Physica A 443 (2016) 399–405

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Dynamics of nonclassical correlations via local quantum uncertainty for atom and field interacting into a lossy cavity QED

J.S. Sales [a], W.B. Cardoso [b,*], A.T. Avelar [b], N.G. de Almeida [b]

[a] *Unucet, Universidvade Estadual de Goiás, 75132-903, Anápolis (GO), Brazil*

[b] *Instituto de Física, Universidade Federal de Goiás, 74.001-970, Goiânia (GO), Brazil*

HIGHLIGHTS

- We study the local quantum uncertainty during an atom–field interaction.
- The field of the cavity-QED is previously prepared in squeezed coherent states.
- The system evolves under a thermal reservoir.
- We observe a sudden change in the LQU for some values of parameters.

ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form 25 July 2015
Available online 9 October 2015

Keywords:
Nonclassical correlations
Atom–field interaction
Cavity QED
Squeezed coherent states

ABSTRACT

We study the dynamics of nonclassical correlations of an atom interacting with a squeezed coherent state or a squeezed coherent states superposition (SCSS) trapped into a lossy thermal cavity QED by using local quantum uncertainty (LQU). By varying several parameters of control, such as the average photon number of the coherent state and the squeezing parameter, we are able to select the atom–field interaction time allowing us to obtain the higher value to LQU. In addition, after the atom leaving the cavity, for certain range of the displacement parameter we have found a sudden change in the LQU as a function of time when the squeezing parameter of the SCSS is very small.

1. Introduction

Quantum correlations have been intensively investigating since the eighties, motivated mainly by the general belief that they are essential to harness the full capability of quantum information processing tasks [1]. In the beginning, quantum correlations of bipartite, named quantum entanglement, was identified and putted on a firm basis by the following definition [2]: entangled states of bipartite system AB cannot be represented by the density operator $\rho_{AB} = \sum p_k \rho_{Ak} \otimes \rho_{Bk}$, where ρ_{Ak} (ρ_{Bk}) is the density of the subsystem $A(B)$. The immediate consequence of this operational definition was the perception that local operations and classical communications cannot prepare entangled states; or, in affirmative way: separable states can be prepared by local operations and classical communications. In this way, one might believe that the power of quantum information comes only from entanglement, justifying the efforts in to quantify and characterize it.

Until this point, quantum correlation seemed to be synonymous of entanglement, and separability equivalent to classicality, however this scenario changed rapidly when it was recognized that even with no entanglement, some mixed

* Corresponding author. Tel.: +55 06235211014.
E-mail address: wesleybcardoso@ufg.br (W.B. Cardoso).

http://dx.doi.org/10.1016/j.physa.2015.09.096
0378-4371/

states could be useful for speed-up tasks in the so-called deterministic quantum computation with one quantum bit [3]. These mixed states possess a new type of quantum correlations other than entanglement with special importance for quantum information processing tasks [3–6]. In this sense, different methods for quantifying these quantum correlations were recently presented in the literature (see Ref. [7] for a detailed review on this point). In particular, the quantum discord (QD) [8,9], which is a measure of the information that cannot be extracted by the reading of the state of the apparatus (i.e., without joint measurements) [7,8], is a good indicator of the quantum nature of correlations. However, due to the complicated optimization involved in the calculation of QD, there are few analytical expressions even for a two-qubit state.

Recently, it was shown that the quantum uncertainty on local observables is directly connected to the concept of quantum discord and leads to an entire class of *bona fide* measures of nonclassical correlations, the so-called local quantum uncertainty (LQU) [6], which quantifies the minimum quantum uncertainty in a measurement performed on the system, admitting a unique closed form for the case of $2 \times d$ systems and presenting a good computability, since it is defined just as the minimization of the uncertainty in the measurement of an observable over all possible observables.

It is worth to note that $2 \times d$ systems are typical in linear optics and in QED cavity, where two-level atom interacts with a field mode inside a cavity corresponding to a d-dimensional Hilbert space in the Fock basis. In these contexts, several schemes for generating nonclassical states have been proposed such as circular superposition of coherent [10,11] and squeezed [12,13] states, superposed phase states [14], Fock states [15,16], and other exotic states [17–23].

Taking advantages of quantum state engineering in QED cavity, in this paper we investigate the behavior of quantum correlation (here measured by $2 \times d$ LQU due to its feasibility as above mentioned) for a two-level atom interacting with a squeezed coherent state (SCS) or a squeezed coherent states superposition (SCSS) trapped into a lossy cavity and evolving under a thermal reservoir at finite temperature. To this aim we consider, as in Ref. [24], initially a SCSS prepared in a single-mode of a high-Q cavity evolving under a thermal reservoir. After preparing the SCSS, a two-level atom, prepared in its excited state, is sent to interact resonantly with the lossy cavity-mode. Finally, we calculate the LQU for several parameters appearing in our model, as for instance the average thermal photon number, the squeeze and displacement parameters, among others. In particular, LQU versus interaction time allows us to determine the time required to maximize quantum correlations, while LQU versus time in the free-interaction space (after the interaction takes place) shows us quantum correlations dynamics.

The paper is structured as follows: In Section 2 we present our model based on Jaynes–Cummings Hamiltonian, in Section 3 we show the numerical results, and finally, we summarize our conclusions in Section 4.

2. The model

We will assume the model described by the following Hamiltonian:

$$H = \hbar\omega a^\dagger a + \sum_k \hbar\omega_k b_k^\dagger b_k + \frac{\hbar\omega_0}{2}\sigma_z + g(a\sigma^+ + a^\dagger\sigma^-) + \sum_k \hbar\left(\lambda_k a^\dagger b_k + \lambda_k^* a b_k^\dagger\right), \tag{1}$$

where σ_z, σ^+, and σ^- are the usual Pauli matrix to the two-level atom of frequency ω_0, $a^\dagger$ and a are the creation and annihilation operators for the cavity mode of frequency ω, respectively, and $b_k^\dagger$ and b_k are the analogous operators for the k*th* reservoir oscillator mode, whose corresponding frequency and coupling are ω_k and λ_k, respectively, and g is the atom–field coupling constant.

The preparation and evolution of the required cavity-field state $\rho_{AB} = U_{jc}\rho(t)U_{jc}^\dagger$ of the composed atom–field system evolving under a thermal reservoir and taking into account the atom–field interaction while the atom crosses the high-Q cavity can be solved using the diagonal representation for the density operator $\rho(t)$ of the cavity field. Assuming that the atom enters the cavity in its excited state, we can write

$$U_{jc}\rho(t)U_{jc}^\dagger = \int d^2\beta P(\beta, t)\, U_{jc}\,|\beta\rangle\langle\beta|\,|e\rangle\langle e|\,U_{jc}^\dagger, \tag{2}$$

where $U_{jc} = \exp\left[-igt(a\sigma^+ + a^\dagger\sigma^-)\right]$ is the Jaynes–Cummings evolution operator. Note that the reduced state $\rho(t)$ for the cavity-field will depend on the initial state, which, here, we will assume to be either the SCS $|\xi, \alpha\rangle$ or the SCSS $c_1|\xi, \alpha\rangle + c_2|\xi, -\alpha\rangle$, where $\xi = r\exp(i\varphi)$ and α are the squeezing and displacement parameters, respectively.

Using $|\beta\rangle = \sum_n^\infty C_n|n\rangle$, where $C_n = \exp\left(-|\beta|^2/2\right)|\beta|^n/\sqrt{n!}$ is the coefficient for the coherent state $|\beta\rangle$, we obtain [24,25]

$$\rho_{AB} = \int d^2\alpha P(\beta, t)\left\{\left[\sum_n C_n\cos\left(\sqrt{n+1}gt\right)|e\rangle|n\rangle - i\sum_n C_n\sin\left(\sqrt{n+1}gt\right)|g\rangle|n+1\rangle\right]\right.$$
$$\left.\otimes\left[\sum_m C_m^*\cos\left(\sqrt{m+1}gt\right)\langle e|\langle m| + i\sum_m C_m^*\sin\left(\sqrt{m+1}gt\right)\langle g|\langle m+1|\right]\right\}. \tag{3}$$

This problem was partially tackled and solved in detail in Refs. [24–28], where the authors showed how to prepare coherent states superposition (CSS) [26] and SCSS [24] into a lossy thermal cavity, studying its statistical dynamical properties [28],