Collaborations et financements

Laboratoire Kastler Brossel — Physique quantique et applications

# Quantum Non-Demolition measurement of light

*Équipe: Électrodynamique quantique en cavité:*
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Tutelles

## Aim of the experiment
- Achieve a Quantum Non-Demolition measurement.
- Count photons without destroying them.

## Methods
- Circular Rydberg atoms in a Ramsey interferometer.
- High finesse superconducting microwave cavity to store photons.

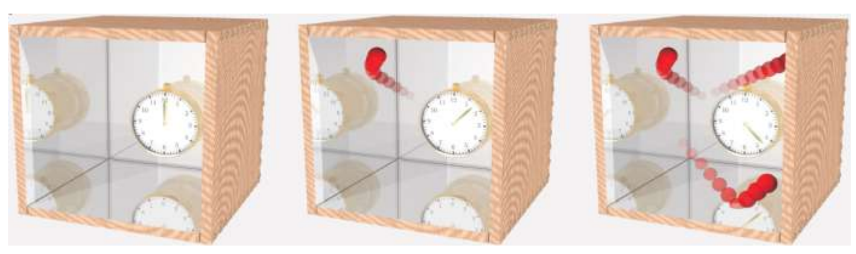
## Results
- Observation of the birth, live and death of individual photons.
- Measurement of up to 7 photon Fock states and monitoring of their collapse down to vacuum.
- Demonstration of the Quantum Mechanics postulates of measurement.

## References
S. Gleyzes *et al.*, Nature **446**, 297 (2007)
C. Guerlin *et al.*, Nature **448**, 889 (2007)

## Quantum non-demolition measurement …
- Described by the Quantum Mechanics measurement postulates: measurement of observable $\hat{A}$ on a system with density matrix $\hat{\rho}$
  - **Possible outcomes:** outcome of a measurement = one of eigenvalues $a_i$ of $\hat{A}$
  - **Probability law of measurement outcomes:** $p(a_i) = \left|\langle\psi_i|\hat{\rho}|\psi_i\rangle\right|^2$
  - **Projection postulate:** system ends up in an eigenstate $|\psi_i\rangle$
- Repeatability: both the system and the measured state $|\psi_i\rangle$ should be preserved

## … of light ?
- Counting photons without destroying them
  - Eigenvalues: number of photons $n$
  - Eigenstates : energy eigenstates = Fock, or photon number, states $|n\rangle$
- Usual photodetectors (photodiodes, eyes): absorb energy ➡ destructive measurement !!

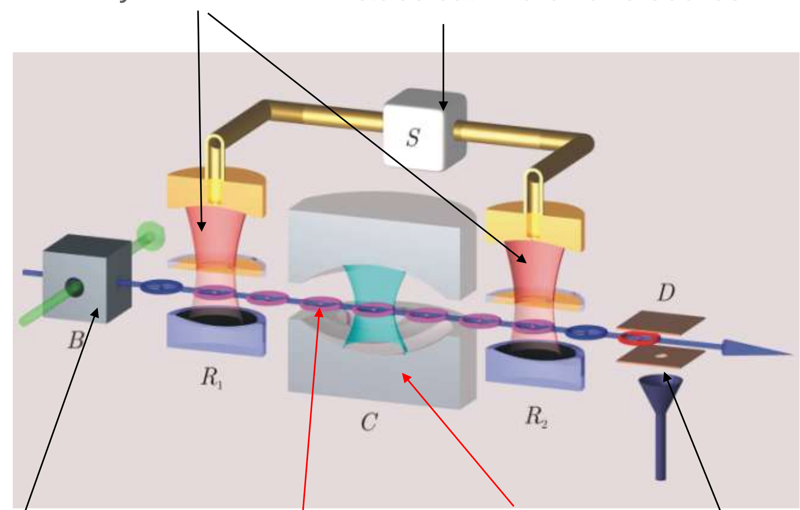
## Thought experiment
**Photon box** containing few photons
**Clock** whose rate is sensitive to photon number
$\pi/q$ **angular shift** of the hand per photon



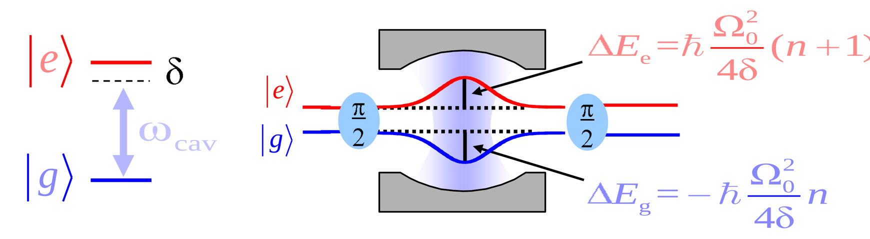

**measure the photon number = read the hour of the clock**

$0 \le n < 2q-1$ : unambiguous measurement of $n$
$n \ge 2q$ : the hand aims periodically toward the same directions
➡ $n$ measured **modulo 2q**

## Field dependent clock delay: Dispersive interaction




Dispersive interaction ➡ no energy exchange, only dephasing effects !




$\Delta E_e = \hbar\frac{\Omega_0^2}{4\delta}(n+1)$, $\Delta E_g = -\hbar\frac{\Omega_0^2}{4\delta}n$

Dephasing between $|e\rangle$ and $|g\rangle$ :

$$|e\rangle + |g\rangle \otimes |n\rangle \rightarrow |e\rangle + e^{i\Delta\varphi(n)}|g\rangle \otimes |n\rangle, \text{ where } \Delta\varphi(n) = \int \Delta E_e - \Delta E_g \, dt$$

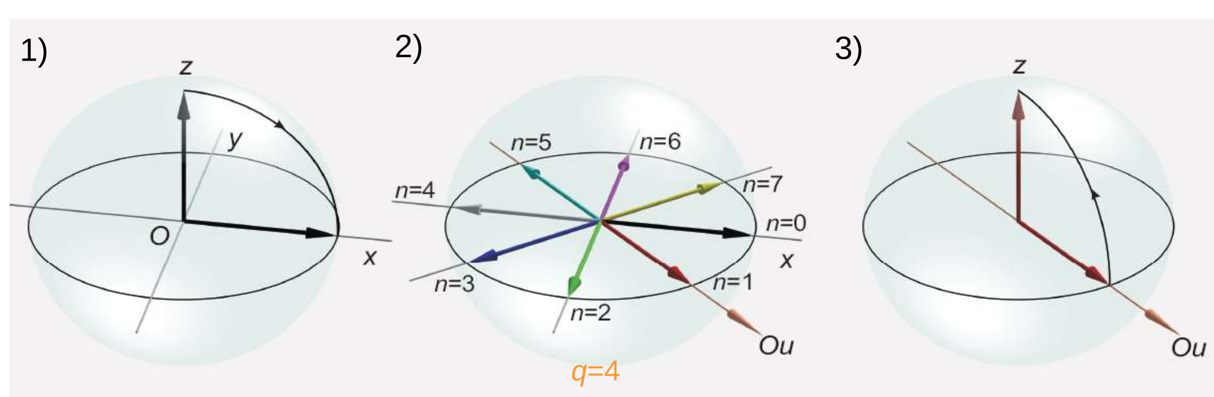
$$\Delta\varphi = \Phi(n+1/2)$$

Dephasing per photon $\Phi = \frac{\Omega_0^2 t}{2\delta}$

set to $\pi/q$ by choosing $\delta$ and the atomic velocity

## Reading the hand of the clock
- Injection of a small coherent field into the cavity
- Atoms prepared in the $|g\rangle$ state
- *1st Ramsey zone:* a first $\pi/2$ pulse (1) brings atoms to the $|e\rangle + |g\rangle$ superposition
- *Cavity:* phase shift (2) dependent on the photon number
  Resulting $|+\rangle_n$ states are not mutually orthogonal:
  final atomic state / number of photons } not determined in a single measurement… …except for q=1 !
- *2nd Ramsey zone:* a second $\pi/2$ pulse (3) combined with atomic state detection

➡ measurement of the atomic spin direction (Ou) dependent on the relative phase η between pulses




Probabilities of measuring $|\pm\rangle$ (e or g), given $n$ and η :

$$p(j,\eta|n) = \left[1 + \cos(n\pi/q - \eta + j\pi)\right]/2$$

angle between $|+\rangle_n$ and Ou
( $j$ = 0/1 for the +/- states )

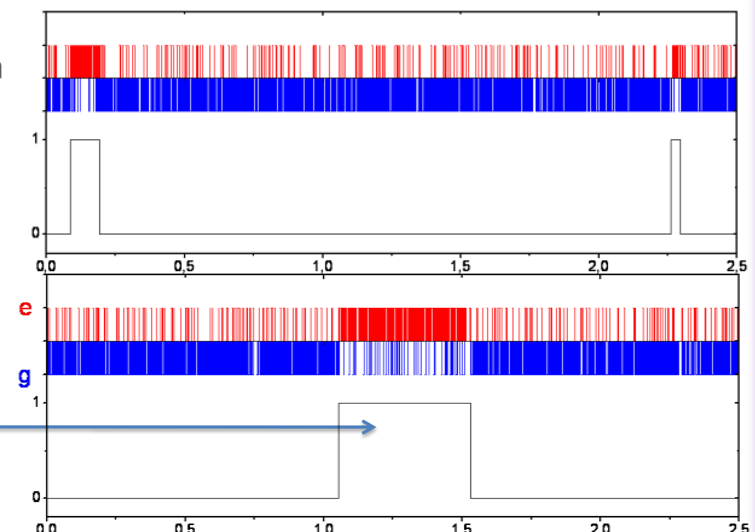
We measure the difference of population $P_e - P_g$, *i.e.* the observable:

$$\hat{T} = \cos\left[\eta + \Phi(\hat{N})\right]$$

## Birth, life and death of photons
- $q$ =1, *i.e.* $\Phi = \pi$ and $\eta = \pi$
  ➡ only 2 possible atomic states after the interaction: $|+\rangle_x$ ⇔ even $n$, $|-\rangle_x$ ⇔ odd $n$ — Parity measurement !
- For a small field: $P(n>1) \ll 1$ ➡ the parity defines $n$ !
  In this case each atomic detection determines completely the state of the field: $g$ ⇔ 0 photon, $e$ ⇔ 1 photon
- Equilibrium probed by sending an atom every ~1 ms.
- Quantum jumps between $|0\rangle$ and $|1\rangle$
- Mean value: $\langle n\rangle = 0.063$

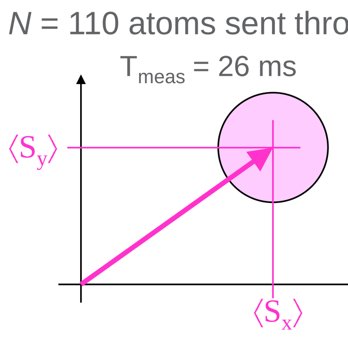
(0.049 for a 0.8 K thermal field)

Duration 0.5 s: exceptionnaly long-lived photon !




## Measurement of the photon number…
- q=4, *i.e.* $\Phi = \pi/4$:
  - Injection of a small coherent field into the cavity: $P(n>7) \ll 1$
  - Approximately 3500 atoms sent, separated by 0.2 ms during 700 ms. Detection phase η varies randomly among 4 different values.

## … by atomic spin tomography
- Measurement of spin components:
  - $N$ = 110 atoms sent through the cavity, $T_{meas}$ = 26 ms



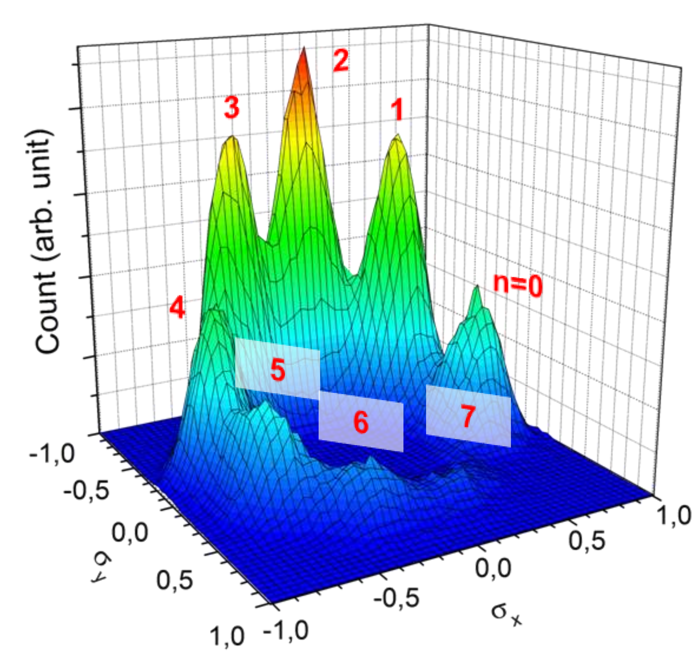

$\Delta S \propto \frac{1}{\sqrt{N}}$

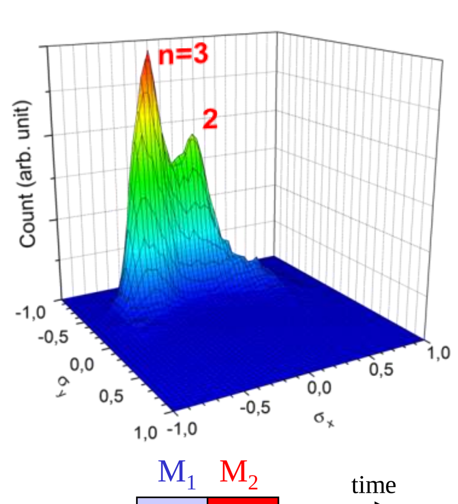
$$|\psi\rangle = \sum_n C_n \left|+_{n\Phi_0}\right\rangle^N \otimes |n\rangle$$

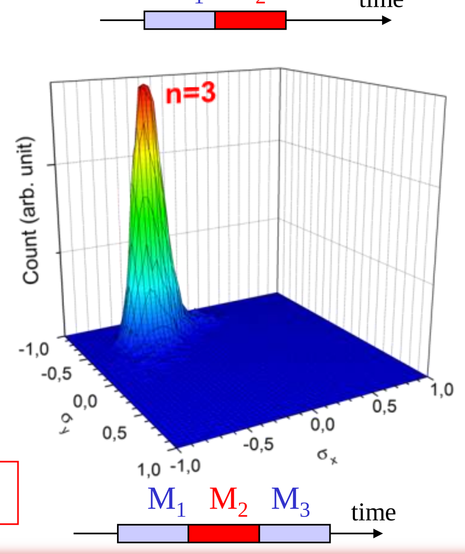
- $N$ copies of the same atomic state for each photon number

N/2 measure $\langle S_X\rangle$
N/2 measure $\langle S_Y\rangle$

- Measurement repeated 2000 times
- Histograms of the global atomic spin measured during these 2000 realizations




Atomic spin clearly points in preferred directions ! Each direction corresponds to one specific value of $n$

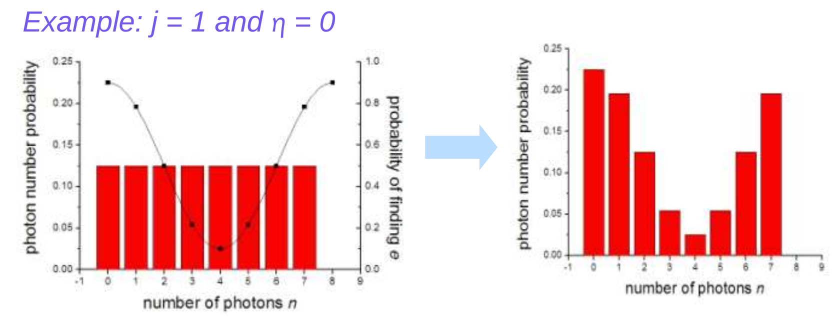
**Quantization of the photon number !**

## … by progressive field collapse
- No *a priori* on the field in the cavity: $P_0(n|n\le 7) = 1/8$
- At each atom detection, we get some information using Bayes' law :

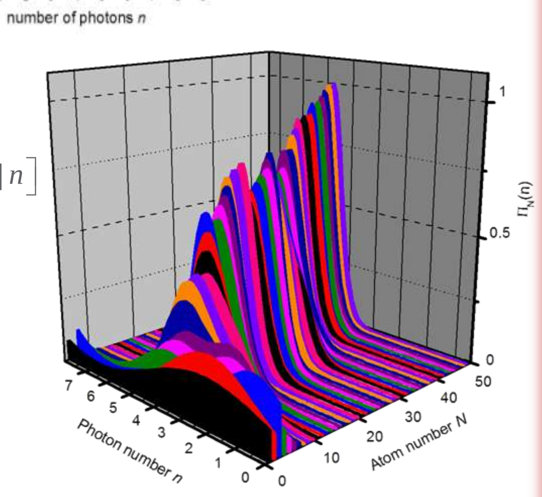
$$P(n|j,\eta) = P_0(n)\,p(j,\eta|n)$$

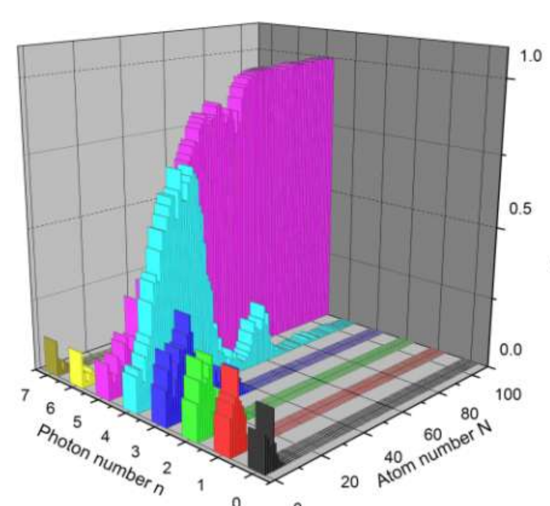
two possible outcomes: $|e\rangle$ (j=1) or $|g\rangle$ (j=0)
detection direction

*Example: j = 1 and η = 0*




- For $N$ detected atoms, we calculate $P_N(n) = \frac{P_0(n)}{Z}\Pi_N(n)$ where $\Pi_N(n) = \prod_{k=1}^{N} p[j_k,\eta_k|n]$
- $\Pi_N(n)$ converges toward a **narrow distribution**
- Thus $P_N(n)$ peaks at one value of $n$, **without any a priori knowledge** on the injected field




j 1 1 0 1 1 1 1 1 1 1 1 1 0 0 1 1 1 0 1 1 0 1 1 1 1
i d d c b c c a b c d a a d a a b a d d d b a d b c

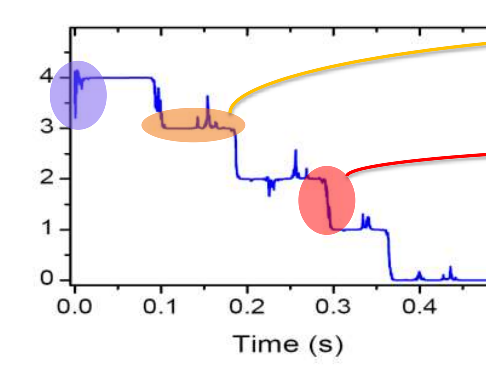
j 0 1 0 1 0 0 1 1 0 1 0 1 0 1 0 1 1 0 1 0 1 1 1 1 1
i d a b a b b a a c b c c d a d c c d c b a a a c c

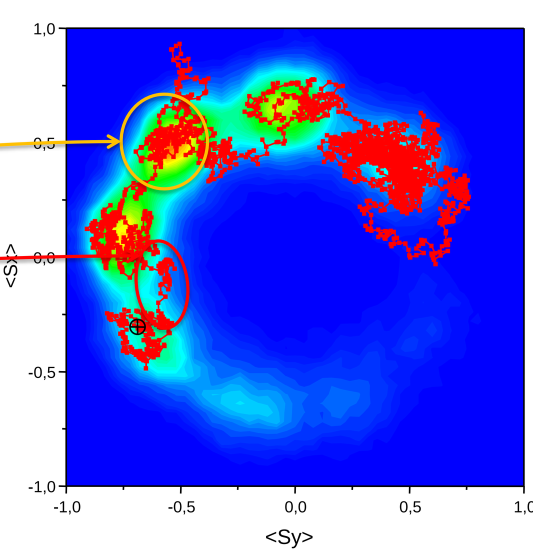
Typical sequence of detection of atoms (j) and their "phase" ($\eta_i$)

$\eta_a/\pi = -0.261 \pm 0.006$ $\eta_b/\pi = 0.015 \pm 0.007$
$\eta_c/\pi = 0.229 \pm 0.009$ $\eta_d/\pi = -0.464 \pm 0.013$

**After ~110 atoms, the unknow initial field collapses to a Fock state !**

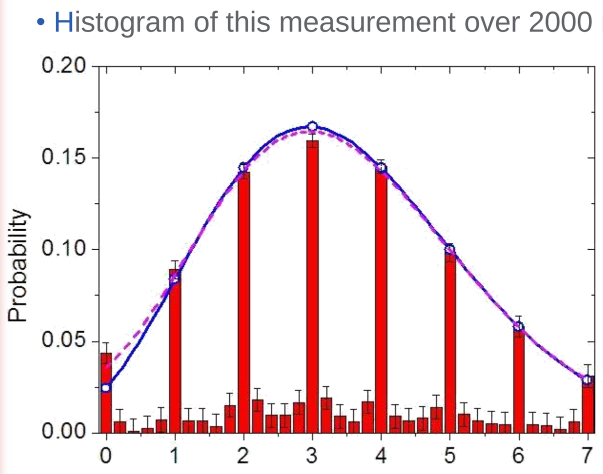
## Real-time field measurement
- Time evolution of the photon number / of $N$ consecutive atom pseudo-spin




- Verification of Quantum Measurement postulates :
  - **Projection** onto one of the discrete values of $n$
  - The same photon number is measured many times ➡ **Repeatability of the measurement**
  - **Quantum jumps** between discrete values of $n$: damping of the field caught in the act

## Measurement of the photon number distribution
- First 110 consecutive atoms ➡ measurement of the photon number of the initially injected field
- Histogram of this measurement over 2000 realizations




*Blue curve*
Excellent agreement with a Poisson law for $\langle n\rangle \cong 3.4 \pm 0.008$

*Magenta curve*
Taking into account the "modulo 8" measurement

**Direct verification of the Projection postulate**