Light Collection from a Trapped Ion in a Cavity

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Synopsis

- We integrate a micron-scale 3D quadrupole Paul trap with a 2 mm Fabry-Pérot cavity in order to enhance the collection of spontaneously emitted fluorescence from a single trapped ytterbium ion into a Gaussian mode.
- We excite the ion with a coherent beam through the side of the cavity and record the cavity photon emission rate while scanning the cavity length, producing emission spectra for various excitation beam strengths and atom-laser detunings.
- We present progress towards the implementation of a protocol for generating entanglement between the ion spin state and the output cavity photon polarization.

Motivation

Heralded Atom-Atom Entanglement

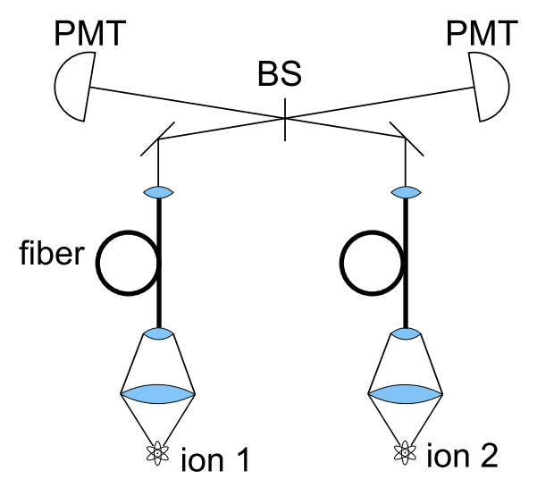
Currently, entanglement of remote ions is generated by collecting emitted photons with a high numerical aperture lens [1]. This light is then coupled into a fiber and interfered on a beam splitter. Coincidence detection heralds entanglement.

Success Rate Limited by Light Collection

The success probability scales as the square of the photon collection probability (p_c):

$$(p_c)^2 = \left(\frac{\Delta\Omega}{4\pi}\right)^2 = (2\%)^2$$
$$\sim 4\times10^{-4}$$

where $\Delta\Omega = 2\pi(1-\cos(\arcsin(\mathrm{NA})))$ is the solid angle subtended by the objective lens with numerical aperture $\mathrm{NA} = 0.27$



Enhance Collection using Cavity QED

Couple the qubit to the fundamental mode of an optical cavity [2-4]

- The ion preferentially spontaneously emits photons into the cavity mode
- The emission is confined to a Gaussian beam that is amenable to higher efficiency fiber coupling

Photon Emission Probability

Using a pulsed scheme to excite a single ion coupled to the undriven cavity mode, the emission probability is given by [5]

Ratio of light scattered into the cavity mode.

$$p_c = \frac{T}{\mathcal{L}}\left(\frac{\kappa}{\kappa+\Gamma}\right)\left(\frac{2C}{1+2C}\right)$$

$$C = \frac{2g^2}{\kappa\Gamma}$$

Cooperativity

Ratio of output coupler transmission to total cavity loss

Ratio of light that leaves the cavity to what leaves the ion-cavity system

For our system, this is only about **1%**. If we instead continuously pump the system, the coherent energy exchange between the cavity mode and the ion results in an increased emission rate. This probability must be calculated using a numerical solution of the master equation [6]:

$$\dot{\rho} = \frac{1}{i\hbar}[\hat{H},\rho] + \sum_k \left\{\hat{C}_k\rho\hat{C}_k^\dagger - \frac{1}{2}\left(\hat{C}_k^\dagger\hat{C}_k\rho + \rho\hat{C}_k^\dagger C_k\right)\right\}$$

where $\hat{C}_c = \sqrt{\kappa}\hat{a}$, $\hat{C}_A = \sqrt{\Gamma}\,\hat{\sigma}$

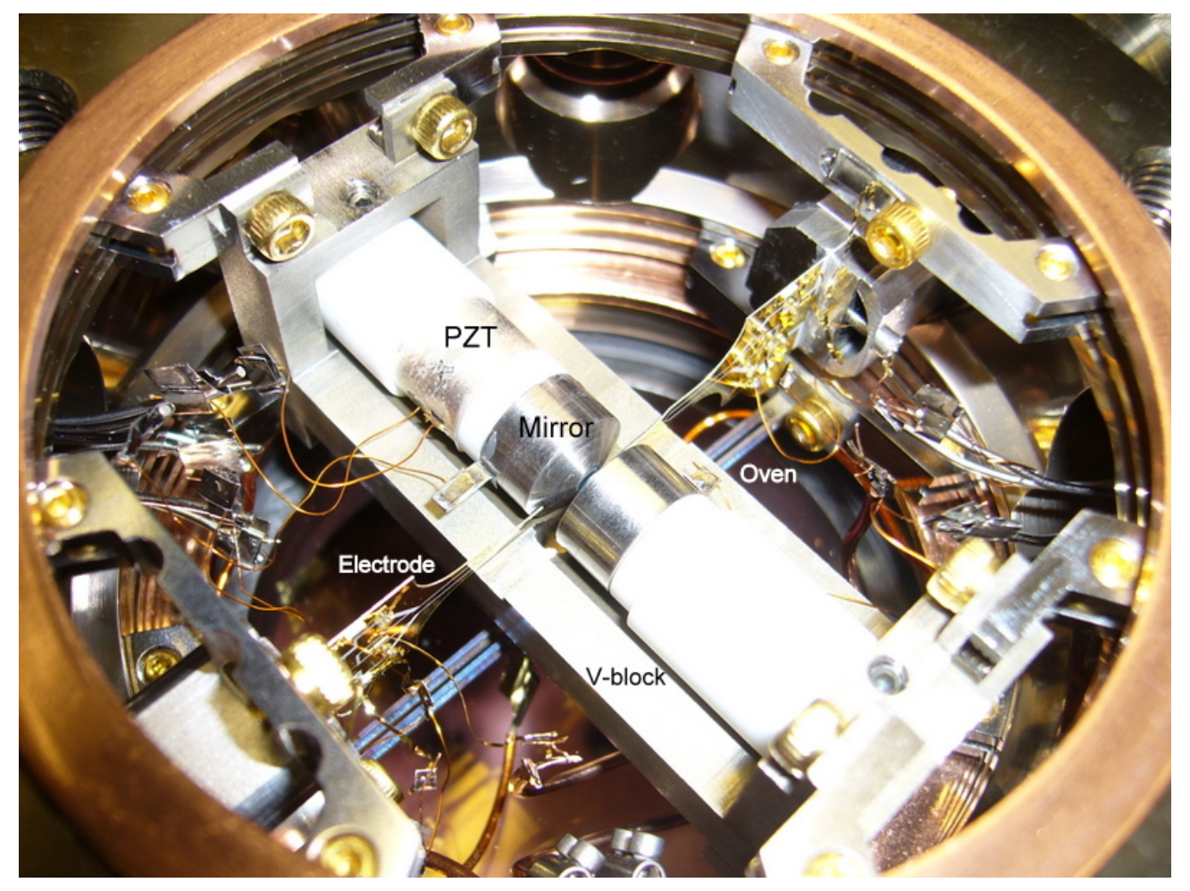
For the entanglement protocol, the emission probability is given by

$$p_c(t) = \int_0^t \kappa\langle\hat{a}^\dagger\hat{a}\rangle\, d\tau$$

which rapidly asymptotes to about **4%** for our system (see bottom right panel).

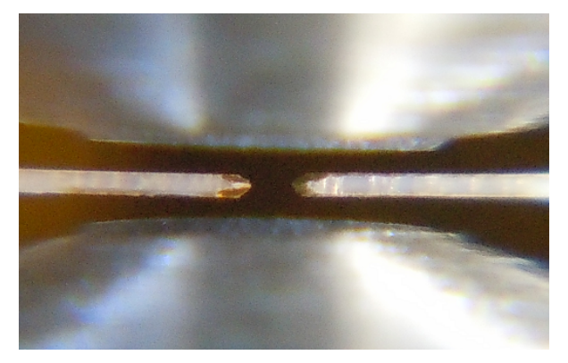
Our System

Chamber

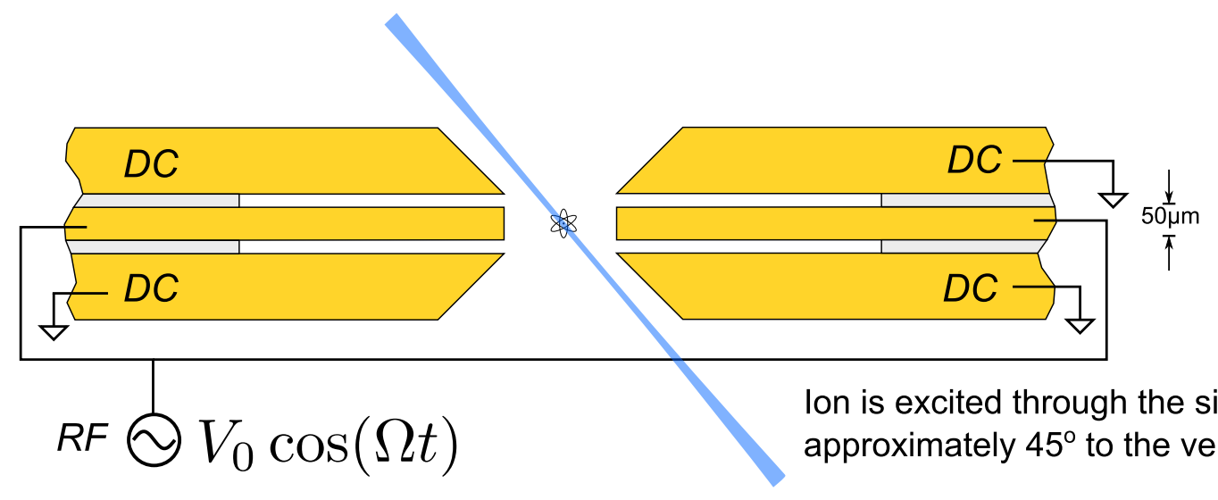


Ion trap

- Needle-like geometry
- Gold evaporated onto laser-machined alumina substrate, 127 μm thick
- Ion trap separation: 190 μm
- DC electrodes provide micromotion compensation and a nearby RF ground
- Secular frequencies: 2π (3.6,1.3,1.3) MHz

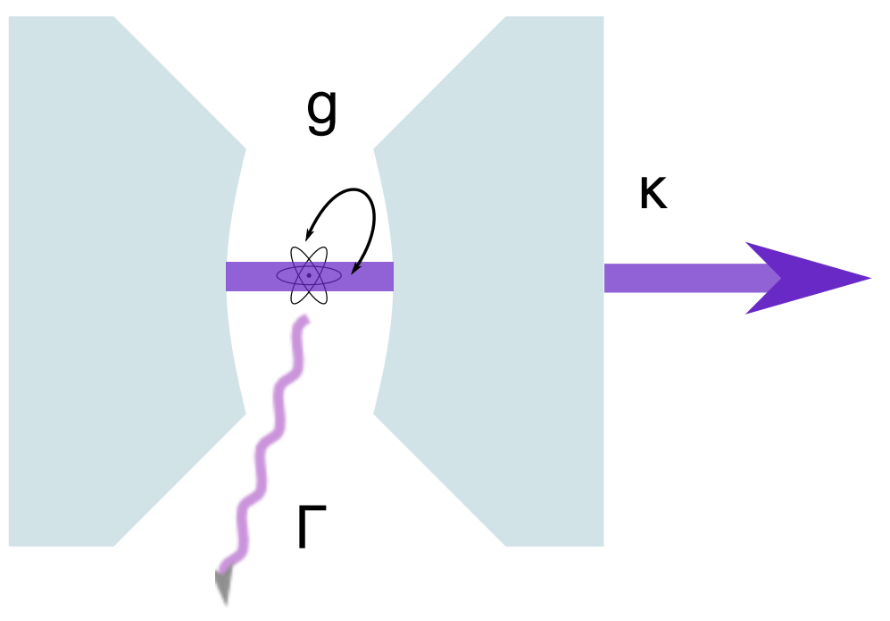


Electrodes are movable, and can be inserted and pulled out of the cavity [7].



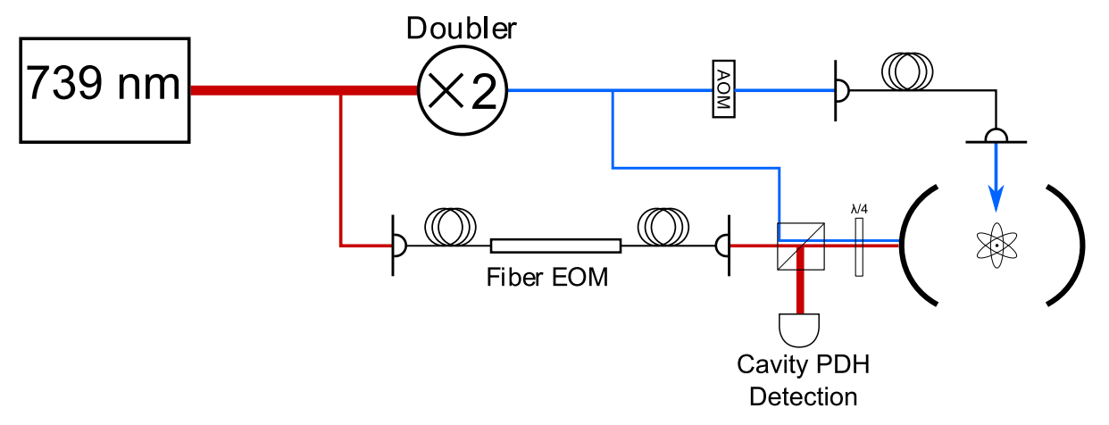
Ion is excited through the side of the cavity, at approximately 45° to the vertical

Cavity

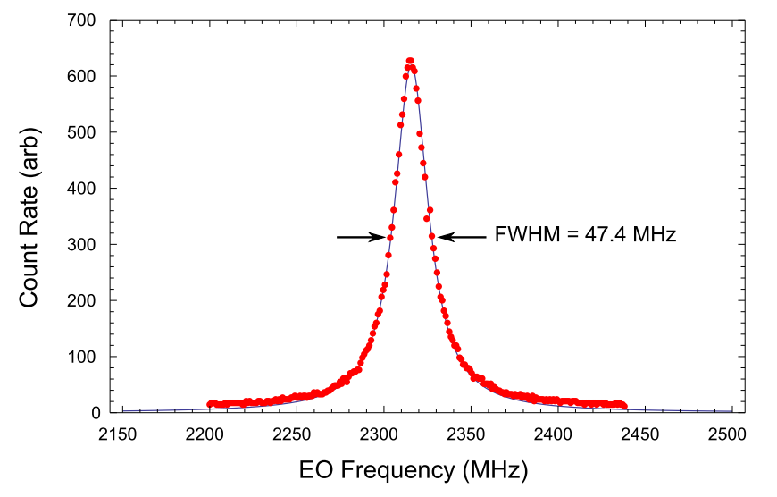


Geometry
- Fabry-Pérot cavity
  Mirror separation: 2.1 mm

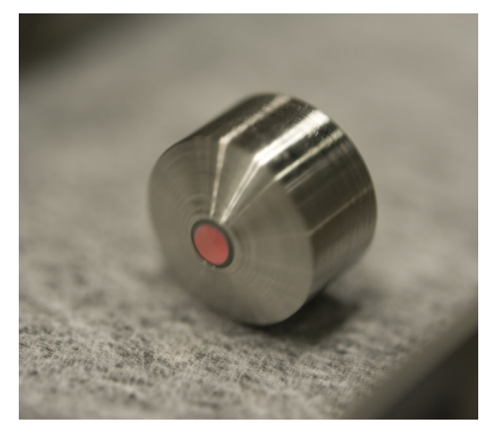
Atom-Cavity Coupling
- Coupling parameter: Calculated g / 2π = 4 MHz
  Effective g / 2π = 2 MHz
  Cavity linewidth (fwhm): κ / 2π = 47.4 MHz
  Atomic linewidth (fwhm): Γ / 2π = 19.6 MHz
  Cooperativity: C = 0.034 (effective: 0.008)
- *Mirrors*
  Finesse = 1500
  Dielectric coating for 739 nm and 369 nm



The UV light used to excite the ion is generated by doubling a 739 nm source. Part of the source beam is diverted to a fiber-EOM, which produces a sideband ~2 GHz away from the carrier. This sideband is coupled into the cavity to lock the cavity via the Pound-Drever-Hall method. The cavity length can thus be scanned independently of the applied UV wavelength by sweeping the EO frequency.



The cavity linewidth is measured directly by pumping the cavity with UV light and scanning the cavity length while recording the cavity emission using a PMT.



The dominant stray fields arise from accumulated charge on the mirror surfaces [8]. Metal sheaths provide DC compensation voltages along the cavity axis. The charging effect is dynamic and unpredictable; it sometimes causes the ion to drift a micron in less than an hour.

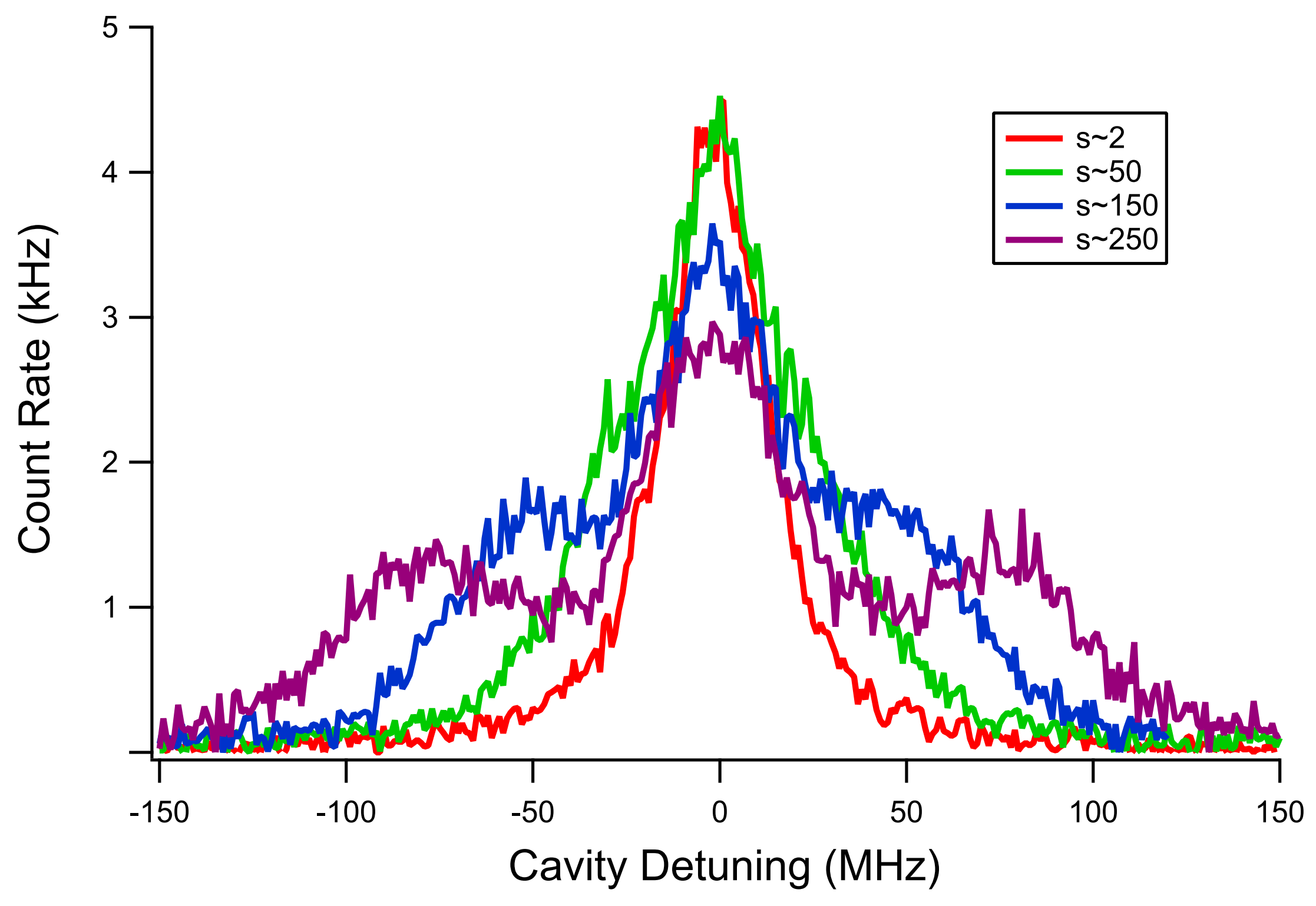
Fluorescence of a Strongly Driven Ion-Cavity System

A laser beam excites a single trapped $^{174}\mathrm{Yb}^+$ ion from the side of the cavity.

Cavity emission spectra are produced by scanning the cavity length at various driving strengths, $s = I/I_s$ and laser-atom detunings, $\Delta = \nu_A - \nu_L$

where I is the excitation beam intensity, and
I_s is the saturation intensity on resonance.

Increasing the excitation intensity exhibits an evolution of the cavity output spectra from a single peak to a three-peak structure, as seen here for a fixed detuning $\Delta = 10$ MHz .

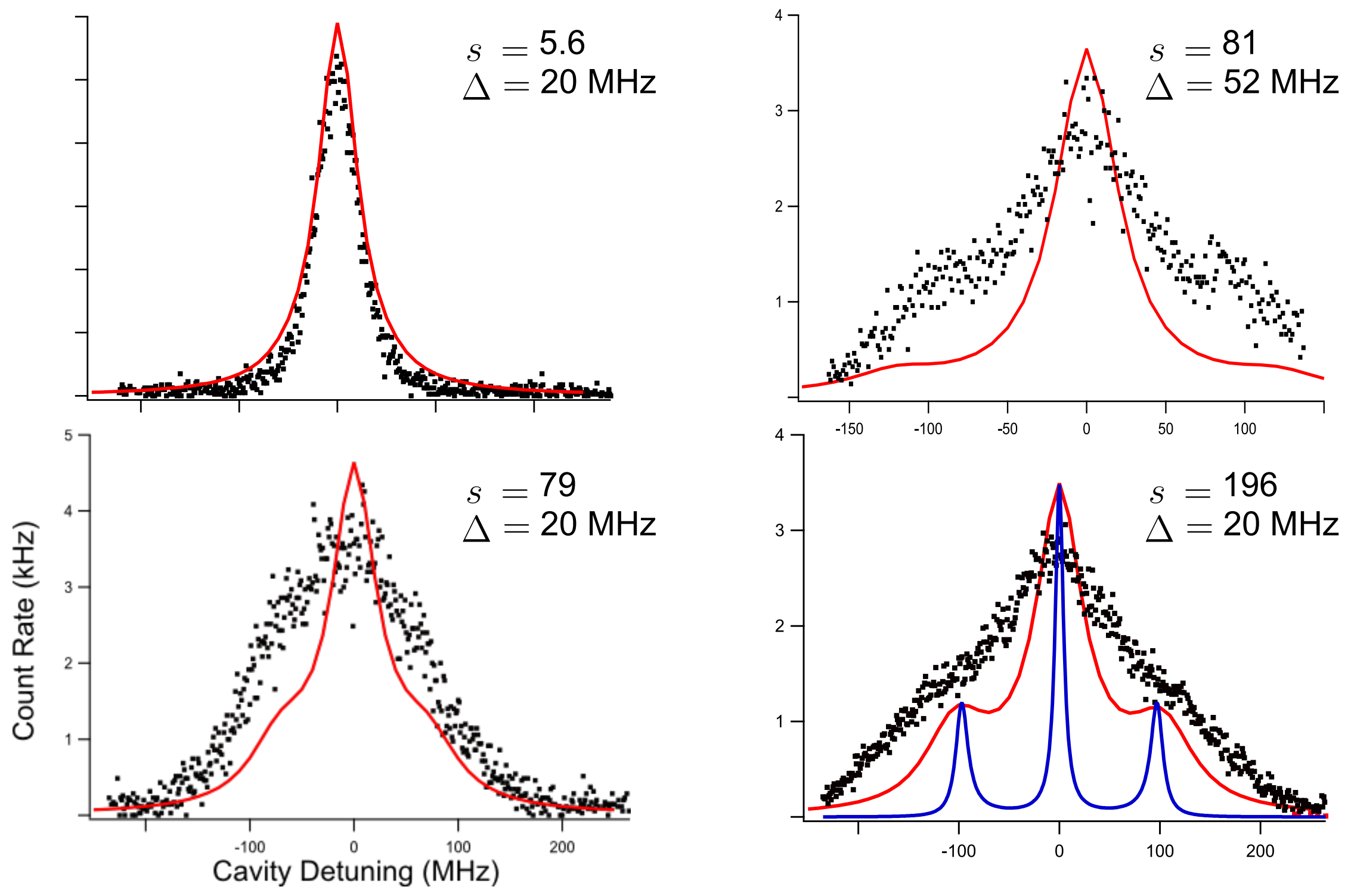


The spectra below illustrate the variation in structure as a function of different intensities. Although we are not in the strong coupling regime, the interaction is strong enough that a convolution of the free-space emission spectrum (Mollow triplet [9]) with the cavity transfer function is an insufficient model. For comparison, the **solid blue line** in the last figure depicts this simple convolution.

The more accurate **solid red curves** are obtained by solving a strongly driven Jaynes-Cummings model for a two-level atomic system that includes both the coherent laser-atom coupling and atom-cavity coupling as well as their dissipative counterparts (see Introduction panel). The Hamiltonian is:

$$\hat{H} = \omega_A\hat{\sigma}_z + \omega_C\hat{a}^\dagger\hat{a} + ig(\hat{\sigma}\hat{a}^\dagger - \hat{\sigma}^\dagger\hat{a}) + \frac{\Gamma}{2}\sqrt{s/8}(\hat{\sigma}^\dagger + \hat{\sigma})$$

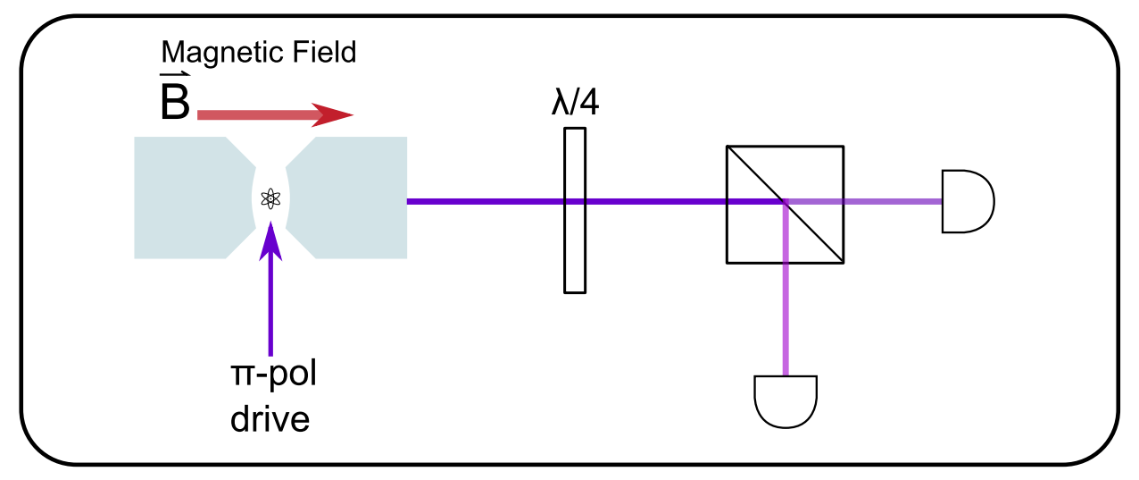
The cavity emission rate is given by $\xi\kappa\langle\hat{a}^\dagger\hat{a}\rangle$ where ξ is a fitting parameter for scale.

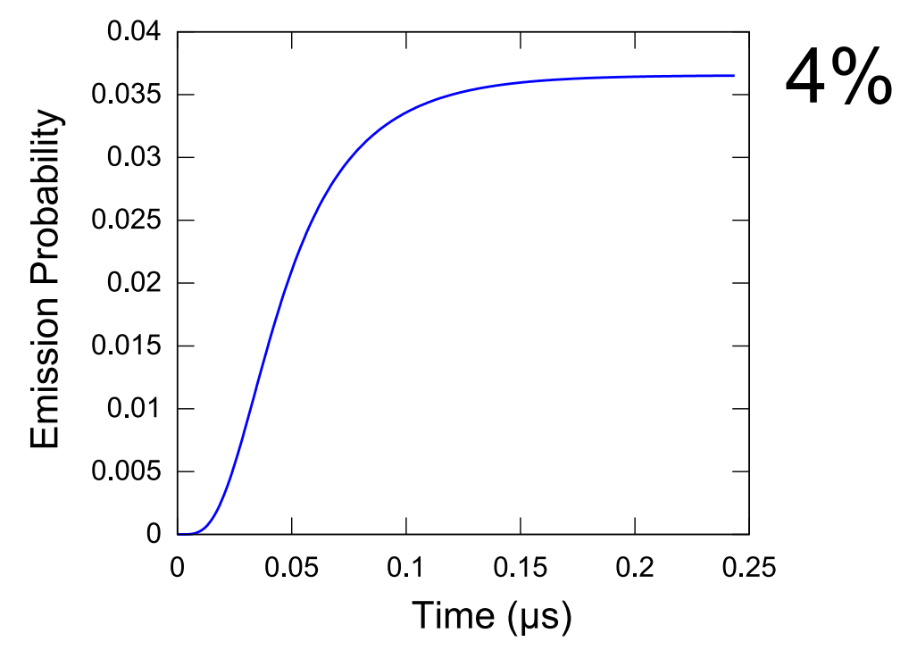


Protocol to generate entangled ion-photon pairs

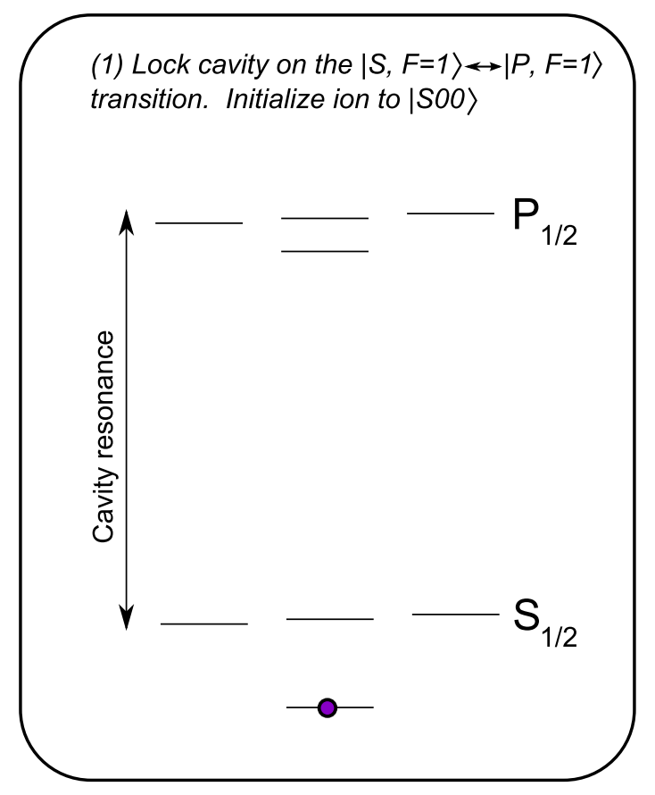
Remote entanglement schemes for quantum networks rely upon faithful creation, collection, and transmission of photons entangled with the atomic state. Here we describe a protocol to generate single photons whose polarization is entangled with the ground state of an ytterbium ion. The photons are coherently transferred to the cavity mode and then emitted through the output coupling mirror.

- Drive the ion with cw light that is off resonant with the cavity
  Avoids background scattered light and beam has very narrow bandwidth
- Orient the quantization axis such that only σ+ and σ- transitions are supported by the cavity
  π-polarized drive beam is not supported, convert output to H and V polarization using a wave plate

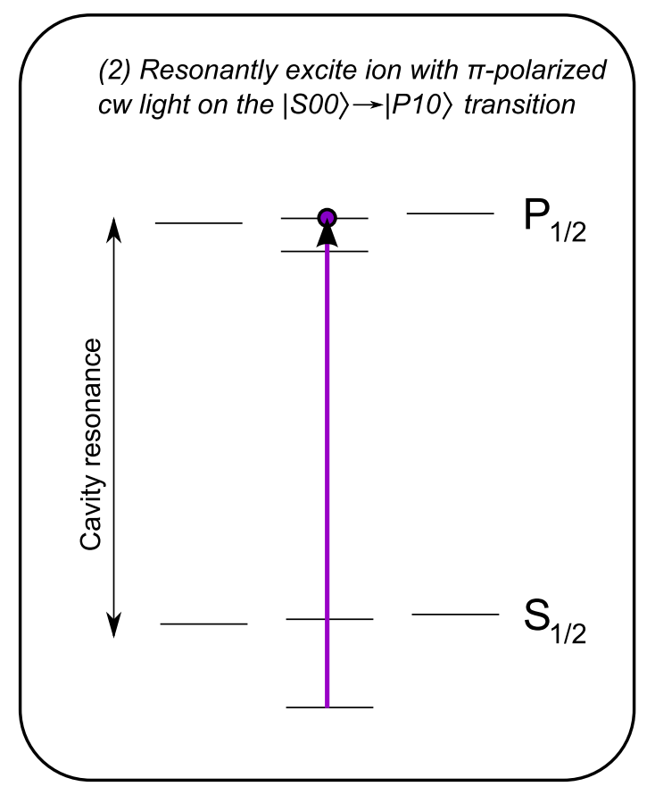




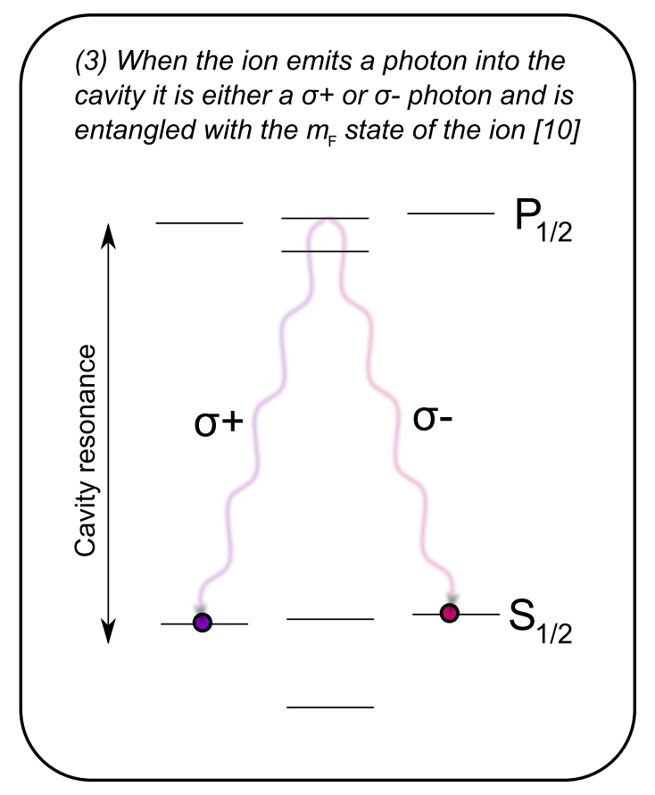
Numerical solution to the master equation employing a Hamiltonian that describes the coherent dynamics of the four relevant $^{171}\mathrm{Yb}^+$ energy levels and the two photon polarization modes.



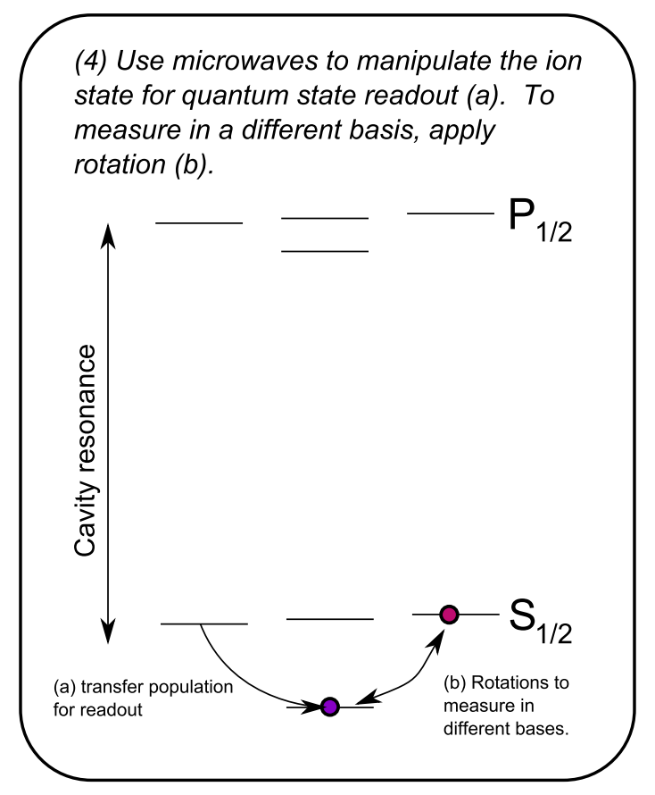
(1) Lock cavity on the |S, F=1⟩↔|P, F=1⟩ transition. Initialize ion to |S00⟩



(2) Resonantly excite ion with π-polarized cw light on the |S00⟩→|P10⟩ transition



(3) When the ion emits a photon into the cavity it is either a σ+ or σ- photon and is entangled with the m_F state of the ion [10]



(4) Use microwaves to manipulate the ion state for quantum state readout (a). To measure in a different basis, apply rotation (b).

Acknowledgements

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