Ultrafast creation of large Schrödinger cat states of an atom

2017/12/18

Oh Seunghoon

2017 Fall Journal club

1. The Research Group

University of Maryland Department of Physics

Joint Quantum Institute

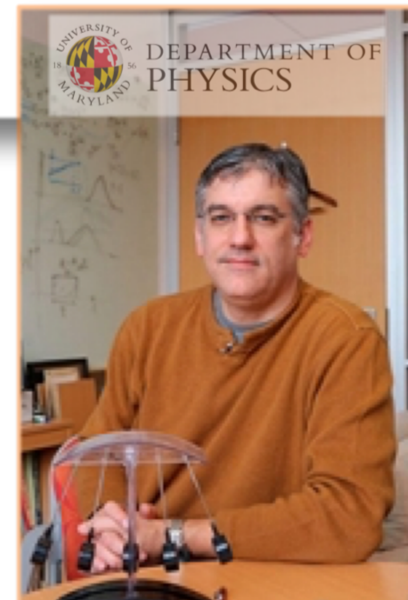
Center for Quantum Information and Computer Science nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-00682-6 OPEN

Ultrafast creation of large Schrödinger cat states of an atom

K.G. Johnson [1], J.D. Wong-Campos[1], B. Neyenhuis[1], J. Mizrahi[1] & C. Monroe[1]



Christopher Monroe

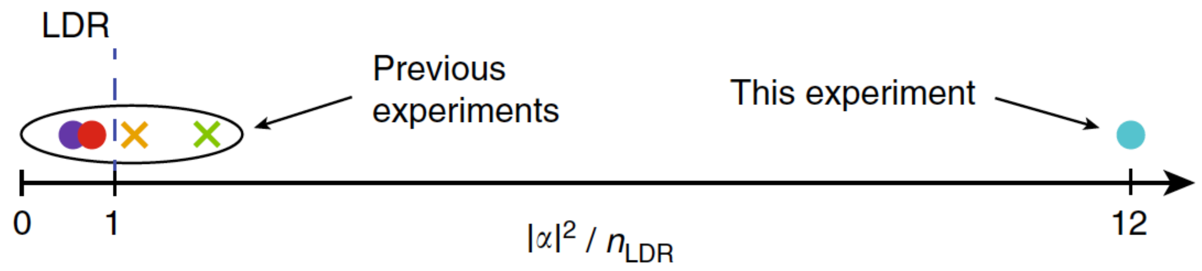
Biography

- Graduated from MIT
- Earned Ph.D. in physics from Univ. of Colorado (1992) under Carl Wieman and Eric Cornell [BEC]
- Postdoctoral work in NIST under the group of David Wineland
- Since 2007, Bice Zorn Professor of Physics at the Univ. of Maryland (Fellow of the Joint Quantum Institute)

Research Project :

- Experimental quantum information science
- Quantum computing and quantum simulations with trapped atomic ions
- Quantum networks with atoms and photons
- Microfabricated ion trap structures

2. Introduction



Schrödinger Cat States
(Mesoscopic quantum superpositions)

Harmonic Oscillator

$|\alpha\rangle$: coherent state (localized quantum state of HO)

$|\alpha|^2$: mean number of oscillator quanta

Cat ← $|\alpha_1\rangle + |\alpha_2\rangle$ with size $\Delta\alpha = |\alpha_1 - \alpha_2|$

$\Delta\alpha \gg 1$

Harmonic motion of massive particle (phonons)

Monroe, C., Meekhof, D. M., King, B. E. & Wineland, D. J.
A "Schrödinger cat" superposition state of an atom
Science 272, 1131–1136 (1996)

Single mode EM field (photons)

Haroche, S. Nobel lecture:
controlling photons in a box and exploring the quantum to classical boundary
Rev. Mod. Phys. 85, 1083–1102 (2013)

1996

RESEARCH ARTICLES

A "Schrödinger Cat" Superposition State of an Atom

C. Monroe,* D. M. Meekhof, B. E. King, D. J. Wineland

A "Schrödinger cat"–like state of matter was generated at the single at
$^9Be^+$ ion was laser-cooled to the zero-point energy and then preparec
of spatially separated coherent harmonic oscillator states. This sta
application of a sequence of laser pulses, which entangles intern
external (motional) states of the ion. The Schrödinger cat superposit
detection of the quantum mechanical interference between the locali
This mesoscopic
sical and quantu
quantum decohe

$^9Be^+$ i

$$T_2 \cong 170\mu s$$

PRL 98, 063603 (2007) PHYSICAL REVIEW LETTERS week ending 9 FEBRUARY 2007

Long-Lived Mesoscopic Entanglement outside the Lamb-Dicke Regime

ch, D. J. Szwer, N. R. Thomas,
Steane
oad, Oxford OX1 3PU, United Kingdom
y 2007)

Ca$^+$ ion in a linear ion trap. We
e Lamb-Dicke regime, where the
become squeezed. We directly ob-
e squeezing. The mesoscopic en-
l mean phonon excitation $\bar{n} = 16$.

.50.Dv, 03.65.Ta, 03.65.Ud, 03.67.Mn

Multi-component

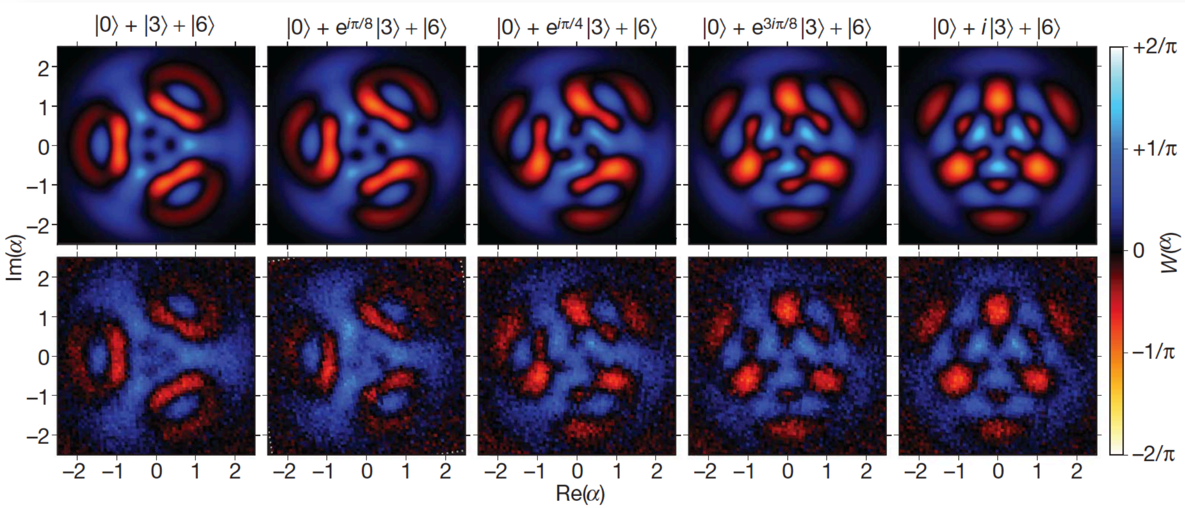
motional states ≪ 1
motional quantum number by

nature Vol 459|28 May 2009|doi:10.1038/nature08005

LETTERS

Synthesizing arbitrary quantum states in a superconducting resonator

Max Hofheinz[1], H. Wang[1], M. Ansmann[1], Radoslaw C. Bialczak[1], Erik Lucero[1], M. Neeley[1], A. D. O'Connell[1], D. Sank[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]



3. The Experiment

Quantum control of qubits and atomic motion using ultrafast laser pulses (2014)

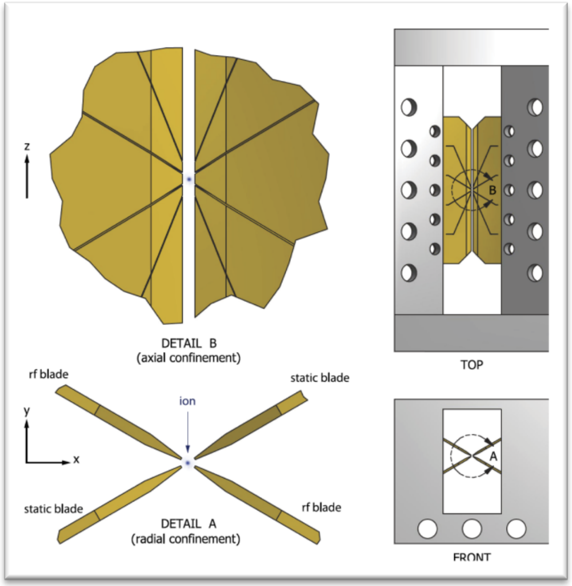
Sensing atomic motion from the zero point to room temperature with ultrafast atom interferometry (2015)

Active stabilization of ion trap radiofrequency potentials (2016)

Experiment general procedure (trap an ion)

Trapping $^{171}Yb^{+}$ ion

Rev. Sci. Instrum. 87, 053110 (2016)



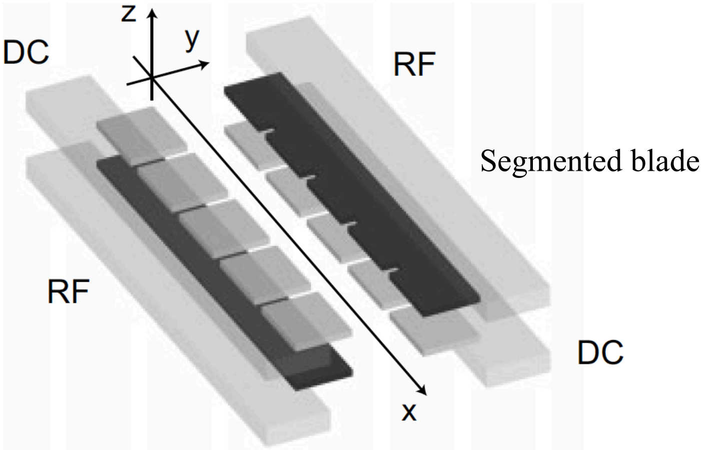
Paul Trap

$(\omega_x \equiv \omega, \omega_y, \omega_z)/2\pi = (1.0, 0.8, 0.6)\mathrm{MHz}$

Initialize the atom's motion

- Doppler laser cooling ➔ $\bar{n}\sim 10$
- Sideband cooling ➔ $\bar{n}\sim 0.15$

$*\ \bar{n}$: average vibrational occupation number

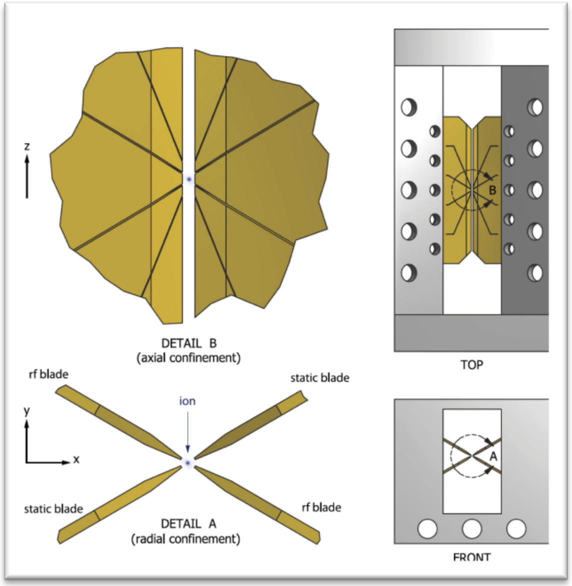


Fortschr. Phys. 54, No. 8 – 10 (2006)

Experiment general procedure (initialization)

Trapping $^{171}Yb^+$ ion

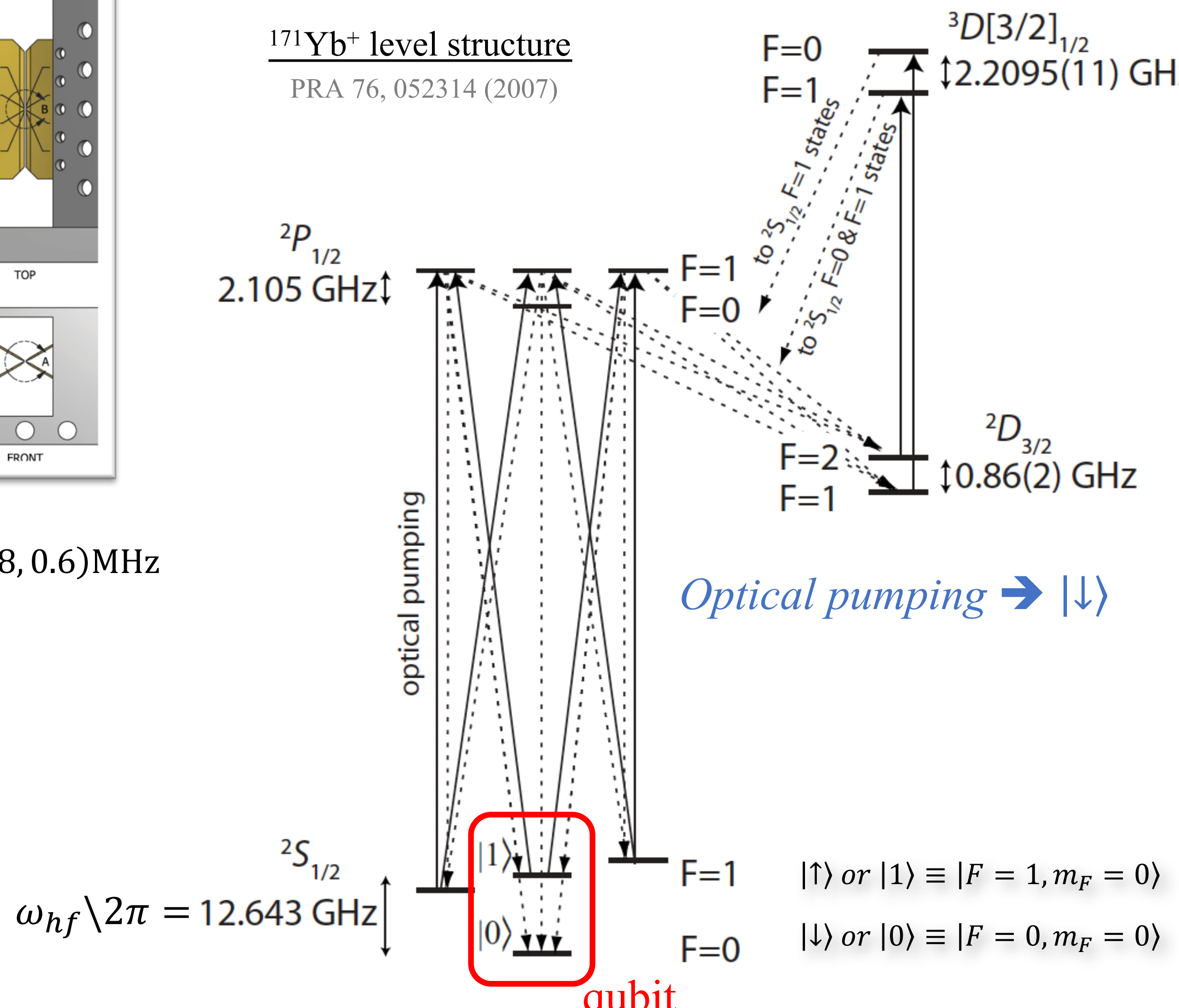
Rev. Sci. Instrum. 87, 053110 (2016)



Paul Trap

$$(\omega_x \equiv \omega, \omega_y, \omega_z)/2\pi = (1.0, 0.8, 0.6)\text{MHz}$$

Qubit State Initialization



Optical pumping ➔ $|\downarrow\rangle$

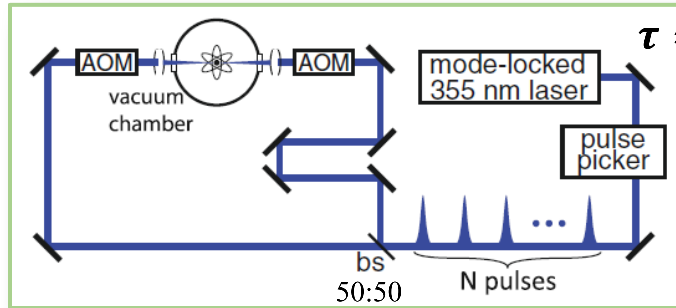
$|\uparrow\rangle$ *or* $|1\rangle \equiv |F = 1, m_F = 0\rangle$

$|\downarrow\rangle$ *or* $|0\rangle \equiv |F = 0, m_F = 0\rangle$

Experiment general procedure

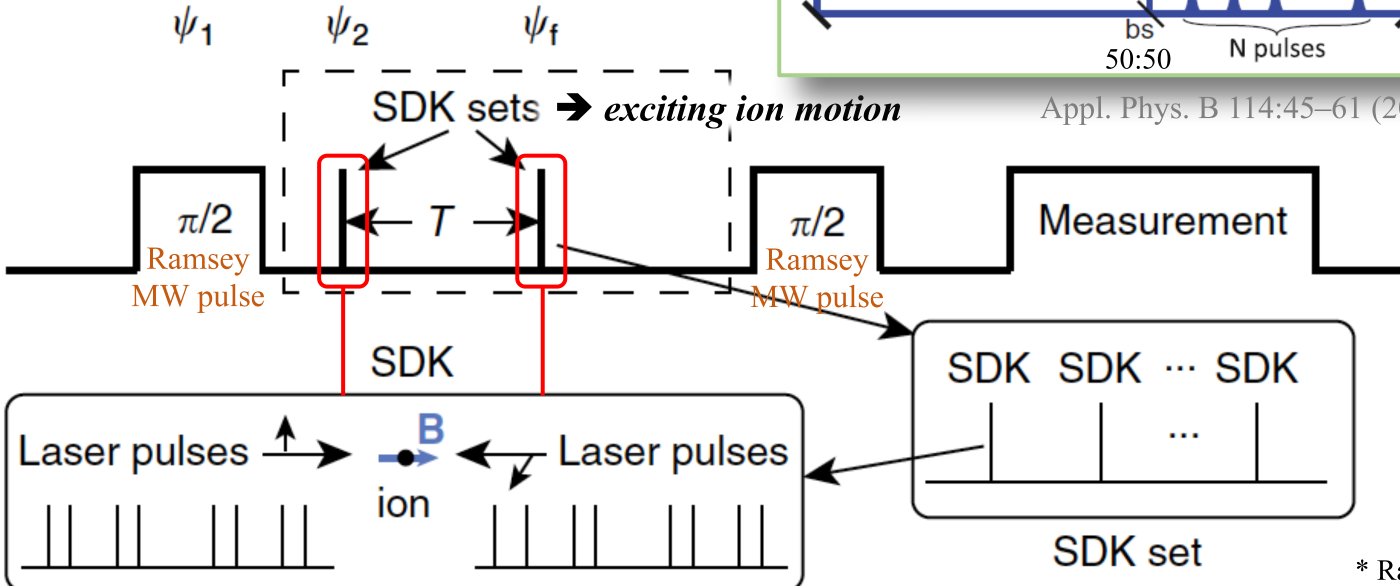
Frequency tripled mode-locked Nd: YVO_4 laser
f_{rep} = 81.4MHz with drift 10Hz over a min.

$\tau \approx$ **10 ps**



Appl. Phys. B 114:45–61 (2014)

$$|\psi_1\rangle = (|\uparrow\rangle + |\downarrow\rangle)|n = 0\rangle$$

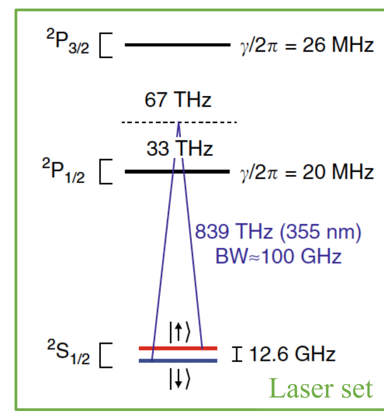


Arrives an atom simultaneously (±70fs)

Reversing the process

Creating a cat state

* Raman Process

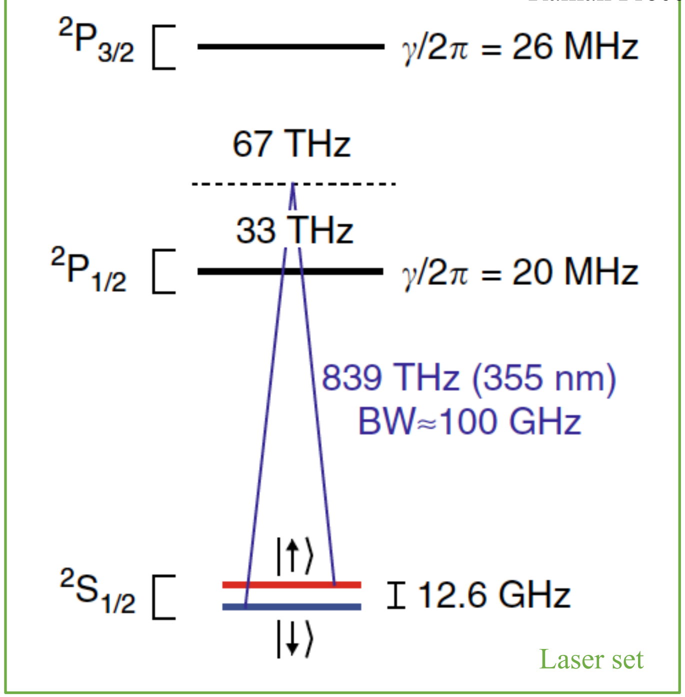


Why mode-locked pulse laser?

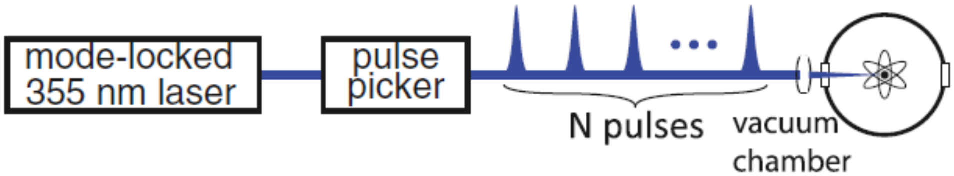
$$\omega_{hf} \ll \frac{1}{\tau} \ll \Delta$$

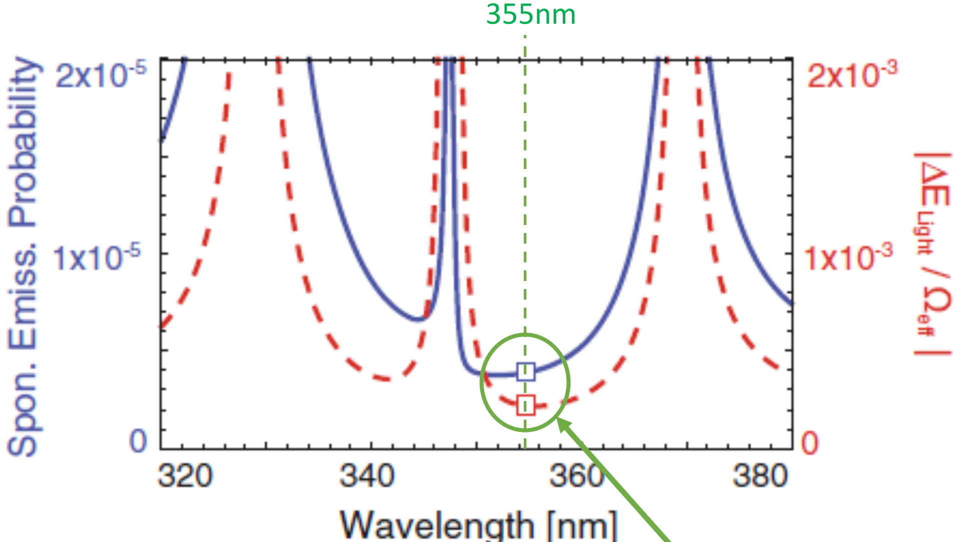
Experiment general procedure (coherence issue)

* Raman Process
* Raman Process



Appl. Phys. B 114:45–61 (2014)





Optimal point for minimal laser-induced decoherence

Laser-induced decoherence

- Spontaneous emission from excited state (Γ_{spon})
- Differential energy shift of qubit states $\left(\Delta E_{stark} \propto \frac{I}{\Delta^2}, \text{with consideration of } \Omega_{eff} \propto I/\Delta\right)$

Entanglement of spin and motion

The polarization gradient creates a standing wave in the Rabi frequency, resulting in the Hamiltonian

The Hamiltonian for ion-pulse interaction

$$H = \omega_t a^\dagger a + \frac{\omega_{hf}}{2}\sigma_z + \frac{\Omega(t)}{2}\sin\left[\eta\left(a^\dagger + a\right) + \phi(t)\right]\sigma_x$$

$H_{int} = -\frac{\theta}{2}\delta(t - t_0)\sin[\Delta k\hat{x} + \phi(t_0)]\hat{\sigma}_x$ for instantaneous pulse approx. ($\tau \approx 0$)

$\phi(t) = \omega_A t + \phi_0$: time dependence of phase diff. (by AOM freq. shift)

With N-pulse train

$$O_N = U_{t_N} \dots U_{FE}(t_3 - t_2)U_{t_2}U_{FE}(t_2)U_{t_1}$$

The evolution operator

$$U_{t_0} = \sum_{n=-\infty}^{\infty} e^{in\phi(t_0)} J_n(\theta) D[in\eta]\hat{\sigma}_x^n$$

The free-evolution operator

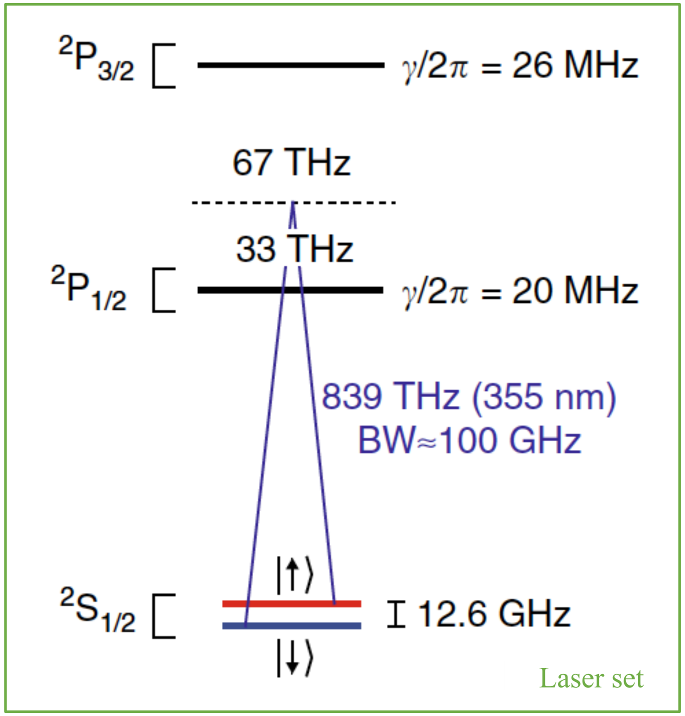
$$U_{FE}(T) = e^{-i\omega_{trap}T a^\dagger a} e^{-i\omega_{hf}T\hat{\sigma}_z/2}$$

$U_{t_k} \approx 1 + \frac{i\Theta}{2N}\left(e^{i\phi(t_k)}D[i\eta] + e^{-i\phi(t_k)}D[-i\eta]\right)\hat{\sigma}_x$ For large N

Kapitza-Dirac scattering

Experiment general procedure

* Stimulated Raman Process



Single pulse Hamiltonian

$$\hat{H}(t) = \Omega(t)\sin\left[2kx_0\left(\hat{a}^\dagger + \hat{a}\right) + \phi\right]\hat{\sigma}_x + \frac{\omega_{hf}}{2}\hat{\sigma}_z$$

$\hat{\sigma}_{x,z}$: Pauli spin operators

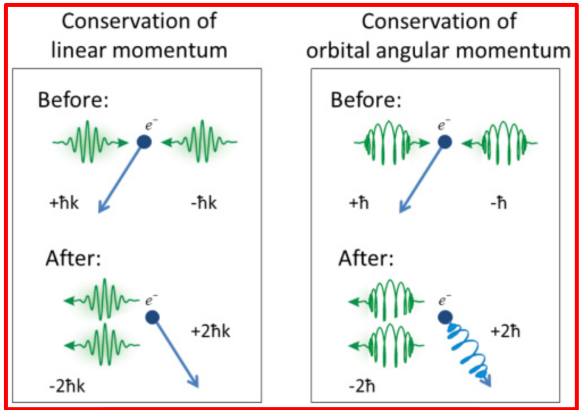
ϕ : relative phase btw the counter-propagating light fields

$\hat{a}^\dagger$ & $\hat{a}$: raising & lowering operators of the ion motion along x

$$\Omega(t) = \frac{\Theta}{2\pi}\operatorname{sech}\left(\frac{\pi t}{\tau}\right) : \text{Rabi freq.}$$

where the pulse area is Θ

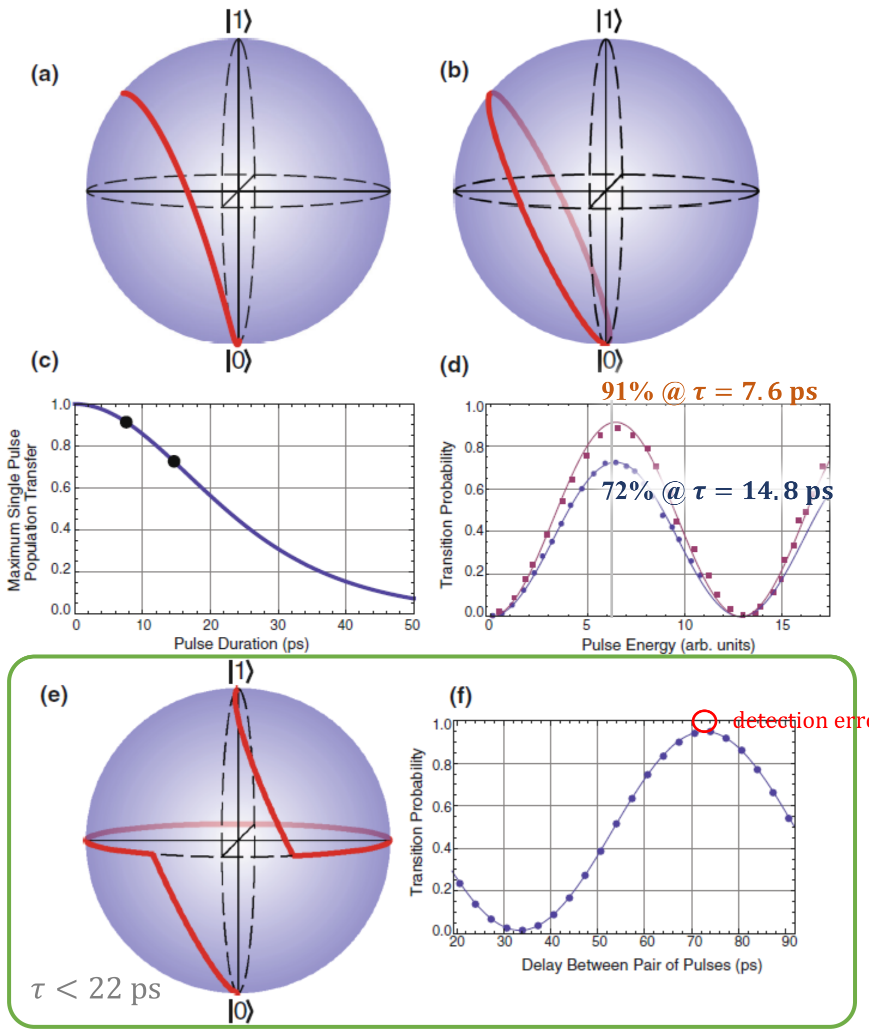
Scattering of the Rubidium-87 BEC matter wave on the standing light field of a 790 nm linearly polarized lattice



Kapitza-Dirac scattering

Spin control with pulses (strong pulses)

Appl. Phys. B 114:45–61 (2014)



single pulse w/ $\sigma_\pm$ polarization

➔ $I(t) = I_0 \operatorname{sech}\left(\frac{\pi t}{\tau}\right)$ having $FWHM = 0.838\tau$

➔ $\Omega(t) = \frac{\theta}{\tau} \operatorname{sech}\left(\frac{\pi t}{\tau}\right)$, θ is pulse area

$$\theta = \frac{I_0 \tau \gamma^2}{2 I_{sat} \Delta}$$

Transition probability

Instant pulse duration ➔ 1

$$P_{0\to1} = \sin^2\left(\frac{\theta}{2}\right) \cancel{\operatorname{sech}^2\left(\frac{\omega_{hf}\tau}{2}\right)}$$

∴ single pulse cannot fully flip the spin of the qubit

Using **two pulses**

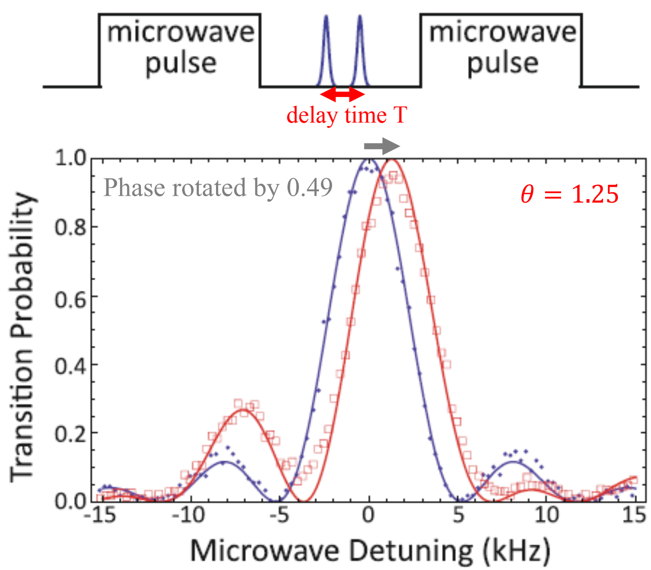
➔ **Rapid qubit rotation & phase rotation** (power of pulse)

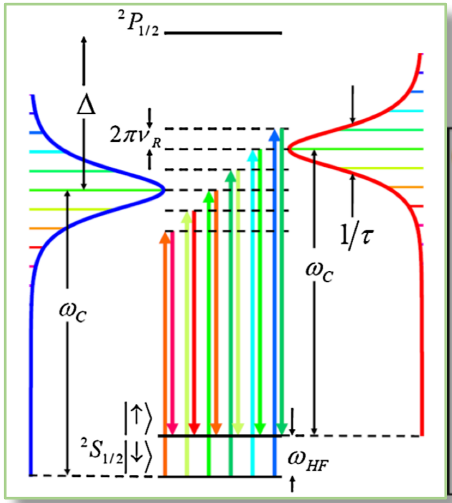
** theoretical researches about this had done by **Rosen and Zener**

PRA **40**, 502 (1932)

Spin control with pulses (weak pulses, $\theta \ll 1$)

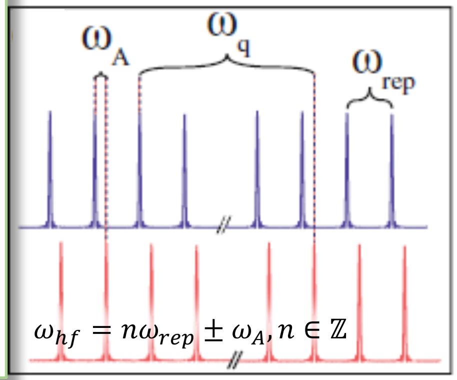
Ramsey interference





$\Omega(t) = \Omega_0 \operatorname{sech}\left(\frac{\pi t}{\tau}\right), \Omega_0 = g_0^2/2\Delta$

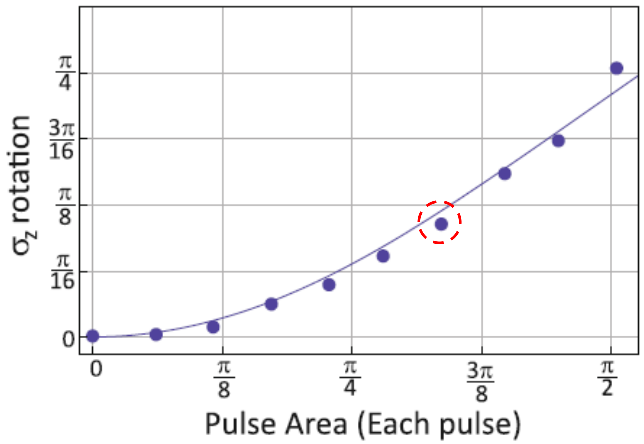
Double comb

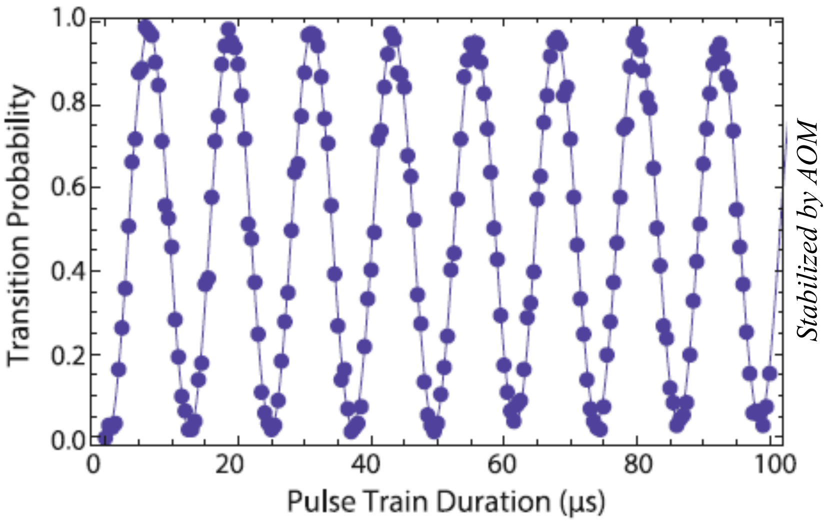


ω_{rep} drifts in the range of $\sim 10^{-7}$ over min.

➔ Active stabilizing (PZT mirror)

* frequency domain





Appl. Phys. B 114:45–61 (2014)

Entanglement of spin and motion (spin dependent kick – SDK)

Fast regime, $\omega_{trap} t_N \ll 1$ ($\omega \approx 0$ during the pulse train ➔ the ion is eff. frozen in place)

The interaction picture evolution operator

$$V_{t_k} = 1 + \frac{i\Theta}{2N}\left(e^{i\phi_0} D[i\eta]\left(e^{iq_+ t_k}\hat{\sigma}_+ + e^{iq_- t_k}\hat{\sigma}_-\right) + H.c.\right)$$

$$q_\pm = \omega_{hf} \pm \omega_A$$

At $q_+ t_k / 2\pi \in \mathbb{Z}$ for all pulses, while $q_- t_k / 2\pi \notin \mathbb{Z}$ (or $\omega_{hf} \neq \frac{n\omega_{rep}}{2}, n \in \mathbb{Z}$)

$$V_{t_k} = 1 + \frac{i\Theta}{2N}\left(e^{i\phi_0} D[i\eta]\hat{\sigma}_+ + e^{-i\phi_0} D[-i\eta]\hat{\sigma}_-\right)$$

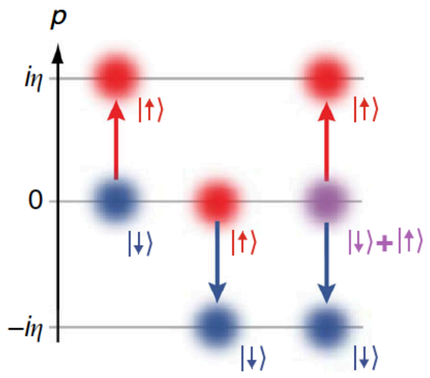
For total pulse Θ and $N \gg 1$

$$\tilde{O} = e^{i\phi_0}\hat{\sigma}_+ \hat{D}[i\eta] + e^{-i\phi_0}\hat{\sigma}_- \hat{D}[-i\eta]$$

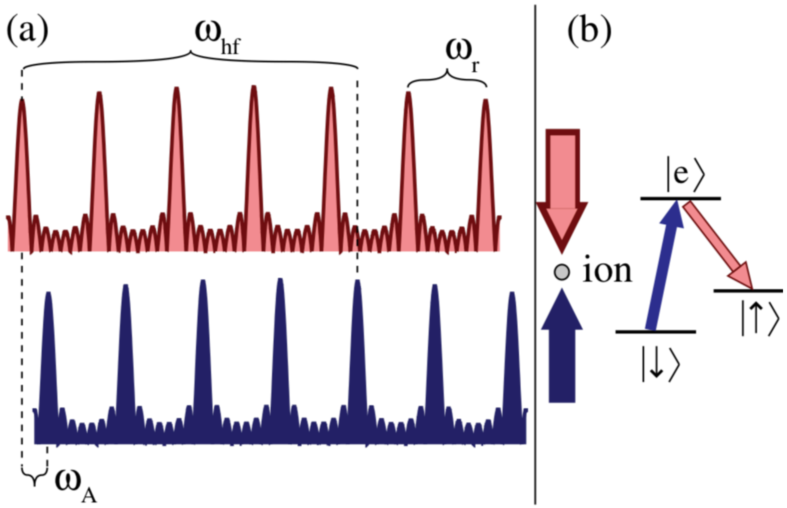
THIS IS THE SDK OPERATOR!!

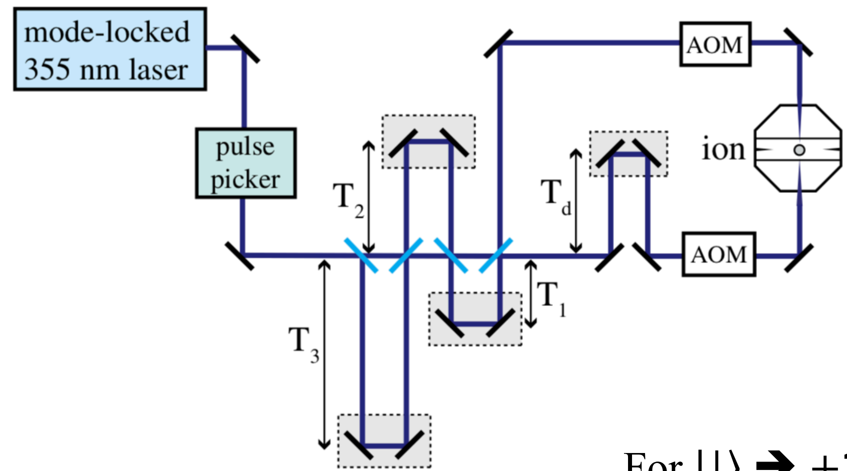
For $|\downarrow\rangle$ ➔ *kick up*

For $|\uparrow\rangle$ ➔ *kick down*



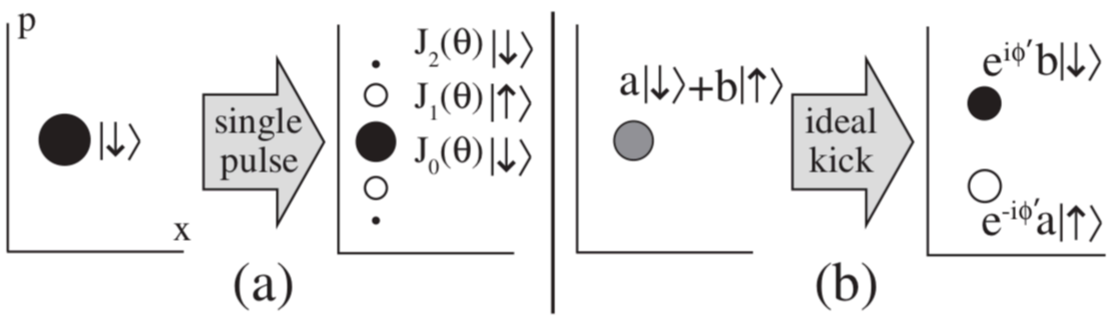
About State-Dependent Kick (SDK) – "spin-motion coupling"

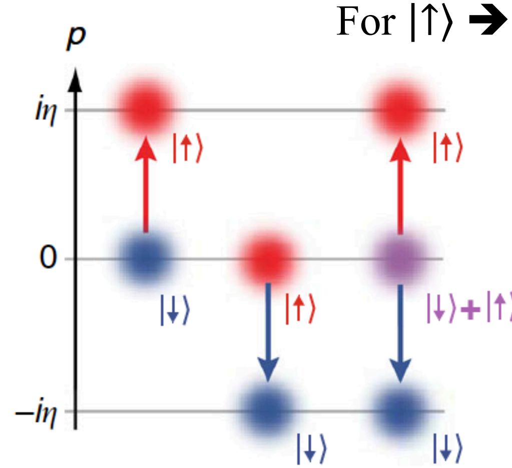




For $|\downarrow\rangle$ ➔ $+2\hbar k$

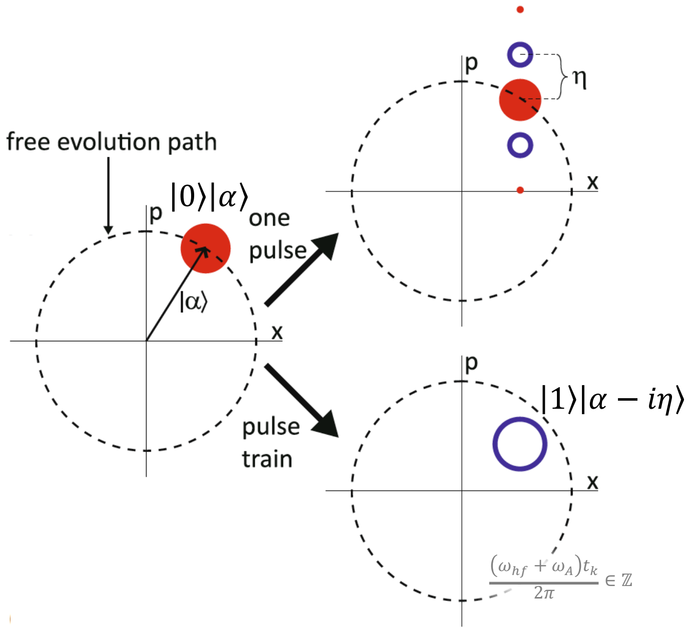
For $|\uparrow\rangle$ ➔ $-2\hbar k$

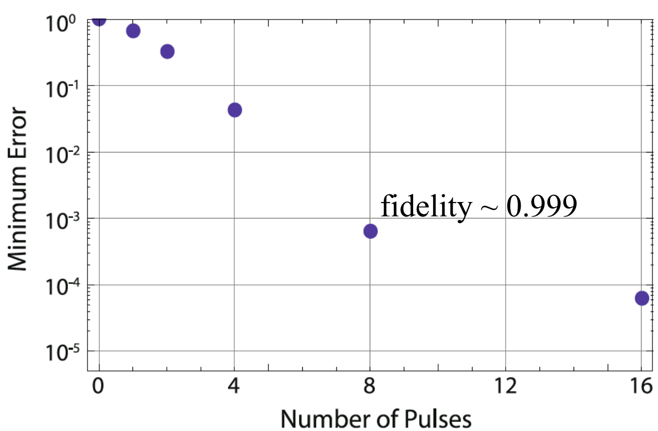


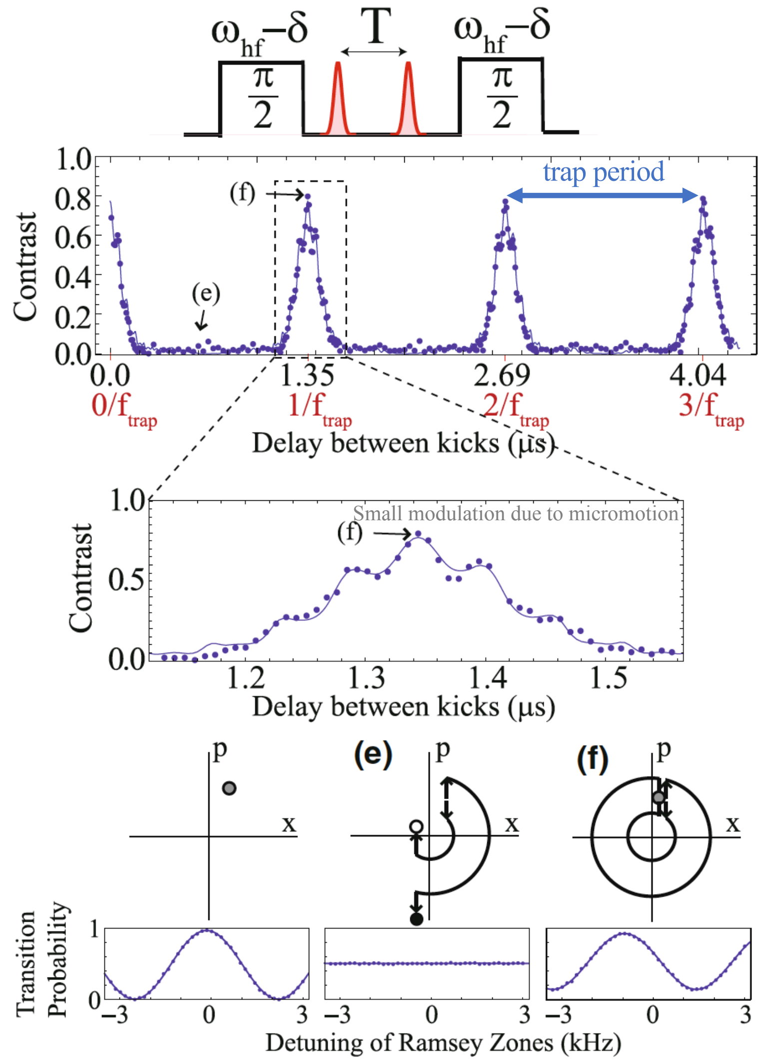


Spin flip !

About State-Dependent Kick (SDK) – “spin-motion coupling”

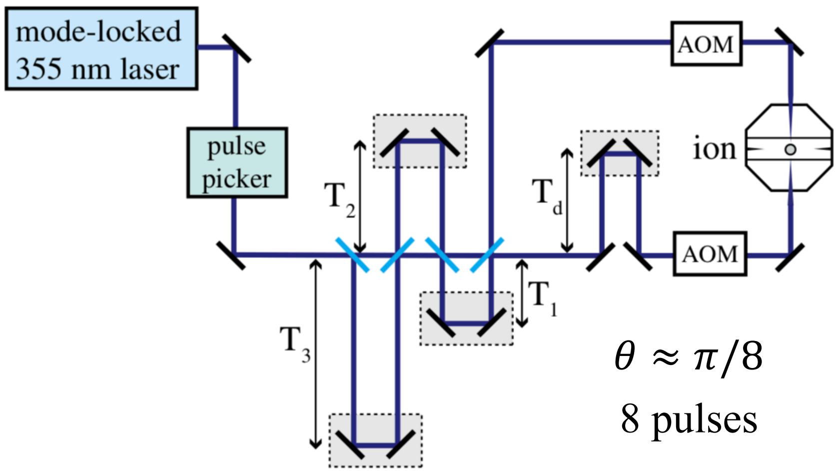






Entanglement of spin and motion

PRL 110, 203001 (2013)



$\theta \approx \pi/8$

8 pulses

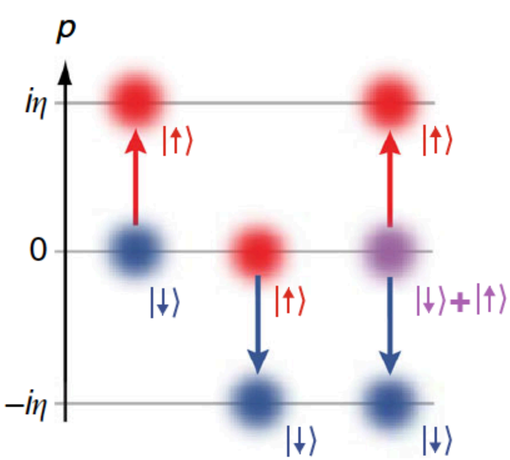
$$\hat{U}_{SDK} = e^{i\phi_1}\hat{\sigma}_+\hat{D}[i\eta] + e^{-i\phi_2}\hat{\sigma}_-\hat{D}[-i\eta]$$

$\hat{\sigma}_\pm$: Qubit raising & lowering operator

$\eta = 2kx_0(= 0.2)$: Lamb-Dicke parameter

$\hat{D}$: phase-space displacement operator

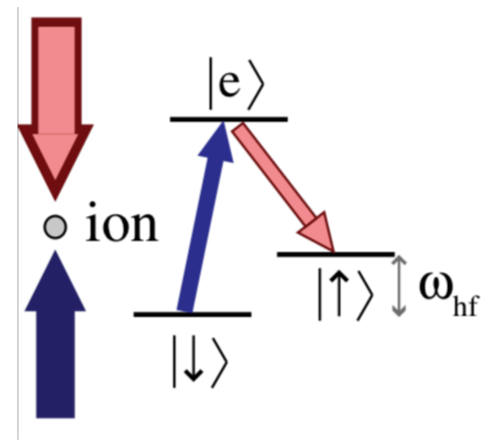
ϕ_λ : optical phase



For $|\downarrow\rangle$ ➔ $+2\hbar k$

For $|\uparrow\rangle$ ➔ $-2\hbar k$

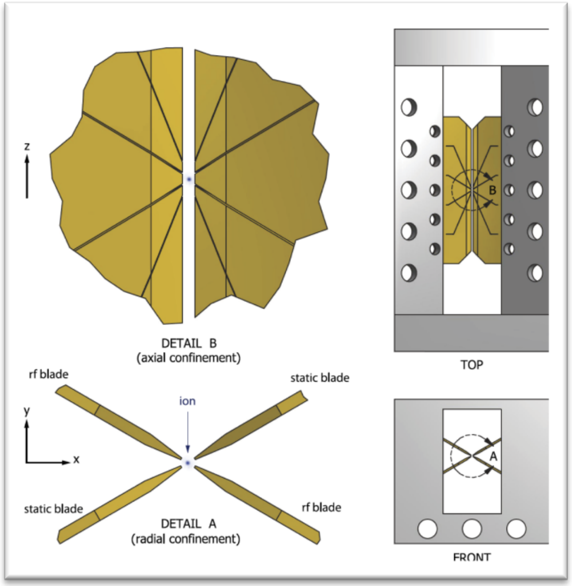
Spin flip !



Experiment general procedure (detection)

Trapping $^{171}Yb^{+}$ ion

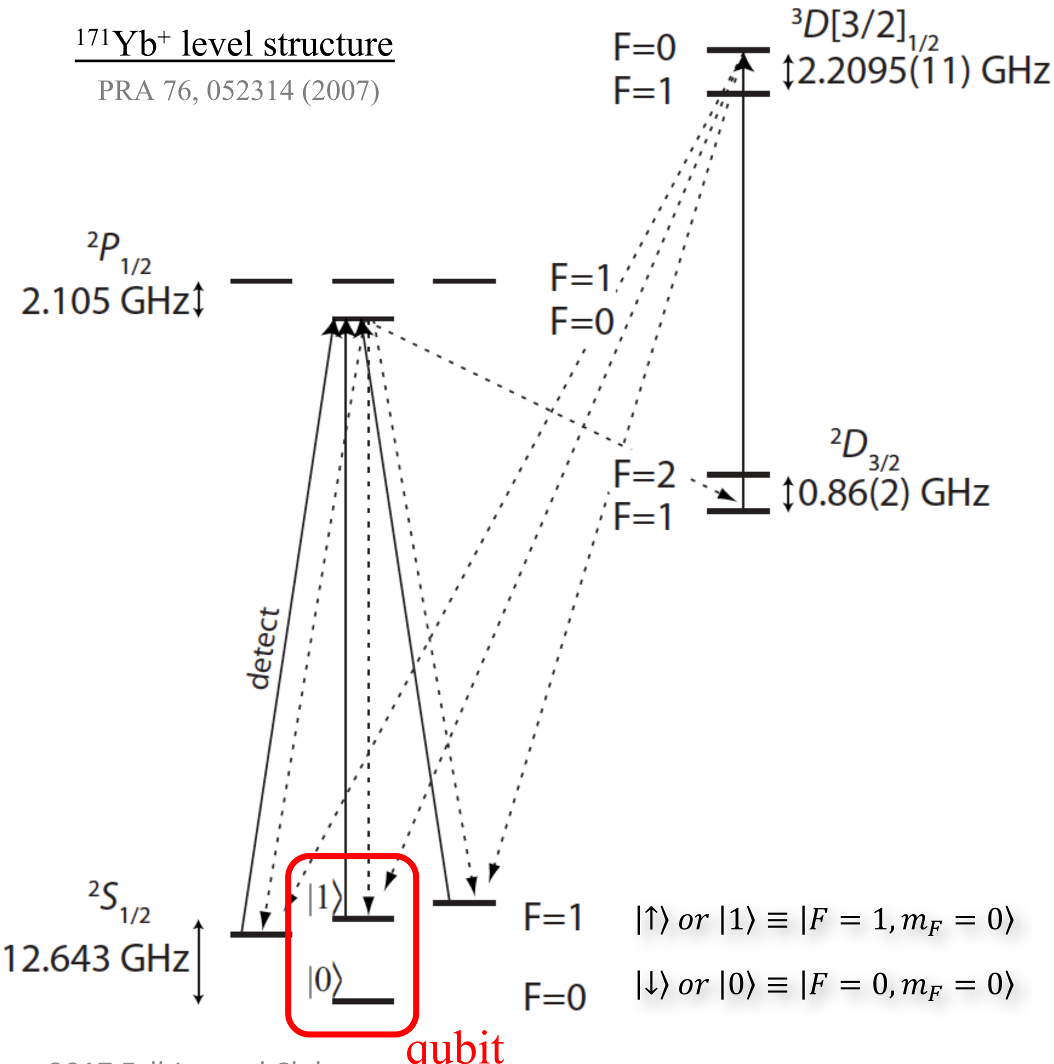
Rev. Sci. Instrum. 87, 053110 (2016)



Paul Trap

$(\omega_x \equiv \omega, \omega_y, \omega_z)/2\pi = (1.0, 0.8, 0.6)\mathrm{MHz}$

Detection of Qubit State



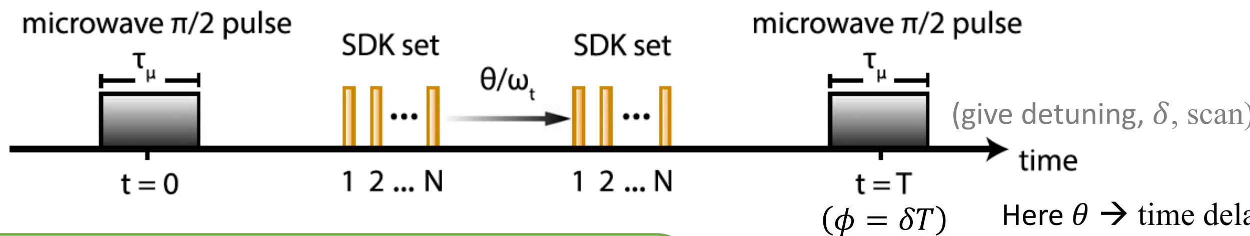
4. The Results

Large two-component cat states

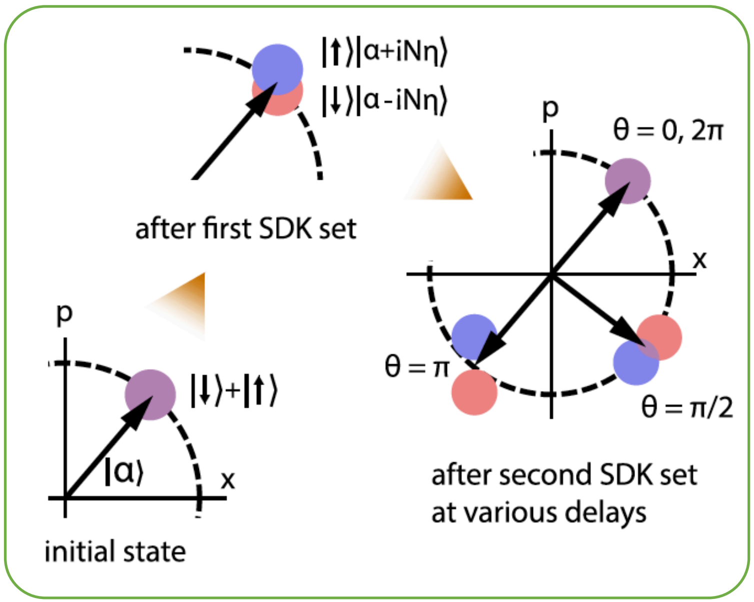
Multicomponent cat states

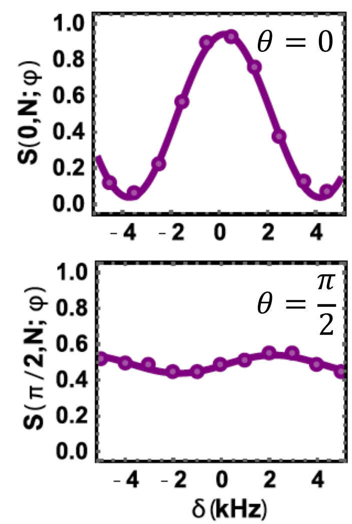
Ramsey contrast

$$S(\theta, N; \phi) = \langle \uparrow | \hat{\rho} | \uparrow \rangle = \frac{1}{2} + \frac{1}{2} \int P(\alpha) e^{-4(N\eta)^2(1-\cos(\theta))} \cos(4\gamma - \phi) d^2\alpha$$



Here $\theta \rightarrow$ time delay btw SDK sets (ω_t is trap frequency, 1 MHz)



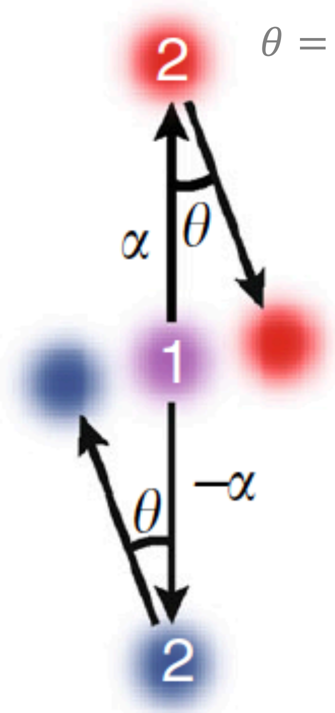


Expected Ramsey fringe pattern (w/ Glauber P function : $P_{therm}(\alpha) = \left(\frac{1}{\pi\bar{n}}\right) e^{-\frac{|\alpha|^2}{n}}$)

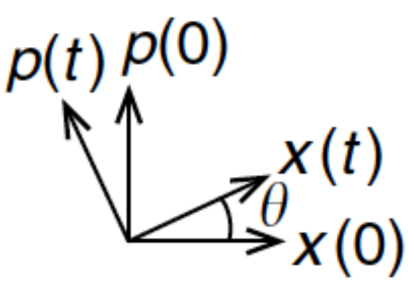
$$S(\theta, N; \phi) = \frac{1}{2} + \frac{1}{2} e^{-4(N\eta)^2(2\bar{n}+1)(1-\cos\theta)} \cos\phi$$

PRL 115, 213001 (2015)

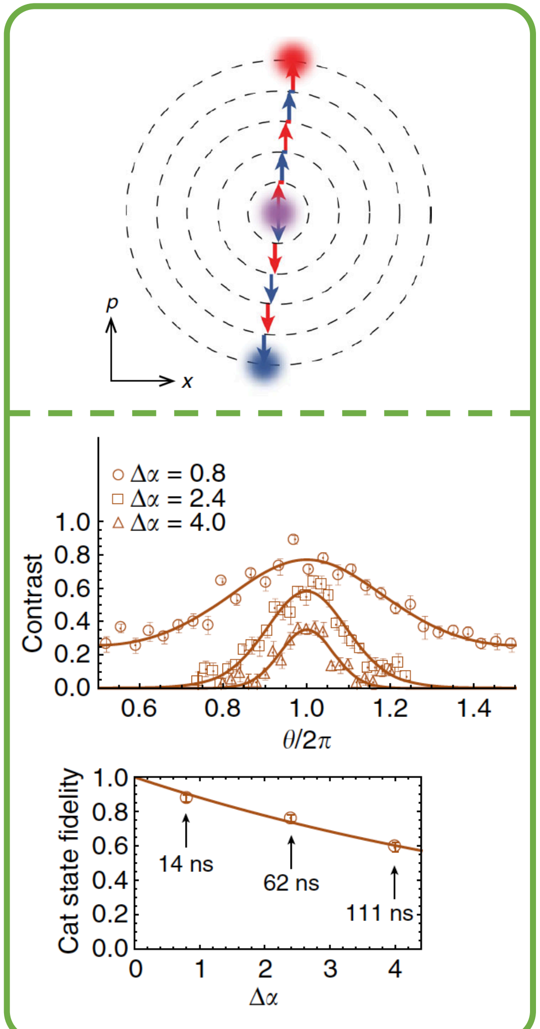
Large two-component Cat State

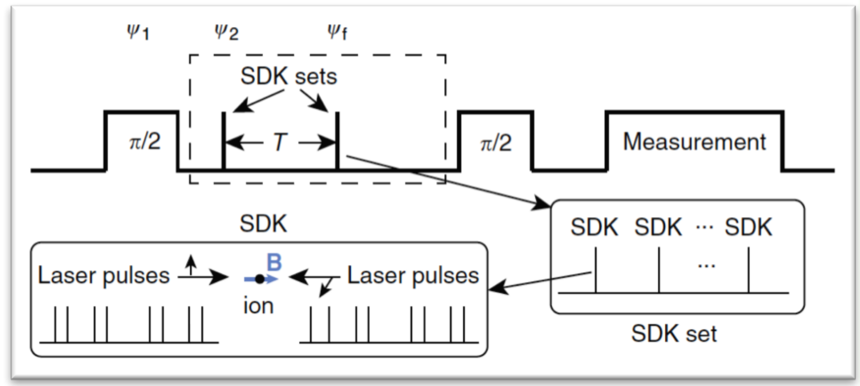


$\theta = \omega T$



Alternating propagation direction (Pockels Cell)





$$|\psi_1\rangle = (|\uparrow\rangle + |\downarrow\rangle)|n = 0\rangle$$

$$|\psi_2\rangle = |\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle$$

$$|\psi_f\rangle = |\uparrow\rangle\left|-\alpha e^{-i\theta} + \alpha\right\rangle + |\downarrow\rangle\left|\alpha e^{-i\theta} - \alpha\right\rangle$$

The interference contrast in the qubit population (up)

$$C(\theta) = C_0 e^{-4|\alpha|^2(1-cos\theta)}$$

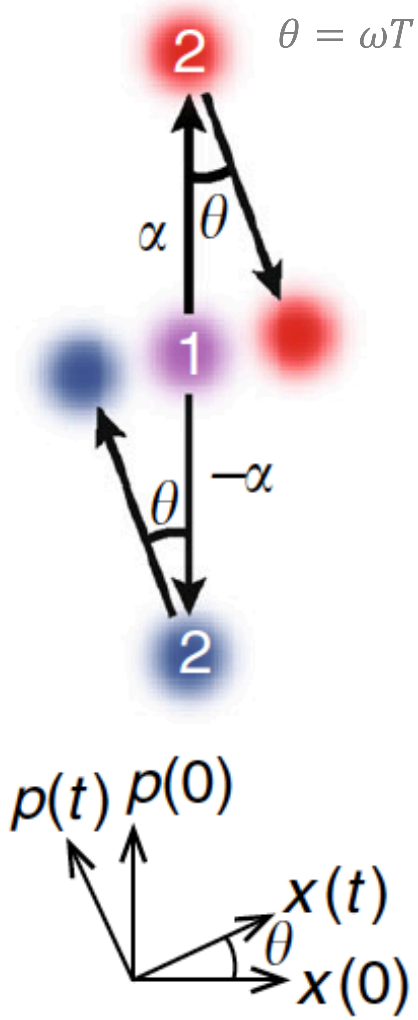
The fidelity, $\mathcal{F} = C_0^{1/2}$

$N \ll 2\pi f_{rep}/\omega$

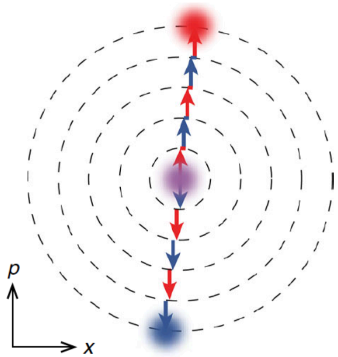
$$\frac{d(\Delta\alpha)}{dt} \approx 2\eta f_{rep}$$

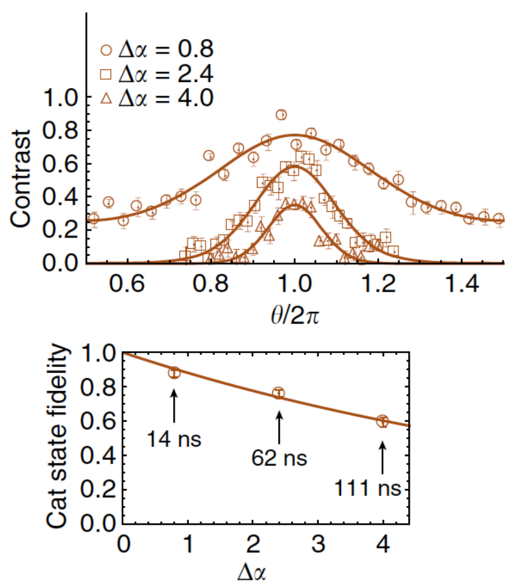
Large two-component Cat State

$\theta = \omega T$

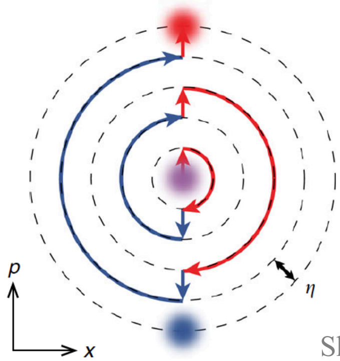


Alternating propagation direction (Pockels Cell)



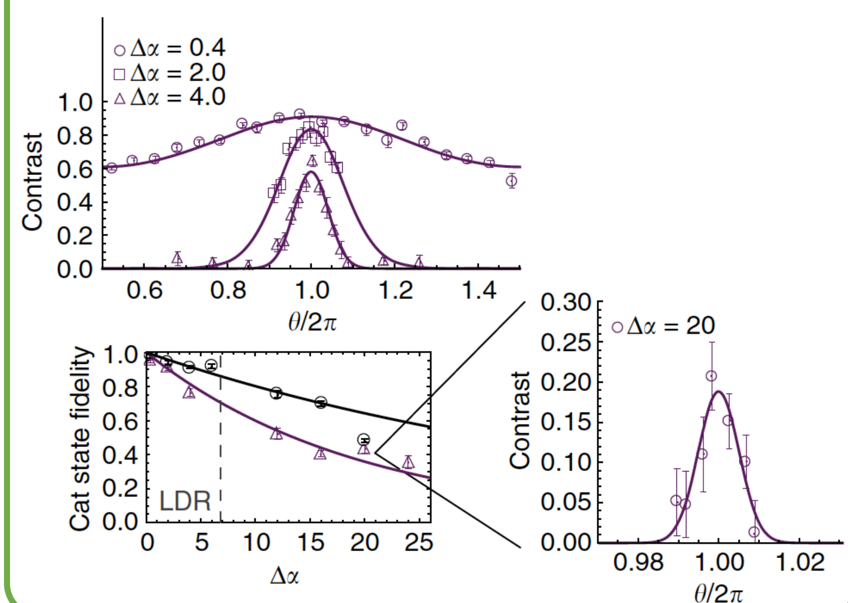


Adjust the pulse timing instead of changing beam path



Slower but higher fidelity

Showing the trace of one qubit state



$N \ll 2\pi f_{rep}/\omega$

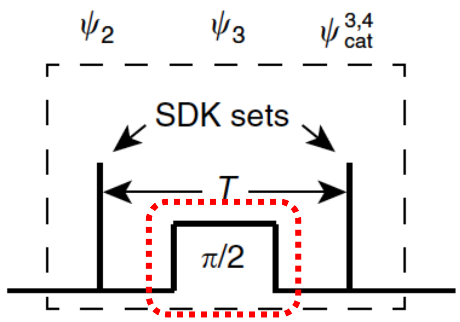
$$\frac{d(\Delta\alpha)}{dt} \approx 2\eta f_{rep}$$

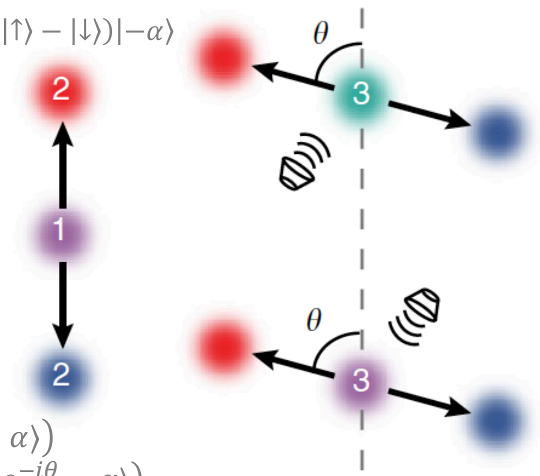
$$\frac{d|\alpha|}{dt} = \eta\omega/\pi$$

Multicomponent Cat State (three-, four-component states)

$$|\psi_2\rangle = |\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle$$

$$|\psi_3\rangle = (|\uparrow\rangle - |\downarrow\rangle)|\alpha\rangle + (|\uparrow\rangle - |\downarrow\rangle)|-\alpha\rangle$$

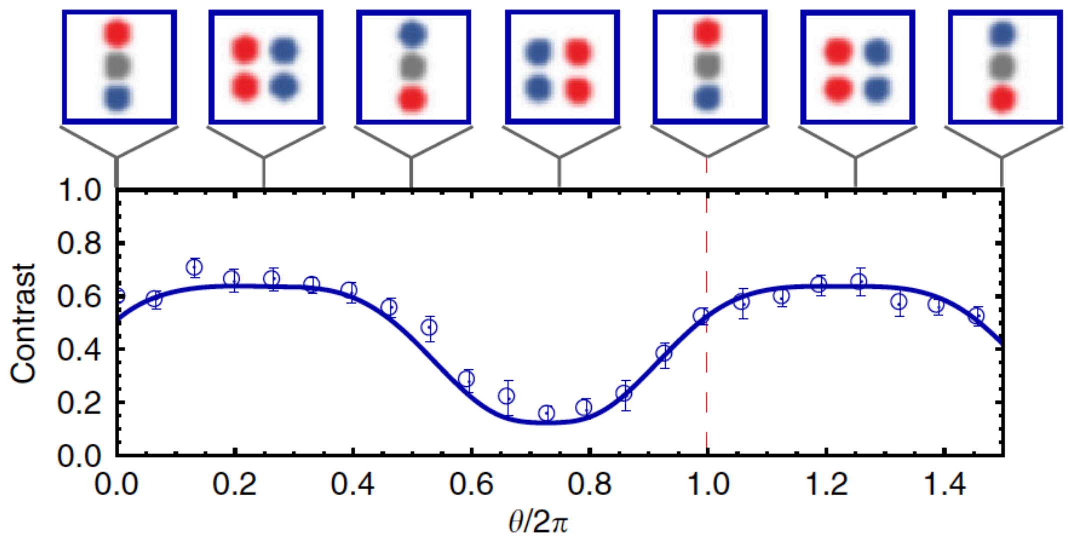




$$\left|\psi_{cat}^{3,4}\right\rangle = |\uparrow\rangle\left(e^{i\phi_1}\left|\alpha e^{-i\theta} + \alpha\right\rangle + e^{i\phi_2}\left|\alpha e^{-i\theta} - \alpha\right\rangle\right) + |\downarrow\rangle\left(e^{i\phi_3}\left|-\alpha e^{-i\theta} + \alpha\right\rangle + e^{i\phi_4}\left| - \alpha e^{-i\theta} - \alpha\right\rangle\right)$$

$|\alpha\rangle + |0\rangle + |-\alpha\rangle$

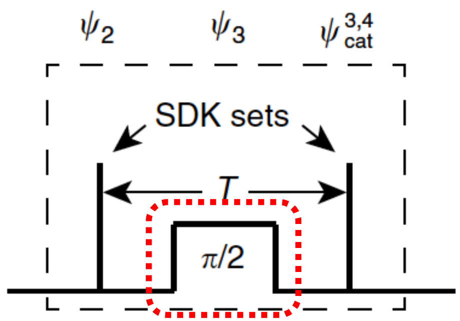
$|\alpha\rangle + |-\alpha\rangle + |i\alpha\rangle + |-i\alpha\rangle$

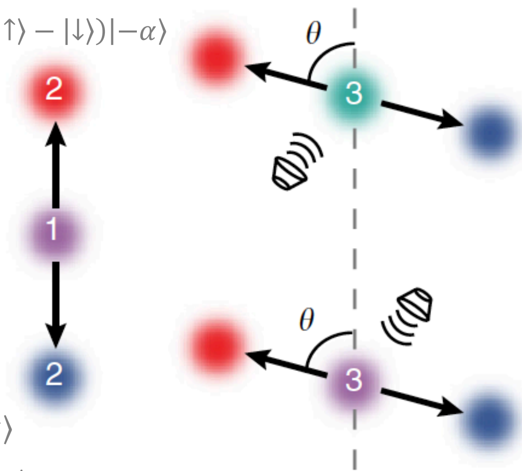


Multicomponent Cat State (back to two-component state)

$|\psi_2\rangle = |\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle$

$|\psi_3\rangle = (|\uparrow\rangle - |\downarrow\rangle)|\alpha\rangle + (|\uparrow\rangle - |\downarrow\rangle)|-\alpha\rangle$

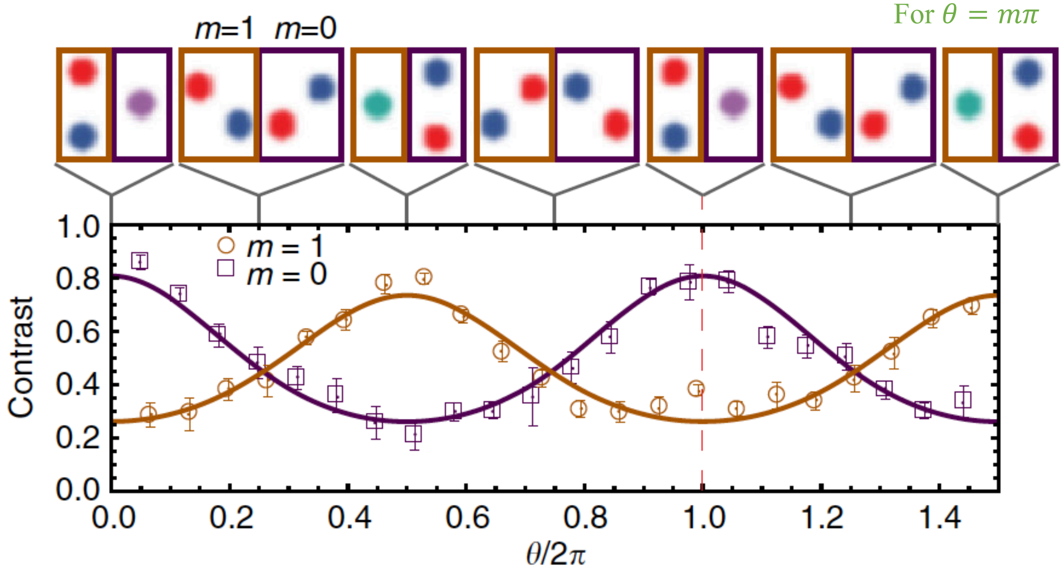




$\left|\psi_{cat,0}\right\rangle = |\uparrow\rangle\left|-\alpha e^{-i\theta} + \alpha\right\rangle + |\downarrow\rangle|\alpha e^{-i\theta} - \alpha\rangle$

$\left|\psi_{cat,\pi}\right\rangle = |\downarrow\rangle\left|\alpha e^{-i\theta} + \alpha\right\rangle + |\uparrow\rangle| - \alpha e^{-i\theta} - \alpha\rangle$

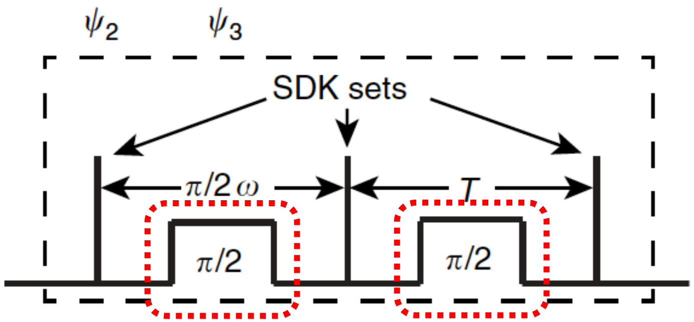
For $\theta = m\pi$

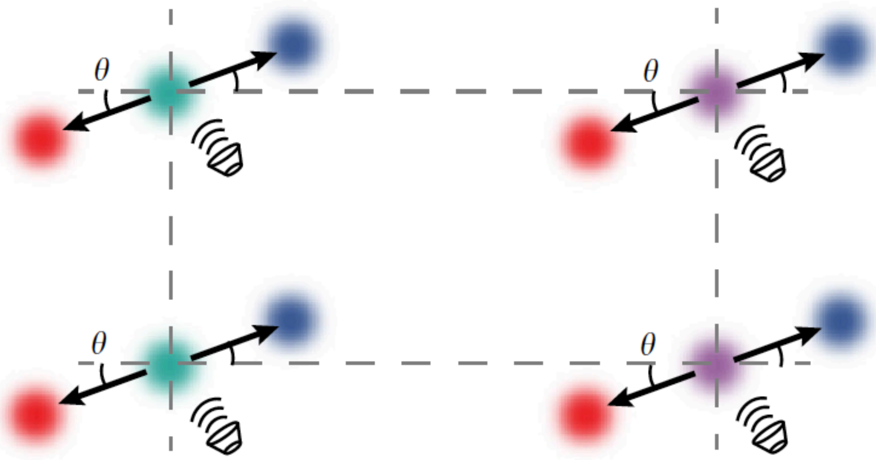


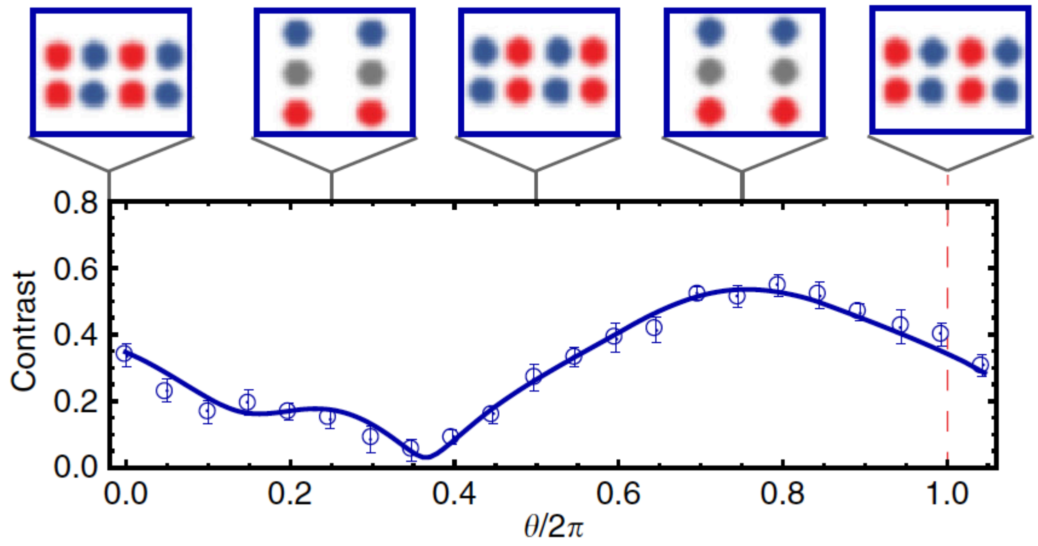
Multicomponent Cat State (six-, eight-component states)

$|\psi_2\rangle = |\uparrow\rangle|\alpha\rangle + |\downarrow\rangle|-\alpha\rangle$

$|\psi_3\rangle = (|\uparrow\rangle - |\downarrow\rangle)|\alpha\rangle + (|\downarrow\rangle + |\uparrow\rangle)|-\alpha\rangle$







5. Discussion

Limited by the size of the laser beam (not by Lamb-Dicke Regime)

Make more complicated multicomponent states → 2D, 3D

As lowing the trap frequency the larger separation could be achieved (20μm)

→ enhance the sensitivity of measuring rotation & E-field gradient(proximal)

→ high-resolution imaging techniques