Cavity QED as a Deterministic Photon Source

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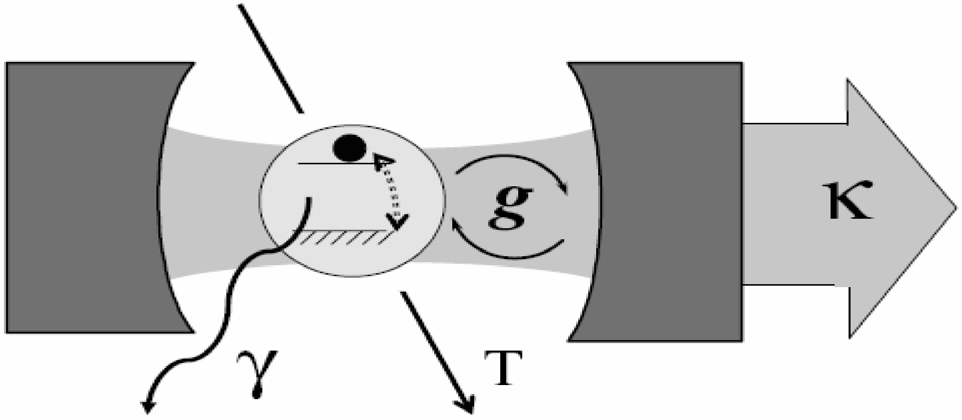
Need for a deterministic photon source (i.e. photons on demand):

1) Quantum cryptography: present approaches use strongly attenuated laser to get single photon, but sometimes there are multiple photons. This enables eavesdropper to use “optimal photon number attack” to determine the key.

2) For use in Linear-optical quantum computing (flying qubits): Need to reliably initialize state of photon.

Part I
Basics of Cavity QED



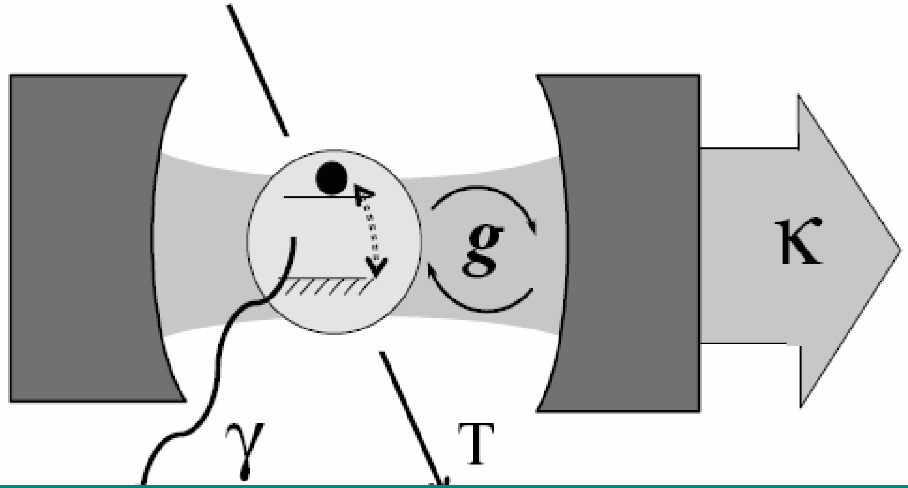
Cavity modes are discrete, instead of a continuum as in free space.
Electric field of single photon goes as 1/√V, where V is the volume of the mode. So interaction of one photon of a particular cavity mode with an atom can be strong, enhancing the emission of photons into this mode if atom is resonant with the mode.
Enhancement over decay rate in free space is approximately Q of cavity.

Simplest system is a 2-level atom interacting with the cavity mode

(but the actual single photon sources use 3-level atom, to be discussed later)

So:

2 –level atom coupled to a cavity mode



$$H = H_C + H_A - \hbar g\left(|e\rangle\langle g|a + a^*|g\rangle\langle e|\right)$$
$$- i\hbar\gamma|e\rangle\langle e| - i\hbar\kappa a^* a$$

Couples e with n-1 photons to g with n photons

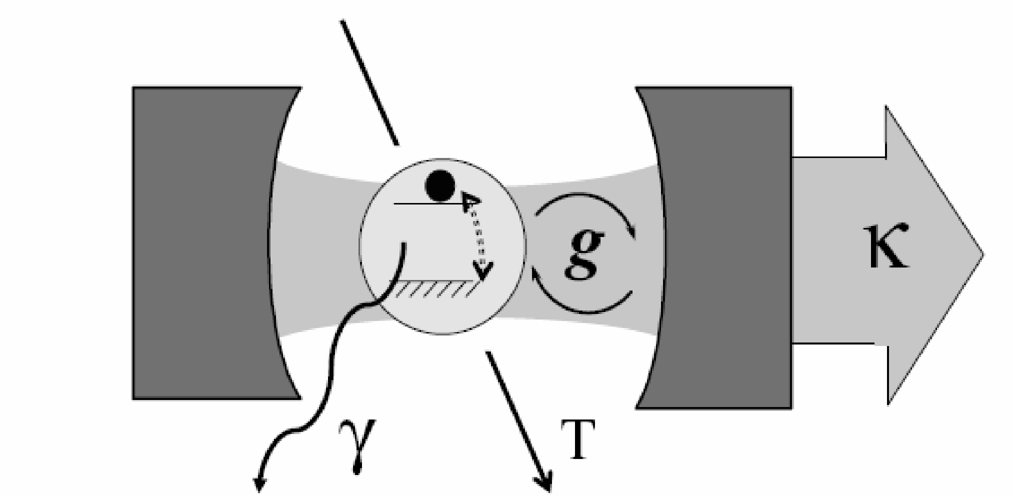
$$|\Psi(t)\rangle = c_e|e,0\rangle + c_g|g,1\rangle + c_0|g,0\rangle$$

$$i\frac{dc_e}{dt} = -g\,c_g - i\gamma\,c_e$$

$$i\frac{dc_g}{dt} = -g\,c_e - i\kappa\,c_g$$

Decay of excited state:

$$c_e(t) = \exp\left[-\left(\gamma + \frac{g^2}{\kappa}\right)t\right]$$



Ratio of probability of emission into cavity mode to spontaneous emission into free space is thus:

$$\frac{g^2}{\kappa\gamma}$$

So for $\frac{g^2}{\kappa\gamma} >> 1$

there is <u>enhanced decay into cavity mode</u>

Strong Coupling and Bad Cavity Regimes

Strong coupling: $g >> \left(\kappa, y\right)$

gives vacuum Rabi oscillations

Bad-cavity: $\kappa >> g$

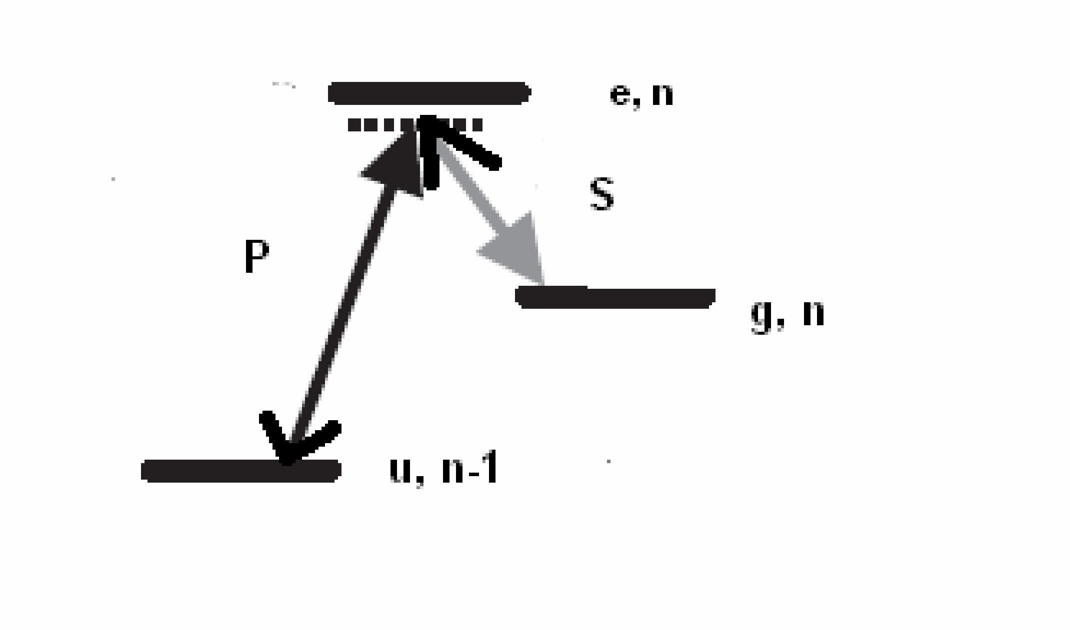
$$\frac{g^2}{\kappa\gamma} >> 1$$

gives exponential decay of excited state (graphs?)

Part II:
3-level Atoms

3-level Atom

All schemes use Raman transitions. Resonant condition is $\Delta_P = \Delta_C$



Can have the cavity mode drive the Stokes transition.

$$H = \hbar\Delta_P |u\rangle\langle u| + \hbar\Delta_C |g\rangle\langle g| - \hbar g\left(|e\rangle\langle g| a + a^* |g\rangle\langle e|\right) - \frac{1}{2}\hbar\Omega_P\left(|e\rangle\langle u| + |u\rangle\langle e|\right)$$

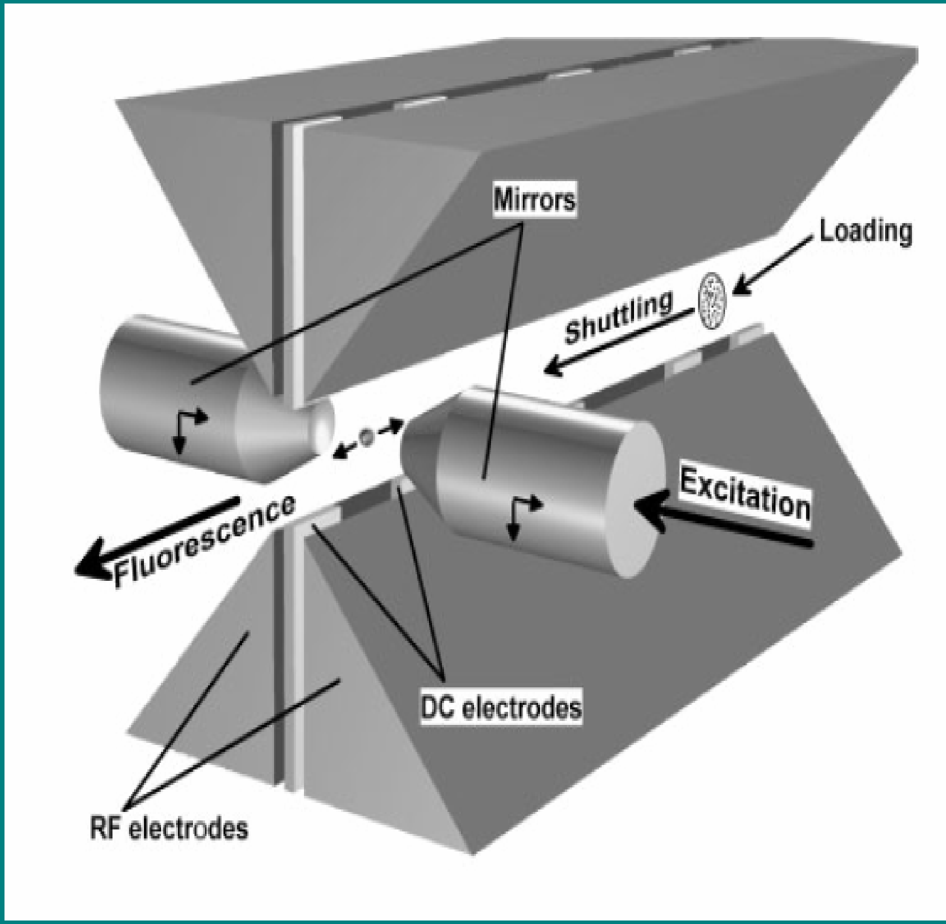
Get Rabi flops between g and u, with emission of a photon into cavity mode.

Part III:
Single Photon Sources

- Walther, et al, Max-Planck Institute
- Kimble, et al, Caltech
- Rempe, et al, Max-Planck Institute

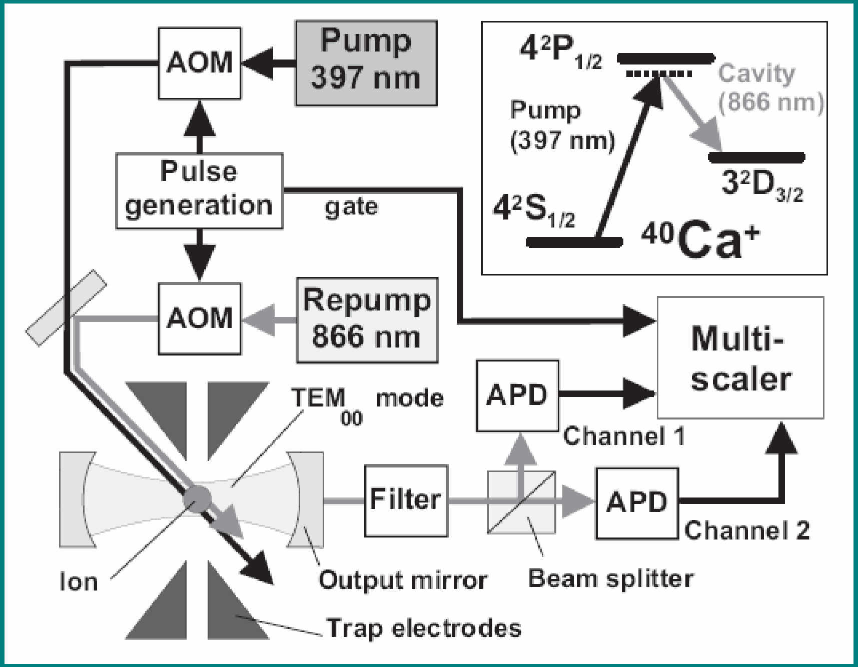
Walther, et al (2005)

- Linear ion trap, Ca ion
- Cavity length = 6 mm



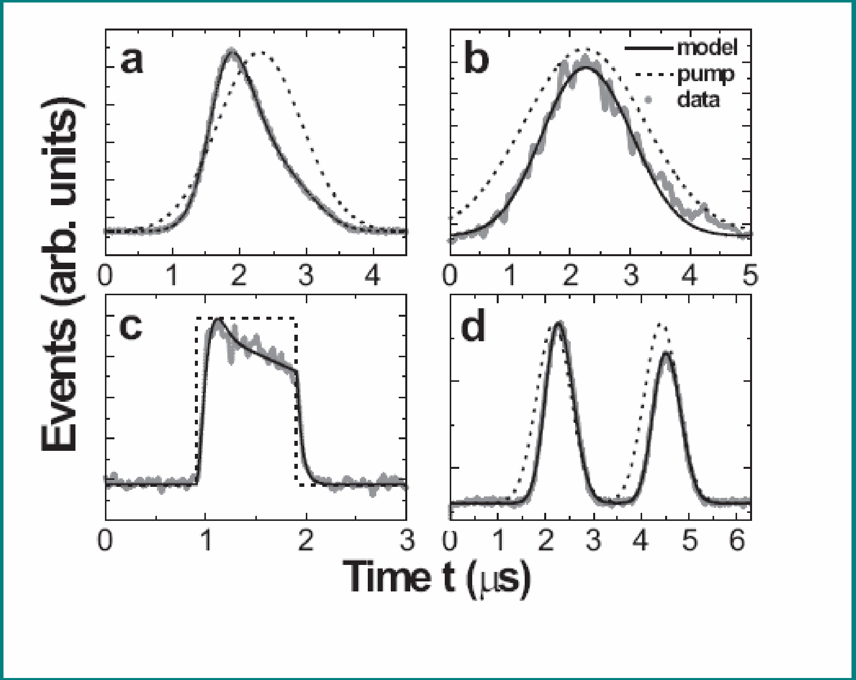
Experimental Setup

- S state prepared by optical pumping
- Raman transition to D state by pump pulse
- Intensity profile of pump pulse determines temporal structure of waveform of photon; can be adjusted arbitrarily
- 100 kHz rep rate



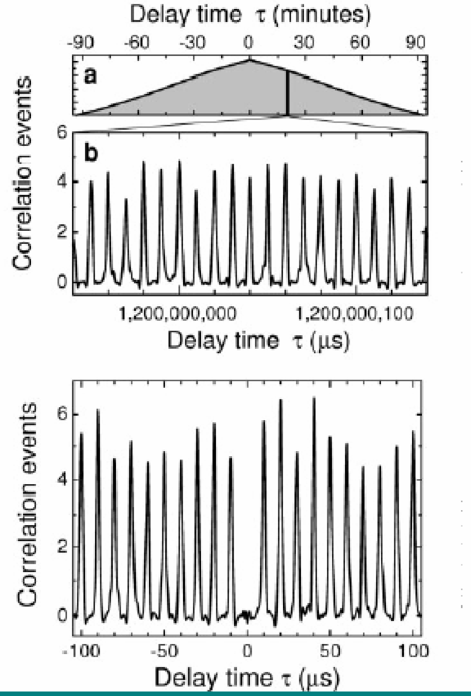
Photon Waveforms

- For a given pump pulse shape, each photon waveform is identical
- In (d) photon is “spread out” over 2 time bins



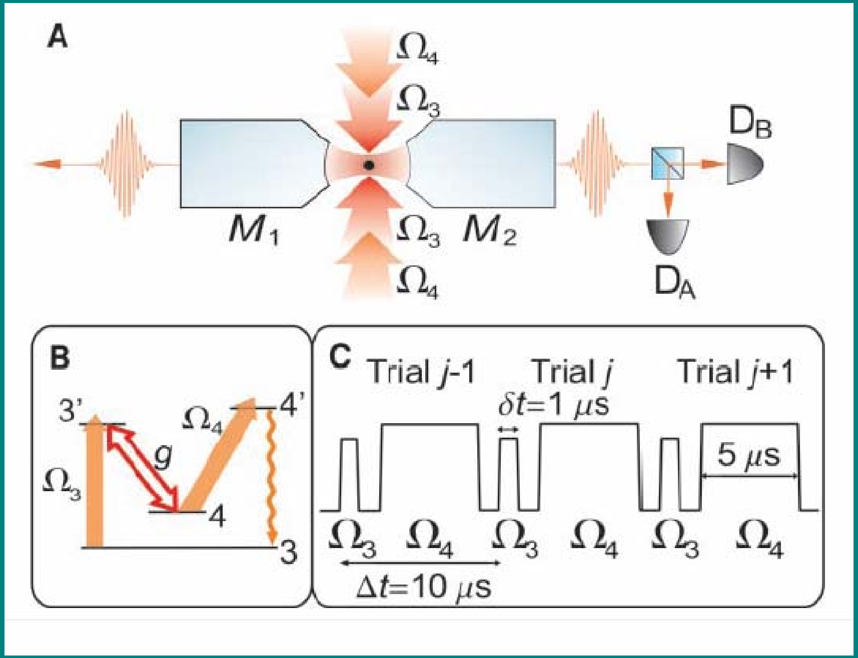
Photon Correlations

- Bottom shows cross-correlation of photon arrival times at the 2 detectors. Absence of a peak at τ=0 indicates source emits <u>single</u> photons

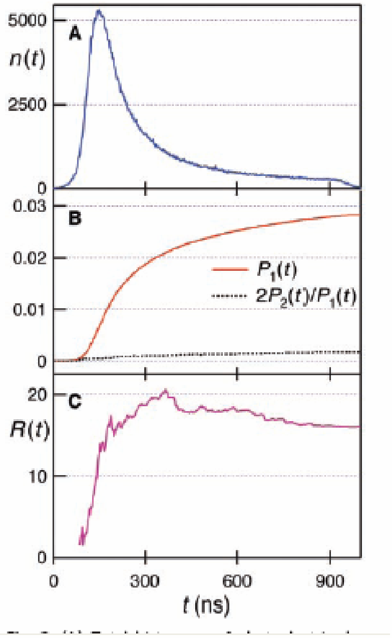


Kimble, et al, Caltech (2004)

- Cs atom in optical trap
- D2 line at 852.4 nm
- Ω_3 pulse drives transfer from F=3 to F=4 hyperfine ground state, emitting one photon into cavity
- Ω_4 recycles atom to original ground state
- 14,000 single-photon pulses from each atom are detected
- Gaussian wave packet



- Fig. A is histogram of detection events, indicating photon waveform



Photon Correlations

- Left figure shows absence of peak at t=0, indicating single-photon source

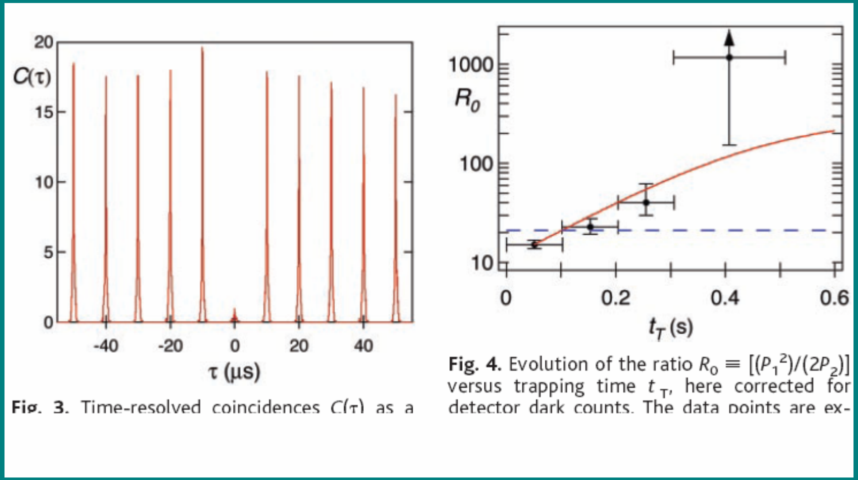
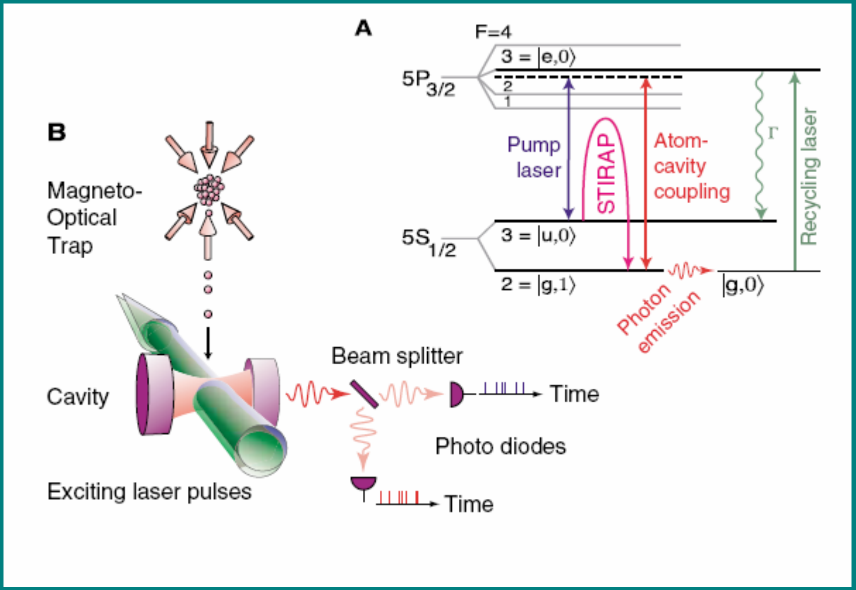


Fig. 3. Time-resolved coincidences $C(\tau)$ as a

Fig. 4. Evolution of the ratio $R_0 \equiv [(P_1^2)/(2P_2)]$ versus trapping time t_T, here corrected for detector dark counts. The data points are ex-

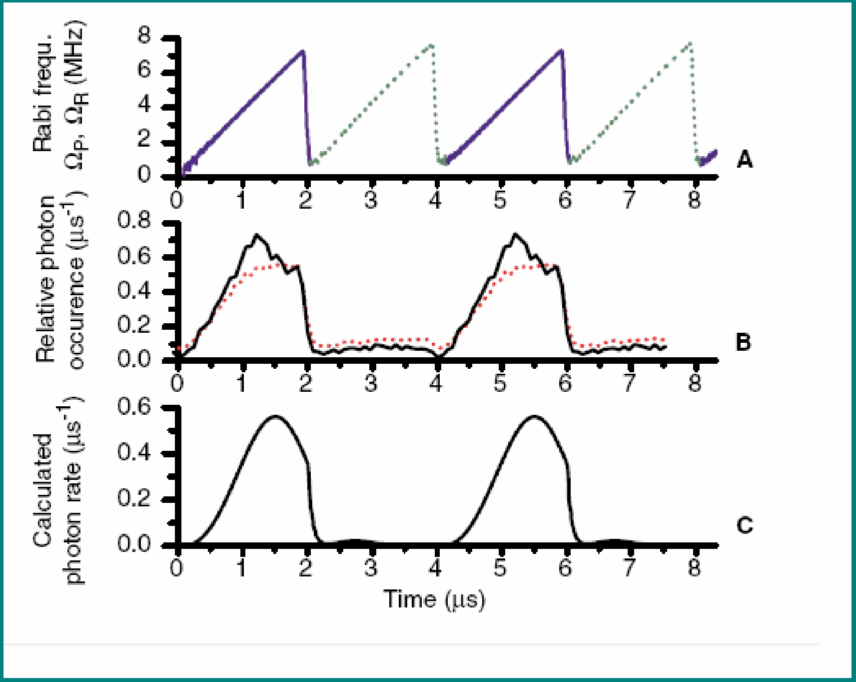
Rempe, et al, 2002

- Rb atom released from magneto-optical trap
- Atom starts in state u
- Pump pulse applied, Raman-resonant excitation results, leaving one photon in cavity
- Recycling pulse followed by decay resets the atom back to u.
- Cavity length = 1mm, finesse = 60,000



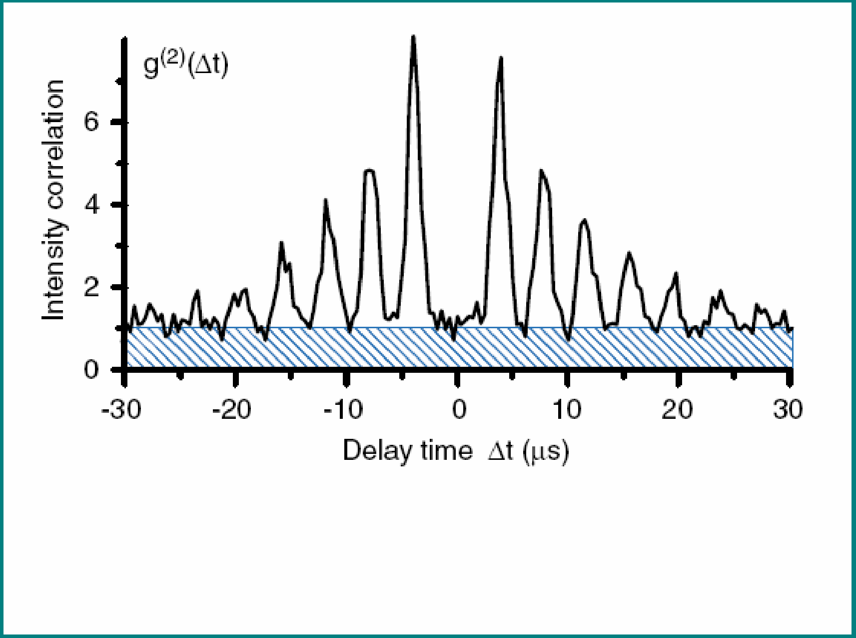
Photon Waveforms

- E-field amplitudes, and hence Rabi frequencies, of pump have sawtooth shape (Fig A)
- Fig B shows measured arrival-time distribution of photons (dotted), and hence photon waveform
- Can shape photon pulse by shaping pump pulse; for symmetric pulse, photon can be used to transfer state to another atom in another cavity (quantum teleportation)



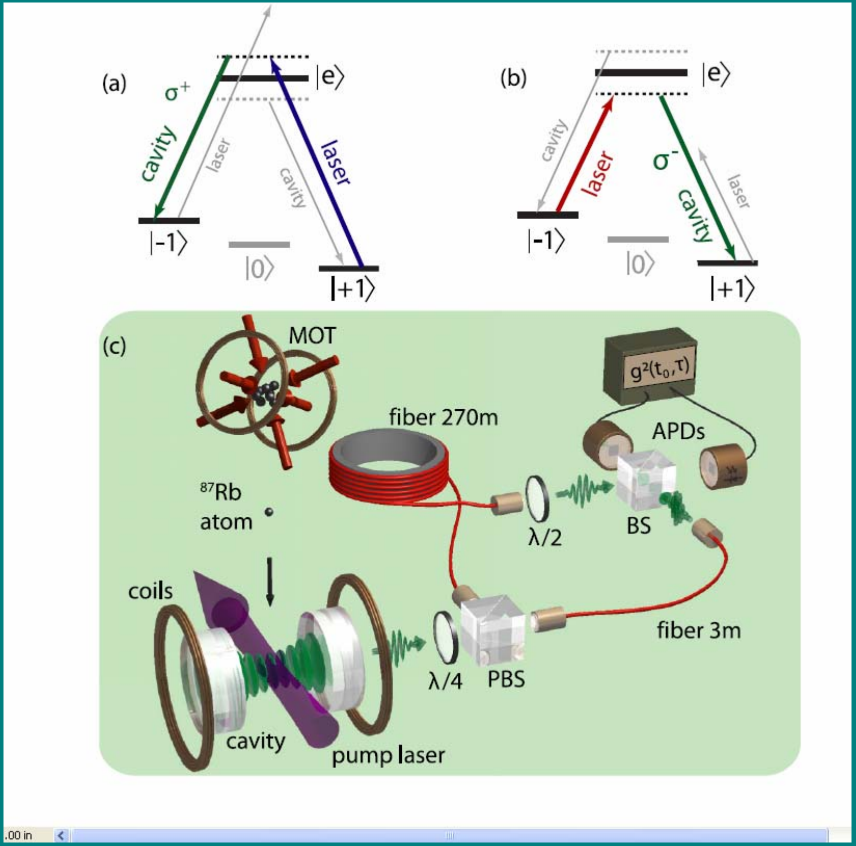
Photon Correlations

- Lack of peak at t=0 indicates single photons emitted



Rempe, et al, 2007 Polarization-Controlled Single Photons

- Linearly polarized pump laser
- Zeeman splitting of hyperfine levels
- Pump-cavity detuning of first pulse is 2Δ = splitting between +1 and -1 state
- Atom starts in +1; pump pulse and cavity vacuum field resonantly drive Raman transition to -1 state, emitting a sigma + photon
- Pump-cavity detuning changes sign on next pulse, -2Δ which gives (b); emits sigma – photon, and atom is back to original state: no need for recycling pulse as in previous slide



Photon Waveforms

- With only one path to beam splitter open, the specific polarization is detected “only” during the corresponding pump pulse
- Again, single-photon source is evident (e)