P↑
~~P[2,2]~~
1
0
-12
-11
11
12
Raman detuning (MHz)

Realization of the Cirac–Zoller controlled-NOT quantum gate

Ferdinand Schmidt-Kaler, Hartmut Häffner, Mark Riebe, Stephan Gulde, Gavin P. T. Lancaster, Thomas Deuschle, Christoph Becher, Christian F. Roos, Jürgen Eschner & Rainer Blatt

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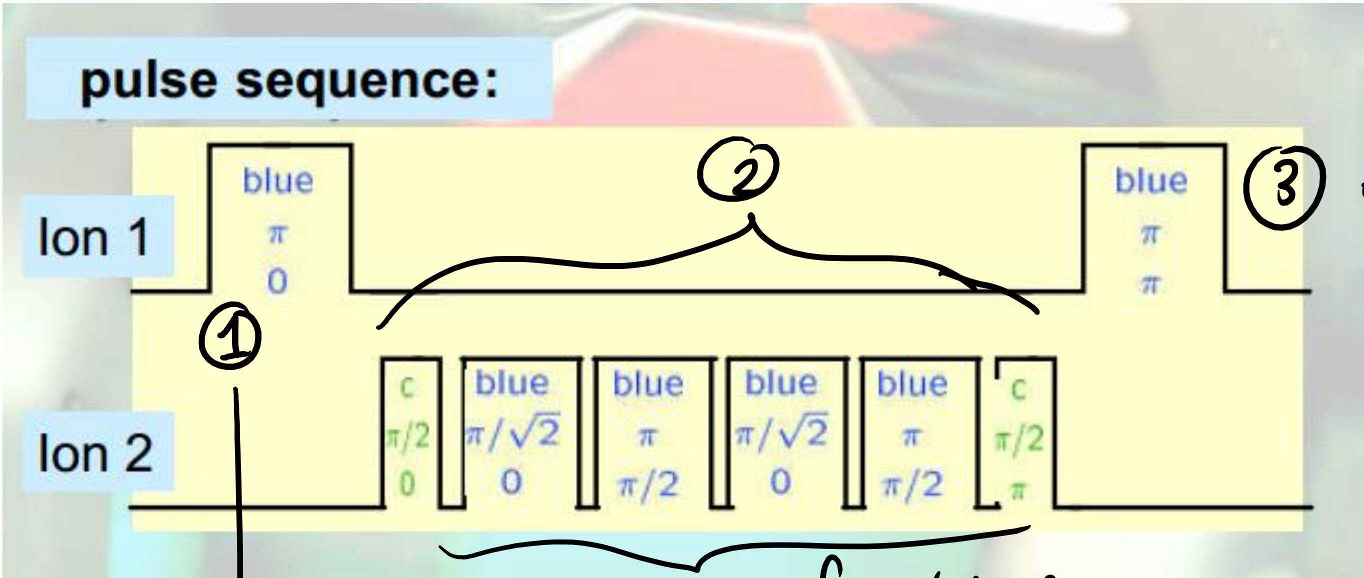
NATURE | VOL 422 | 27 MARCH 2003 | www.nature.com/nature

control

target



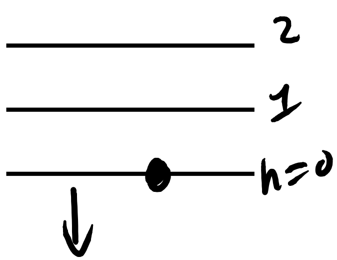
1 2 3

unmap motion of c

c → motion

motion: flip state of t

c t		c' t'
↓0 ↓0	CNOT	↓0 ↓0
↓0 ↑0	⇒	↓0 ↑0
↑0 ↓0		↑0 ↑0
↑0 ↑0		↑0 ↓0

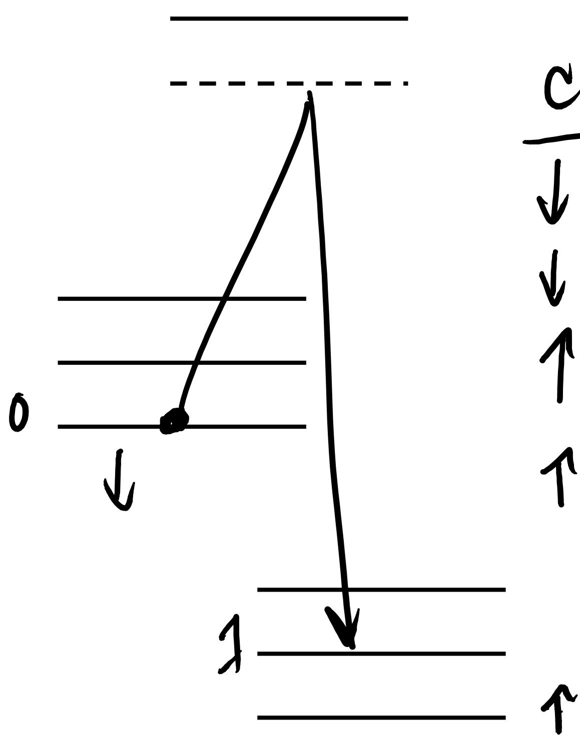


↑

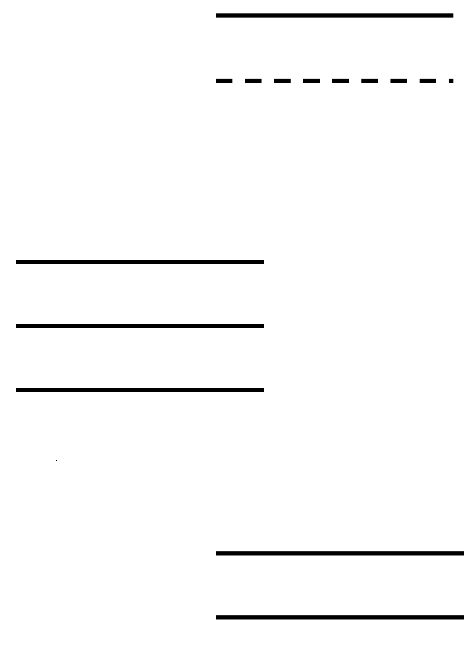
↓

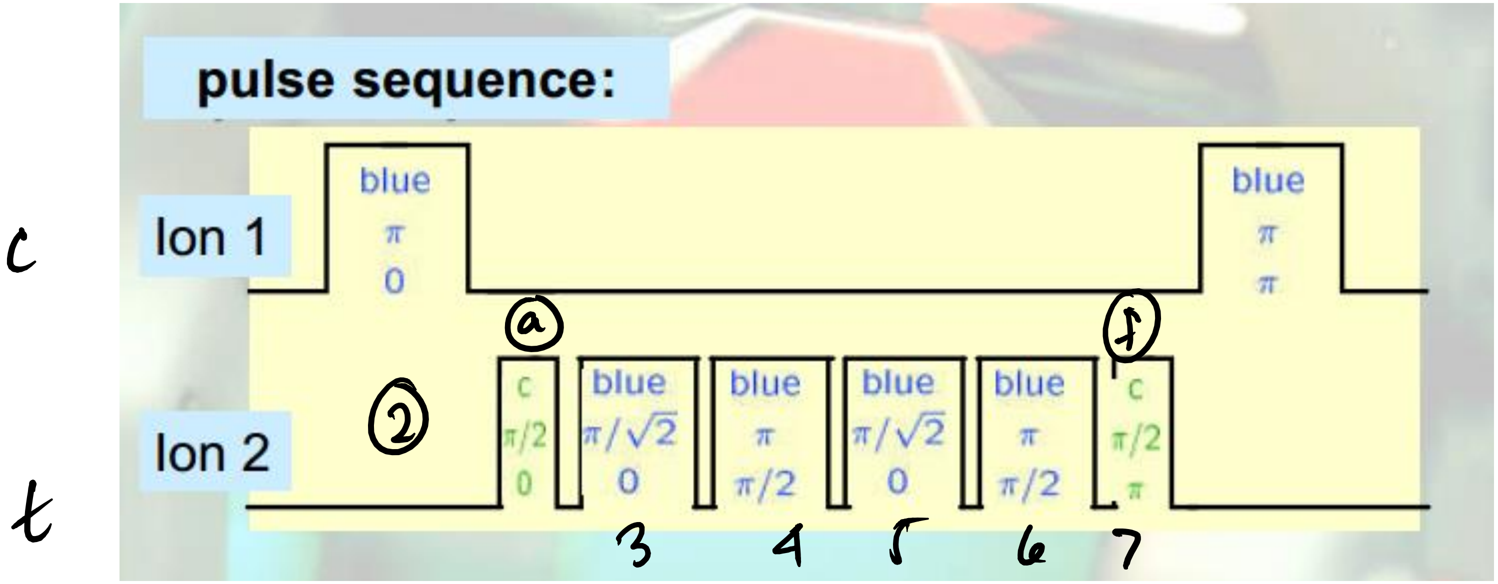
↑

control



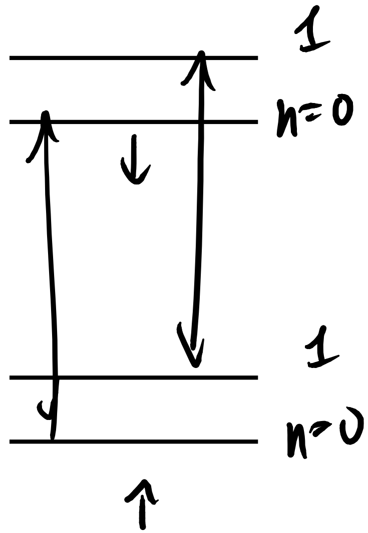
c	t		c'	t'
↓0	↓0	1	↑1	↓1
↓0	↑0	⇒	↑1	↑1
↑0	↓0		↑0	↓0
↑0	↑0		↑0	↑0





c

t

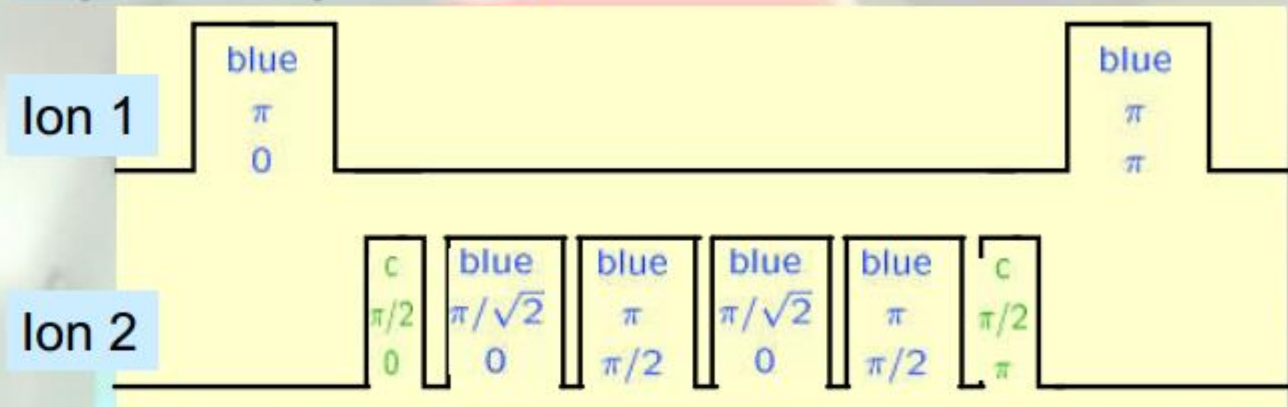


<u>t</u>

$\downarrow n \rightarrow (\downarrow + \uparrow) n$ a

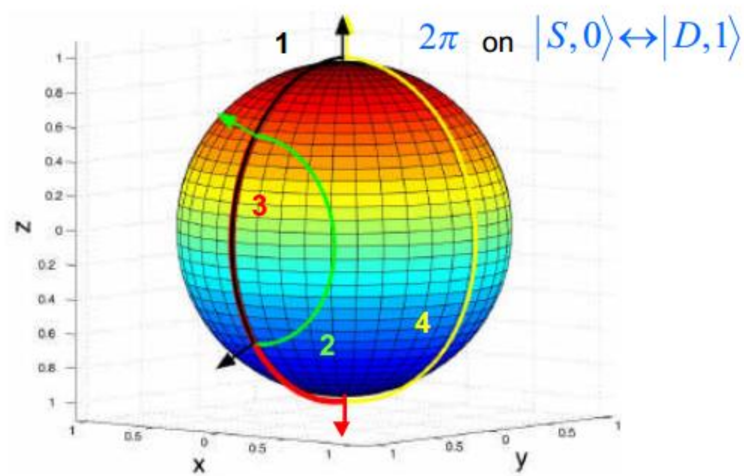
$\uparrow n \rightarrow (\downarrow - \uparrow) n$

pulse sequence:



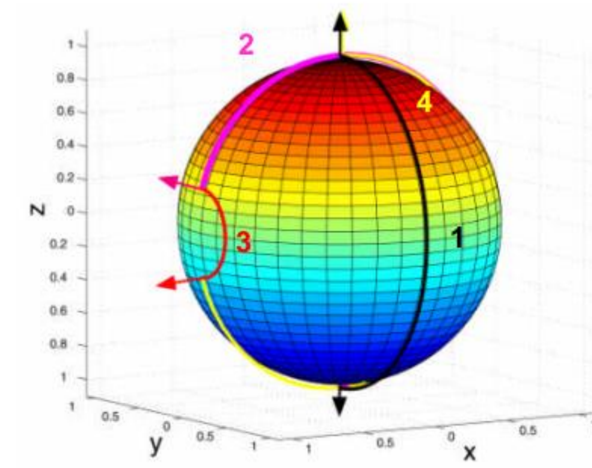
Composite phase gate (2π rotation)

$$R(\theta,\phi) = R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)$$

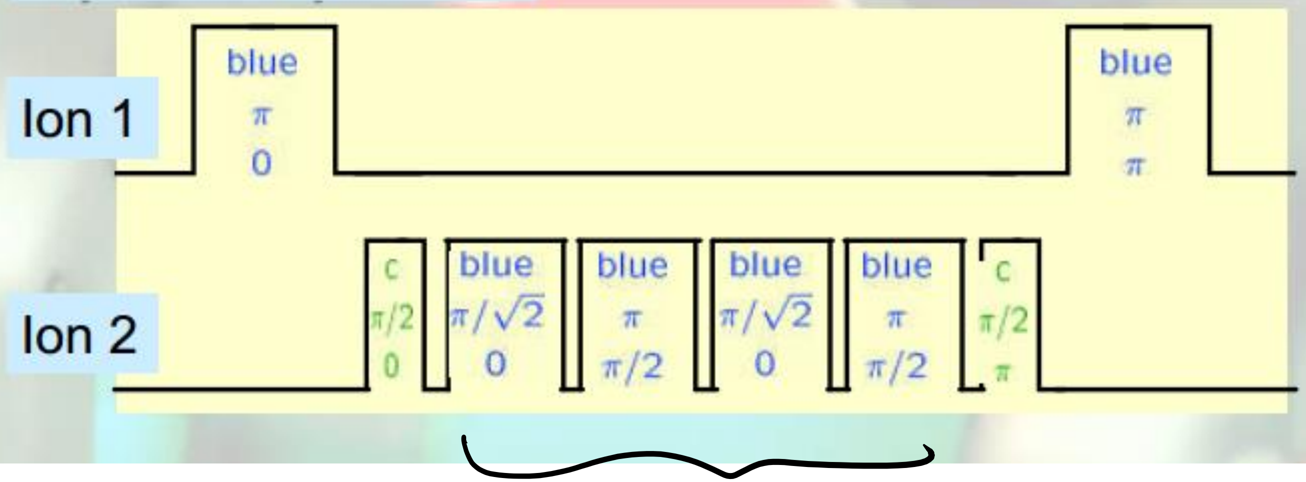


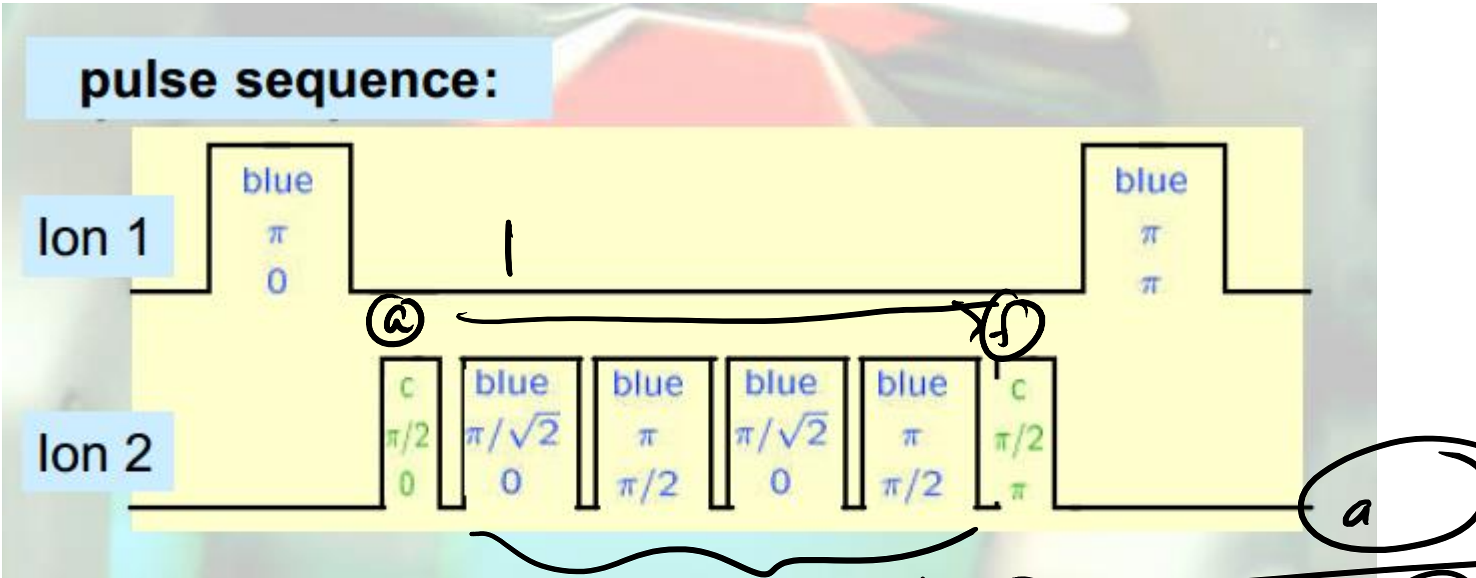
Population of |S,1> - |D,2> remains unaffected

$$R(\theta,\phi) = R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+(\pi,0)\,R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+(\pi,0)$$



pulse sequence:





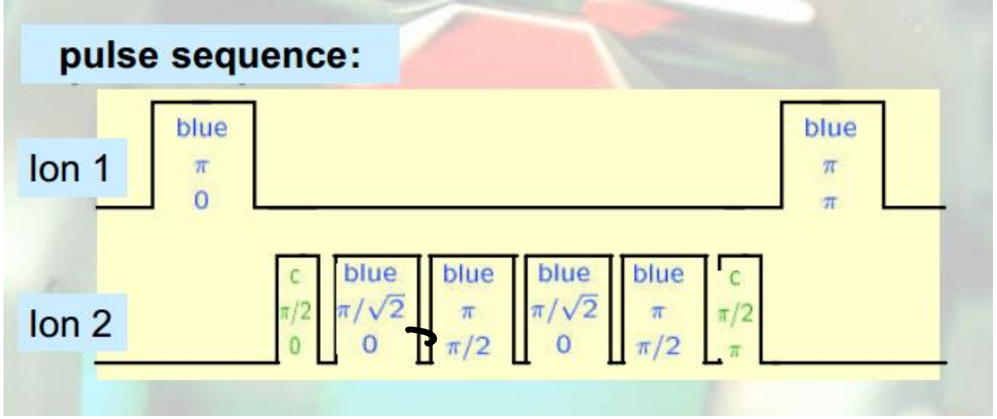
t
$\downarrow 0$
$\downarrow 1$
$\uparrow 0$
$\uparrow 1$

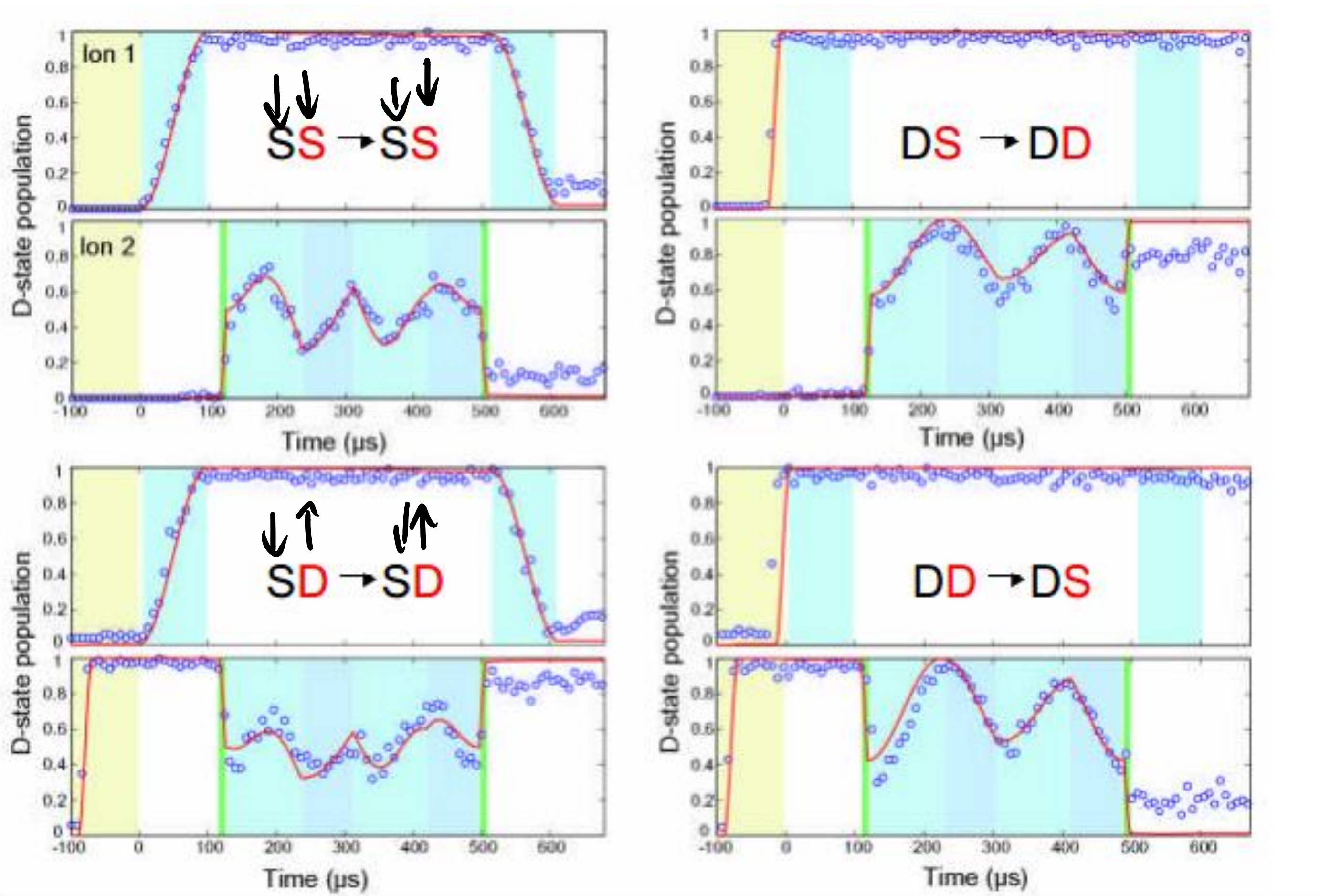
$\Rightarrow$

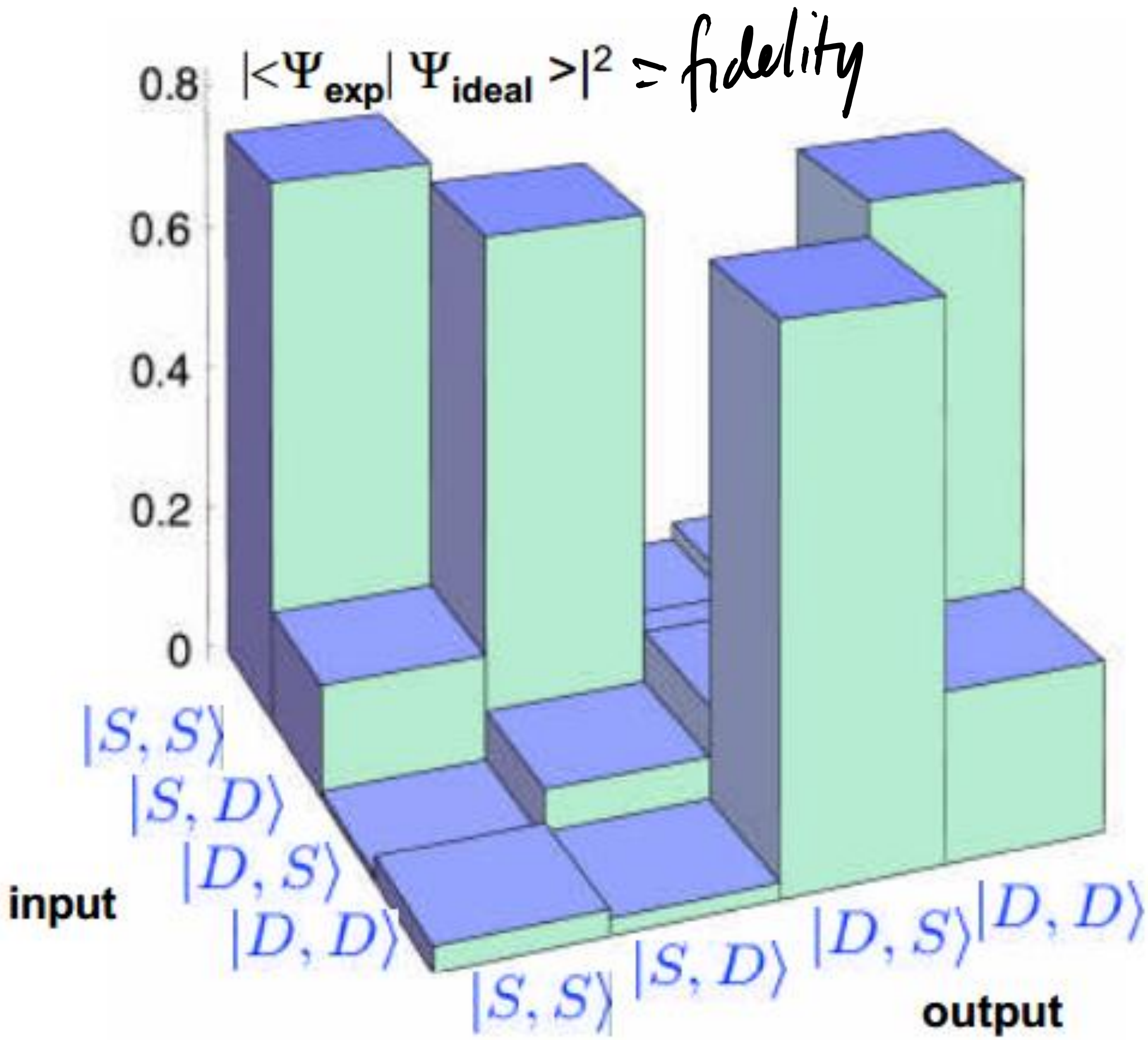
t
$-\downarrow 0$
$-\downarrow 1$
$\uparrow 0$
$-\uparrow 1$

b-e

t	a	
$\downarrow 0$	$(\downarrow+\uparrow)0$	$(-\downarrow+\uparrow)0$
$\downarrow 1$	$(\downarrow+\uparrow)1$	$\to (-\downarrow-\uparrow)1$
$\uparrow 0$	$\to (\downarrow-\uparrow)0$	$(-\downarrow-\uparrow)0$
$\uparrow 1$	$(\downarrow-\uparrow)0$	$(-\downarrow+\uparrow)1$


pulse sequence:
Ion 1
blue
π
0
blue
π
π
Ion 2
c
π/2
0
blue
π/√2
0
blue
π
π/2
blue
π/√2
0
blue
π
π/2
c
π/2
π


Ion 1
Ion 2
SS → SS
DS → DD
SD → SD
DD → DS
D-state population
Time (μs)



$|<\Psi_{exp}|\Psi_{ideal}>|^2$ = fidelity
0.8
0.6
0.4
0.2
0
$|S,S\rangle$
$|S,D\rangle$
$|D,S\rangle$
$|D,D\rangle$
input
$|S,S\rangle$
$|S,D\rangle$
$|D,S\rangle$
$|D,D\rangle$
output