Enhanced Quantum Interface with Collective Ion-Cavity Coupling

150316

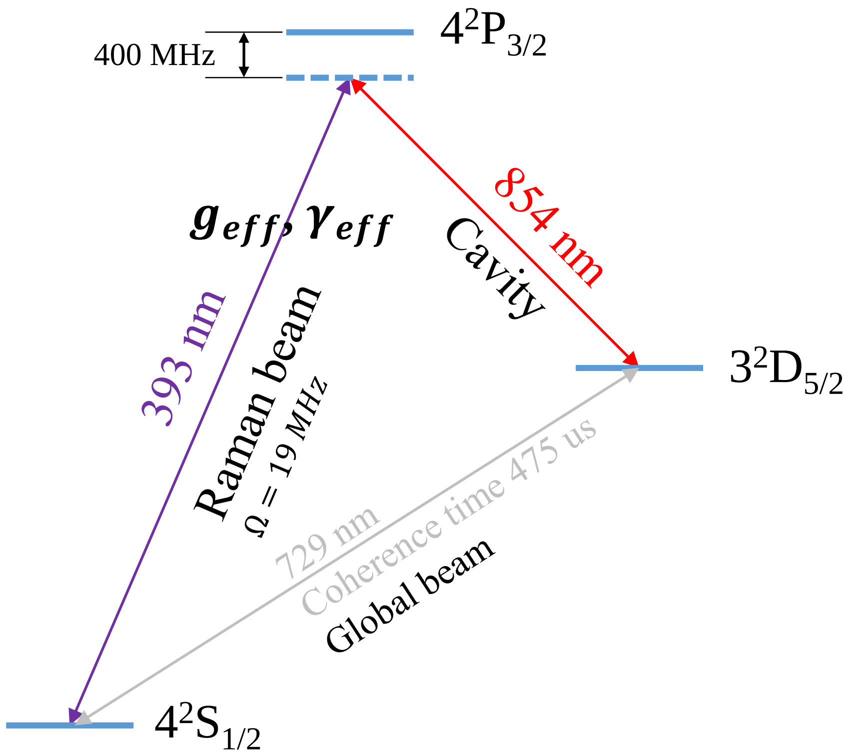
What they have done
in this paper

- Made entangled two-ion state

1. Observed enhanced/suppressed emission by maki ng $|\psi_{super}\rangle/|\psi_{sub}\rangle$

2. Transferred quantum information onto a single ph oton with enhanced emission probability

Level tree of Ca^+

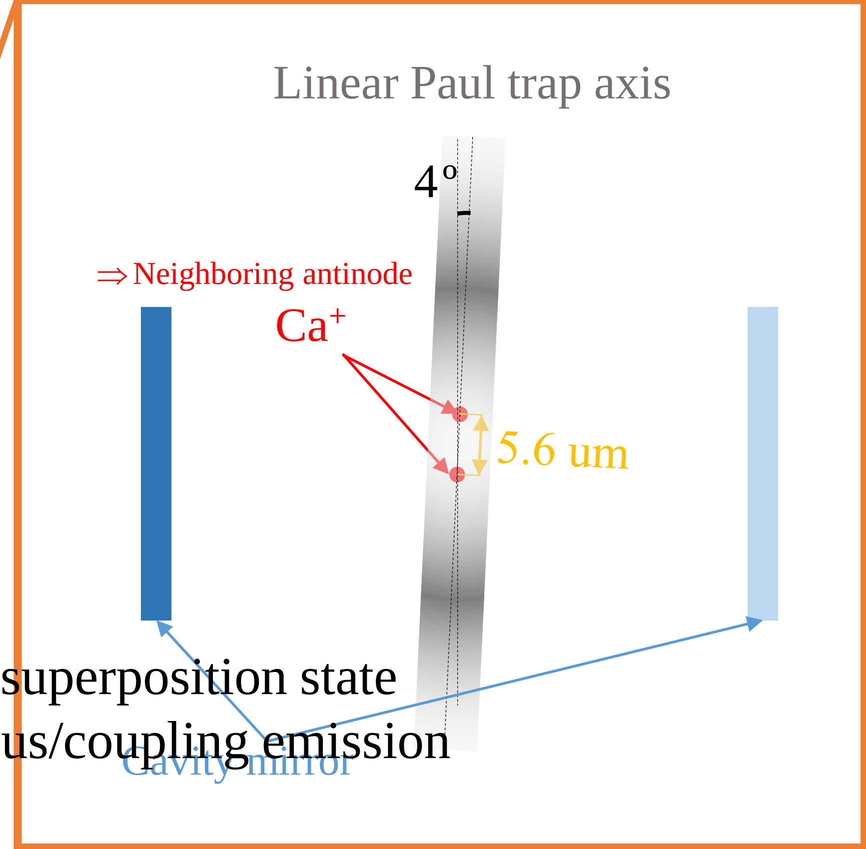


- $g_{\mathrm{eff}} = \frac{\zeta_{SD}\Omega g_{PD}}{2\Delta}$
- $\gamma_{\mathrm{eff}} = \gamma\left(\frac{\Omega}{2\Delta}\right)^2$
  - Ω = 19 MHz
  - Δ = 400 MHz
  - γ = 11.5 MHz
  - g_{PD} = 1 MHz

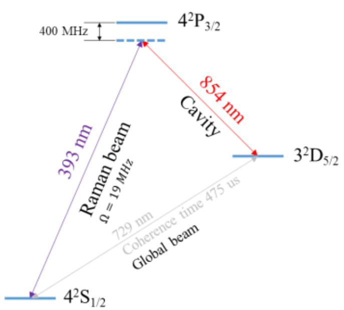
- $(g_{\mathrm{eff}}, \kappa, \gamma_{\mathrm{eff}}) = 2\pi \times (18{,}50, 6)kHz$

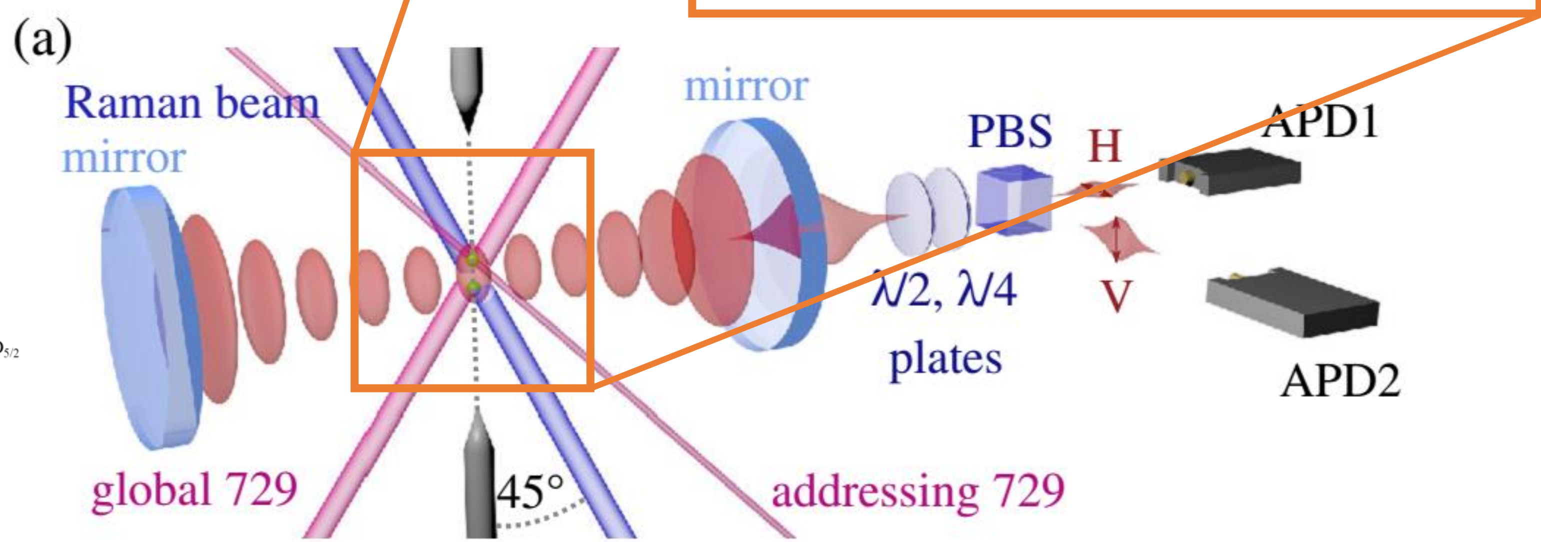
Schematic view

$$(g_{\text{eff}}, \kappa, \gamma_{\text{eff}}) = 2\pi \times (18, 50, 6)kHz$$



Global/Addressing 729 : Prepares superposition state
Raman beam : Controls spontaneous/coupling emission

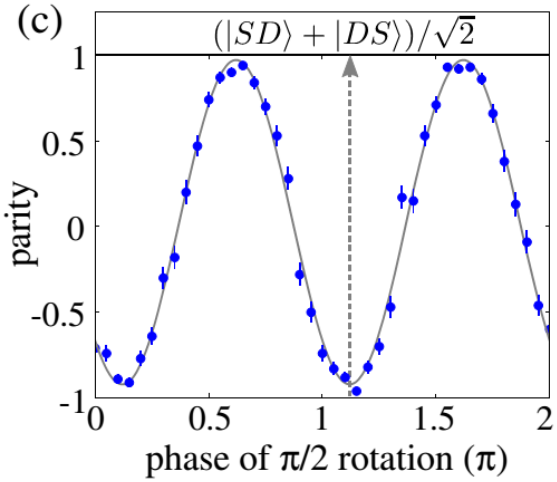




State preparation

- By using Mølmer-Sørensen gate operation,
- prepares $|\Phi\rangle = (|S\rangle|S\rangle + i|D\rangle|D\rangle)/\sqrt{2}$

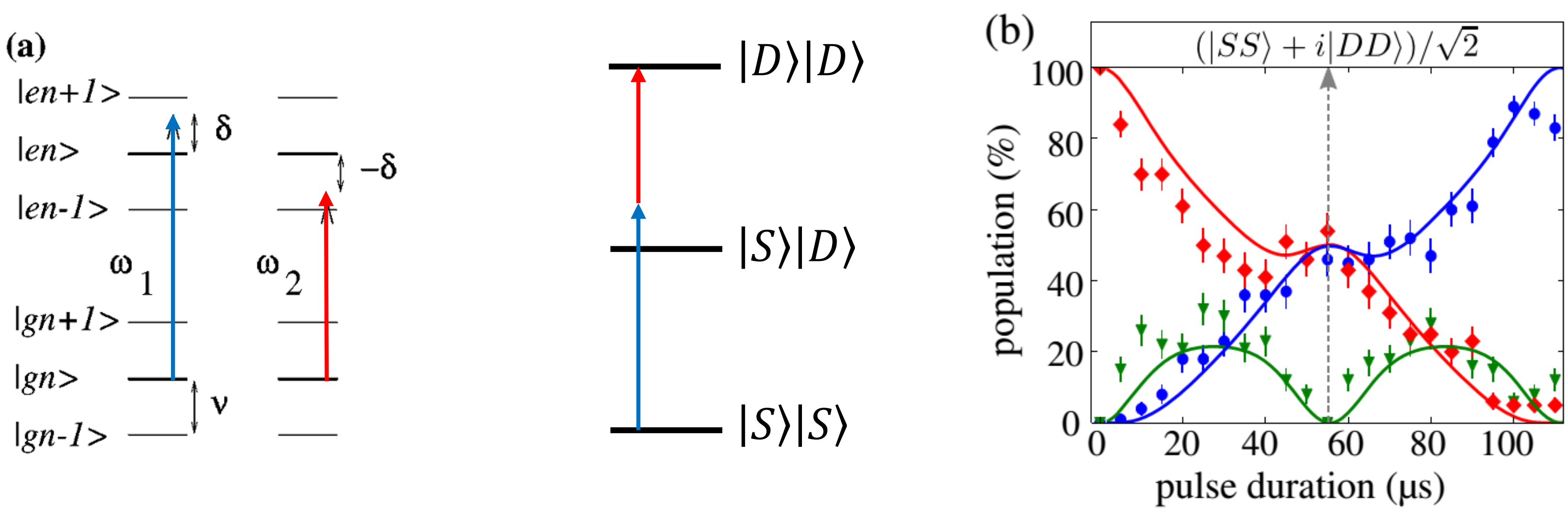
- "global" 729 nm laser rotates the state $\pi/2$.
- $|\Psi^+\rangle = (|S\rangle|D\rangle + |D\rangle|S\rangle)/\sqrt{2}$



- "addressing" 729 nm laser, coupled only one ion, contributes a phase ϕ to the entangled state. (By inducing ac-Stark shifts)
- $|\Psi(\phi)\rangle = \left(|S\rangle|D\rangle + e^{i\phi}|D\rangle|S\rangle\right)/\sqrt{2}$

Mølmer-Sørensen gate operation

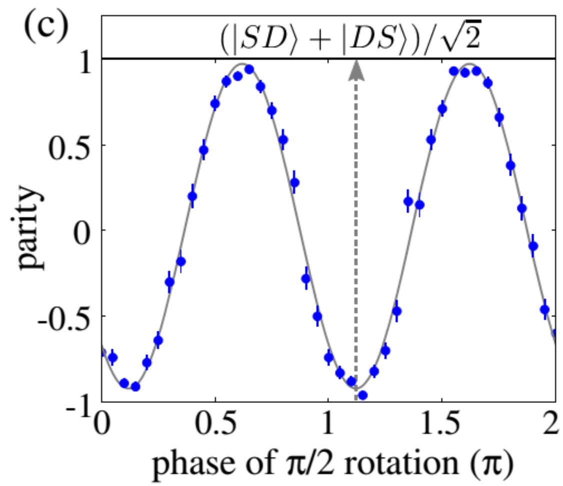
- The ions are initialized in $|S\rangle|S\rangle$.
- After a time T=1/δ=55us, with a detuning δ = 18.2 kHz, the two ions are prepared in the entangled state $|\Phi\rangle = (|S\rangle|S\rangle + i|D\rangle|D\rangle)/\sqrt{2}$.



Populations of the states $|S\rangle|S\rangle$ (red diamonds), $|D\rangle|D\rangle$ (blue circles), and $|S\rangle|D\rangle$ or $|D\rangle|S\rangle$ (green triangles) as a function of the Mølmer–Sørensen gate duration.

State preparation

- By using Mølmer-Sørensen gate operation,
- prepares $|\Phi\rangle = (|S\rangle|S\rangle + i|D\rangle|D\rangle)/\sqrt{2}$



- "global" 729 nm laser rotates the state $\pi/2$.
- $|\Psi^+\rangle = (|S\rangle|D\rangle + |D\rangle|S\rangle)/\sqrt{2}$

- "addressing" 729 nm laser, coupled only one ion, contributes a phase ϕ t o the entangled state. (By inducing ac-Stark shifts)
- $|\Psi(\phi)\rangle = \left(|S\rangle|D\rangle + e^{i\phi}|D\rangle|S\rangle\right)/\sqrt{2}$

$$|Super\rangle = (|S\rangle|D\rangle + |D\rangle|S\rangle)/\sqrt{2}$$

$$|Sub\rangle = (|S\rangle|D\rangle - |D\rangle|S\rangle)/\sqrt{2}$$

Sub/Superradiant states

- Interaction Hamiltonian

$$H_{\mathrm{int}} = g_{PD}\left(\sigma_{PD}^{(1)} - \sigma_{PD}^{(2)}\right)a^{\dagger} + \Omega\left(e^{i\phi_{R_1}}\sigma_{SP}^{(1)} + e^{i\phi_{R_2}}\sigma_{SP}^{(2)}\right) + \mathrm{h.c.},$$

Under Raman resonance condition

=> $$H_{\mathrm{int}} = \hbar g(\sigma_{-}^{(1)} + e^{i\zeta}\sigma_{-}^{(2)})a^{\dagger} + \mathrm{H.c.},$$

Where $\zeta = \phi_{R1} - \phi_{R2}$

$$|\Psi_{super}\rangle = |\Psi(\phi = -\zeta)\rangle$$

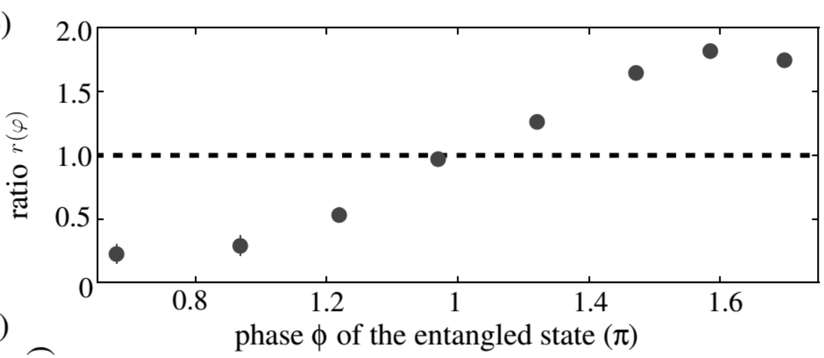
$$|\Psi_{sub}\rangle = |\Psi(\phi = -\zeta + \pi)\rangle$$

Photon detection prob.

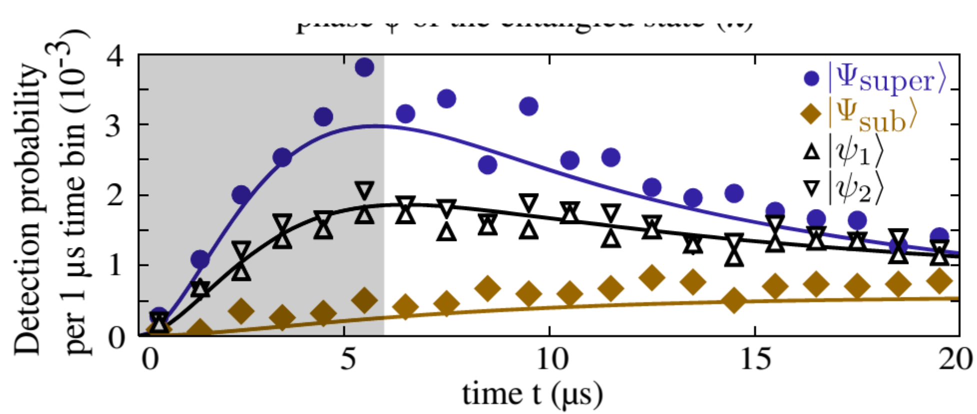
- Photon detection prob. had been measured on states, $|\Psi(\phi)\rangle$, $|\Psi_1\rangle$ and $|\Psi_2\rangle$.
    - Where, $|\Psi_1\rangle = |S\rangle|D'\rangle$, $|\Psi_2\rangle = |D'\rangle|S\rangle$, $|D'\rangle \equiv |3^2D_{5/2}, m_j = 3/2\rangle$
- For $\phi = 0.68\pi$, the ratio is 0.22(9) => $|\Psi_{sub}\rangle = |\Psi(\phi = 0.68\pi)\rangle$
- For $\phi = 1.58\pi$, the ratio is 1.84(4) => $|\Psi_{super}\rangle = |\Psi(\phi = 1.58\pi)\rangle$

- A temporal shape is determined by g_{eff} for initial time.
- A temporal shape is determined by cavity decay rates and off-resonant scatte ring rates for later time.

(b)



(c)



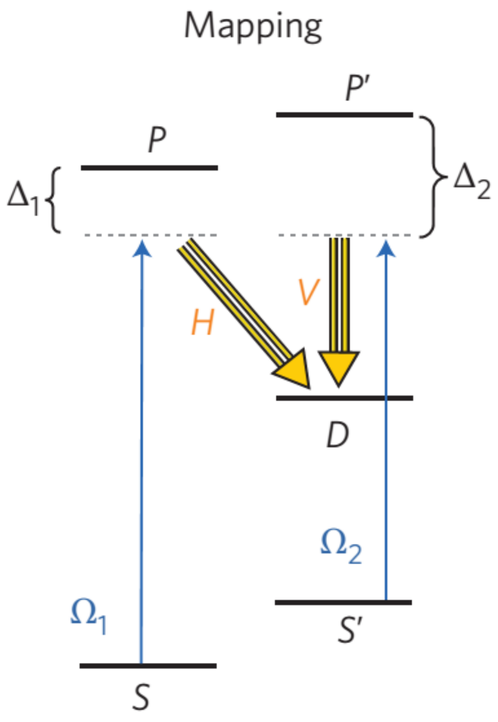
A quantum interface

with enhanced coupling of the superradiant state

- $|\Psi(\phi)\rangle = \left(|S\rangle|D\rangle + e^{i\phi}|D\rangle|S\rangle\right)/\sqrt{2}$
- $|S\rangle \rightarrow |\alpha,\beta\rangle \equiv \cos\alpha\,|S\rangle + e^{i\beta}\sin\alpha\,|S'\rangle$

- $|S\rangle \rightarrow |D\rangle$ transition produces a horizontally polarized photon $|H\rangle$
- $|S'\rangle \rightarrow |D\rangle$ transition produces a vertically polarized photon $|V\rangle$

- $\left(|\alpha,\beta\rangle|D\rangle + e^{i\phi}|D\rangle|\alpha,\beta\rangle\right)|0\rangle/\sqrt{2}$
- $\rightarrow |D\rangle|D\rangle\left(\cos\alpha\,|H\rangle + e^{i\beta}\sin\alpha\,|V\rangle\right)$
    - Where $\phi = 1.58\pi$



$|S\rangle \equiv \left|4^2S_{1/2}, m = -1/2\right\rangle$

$|S'\rangle \equiv \left|4^2S_{1/2}, m = +1/2\right\rangle$

A quantum interface

with enhanced coupling of the superradiant state

- Reconstruct process matrix by using 4 orthogonal states
- $|\alpha, \beta\rangle = |S\rangle, |S'\rangle, |S\rangle + |S'\rangle, |S\rangle - |S'\rangle$
- Reference state : $|\alpha, \beta\rangle|D'\rangle|0\rangle \rightarrow |D\rangle|D'\rangle\left(\cos\alpha\,|H\rangle + e^{i\beta}\sin\alpha\,|V\rangle\right)$

Fidelity between 6 us time window : 93.3% vs. 90.9%

Enhanced coupling also increases cumulative process efficiency in the short time window (~55 us)

$$g\sqrt{N/2\left((N/2)+1\right)}$$