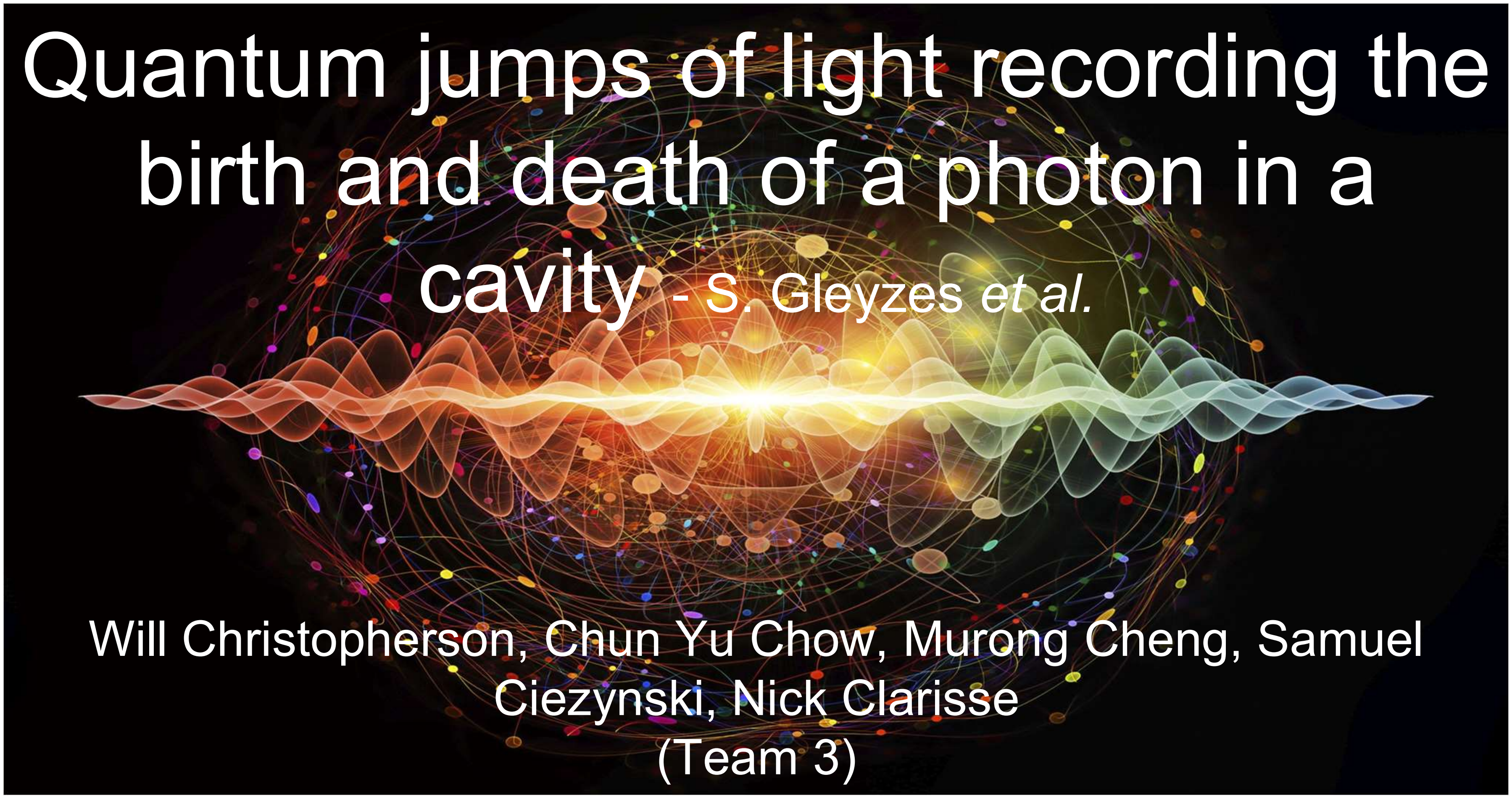


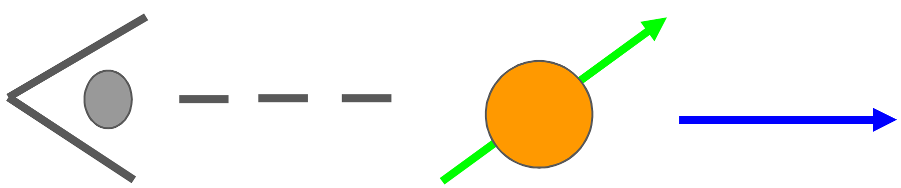
Quantum jumps of light recording the birth and death of a photon in a cavity - S. Gleyzes *et al.*

Will Christopherson, Chun Yu Chow, Murong Cheng, Samuel Ciezynski, Nick Clarisse
(Team 3)

Gleyzes, S., Kuhr, S., Guerlin, C. *et al*. Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

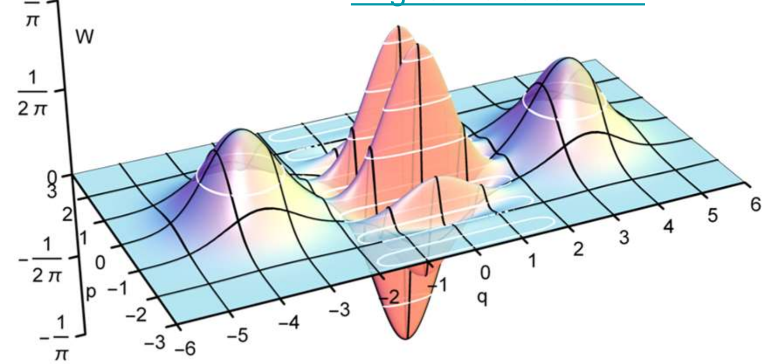
Requirements for a Quantum Measurement

- Quantum states, observables, operators, the environment
- Quantum measurement is statistical (repeatable measurements, large in number)
- Often need very well isolated systems (High Q; low energy loss)
- Decoherence rates must outlive measurement times



observer quantum system

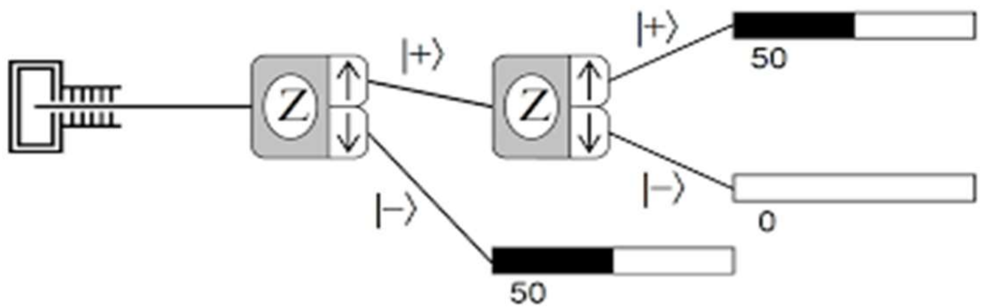
Wigner Function wiki



reconstructing the quantum information

Repeatable Quantum Measurements

- What quantum behavior can we observe and how do we do that?
- Quantum non-demolition (QND) measurement of quantum state fluctuations
  - QND preserves observable uncertainty and evolution; repeatable

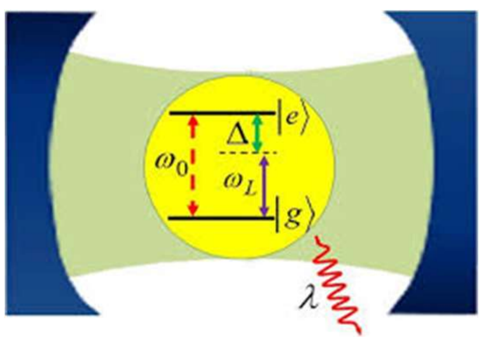


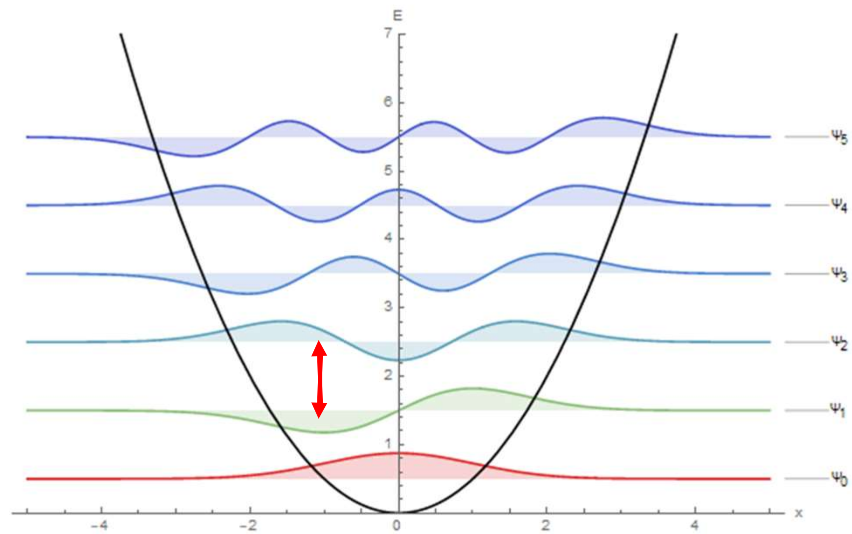
- Quantum jumps have been observed in trapped massive particles, but what about light quanta?

McIntyre, David H., et al. Quantum Mechanics. Pearson, 2016.

Measuring Quantum Jumps in Light

- Quantum jumps in photon number
- QND probes are Rb atoms in Rydberg states (dipole polarizability)
  - Detectable light shifts of single-photon resolution
- High Q cavity coupled to qubit (atom)
  - Enables measuring n(t)
  - Photon exchange (qubit and cavity)



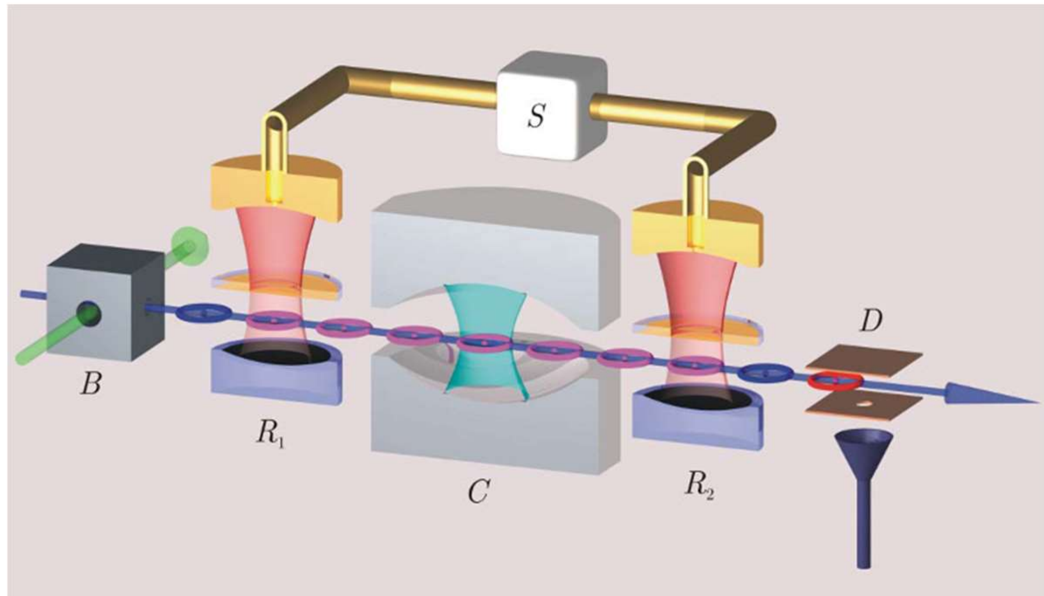


A. Mortezapour,Quantum Inf Process 19, 136 (2020).

QMHO-stackoverflow

Experimental Set-up for Detecting Quantum Jumps

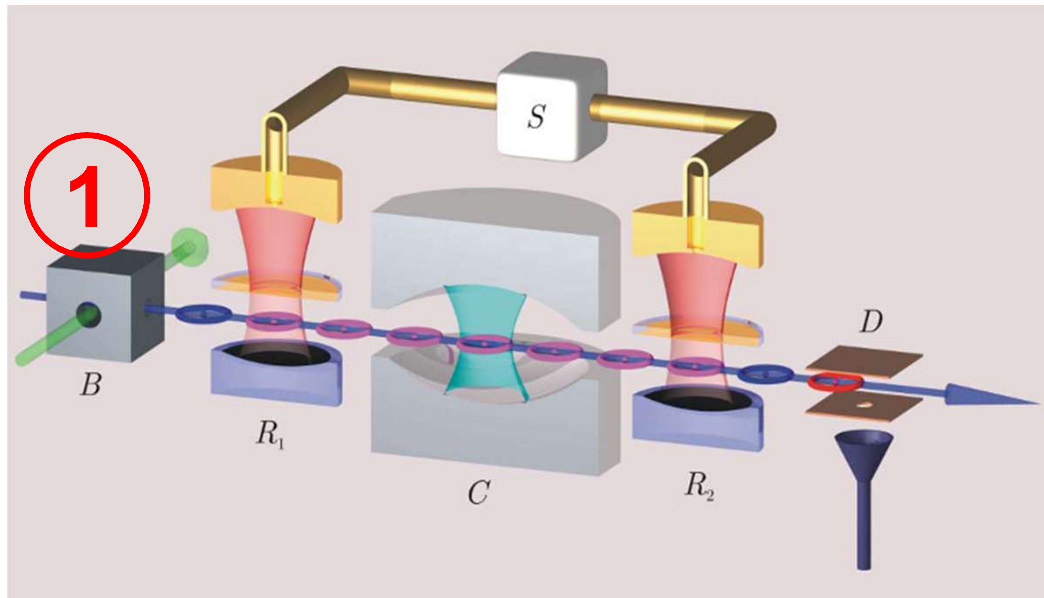
- *B*: box containing rubidium atoms, prepared in state $|g\rangle$
- R_1, R_2: Ramsey cavities
- *S*: classical microwave source
- *C*: photon box, a cavity that hosts the photons to be detected
- *D*: state selective field ionization detector
- R_1-C-R_2 interferometric arrangement cooled to 0.8K and shielded from thermal radiation



Gleyzes, S., Kuhr, S., Guerlin, C. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

Experiment 1: Birth, life and death of a photon

1. Rubidium atoms in the circular Rydberg state |g⟩ (n=50) are prepared and emitted from the box *B*. Travel along the blue axis at 250 ms^{-1}.



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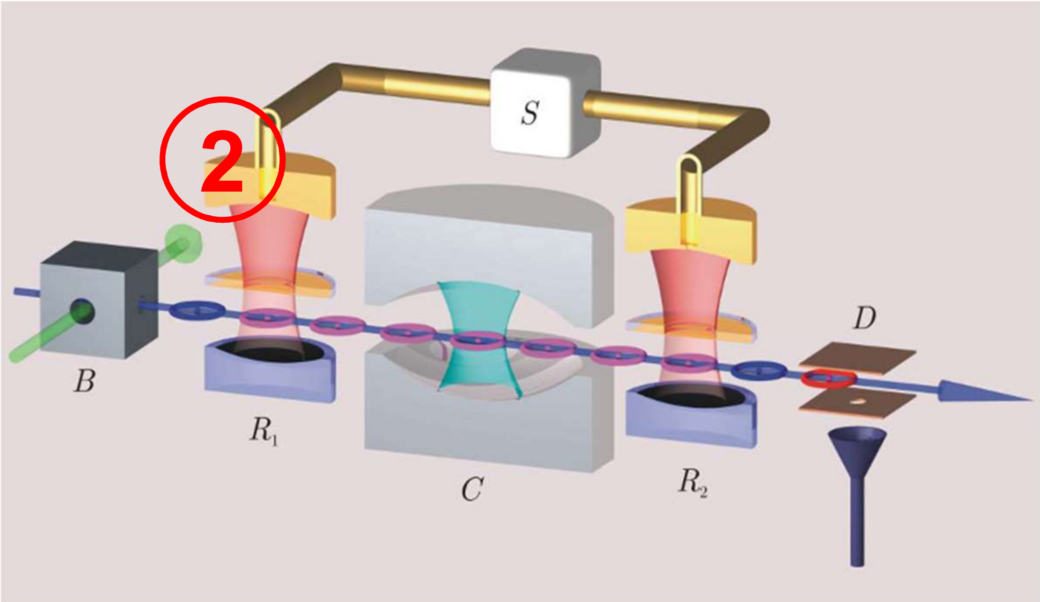
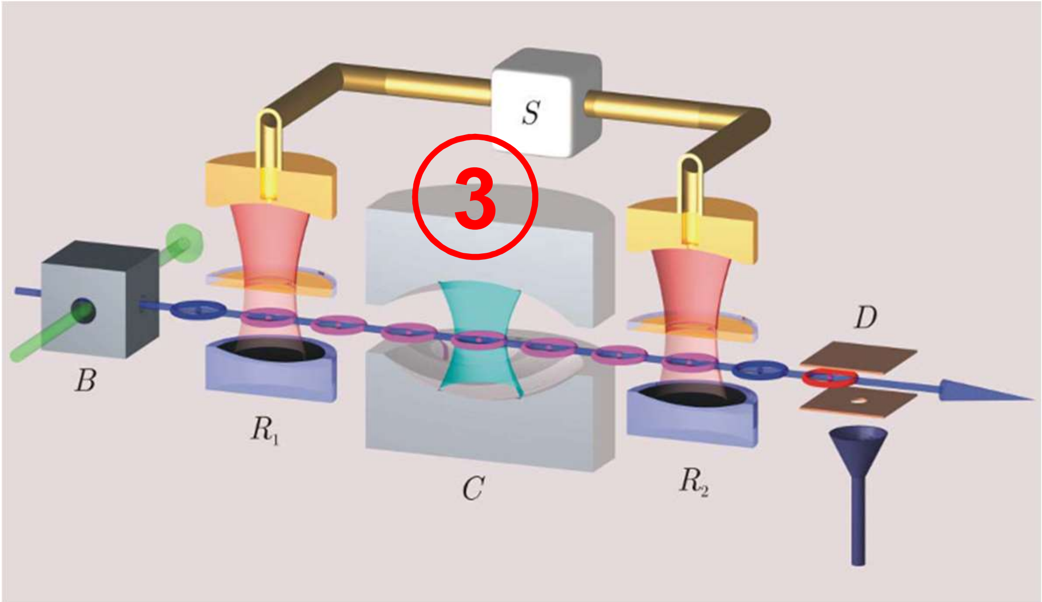


Gleyzes, S., Kuhr, S., Guerlin, C. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

1. In R_1, atoms undergo a change to a superposition state of |e⟩ (n=51) and |g⟩, $(|e\rangle + |g\rangle)/\sqrt{2}$

Experiment 1: Birth, life and death of a photon

3. Interaction of the atom with cavity *C*. Different photon state in cavity → different interaction. Atomic state gains a phase shift $\Phi(n,\delta)$, become $(|e\rangle + \exp[i\Phi(n,\delta)]|g\rangle)/\sqrt{2}$



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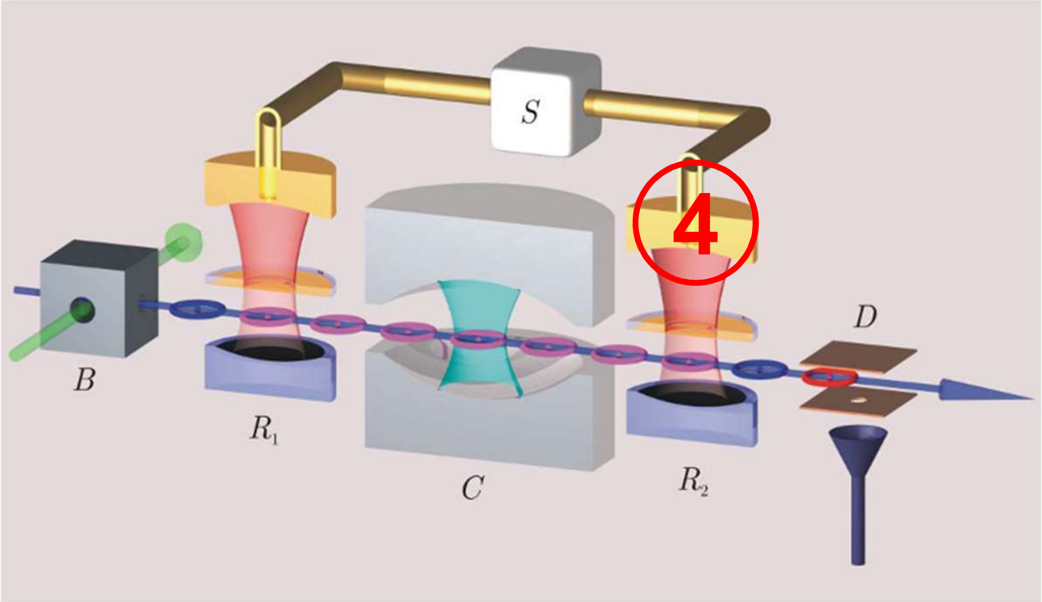
3. In R_2, the Ramsey pulse brings the atom to state |g⟩ if *n=0*, and to state |e⟩ if *n=1*



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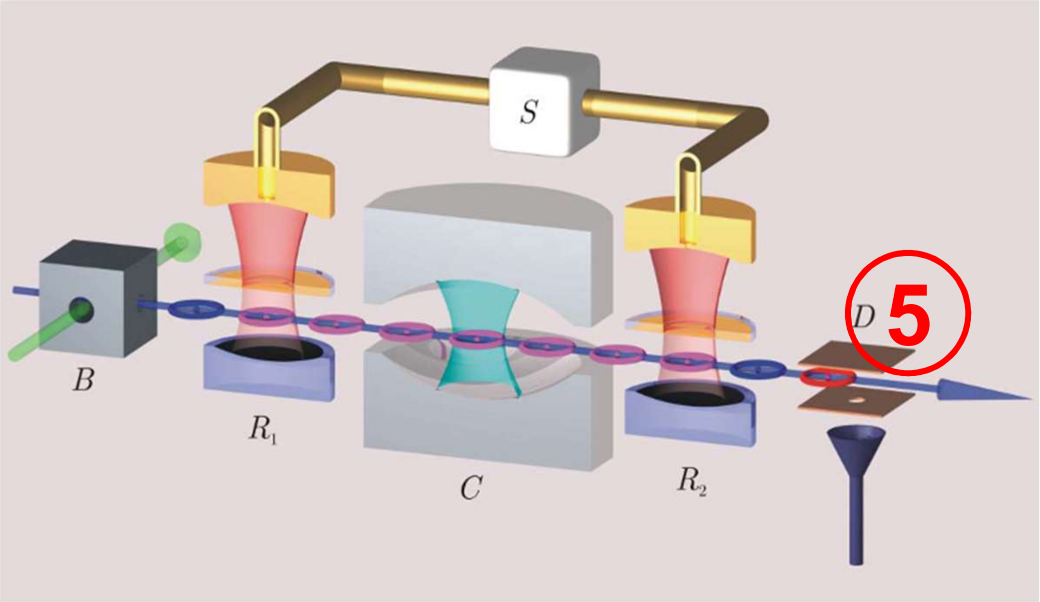


Gleyzes, S., Kuhr, S., Guerlin, C. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

5. Detector counts the number of atoms

Experiment 1: How does it detect quantum jumps?

Detecting quantum jumps

- Measuring the states of atoms → infer the photonic state
- If $|g\rangle \rightarrow |0\rangle$, if $|e\rangle \rightarrow |1\rangle$
- Obtain photon numbers as a function of time

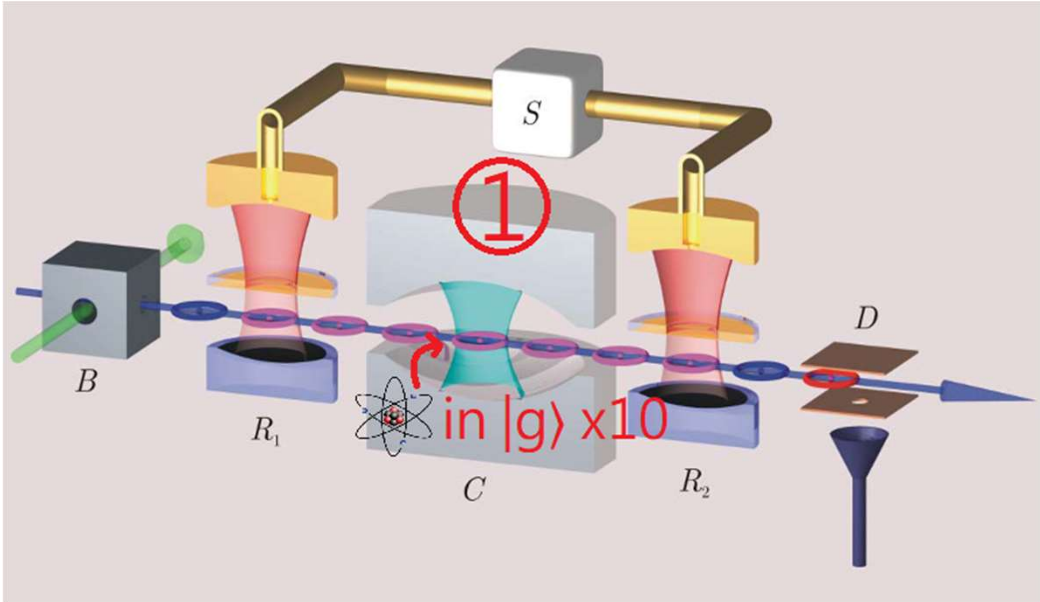
Is it perfect?

- No! Conditional probability: $P(g|1) = 13\%$, $P(e|0) = 9\%$
- Majority vote involving 7 more atoms at any time
- Reduced probabilities: $P(g|1) = 0.14\%$, $P(e|0) = 0.025\%$

Experiment 2: Decay of the |1⟩ state

- Just some additional steps compared to experiment 1

1. Photonic state initialized to |0⟩ by using ~10 atoms in |g⟩, tuned to resonance with cavity mode. No photon left in *C*.

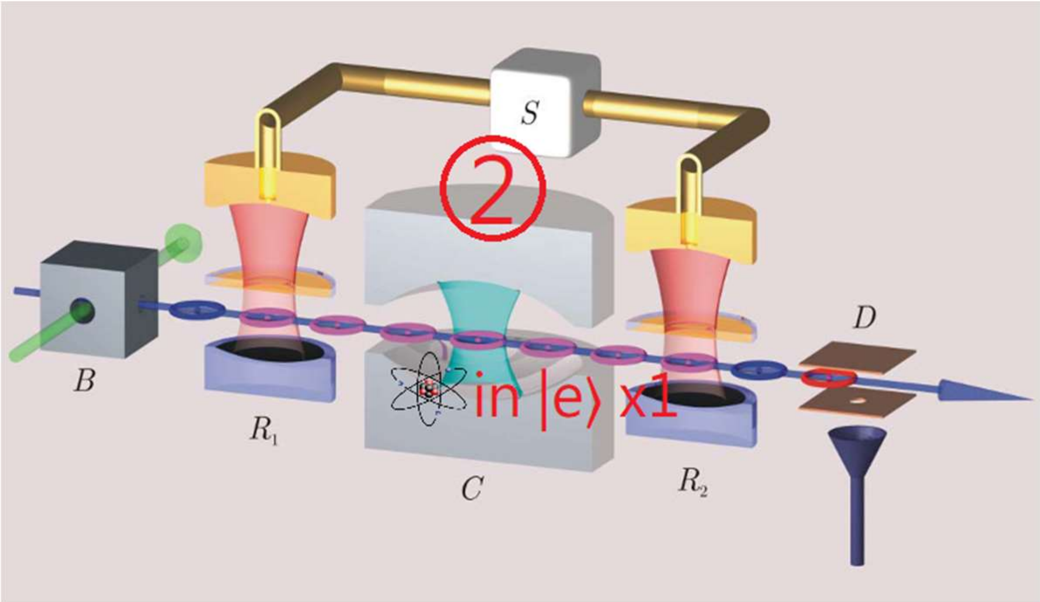


Gleyzes, S., Kuhr, S., Guerlin, C. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

Experiment 2: Decay of the |1⟩ state

2. 1 rubidium atom in state |e⟩ sent to *C*. Interaction time adjusted such that it exits *C* in |g⟩ and leaves *C* in |1⟩

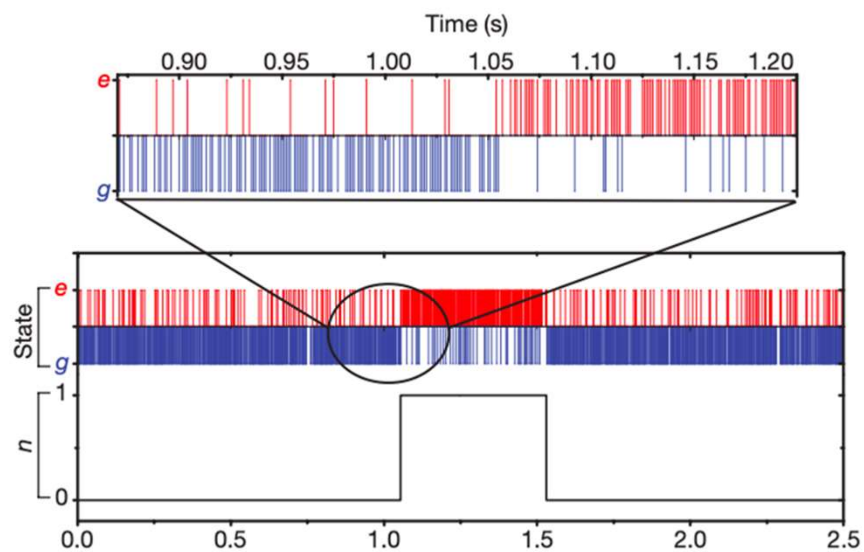
2. Same as the steps in experiment 1



Gleyzes, S., Kuhr, S., Guerlin, C. *et al.* Quantum jumps of light recording the birth and death of a photon in a cavity. *Nature* 446, 297–300 (2007).

Data and Results - Field Fluctuations

- 2.5 s experiment of 2241 counts
- Creation event at t = 1.054 s
  - 0.476 s lifetime



- Background average occupation
  $n_0 = 0.063 \pm 0.005$
  $n_t = 0.049 \pm 0.004$
- Characterize atom emission heating as 10^{-4} per atom per second

Data and Results - Single Photon State Decay

- Progressive averaging reveals exponential in ensemble decay evolution
- First-quantum-jump histograms

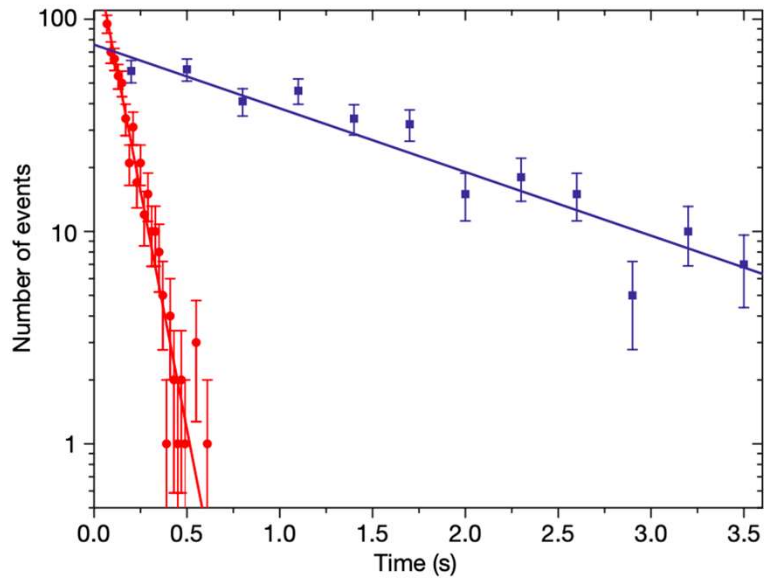
Time Constants

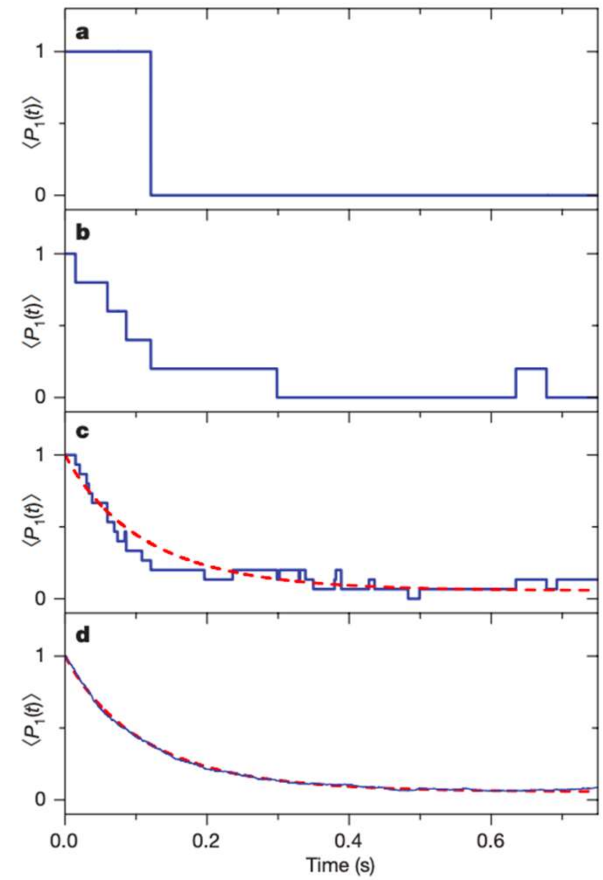
$$|1\rangle : \quad \frac{T_c}{1+3n_0} = 0.109\ s$$

$$T_1 = 0.097 \pm 0.005\ s$$

$$|0\rangle : \quad \frac{T_c}{n_0} = 2.05\ s$$

$$T_0 = 1.45 \pm 0.12\ s$$

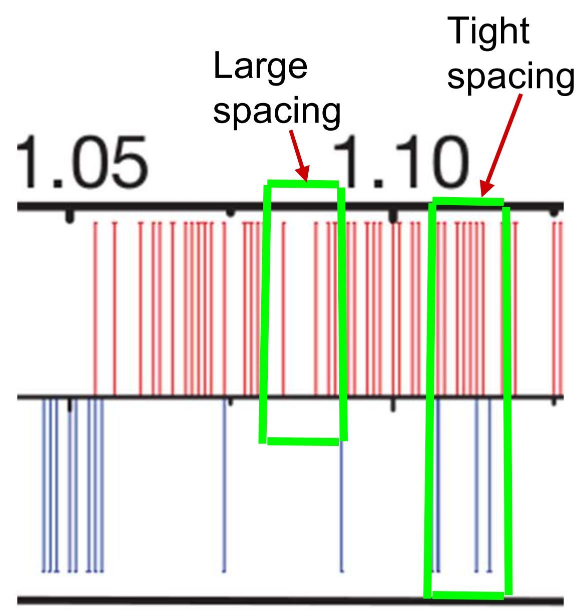




Critiques

- Multiple readings required to find critical details.
- Claiming to record the birth and death of photons is contrived when using a polling method.
- Setup measures n=1 and n!=1.
- Setup is not precise enough to distinguish expected stimulated decay contributions in experiment 2.
    - $T_{1,measured} = 0.097 \pm 0.005s$; $T_{1,expected} = 0.102 \pm 0.004s$
    - What do the error bars mean?
- Time between atomic detections is random.
    - $P_{measurement} = 0.063$

"In this experiment, the detection does not distinguish between [state 2] and [state 0]."



Author’s Conclusions

- Successful quantum non-demolition measurements on photons
- Observation of cavity photon’s “birth” and “death”
- Demonstration of well-established ensemble behavior

Citation Evaluation

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Nature
Volume 446, Issue 7133, 15 March 2007, Pages 297-300

Quantum jumps of light recording the birth and death of a photon in a cavity (Article)
(Open Access)

Gleyzes, S.[a], Kuhr, S.[a,c], Guerlin, C.[a], Bernu, J.[a], Deléglise, S.[a], Busk Hoff, U.[a], Brune, M.[a], Raimond, J.-M.[a], Haroche, S.[a,b]

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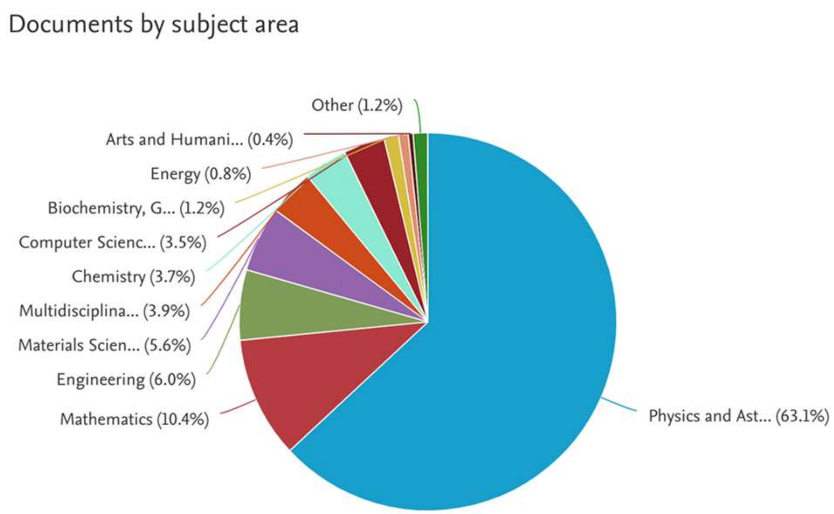

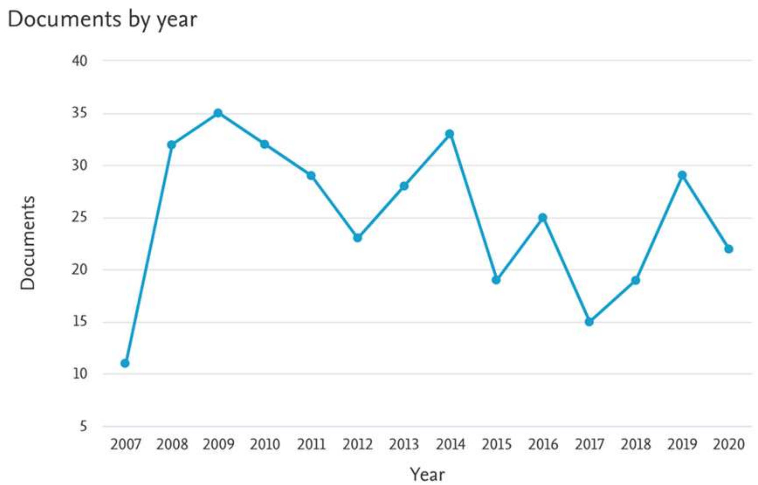

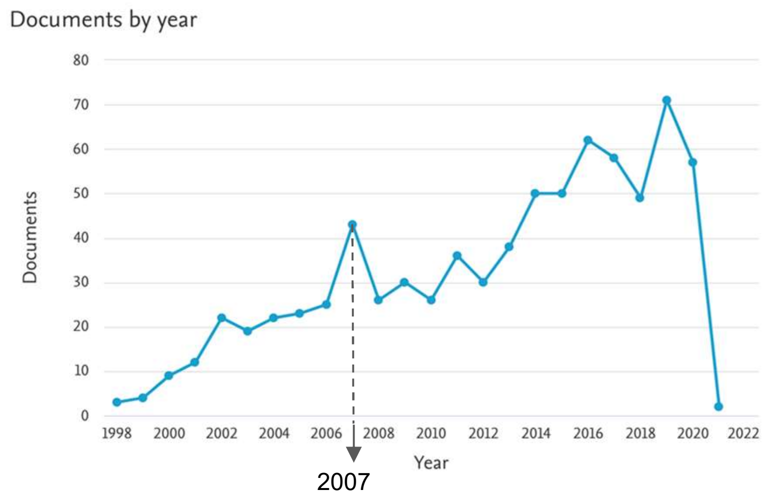

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Citation Evaluation

- *“A spectacular recent achievement is the ability to perform quantum 'non-demolition' experiments, in which photons in a microwave cavity can be monitored without destroying them, revealing the progressive collapse of the wavefunction under successive measurements.” (R. J. Schoelkopf & S. M. Girvin, 2008)*
- *“As their most spectacular sensing application, Rydberg atoms in vacuum have been employed as single-photon detectors for microwave photons in a cryogenic cavity in a series of experiments that was highlighted by the Nobel prize in physics in 2012.” (Degen et al., 2017)*