Collaborations et financements

Laboratoire Kastler Brossel
Physique quantique et applications

Complete time-resolved reconstruction of cavity field quantum states

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Tutelles

Aim of the experiment

- Complete reconstruction of quantum states of trapped light fields.
- Observe time evolution of the cavity field and study its decoherence by performing time-resolved state reconstruction.

Methods

- Quantum non-demolition (QND) measurement of the photon number distribution after displacing a cavity field providing information on a whole density operator ρ.
- Reconstruction of ρ from measured raw data using maximum entropy principle.

Results

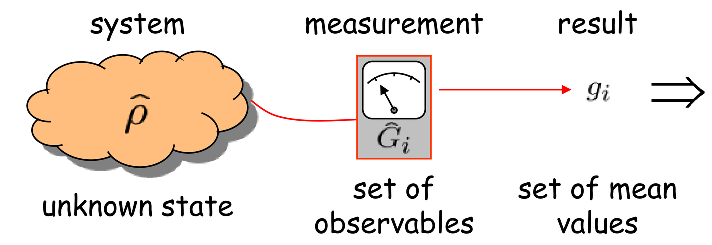
- Reconstruction of various field states illustrated by classical states, photon-number states and quantum superpositions of classical states ("Schrödinger's cat" states).
- Real-time observation of decoherence of the cat states revealing their fast evolution from initial quantum superposition to final classical mixture.

Reference

S. Deléglise *et al*., Nature **455**, 510 (2008)

Quantum state measurement

Being a statistical concept, the state cannot be inferred from a single system's realization, but can be reconstructed from an ensemble of copies by measuring non-commuting observables on different realizations.



Density operator satisfies: $\mathrm{Tr}[\hat\rho\,\hat G_i] = g_i$ (for all i)

General principle:

- QND of photon number ⇒ information only on diagonal elements of a density operator ρ (in a photon-number basis)
- QND after displacing ρ in a phase-space (i.e. controlled mixing of all matrix elements) ⇒ off-diagonal elements of ρ

Wigner function

a quasi-probability distribution in a phase-space (x,p):

$$W(\alpha) = \frac{2}{\pi}\,\mathrm{Tr}\left[\hat\rho\,\hat D(\alpha)\,e^{i\pi\hat a^\dagger\hat a}\,\hat D(-\alpha)\right], \quad (\alpha = x + i\,p)$$

Important properties of Wigner function
- completely characterizes a quantum state
- is easily adapted for a mode of an electro-magnetic field
- is negative for non-Gaussian non-classical states

Measurement operator:

"Generalized parity" operator in the displaced phase space

$$\hat G_i = \hat D(\alpha_i)\,\hat T\,\hat D(-\alpha_i)$$

Measurement procedure:

- Displace the cavity field by injecting in coherent field α_i:

$$\hat\rho^{(\alpha_i)} = \hat D(-\alpha_i)\,\hat\rho\,\hat D(\alpha_i)$$

$$\hat D(\alpha) = \exp(\alpha\hat a^\dagger - \alpha^*\hat a)$$

- Repeated QND measurement on the displaced field:

$$g_i = \mathrm{Tr}[\hat\rho^{(\alpha_i)}\hat T]$$

$$\hat T = \cos\left(\eta + \Phi(\hat N)\right)$$

Schrödinger's cat states

Preparation of phase cat states

1. Inject a small coherent field into the cavity:

$$|\beta\rangle = \frac{1}{2}(|\beta\rangle + |-\beta\rangle) + \frac{1}{2}(|\beta\rangle - |-\beta\rangle)$$

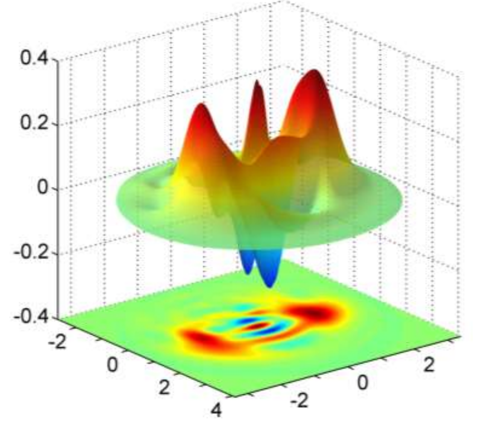
even n — odd n — Eigenstates of parity

2. Measure the field parity with one atom: $|e\rangle \to$ "odd" field; $|g\rangle \to$ "even" field

⇒ Parity measurement projects a coherent field onto a cat state:

$$\Psi_{\mathrm{even}} = \frac{1}{N}\left(|\beta\rangle + |-\beta\rangle\right) \quad \text{or} \quad \Psi_{\mathrm{odd}} = \frac{1}{N'}\left(|\beta\rangle - |-\beta\rangle\right)$$

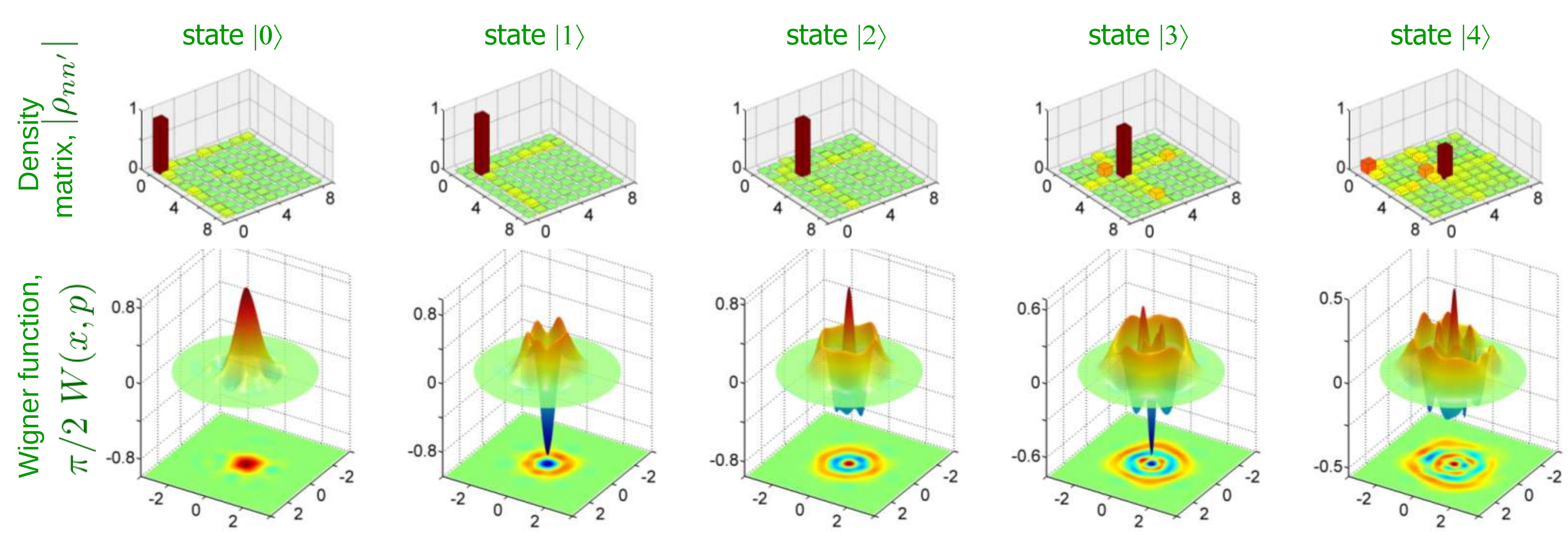
Wigner function – state tomography



Fock states

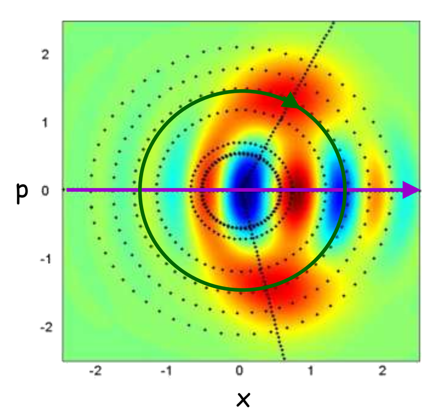
Reconstruction parameters:
- mean photon number per photon ϕ = 0.5 π
- two Ramsey phases η = 0 and π/2, sensitive to even and odd n

Wigner function properties:
- number of rings = number of photons
- value @ origin = state parity

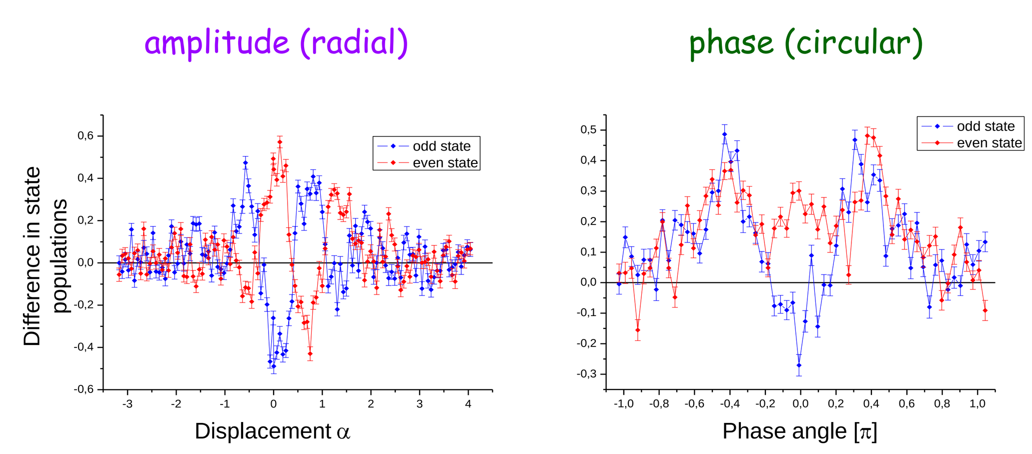


Measurement of cat states

Expected distribution in phase-space:
- Amplitudes of coherent fields β = 3.5
- Their angular separation 2ϕ = 0.8 π
- Cat size (separation of coherent components) D^2 = 11 photons

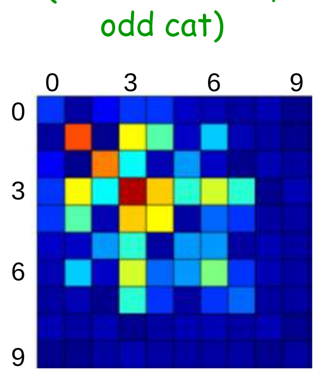


Two ways to scan the field displacement:



Coherence measure

Reconstructed ρ (absolute value, odd cat)



Translated ρ

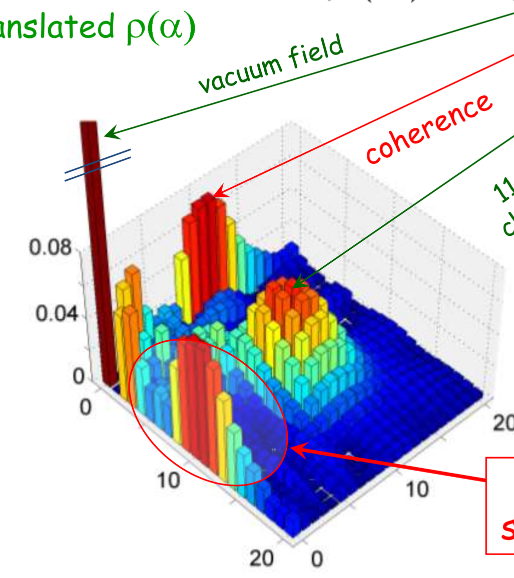
mathematical transformation

$$\hat\rho(\alpha) = \hat D(\alpha)\,\hat\rho\,\hat D(-\alpha)$$

α is adjusted to shift one classical component of the cat to vacuum

Absolute value of the translated ρ(α)

$$\hat\rho(\alpha) = (|0\rangle + |2\alpha\rangle)/\sqrt{2}$$



Decoherence of cat states

Interaction with environment leads to mixing of the cat states: The information on quantum phase gets completely lost, resulting in decoherence.

Although a random loss of one photon does not change a coherent field, it changes the parity of a cat state, inducing its decay.

Cavity damping

$$T_{\mathrm{dec}} = \frac{2T_{\mathrm{cav}}}{D^2_{\mathrm{cat}}}$$

(cavity decay time; cat size)

$T_{\mathrm{cav}} = 130\,\mathrm{ms}$, $D^2_{\mathrm{cat}} \approx 11.8\,\mathrm{ph}$ ⇒ $T_{\mathrm{dec}} \approx 22\,\mathrm{ms}$

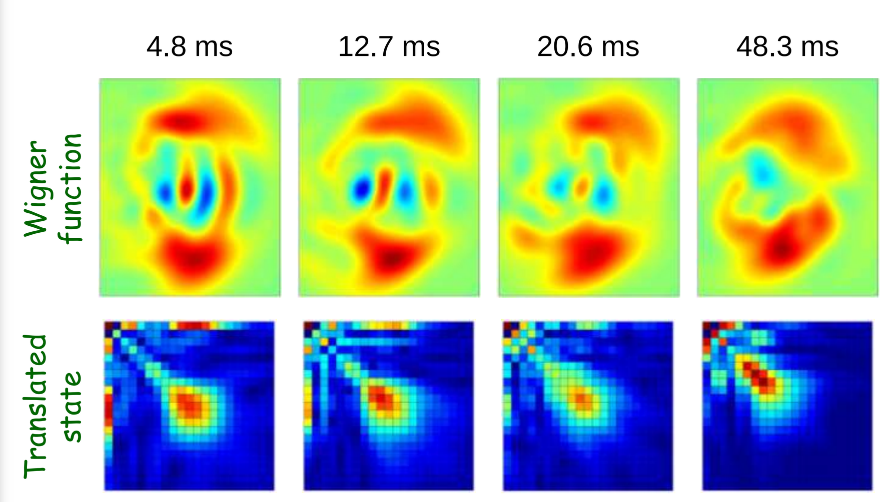
Coupling to thermal bath

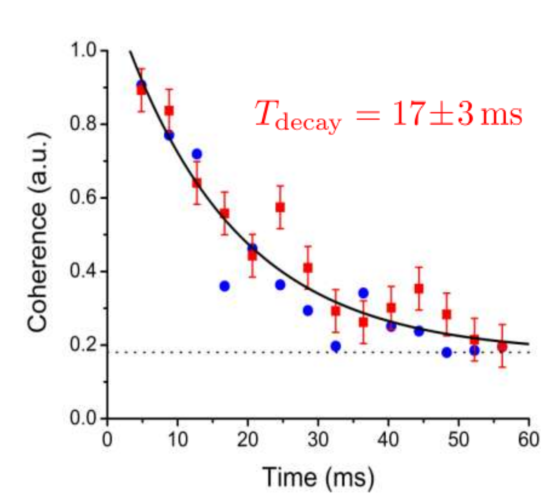
$$T_{\mathrm{dec},\bar n_{\mathrm{th}}} = \left(1 + \frac{4\bar n_{\mathrm{th}}}{D^2_{\mathrm{cat}}} + 2\bar n_{\mathrm{th}}\right)^{-1} T_{\mathrm{dec}}$$

(mean number of thermal photons)

$\bar n_{\mathrm{th}} = 0.05\,\mathrm{ph}$ (@ 0.8 K) ⇒ $T_{\mathrm{dec},\bar n_{\mathrm{th}}} \approx 19.5\,\mathrm{ms}$

$T_{\mathrm{meas}} \approx 4\,\mathrm{ms} < T_{\mathrm{dec},\bar n_{\mathrm{th}}}$





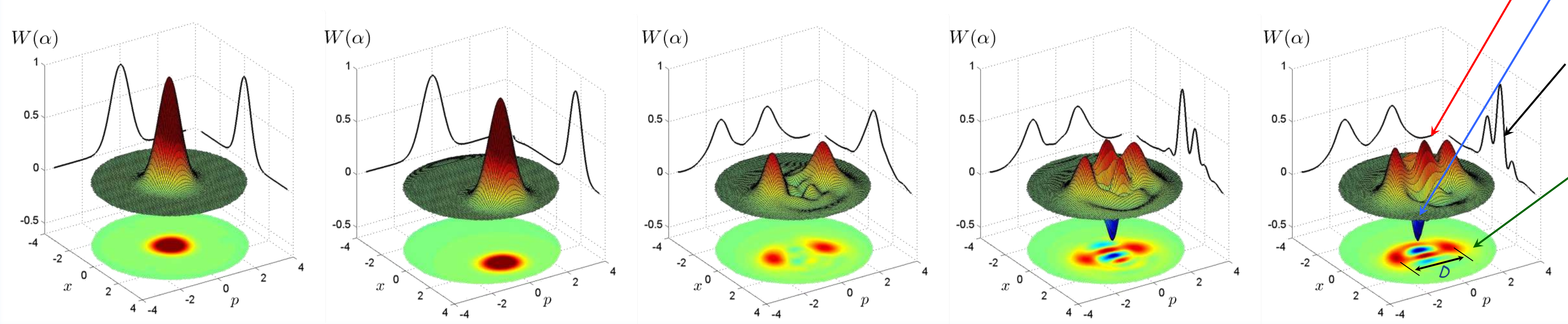
Step-by-step generation of phase cat states

after sweeping the cavity with resonant atoms — **vacuum state**

after MW injection of amplitude β — **coherent state**

after interacting with an atom in the superposition state — **statistical mixture**

after detecting the atom's state, the field is projected onto one of two cat states — **even cat state**, **odd cat state**



Interference fringes ⇒ quantum superposition of classical fields

Negative values ⇒ quantum signature of the prepared state

Real and positive marginal distributions of field quadratures

As expected, both cat states have:
- about 2.1 photons in each coherent component *(amplitude of the initial coherent field)*
- an angular separation of 0.8 π *(chosen phase shift per photon)*
- cat size D^2 ≈ 7.5 photons
- completely separated classical parts (D > 1)