Experimental realizations of quantum trajectories: the quantum jumps of light

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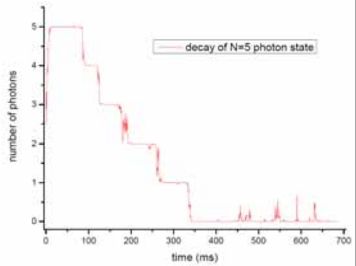

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Quantum jumps

- A striking quantum trajectory
  - a single quantum system
    - slowly evolving
    - frequently measured by an ideal projective quantum measurement
      - Evolves, in a single realization of the experiment, by sudden jumps between eigenstates of the measured observable
  - Evolution in a particular trajectory
    - differs from classical evolution
    - differs from usual continuous evolution predicted by quantum statistical averages.

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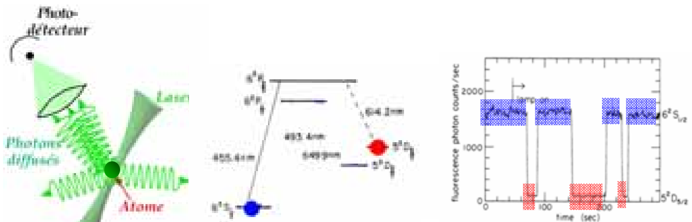
Quantum jumps for a trapped ion

- A paradigmatic example of quantum jumps



Nagourney et al. (1986)

- First experimental realization of quantum trajectories
- Quantum jumps also observed for other matter particles (electrons, molecules, atoms, artificial qubits)
- In all these experiments, a matter particle is interrogated by light
- Is is possible to observe the quantum jumps of light?
  - need an ideal photodetector, realizing a projective measurement

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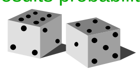
Ideal quantum measurement

- The most intriguing aspect of quantum theory
  - Simple postulates for an ideal (projective) measurement
    - Quantum discontinuity
      - not all results allowed
        - » eigenvalues of the measured observable
    - Statistical results
      - predict only measurement results probabilities
        - » 'God is playing dice'



- State collapse and repeatability
  - two identical measurements in a short time interval always give identical results
    - » state projected onto an eigenstate of the observable

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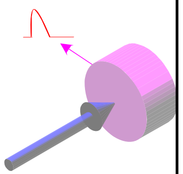
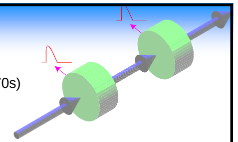
Ideal and real quantum measurements

- Most quantum measurements are far from ideal

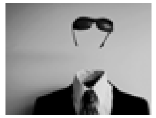


  – e.g. Photodetection (counting photons)
    - measurement of light field energy
      – quantized result: number of photons
      – statistical: photon number statistics
      – repeatable?
    - Photodetectors (PM's, photodiode, retina) absorb incoming photons, converting their energy into an electrical/chemical signal.
      – A second detection always gives zero: impossible to 'see' the same photon twice
      – The field state is demolished by the detection
    - This demolition is not a requirement of quantum mechanics

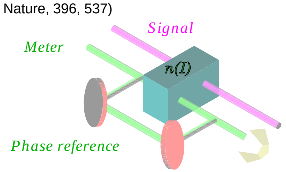
Ideal photon number counting



- Quantum non-demolition measurements (Braginsky, 70s)
  – A transparent photocounter
    - 'see' the same photon twice
  – provides vision to the invisible man…



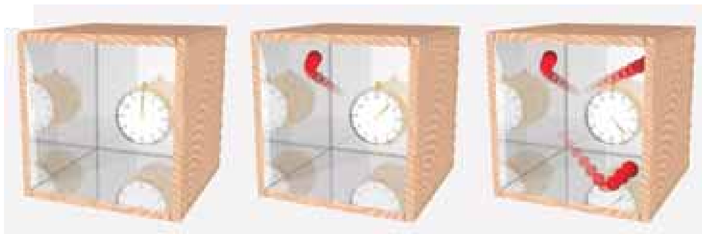
- Realized in the optical domain (Grangier et al, Nature, 396, 537)
  – no single photon resolution
    - weak non-linearity
  – propagating fields:
    - repetition difficult
  – Not appropriate for quantum jumps observation



Quantum jumps of photons?

- A QND photodetector operating at the individual photon level
- A photon 'box' able to store a photon for a long time
  - back to Einstein's dream

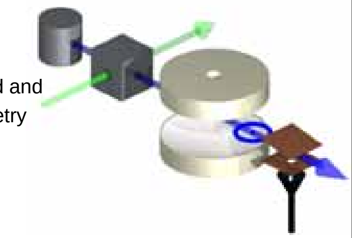
Yet another gedankenexperiment



- A clock whose ticking rate is determined by the number of photons in a box
- The final clock hand's position directly measures the photon number

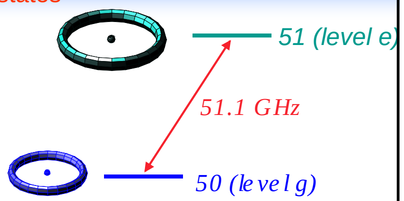
Our boxes and clocks

- Photon box
  - a superconducting microwave cavity
    - longest available photon storage time
- Clock
  - circular Rydberg states
    - state superpositions prepared and probed by atomic interferometry
- Interaction
  - Cavity quantum electrodynamics
    - spin/spring system
      - matter-field coupling at its simplest
      - also in optical CQED, circuit QED, ion trap physics

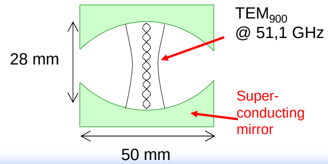


Circular Rydberg states

- Nearly ideal atoms
  - Mesoscopic orbit size
    - 0.25 µm diameter
  - Long lifetime (30ms)
  - Large coupling to radiation
  - tunable via the Stark effect
  - Efficient (> 80%) state sensitive detection

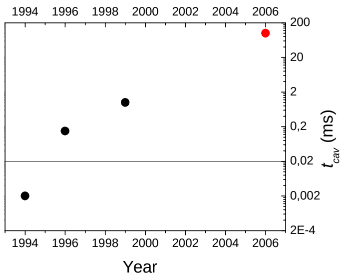


  - compatible only with open cavities
    - static directing electric field
  - Fabry Perot (open) cavities
  - essential parameter
    - photon lifetime



A box for microwave photons

- optimization of the cavity quality
  - a long (painful !!) process
    - our pet Moore's law



- extrapolations might not be safe….

A box for microwave photons

- An ultra-high finesse cavity
  - Best lifetime: 0.13 s @ 0.8 K

• quality factor:
• $Q = \omega T_c = 4.2 \cdot 10^{10}$
• Finesse
• $F = 4.6 \cdot 10^9$

- during this macroscopic time interval a photon
  - bounces 1.1 billion times on the mirrors
  - travels 40 000 km
    - » if it was in an optical fiber: attenuation 0.00011 dB/km !!
- Best mirrors so far, in any frequency domain !

S. Kuhr et al, APL **90**, 164101 (2007)

A new mirror technology

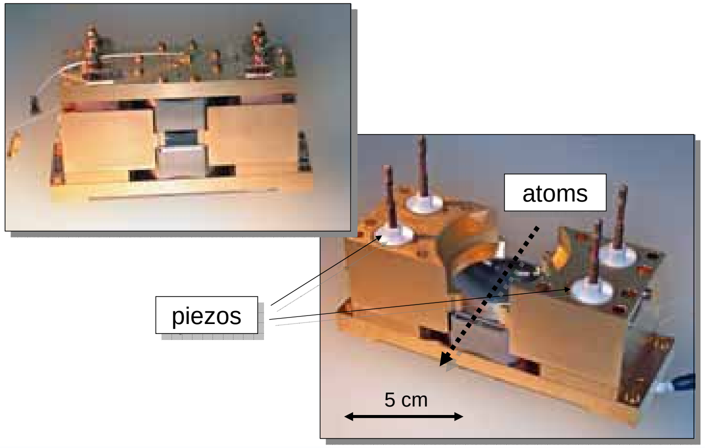
- Copper substrates
  diamond machining
  ~shape accuracy 300 nm ptv
  ~rugosity 10 nm
  Toroidal surface ➔ single mode

- 12 µm Niobium layer
  Cathode plasma sputtering
  CEA, Saclay

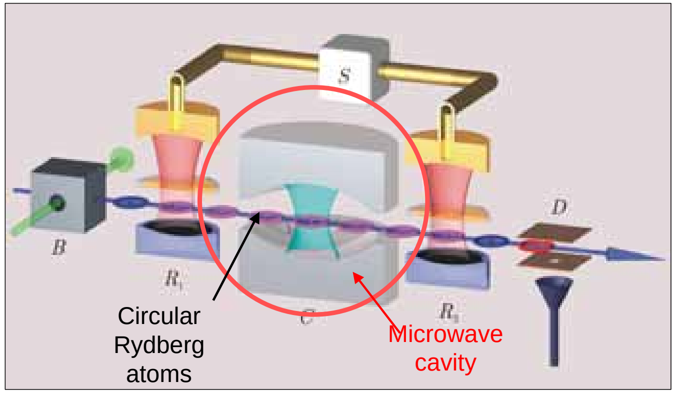
  [E. Jacques, B. Visentin, P. Bosland]

S. Kuhr et al, APL, **90**, 164101

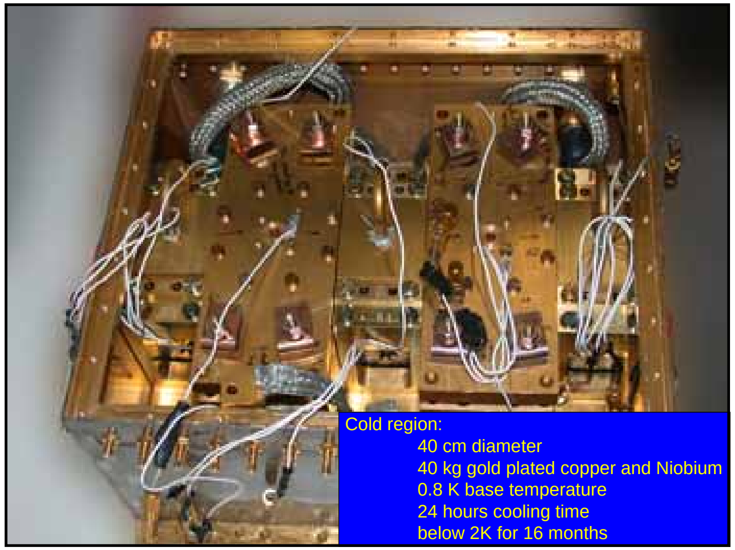
Cavity assembly



Experimental set-up



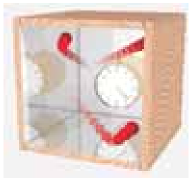
RMP **73**, 565



Cold region:
- 40 cm diameter
- 40 kg gold plated copper and Niobium
- 0.8 K base temperature
- 24 hours cooling time
- below 2K for 16 months

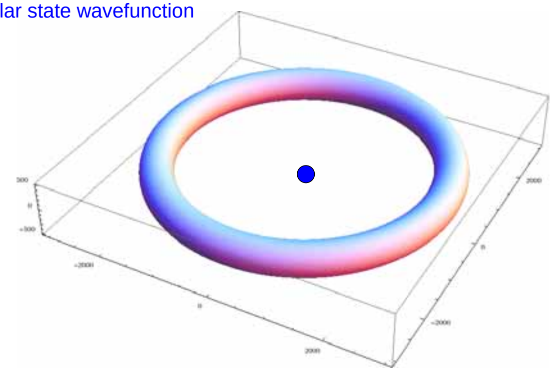
A QND photon measurement process

- How to 'see' a photon with an atom without absorbing it ?
  - non-resonant (dispersive) atom-field interaction
  - no energy exchange
    - no photon emission or absorption
  - Light shifts
    - atomic levels shifted by the photon field
      - Photon number-dependent light shifts
    - Find a clock's hand on the atom ?



An atomic clock

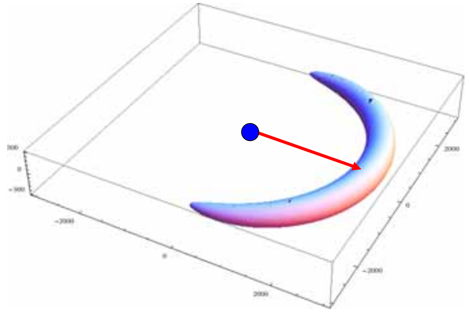
- Circular state wavefunction



  - Electron delocalized on Bohr's orbit: No phase information
  - Zero atomic dipole
  - Not a very good clock: no hands…

An atomic clock

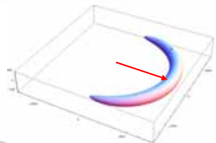
- A superposition of *e* and *g*
  - |*e*>+|*g*>
  - Prepared by a $\pi/2$ pulse of resonant classical microwave

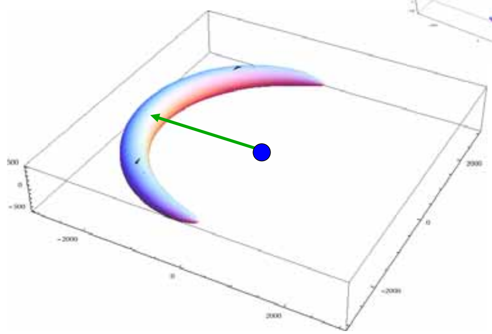


- 'well defined' phase of the electron on the orbit
- Non-zero electric dipole: the clock's hand

An atomic clock

- A superposition of *e* and *g*
  - |*e*>-|*g*>



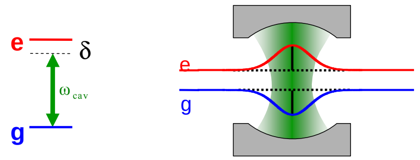


- Opposite dipole
- quantum state orthogonal with |*e*>+|*g*>

An atomic clock

- Distinguishing orthogonal states
  - A second $\pi/2$ pulse (identical to that preparing |e>+|g>) transforms
    - |*e*>+|*g*> into |*g*>
      - Addition of the two pulses
    - |*e*>-|*g*> into |*e*>
      - Subtraction of the two pulses
        - » A consequence of unitarity
      - Different final atomic energies, easily distinguished by the field ionization detection
      - Note: the energy for the transition is provided by the classical resonant microwave field

Dispersive atom-field interaction

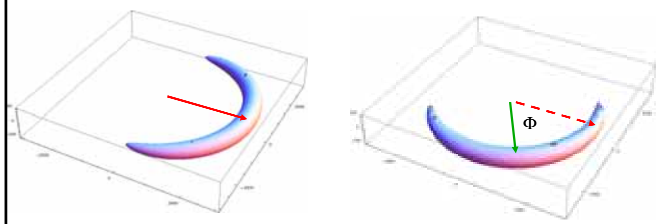


- Atomic frequency shift inside the cavity
  - 'clock' ticking rate modification $\frac{\Omega_0^2}{2\delta}(n+1/2)$ $\Omega_0/2\pi = 50\,\mathrm{kHz}$
    - ½ contribution: cavity-induced Lamb shift effect (PRL **72**, 3339)
      - fixed shift: no influence on QND measurement
    - *n* contribution: light shift at the single photon level (also observed in circuit QED -- Nature **445**, 515)
- Adiabatic coupling in and out of the atom-cavity interaction
  - negligible spurious absorption rate ($<10^{-4}$ for $\delta \sim \Omega$)

Phase shift of the atomic dipole

- A $\pi/2$ microwave pulse prepares the |*e*>+|*g*> superposition before atom-cavity interaction
- Light shift accumulated over atom-cavity interaction time t_i
  - A phase shift of the atomic dipole

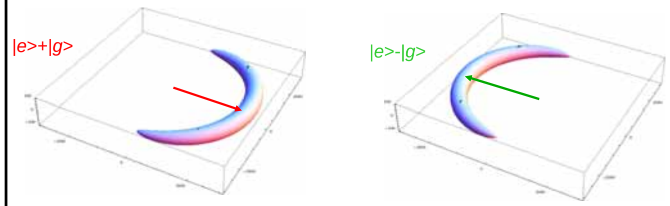
$$\Phi = \Phi_0 n \qquad \Phi_0 = \frac{\Omega_0^2}{2\delta} t_i$$



- Final states are generally not orthogonal

A simple case

- Field containing zero or one photon
  - π phase shift per photon for the dipole: $\Phi_0=\pi$
  - Two orthogonal final states

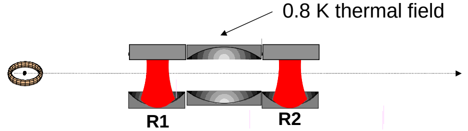


Zero photon (no shift) One photon (π phase shift)

- A second $\pi/2$ pulse of resonant microwave leads to *e* and *g*
  - *g* for zero photon
  - *e* for one photon

Repeated measurement of a small thermal field

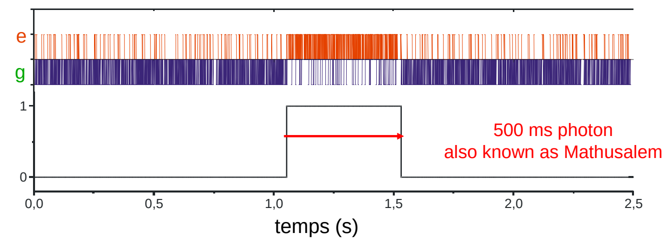
- Probe the cavity equilibrium thermal field
  - 0.8 K, 0.05 photon on the average



  - 50 000 atomic probe samples
    - separated by 70 µs
    - over a 3.5 s time interval
    - each undergoing the full Ramsey sequence
  - 0.1 atom in each sample (no two-atoms events)

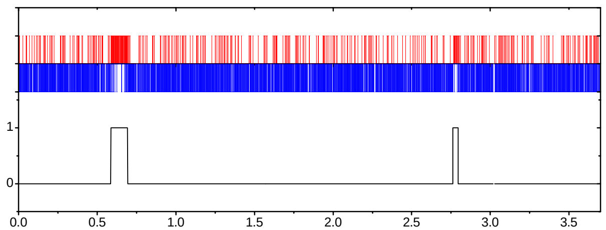
Birth, life and death of a photon

T=0.8 K n_{th}=0.05



Gleyzes et al, Nature, **446**, 297 (2007)

Birth, life and death of two photons



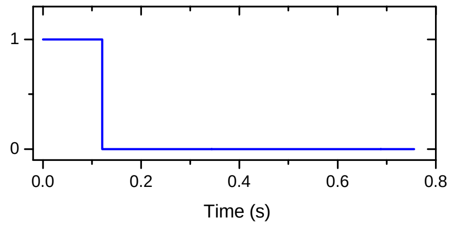
Gleyzes et al, Nature, **446**, 297 (2007)

Witnessing the death of a photon

- Quantum trajectories starting from n=1:
  - Erase cavity field with atomic samples in *g*, tuned at resonance (via the Stark effect). High efficiency preparation of the vacuum state.
  - Prepare the one-photon Fock state
    - emission of a single atom prepared in *e*, tuned at resonance
  - Repeatedly probe the cavity
    - 10 000 atomic samples over 700 ms

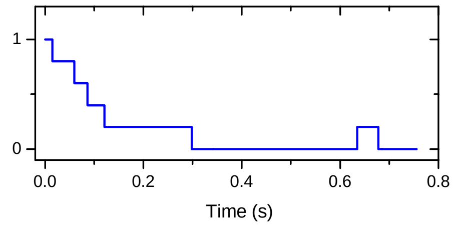
Witnessing the death of a photon

1 sequence :



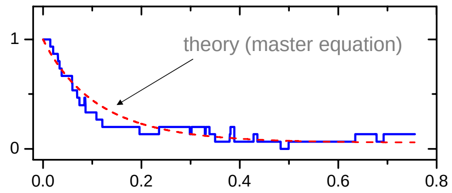
Witnessing the death of a photon

5 sequences :



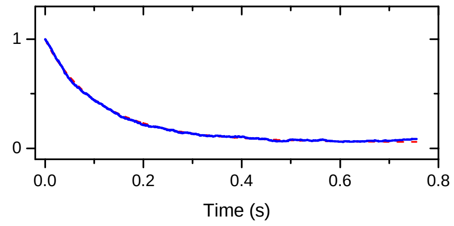
Witnessing the death of a photon

15 sequences :



Witnessing the death of a photon

904 sequences :

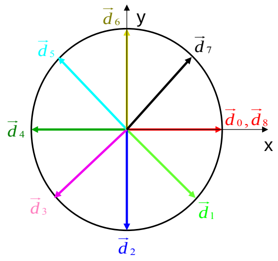


Smooth decay predicted by master equation retrieved by an ensemble average

A direct illustration of the difference between individual realizations of quantum trajectories and quantum averages

Counting up to seven ?

- $\Phi_0=\pi/4$ phase shift per photon
  - Eight different final orientations of the atomic dipole



Quantum ambiguity: non-orthogonal final states
How can we distinguish them ?

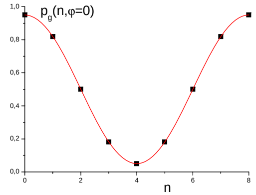
Final detection probabilities

- State after a second $\pi/2$ pulse (identical to the first, phase $\varphi=0$)

Probability $p_g(n,\varphi)$ for detecting g:

$$p_g(n,\varphi=0)=\frac{1}{2}\left(1+\overrightarrow{d_n}\bullet\overrightarrow{u_x}\right)$$

Linear function of the x component of the (normalized) atomic dipole

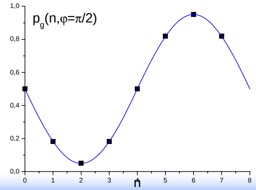


- State after a second $\pi/2$ pulse (in quadrature with the first, phase $\varphi=\pi/2$)

Probability $p_g(n,\varphi)$ for detecting g

$$p_g(n,\varphi=\pi/2)=\frac{1}{2}\left(1+\overrightarrow{d_n}\bullet\overrightarrow{u_y}\right)$$

Linear function of the y component of the (normalized) atomic dipole

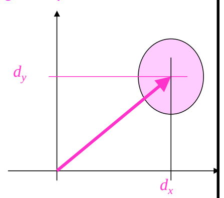


One atom is not enough

- Knowledge of $p_g(\varphi=0)$ and $p_g(\varphi=\pi/2)$ determines d_x and d_y and hence n
- A single atomic detection provides only binary information
  - *e* or *g*
  - Not enough information to determine *n*
  - Two no-go theorems
    - The state of a single quantum system cannot be measured
    - A single bit is not enough to count from zero to seven
- More than one atom needed to determine the photon number

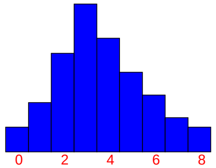
Counting by accumulating information

- Initial cavity state: $\sum_n c_n|n\rangle$
- One-atom cavity state: $\sum_n c_n|n\rangle\otimes|\vec{d}_n\rangle$
- *N* atoms-cavity state: $\sum_n c_n|n\rangle\otimes\left(|\vec{d}_n\rangle\right)^{\otimes N}$
  - Entanglement of the photon number with a mesoscopic atomic sample
  - All atoms have the same dipole orientation for a given photon number
- Split atomic sample in two parts
  - On *N*/2 atoms, second $\pi/2$ pulse with $\varphi=0$
    - Measure p_g i.e. *x*-component of dipole, d_x
  - On *N/2* atoms, second $\pi/2$ pulse with $\varphi=\pi/2$
    - Measure p_g i.e. *y*-component of dipole, d_y
  - Estimate dipole direction with $1/\sqrt{N}$uncertainty



Estimating the dipole direction

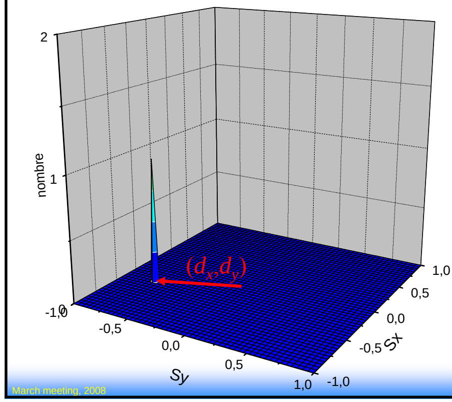
- A measurement sequence
  - initialize the cavity field
    - remove leftovers of previous experiments
    - inject a 3.5 photon coherent field
      - Poisson photon number distribution



  - measure the spin direction
    - send 110 atoms
      - analyze the final state with two Ramsey phase settings
      - compile the measurement results

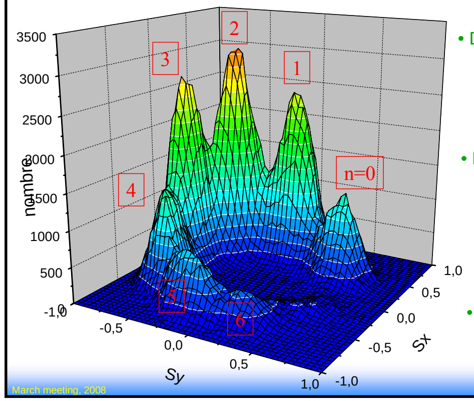
Dipole directions

- One measurement



Dipole directions

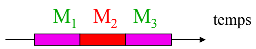
- Thousands of measurements



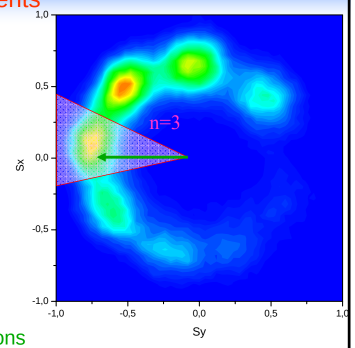
- Rotation of the dipole
  - evidence of light shifts
- Discrete priviledged directions:
  - field intensity quantized !!
  - quantum discontinuity
- Probability distribution
  - reveals the photon distribution
    - more on that soon
- Looks like a measurement
  - is it repeatable ???

Sequential measurements

- Three adjacent 110 atoms samples
  - three dipole measurements



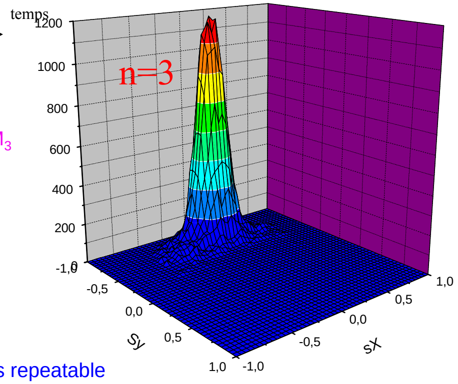
  - select those measurements such that n=3 for M_1 and M_3 (get rid of cavity relaxation)
  - plot the statistics of dipole directions for M_2



Sequential measurements

- Three adjacent 110 atoms samples

  - M2 always give the same result as M_1/M_3



  - The measurement is repeatable
    - ideal projective measurement of photon number !!

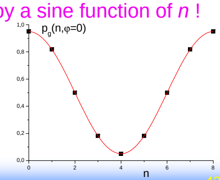
Progressive collapse of the field state

- Another view on the *N* atoms measurement sequence
  - each atom brings partial information on the field
  - each detection changes our knowledge of the field
    - each detection changes the photon number distribution we can infer
      - » Initial inferred distribution flat (no information)
      - » Each atomic detection changes it
      - » Final distribution (after enough atoms recorded): a single Fock state
  - Describe this progressive information acquisition by the Bayes law
    - an information-theory point of view equivalent to the state projection postulate.

C. Guerlin et al, Nature, **448**, 889

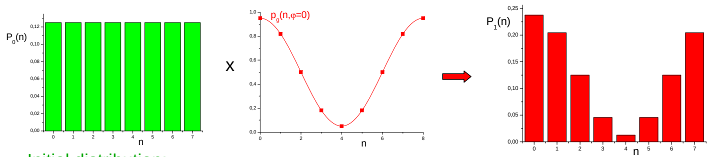
An elementary step in the collapse

- Inferred probability distribution after *k* atoms have been detected $P_k(n)$
- *k+1* th atom analyzed with phase φ for second $\pi/2$ pulse
  - Found to be in level *j* (*j=e* or *g*)
- New photon number distribution: $P_{k+1}(n) = P_k(n)\dfrac{p_j(n,\varphi)}{p_j(\varphi)}$
  - where $p_j(\varphi) = \sum_n P_k(n) p_j(n,\varphi)$ is the *a priori* probability for getting the atom in state j
- At each step, the inferred distribution is multiplied by a sine function of *n* !
  - Some photon numbers become less likely
  - Photon number distribution decimation



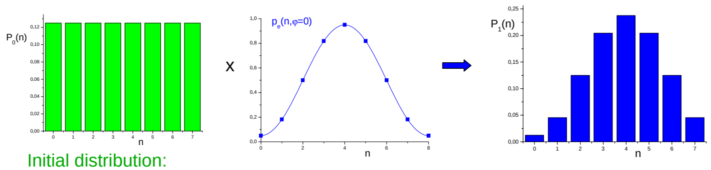
A photon number decimation process

- First step in the decimation process (*k*=0)



Initial distribution: no information

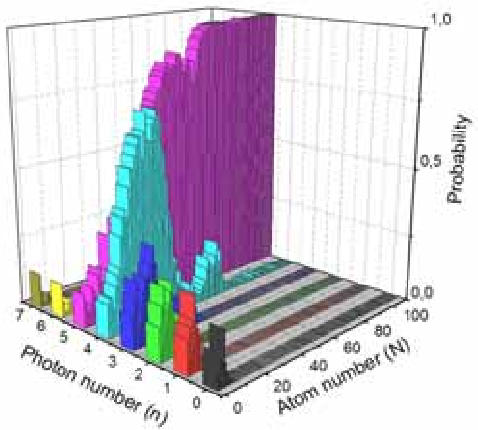
Atom detected in *g*



Initial distribution: no information

Atom detected in *e*

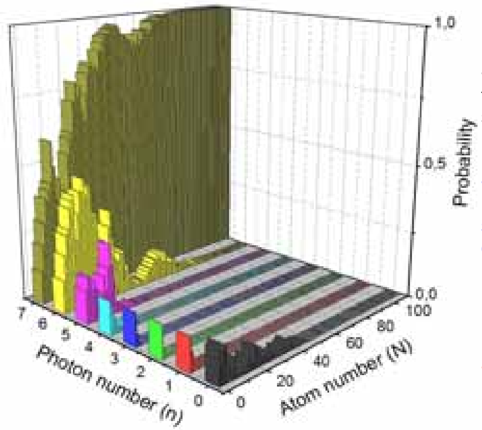
Wave-function collapse in real time



- Evolution of $P_k(n)$ while detecting 110 atoms in a single sequence
- Initial coherent field with 3.7photons
- Initial inferred distribution flat (no information) but final result independent of initial choice
- Progressive collapse of the field state vector during information acquisition

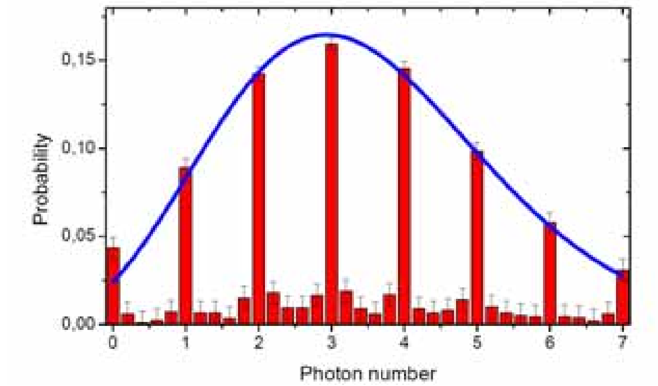
C. Guerlin et al, Nature, **448**, 889

Another sequence



- Final photon number flucutates randomly from sequence to sequence
- Statistics of final photon number should reveal the statistics of the initial quantum field (quantum measurement postulates)
- What about the measurement outcomes probabilities ?

Photon number statistics

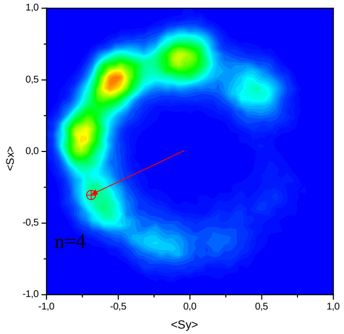


Excellent agreement with the expected Poisson distribution

Quantum jumps of light

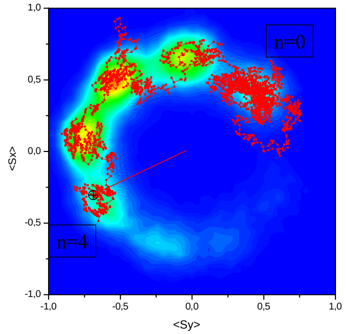
- Keep measuring the photon number over a long time
  - prepare a 3.5 photons coherent field
  - send atoms repeatedly
  - at each time infer the photon number from the last 110 atomic detections
    - dipole direction measurement
    - decimation process

Quantum jumps



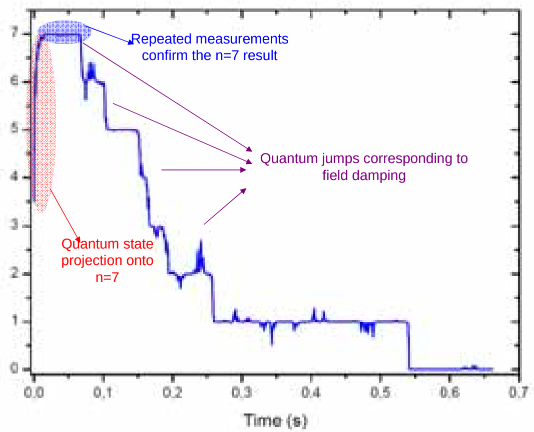
- A single realization of the experiment
- first 110 atoms detect 4 photons

Quantum jumps



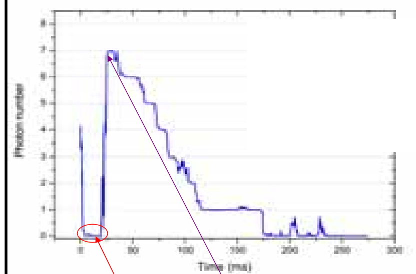
- A single realization of the experiment
- each new atomic detection used to estimate a new dipole direction
- A series of quantum jumps from 4 to 0 photons

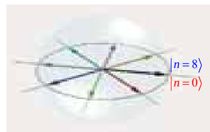
A quantum trajectory



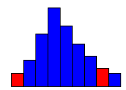
C. Guerlin et al, Nature, **448**, 889

An interesting trajectory: non-classical states





Interferometer counts n modulo 8: does not distinguish 0 and 8



$c_0|0\rangle + c_8|8\rangle$

QND detection modulo 8 can collapse field into a coherent superposition of vacuum and 8 photons!

This state decays according to:

$c_0|0\rangle + c_8|8\rangle \longrightarrow |7\rangle$

Measurement and dynamics

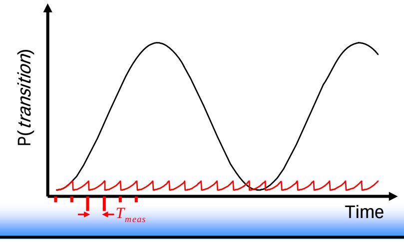
- For an incoherent (relaxation) process, the QND measurement does not affect the dynamics
  - – Relaxation is not sensitive to coherence
  - – Lifetime of the cavity states unchanged by the continuous monitoring
- A completely different situation for a coherent evolution

Quantum Zeno effect

- A watched kettle never boils
  - – coherent evolution of a system and frequently repeated quantum measurements
    - a quantum jumps evolution between eigenstates of the measured quantity
    - an evolution much slower than without measurements
    - no evolution at all in the limit of zero delay between measurements

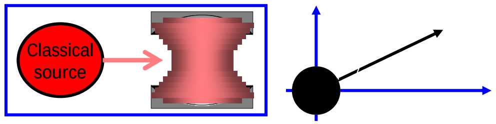
e.g. coherent evolution of a two-level system

Note: no Zeno effect for relaxation processes

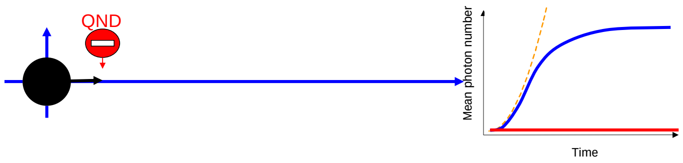


Quantum Zeno effect

- Coherent evolution: injection of a coherent field by a classical source



–Repeated injection of phase coherent pulses: an amplitude varying linearly with the number of injections (photon number varies quadratically).



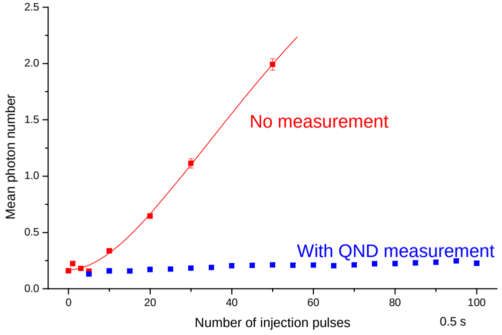
Principle of the experiment: perform QND measurements of photon number between two pulses

A difficult experiment

- Phase coherent injections over a second
  - – excellent control of cavity frequency (sub Hz stability)
    - The cavity is a quite sensitive multimeter!
      - – removal of acoustic noise, vibrations insulation
      - – temperature stabilization within 0.1 mK
      - – He bath pressure regulation below 1mb!
      - – PZT voltage regulated to 0.1 mV
  - – <0.3Hz drift over 15 minutes
  - – Measured cavity linewidth matches damping time
  - – inferred phase noise of a few degrees only over T_c

Quantum Zeno effect

- Field growth inhibition
  - 0.0018 photon per pulse (α= 0.042)
  - injection period: 5ms



A direct evidence of the quantum Zeno effect

Conclusion and perspectives

- Quantum jumps of light observed for the first time
  - a direct illustration of quantum measurement postulates
  - a single quantum controls the states of hundreds of atoms
    - promising for quantum information processing
  - preparation of highly non-classical field states
    - high photon number Fock states
    - Schrödinger-cat like superpositions
- Perspectives
  - exploration of the non-classical states
    - direct measurement of their Wigner function
    - decoherence studies
  - Towards non-local cat states shared by two cavities
    - interplay of Bell inequalities with decoherence

The ENS team

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  - S. Kuhr, I. Dotsenko
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  - EC (Conquest, Qgates, Scala)
  - CNRS
  - UMPC
  - IUF
  - CdF