Controlling the nonclassical properties of a hybrid Cooper pair box system and an intensity dependent nanomechanical resonator.

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We employ a more realistic treatment to investigate the entropy and the excitation-inversion of a coupled system that consists of a nanomechanical resonator and a superconducting Cooper pair box. The procedure uses the Buck-Sukumar model in the microwave domain, considers the nanoresonator with a time dependent frequency and both subsystems in the presence of losses. Interesting results were found for the temporal evolutions of the entropy of each subsystem and of the excitation-inversion in the Cooper pair box. A comparison was also performed about which of these two subsystems is more sensitive to the presence of losses. The results suggest that appropriate choices of the involved time dependent parameters allow us to monitor these two features of the subsystems and may offer potential applications, e.g., in the generation of nonclassical states, quantum communication, quantum lithography.

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I. INTRODUCTION

In the last years the investigations on nanomechanical systems have rapidly been developed. The rush in this direction was estmated by various perspectives and applications before unsuspected. The enormous progress in the research of nanomechanical systems has also placed the dream of controlling the interface between the quantum and classic worlds in a realistic way. This was shown by the emergence of hybrid quantum systems, which are intended to achieve a coherent transfer of quantum information from a single quantum emitter (e.g., superconducting qubits, cooper pair box, microwave resonators, quantum dots, etc) and a solid state mechanical resonator, which moves in quantum physics giving birth to a new paradigm. In addition, these systems have received considerable attention due to their diverse potential applications, including metrology (mass force or spin ultra-sensitive detectors), based on the remarkable sensing properties of nanomechanical resonators and their very low mass and lightness.

An important focus of quantum optics is concerned with the atom-photon system. Inspired on the various tests applied to this coupled system and on the several results obtained, including the limitations, the researchers have passed from the light domain to the microwave domain of the superconducting version, the quantum electrodynamics circuit. This system furnishes a new test for microwave “photons” that interact with superconducting qubits. In this scenario the atom is substituted by a Cooper pair box (CPB) while the photon is substituted by a nanomechanical resonator (NR). So, the atom-field interacting system goes to the CPB - NR interacting system with the concomitant passage from the optical domain to the microwave domain.

There are few works in the literature that treat the interaction between a CPB and a NR when the later has either a time dependent frequency or a time dependent amplitude of oscillation. The well known Jaynes-Cummings model (JCM), which describes the interaction of a single two-level atom and a single mode of a quantized radiation field, is the simplest model for this system and provides exact solutions. Analogous to the CPB - NR system, but since the year 1963, many others studies have previously implemented the JCM to describe the atom-field interaction. Some generalized models were also constructed and extensively studied. The examples include the study of the mentioned systems in presence of the Stark effect, e.g., to investigate quantum nondemolition measurements. Usually the investigations assume the field initially in a (pure) coherent state. As the atom-field interaction is turned on, the field state changes with time the evolution. Then, if its coherence is lost, the field state becomes nonclassical. Some references to this subject are, e.g., on nonclassical properties of a state; generation of superposition states; on the degree of nonclassicality of a state and: sculpturing coherent states to get Fock states - plus references therein.

The traditional JCM was extended to the case of intensity-dependent coupling, proposed by B. Buck and C.V. Sukumar in order to study the influence of the field intensity, via its excitation number, upon the atom-field system, where a single atom interacts with a single mode of an optical field. This model was generalized by

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V. Buzek \cite{56} to include a new coupling, with time dependent intensity. In the present work we will employ the model by Buck-Sukumar (BS) to study the CPB - NR system, namely: we will suppose the coupling being dependent of the intensity of the NR oscillations and also that it changes with time, as assumed in \cite{56}. In addition, we consider a more realistic scenario with the presence of dissipation effects and verify in which way they affect the excited level of the CPB, the excitations of the NR, and the dynamical properties of the entire CPB - NR system. Some points considered here are: how dissipation spoils the system operation and in which way the detuning could prevent it, allowing us the control of entanglement features, collapse-revival effects, and others. The results obtained indicate the possibility of some potential applications \cite{57,58}.

\[
\hat{H} = \omega(t)\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\omega_c(t)\hat{\sigma}_z + \lambda(t)\left(\hat{a}\sqrt{\hat{a}^{\dagger}\hat{a}}\hat{\sigma}_+ + \sqrt{\hat{a}^{\dagger}\hat{a}}\hat{\sigma}_-\right) - \gamma(t)|\psi\rangle\langle\psi| - i\delta(t)\hat{a}^{\dagger}\hat{a}.
\]

II. THE HAMILTONIAN SYSTEM

A superconductor CPB charge qubit is adjusted to the input voltage \(V_1\) of the system, through a capacitor with an input capacitance \(C_1\). Following the configuration shown in Fig. \text{1} we observe three loops: a small loop in the left, another in the right, and a great loop in the center. The control of the external parameters of the system can be implemented via the input voltage \(V_1\) and the three external fluxes \(\Phi_L, \Phi_r, \Phi_f\). The control of theses parameters allows us to make the coupling between the CPB and the NR. We consider \(\hbar = 1\) and assume as identical the four Josephson junctions of the circuit system, having the same Josephson energy \(E_J^\text{c}\); the external fluxes \(\Phi_L, \Phi_r\), and \(\Phi_f\) are also assumed as identical in magnitude, although they have opposite signs \(\Phi_L = -\Phi_r = \Phi_f\) (see Ref. \cite{8}). So, taking into account the decay in the excited level of the CPB and dissipation in the NR, we can write the total Hamiltonian of the system as follows,
the coupling coefficient between the CPB and the NR.
As known in the literature the coupling parameter \( \lambda (t) \) can be written in the form [65].

\[
\lambda (t) = |\vec{d}_{ij}| \frac{\omega (t)}{2 \epsilon_0 V (t)},
\]

(2)

where the quantization volume \( V (t) \) is dependent on time and takes the form \( V (t) = \frac{V_0}{\epsilon_0 (t)/\omega_0} \); \( \epsilon_0 \) is the permittivity constant; \( \vec{d}_{ij} = e \langle i | \vec{r} | j \rangle \) is the matrix element of the dipole between the two CPB states \( |i\rangle \) and \( |j\rangle \); \( e \) is the elementary charge, \( \vec{r} \) is the position vector and, \( |i\rangle \) and \( |j\rangle \) play similar roles of the atomic states \( |e\rangle \) and \( |g\rangle \) in the scenario of atom-field interaction. The notation \( |e\rangle \), \( |g\rangle \) will be used from now on. It stands respectively for the excited and ground states of the CPB.

Substituting the expressions of the field frequency \( \omega (t) \) and quantum volume \( V (t) \) in Eq. (2), we can write it as

\[
\lambda (t) = \lambda_0 \sqrt{1 + \frac{f(t)}{\omega_0}},
\]

(3)

where \( \lambda_0 = |\vec{d}_{eg}| \frac{\omega_0}{\epsilon_0 V_0} \). The control of the parameters \( \omega (t) \) and \( \lambda (t) \) is provided by an external field that acts upon the NR and changes the magnetic flux \( \Phi_e \) (cf. Fig. 1).

The wave function that describes the CPB - NR system as function of the time \( t \) can be written in the form,

\[
|\Psi (t)\rangle = \sum_{n=0}^{\infty} [C_{e,n} (t) |e,n\rangle + C_{g,n} (t) |g,n\rangle],
\]

(4)

where the coefficients \( C_{e,n} (t) \) and \( C_{g,n} (t) \) stand respectively for the probability amplitudes to find the entire system in the states \( |e,n\rangle \) and \( |g,n\rangle \). This notation represents the CPB in its excited state \( |e\rangle \) and fundamental state \( |g\rangle \) with \( n \) excitations in the NR. We will assume the subsystems CPB and the NR are decoupled at \( t = 0 \) with the CPB in its excited state \( |e\rangle \) and the NR prepared in a coherent state \( |\alpha\rangle \), this later expressed by the superposition of Fock states,

\[
|\alpha\rangle = \sum_{n=0}^{\infty} F_n |n\rangle,
\]

(5)

where \( F_n = \frac{\alpha^n}{\sqrt{n!}} e^{-|\alpha|^2/2} \). In this way the wave function of the whole system in the the initial state can be written as \( |\Psi(0)\rangle = |e\rangle |\alpha\rangle = \sum_{n=0}^{\infty} F_n |e,n\rangle \), since the initial conditions restrict the probability amplitudes to \( C_{g,n}(0) = 0 \) for all values of \( n = 0, 1, 2, 3, \ldots \) and \( \sum_{n=0}^{\infty} |C_{e,n}(0)|^2 = 1 \).

By analyzing the time evolution of the CPB - NR system, described by the time dependent Schrödinger equation,

\[
\hat{H} \frac{d|\Psi (t)\rangle}{dt} = \hat{H} |\Psi (t)\rangle,
\]

(6)

and the Hamiltonian \( \hat{H} \) given in the Eq.[1], we find the set of equations of motion for the coefficients \( C_{e,n} (t) \) and \( C_{g,n+1} (t) \),

\[
\frac{\partial C_{e,n} (t)}{\partial t} = \left( -i n \omega (t) - i \frac{\omega (t)}{2} - \gamma (t) - n \delta (t) \right) C_{e,n} (t) - i \lambda (t) (n + 1) C_{g,n+1} (t),
\]

(7)
Solving the set of equations (7) and (8) we obtain the solutions for \( C_{e,n}(t) \) and \( C_{g,n+1}(t) \). To this end, we have used the Runge-Kutta method of 4th order; with these solutions we determine the quantum dynamical properties of the system, including the entanglement that affects the subsystems CPB and NR.

### III. ENTROPY OF THE CPB - NR SYSTEM

Recently, several authors have employed various methods to investigate the dynamics of entanglement [12, 66-68]. Here the name “entanglement” means “mixing of states”, whose degree can be measured by the entropy. The Von Neumann entropy offers a quantitative measure of the system disorder or the degree of a quantum state purity, e.g., as shown by Phoenix and Knight [69]. Here the entropy defined in the form,

\[
S_{NR}(CPB) = -Tr[C_{NR}(\hat{\rho}_{NR}) \ln \hat{\rho}_{NR}],
\]

is a measure related to the entanglement of one of the two interacting subsystems, with \( \hat{\rho}_{NR} = Tr[C(\hat{\rho}_{NC})] \) where \( \hat{\rho}_{NC} \) is the density operator that describes the state of the subsystem NR(CPB) and \( \hat{\rho}_{NC} \) is the same operator for the entire system CPB - NR. The quantum dynamics represented by the Hamiltonian in Eq. (1) creates the entanglement in both subsystems of the CPB - NR. In the following discussion we use the quantum entropy of Von Neumann as a measure of the degree of entanglement. For a quantum system with two components the entropy obeys the Araki-Lieb theorem, which states that \(|S_{CPB} - S_{NR}| \leq S \leq S_{CPB} + S_{NR}\). One consequence of this inequality is that, if the total system is initially prepared in a pure state, then the entropies of the components of the system remain with equal value in their subsequent time evolution. Then it is sufficient to study one of them to know both.

So, assuming the two subsystems in pure states at \( t = 0 \) the entropies of the CPB and NR subsystems, which are found via the BS model, are identical: \( S_{CPB}(t) = S_{NR}(t) \). For example, the entropy of the NR is found from the equation,

\[
S_{NR}(t) = - \left[ S_{NR}^+(t) \ln (S_{NR}^+(t)) + S_{NR}^-(t) \ln (S_{NR}^-(t)) \right] \]

where:

\[
S_{NR}^\pm(t) = \frac{1}{2} \left\{ \sum_{n=0}^\infty |C_{e,n}(t)|^2 + \sum_{n=0}^\infty |C_{g,n+1}(t)|^2 \right\} \mp \frac{1}{2} \left[ \left( \sum_{n=0}^\infty |C_{e,n}(t)|^2 - \sum_{n=0}^\infty |C_{g,n+1}(t)|^2 \right)^2 \right]^{1/2},
\]

The results obtained from the calculations are shown in the Figs. 2, 3, 4, and 5.

### IV. THE CPB EXCITATION INVERSION

The CPB excitation inversion, denoted by \( I(t) \), is an important observable of the two-level systems. It is defined as the difference of probabilities of finding the CPB in the excited and fundamental states. The mathematical expression representing this property is,

\[
I(t) = \sum_{n=0}^\infty \left[ |C_{e,n}(t)|^2 - |C_{g,n+1}(t)|^2 \right].
\]

The results achieved from the Eq. (12), for various values of parameters, are shown in Figs. 6 and 7.
FIG. 2. Time evolution of the entropy for different values of the parameters \( \gamma(t) \) and \( \delta(t) \) for: \( \langle n \rangle = 9, \omega_0 = \omega_c = 2000\lambda_0, f(t) = 0 \). (a) \( \gamma = 0.0\lambda_0 \) and \( \delta = 0.0.0\lambda_0 \); (b) \( \gamma = 0.001\lambda_0 \) and \( \delta = 0.001\lambda_0 \).

FIG. 3. Time evolution of the entropy for different values of the parameters \( \gamma(t) \) and \( \delta(t) \) for: \( \langle n \rangle = 9, \omega_0 = \omega_c = 2000\lambda_0, f(t) = 0 \). (a) \( \gamma = 0.001\lambda_0 \) and \( \delta = 0.001\lambda_0 \); (b) \( \gamma = 0.001\lambda_0 \) and \( \delta = 0.01\lambda_0 \).

FIG. 4. Time evolution of the entropy for different values of the parameters \( \gamma(t) \) and \( \delta(t) \) for: \( \langle n \rangle = 9, \omega_0 = \omega_c = 2000\lambda_0, f(t) = 0 \). (a) \( \gamma = 0.001\lambda_0 \) and \( \delta = 0.001\lambda_0 \); (b) \( \gamma = 0.001\lambda_0 \) and \( \delta = 0.01\lambda_0 \).

The entropy itself moves away from the value \( S(t) = 0 \). If instead we include a small decay in the NR, as \( \delta = 0.001\lambda_0 \), the entropy changes as follows: although the amplitude of the entropy oscillations again decreases, now the entropy moves slowly to its minimum value \( S(t) = 0 \) (cf. Fig. 3 (a)). For larger value of \( \delta(t) \) the entropy movies rapidly to zero, which is due to the passage of both subsystems to their respective ground states. In this case the entropy loses its periodicity (cf. Fig. 2 (b)).

Here we consider the nonresonant case, namely, for \( f(t) = \Delta = \text{const.} \) with \( \Delta \ll \omega_c, \omega_0 \). Comparing the Fig. 4(a) with Fig. 2(b), both have the same values of the decay coefficients \( \gamma(t) \) and \( \delta(t) \), we observe the amplitude of entanglement decreasing as the detuning \( \Delta \) increases, i.e., the detuning turns the entropy oscillation greater while destroying its periodicity. In this scenario \( \Delta \neq 0 \) if the CPB decay parameter \( \gamma(t) \) increases the entropy goes quickly to zero (not shown in figures). Comparing the Fig. 4(b) with Fig. 3(a) we see a similar behavior of the average values of the entropies whereas the amplitude of oscillations diminishes in the case \( \Delta \neq 0 \). All these comparisons show that the influence of detuning upon the NR entropy is greater in the ideal NR \( (\delta = 0) \). In the resonant case, when the decay parameters \( \gamma(t) \) and \( \delta(t) \) increase the NR entropy tends to zero. As a consequence of the mentioned Araki-Lieb theorem, the same occurs in the CPB.

Let us now consider the variation in the detuning parameter \( \Delta \): we fist take \( \Delta \neq 0 \) and \( f(t) = \eta \sin(\omega t) \), where \( \eta \) and \( \omega t \) are parameters that modulates the NR frequency. Our discussion is limited to the condition \( \eta \ll \omega_c, \omega_0 \) and also assuming that \( \omega t \) is small to avoid interaction of the CPB with other modes of the NR. We have chosen various values of amplitude modulations \( \eta \) to verify the entanglement properties between the CPB
and NR. We use various values of frequency modulation $\omega t$ to see its influence upon the CPB - NR entanglement (cf. Figs. 5).

FIG. 5. Time evolution of the entropy for different values of the parameters $\gamma(t)$ and $\delta(t)$ for: (a) $\langle n \rangle = 9$, $\omega_0 = \omega_c = 2000\lambda_0$, $\gamma = 0.001\lambda_0$ and $\delta = 0.001\lambda_0$; (b) $\gamma = 20\lambda_0$, $\omega = \lambda_0$; (b) $\eta = 20\lambda_0$, $\omega = 20\lambda_0$.

Comparing the Fig. 4 (b) with the Figs. 5 (a), 5 (b) we note the entropy exhibiting periodic and quasi-periodic oscillations: when the parameter $\eta$ increases the amplitude of these oscillations diminishes. This means that the modulation of the NR sinusoidal frequency is important to stabilize entanglements in the CPB - NR system.

Next we consider the time evolution of the excitation inversion (EI) for different values of the coefficients $\gamma(t)$ and $\delta(t)$. In the resonant case, $f(t) = 0$, we have fixed again the NR with average number of excitations $\langle n \rangle = |\alpha|^2 = 9$ and $\omega_0 = \omega_c = 2000\lambda_0$ to calculate the EI of the CPB (cf. Figs. 6 (a), 6 (b) and 6 (c)): we see in these three cases the EI exhibiting similar collapse-revival effects, but different amplitudes; these amplitudes diminishes for larger values of the parameters $\gamma(t)$, $\delta(t)$. In case of detuning, with $f(t) = \Delta = const.$, $\Delta \ll \omega_c, \omega_0$, Fig. 7 (a) shows absence of the collapse-revival effect; indeed even the EI is also absent since these oscillations of the NR excitation characterize no inversion, as explained in the “alert” below. On the other hand, for $f(t) = \eta\sin(\omega t)$ the Fig. 7 (b) stands for a variable detuning with maximum value $\eta$, equal to the value of the fixed value $\eta = \Delta = 20$, Fig. 7 (a). For small times the system presents the collapse-revival effect, whereas for large times this effect vanishes, with concomitant attenuation in the EI. In the 7 (c) we use a large value for $\omega t$ and the same maximum value $\eta = 20$ employed in the Fig. 7 (b): here we observe no occurrence of the collapse-revival effect, whereas the amplitude of oscillations decreases for long times which is due to the losses affecting both subsystems. This later result differs from the case $f(t) = \Delta$, as shown in Figs. 6 (a), 6 (b) and 6 (c). Alert: two different properties must be distinguished in the Fig. 7 (a): one of them is the excitation inversion, the other is the oscillation of excitation. The first is identified when the oscillations changes the signs (+) $\leftrightarrow$ (−) successively; the second neglects these signs. Ignoring these aspects can confuse fluctuations with inversion. For example, Fig. 6 (a) shows oscillations, but not inversion; then, what is really shown in this figure is a collapse of oscillations, not a collapse of the excitation inversion.
We have studied the dynamical properties (entropy and excitation inversion) of an interacting system composed by a CPB and a quantized NR. We have assumed the CPB initially in its excited state $|e\rangle$ and the NR initially prepared in a coherent state $|\alpha\rangle$. We also assumed the whole system CPB - NR described by the BS model via single excitation transition. Concerning the entropy, which is connected with entanglement (mixture) of states, we have studied its time evolution in the presence of loss in both subsystems, for the resonant case ($\Delta = 0$) and nonresonant case. The influence upon the entropy of a (sinusoidal) time dependent frequency, via the NR and coupling, was also considered. The EI was also investigated under the same conditions. The inclusion of losses in the CPB and NR turns this scenario more realistic and the time dependence of the coupling $\lambda(t)$ and also the NR frequency $\omega(t)$ make our results closer to experimental conditions. The results drastically differ from those obtained in the resonant case. The following scenarios were considered: (i) the resonant case ($f = 0$); (ii) the nonresonant case, with fixed detuning, $f = \Delta \neq 0$, and (iii) nonresonant case with time dependent detuning, $f(t) = \eta \sin(\omega t)$. An interesting result emerges: for a fixed detuning the collapse-revival effect does not occurs, the same being true for the EI since the system oscillates around a value that differs from zero (cf. Fig. 7 (a)) as also alerted before. However, it is surprising that in the case $f(t) = \eta \sin(\omega t)$, with the same conditions assumed for fixed detuning, we can see the EI effect remaining, even in the presence of decay (cf. Fig. 4 (b), Fig. 7 (c)). This behavior is not shown with fixed detuning. In summary, we have shown that the use of a (time-dependent) modified BS model, which is extended to a more realistic scenario where the influence of the losses is considered, new interesting findings emerge. They also indicate that it is possible to perform a dynamic control of the system properties by changing the parameters involved. Convenient choices of the frequency modulation can be made to manipulate environmental noisy and inaccuracies, including potential applications in the dynamical control of quantum information processes. We hope that these results can offer a reference to put the issue with force.

VI. CONCLUSION

We have studied the dynamical properties (entropy and excitation inversion) of an interacting system composed by a CPB and a quantized NR. We have assumed the CPB initially in its excited state $|e\rangle$ and the NR initially prepared in a coherent state $|\alpha\rangle$. We also assumed the whole system CPB - NR described by the BS model via single excitation transition. Concerning the entropy, which is connected with entanglement (mixture) of states, we have studied its time evolution in the presence of loss in both subsystems, for the resonant case ($\Delta = 0$) and nonresonant case. The influence upon the entropy of a (sinusoidal) time dependent frequency, via the NR and coupling, was also considered. The EI was also investigated under the same conditions. The inclusion of losses in the CPB and NR turns this scenario more realistic and the time dependence of the coupling $\lambda(t)$ and also the NR frequency $\omega(t)$ make our results closer to experimental conditions. The results drastically differ from those obtained in the resonant case. The following scenarios were considered: (i) the resonant case ($f = 0$); (ii) the nonresonant case, with fixed detuning, $f = \Delta \neq 0$, and (iii) nonresonant case with time dependent detuning, $f(t) = \eta \sin(\omega t)$. An interesting result emerges: for a fixed detuning the collapse-revival effect does not occurs, the same being true for the EI since the system oscillates around a value that differs from zero (cf. Fig. 7 (a)) as also alerted before. However, it is surprising that in the case $f(t) = \eta \sin(\omega t)$, with the same conditions assumed for fixed detuning, we can see the EI effect remaining, even in the presence of decay (cf. Fig. 4 (b), Fig. 7 (c)). This behavior is not shown with fixed detuning. In summary, we have shown that the use of a (time-dependent) modified BS model, which is extended to a more realistic scenario where the influence of the losses is considered, new interesting findings emerge. They also indicate that it is possible to perform a dynamic control of the system properties by changing the parameters involved. Convenient choices of the frequency modulation can be made to manipulate environmental noisy and inaccuracies, including potential applications in the dynamical control of quantum information processes. We hope that these results can offer a reference to put the issue with force.

VII. ACKNOWLEDGMENTS

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