Preparation of optimal entropy squeezing state of atomic qubit inside the cavity via two-photon process and manipulation of atomic qubit outside the cavity*

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Considering two atomic qubits initially in Bell states, we send one qubit into a vacuum cavity with two-photon resonance and leave the other one outside. Using quantum information entropy squeezing theory, the time evolutions of the entropy squeezing factor of the atomic qubit inside the cavity are discussed for two cases, i.e., before and after rotation and measurement of the atomic qubit outside the cavity. It is shown that the atomic qubit inside the cavity has no entropy squeezing phenomenon and is always in a decoherent state before the operating atomic qubit outside the cavity. However, the periodical entropy squeezing phenomenon emerges and the optimal entropy squeezing state can be prepared for the atomic qubit inside the cavity by adjusting the rotation angle, choosing the interaction time between the atomic qubit and the cavity, controlling the probability amplitudes of subsystem states. Its physical essence is cutting the entanglement between the atomic qubit and its environment, causing the atomic qubit inside the cavity to change from the initial decoherent state into maximum coherent superposition state, which is a possible way of recovering the coherence of a single atomic qubit in the noise environment.

Keywords: atomic qubit, rotation operation, optimal entropy squeezing state, two-photon process

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1. Introduction

A two-level atom, called an atomic qubit (AQB), is a typical two-state quantum system. It is a basic unit of information storage in quantum computation (QC) which is a novel information processing approach using coherent superposition states of AQB and has become a research focus because of its capability for breaking through the classical limit.[1] AQB is widely used in the universal quantum logic gate,[2,3] and it is usual to transfer quantum information of a moving photonic qubit to the stationary AQB. If it does not lose its quantum coherence, AQB will become an important part of quantum information processing in the future.[4] However, AQB interacts with its environment and quantum fluctuation or quantum noise (QN) is caused. QN is a main obstacle of experimentally realizing QC because it causes distortion of the encoded quantum state and leads to the decoherence of QC.[5,6]

Over the past decades, much attention has been paid to the atomic squeezing. On the one hand, atomic squeezing has potential applications in the field of quantum optics[7,8] and quantum information,[9] and can effectively inhibit QN.[10] Because an atomic optimal squeezing state corresponds to a quantum state with minimum QN,[11] its preparation and control are very important tasks in the relevant research field. In recent years, entropy squeezing of a two-level atom has become a research hotspot. Fang *et al.*[12] have defined the entropy squeezing for a two-level atom by using the quantum information theory according to entropic uncertainty relation (EUR) based on position and momentum, which overcomes the limitation of Heisenberg uncertainty relation formulated according to the variance of the system observable. They have shown that quantum information theory is a remarkably accurate measure of atomic squeezing.[13] More recently, many investigations on atomic entropy squeezing have been reported.[14–16] The sudden generation and control of an atomic optimal entropy squeezing state (OESS) have also been studied in our previous work with different Jaynes–Cumming models (JCM).[17,18]

On the other hand, two-photon JCM (TPJCM) has aroused much interest in recent years because of two-photon microwave maser running successfully and its property of the periodicity of quantum mechanical channels.[19] Therefore it is an important tool for transmitting quantum information correctly in the quantum communication field.[20,21] In Ref. [22] Wang and Fang have studied the quantum-reduced entropy of two-photon process. We have also investigated the control of periodical quantum echo of arbitrary initial AQB state in two-photon channel.[23]

In the present paper, we consider the case of two AQBs initially in Bell states, and one is in a vacuum cavity with two-photon resonance. The AQB outside and the cavity field are regarded as the environment of AQB inside the cavity. Using

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quantum information entropy squeezing theory, we investigate the entropy squeezing properties of AQB inside the cavity by operating its environment and prepare OESS of AQB inside the cavity via the two-photon process. Our study theoretically provides an alternative way of inhibiting decoherence of single AQB in the QN environment.

2. Model and density matrix

Our model is depicted in Fig. 1[24] where two AQBs (1 and 2) are initially entangled. AQB2, whose entropy squeezing properties will be investigated, is sent into a single-mode resonant cavity initially in a vacuum state, while AQB1 will undergo rotation operation $\hat{R}(\theta)$ with the rotation angle θ and measurement of quantum state by detector M. Assume that AQB1 and AQB2 are initially in a general entangled state as follows:

$$\begin{aligned}|\psi_{12}(0)\rangle &= r_1|e_1,e_2\rangle + r_2|e_1,g_2\rangle \\ &\quad + r_3|g_1,e_2\rangle + r_4|g_1,g_2\rangle, \end{aligned} \tag{1}$$

where $|g_i\rangle$ and $|e_i\rangle$ $(i=1,\ 2)$ are the ground state and excited state of AQB1 and AQB2 respectively, and the probability amplitudes r_i $(i=1,2,3,4)$ satisfy the normalization condition $\sum_{i=1}^{4} r_i^2 = 1$. The interaction Hamiltonian of AQB2 and cavity field via two-photon process, in the rotating-wave approximation, can be written as

$$H_I = g(a^{\dagger 2}S_- + a^2 S_+), \tag{2}$$

where $a^\dagger$ and a are creation and annihilation operators of the cavity field, S_+ and S_- are raising and lowering operators of the AQB, respectively, and g is the coupling strength. The time evolutions of AQB2 and the cavity field are

$$\begin{aligned}&|e_2,0\rangle \to \cos(\sqrt{2}gt)|e_2,0\rangle - \mathrm{i}\sin(\sqrt{2}gt)|g_2,2\rangle, \\ &|g_2,0\rangle \to |g_2,0\rangle, \end{aligned} \tag{3}$$

where $|0\rangle$ and $|2\rangle$ are vacuum state and two-photon Fock state of the cavity field respectively. The initial state of the system (denoted as S) composed of two AQBs and the cavity field is $|\psi_S(0)\rangle = |\psi_{12}(0)\rangle \otimes |0\rangle$. According to the evolution of Eq. (3), we obtain the following quantum state of system:

$$\begin{aligned}|\psi_{S0}(t)\rangle &= A_0|e_1e_20\rangle + B_0|e_1g_20\rangle + C_0|e_1g_22\rangle + D_0|g_1e_20\rangle \\ &\quad + E_0|g_1g_20\rangle + F_0|g_1g_22\rangle, \end{aligned} \tag{4}$$

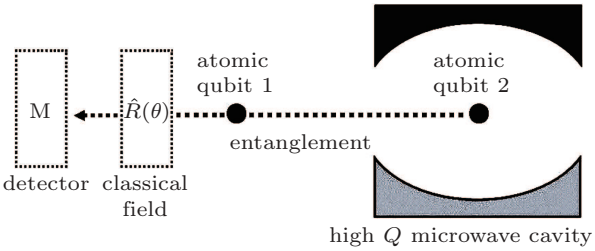


Fig. 1. The schematic diagram of our system.

where the probability amplitudes of six substates are

$$\begin{aligned}&A_0 = r_1\cos(\sqrt{2}gt),\ \ B_0 = r_2,\ \ C_0 = -\mathrm{i}r_1\sin(\sqrt{2}gt), \\ &D_0 = r_3\cos(\sqrt{2}gt),\ \ E_0 = r_4,\ \ F_0 = -\mathrm{i}r_3\sin(\sqrt{2}gt). \end{aligned} \tag{5}$$

After tracing over AQB1 and the cavity field, we have the reduced density matrix of AQB2 inside the cavity as follows:

$$\rho_{20}(t) = \begin{bmatrix} \rho_{220} & \rho_{210} \\ \rho_{120} & \rho_{110} \end{bmatrix}, \tag{6}$$

where matrix elements

$$\begin{aligned}&\rho_{220} = |A_0|^2 + |D_0|^2, \\ &\rho_{210} = \rho_{120}^* = A_0B_0^* + D_0E_0^*, \\ &\rho_{110} = |C_0|^2 + |B_0|^2 + |E_0|^2 + |F_0|^2. \end{aligned} \tag{7}$$

The subscript 0 in $|\psi_{S0}(t)\rangle$, $\rho_{20}(t)$, and $\rho_{ij0}(t)$ $(i,j=1,\ 2)$ means that no manipulation has been performed on the AQB1.

In Fig. 1, the arbitrary rotation of AQB1 can be realized by choosing appropriate frequency and amplitude of classical field as follows:[24]

$$\hat{R}(\theta)|e_1\rangle = -\sin\theta|g_1\rangle + \cos\theta|e_1\rangle, \tag{8}$$

$$\hat{R}(\theta)|g_1\rangle = \cos\theta|g_1\rangle + \sin\theta|e_1\rangle. \tag{9}$$

Inserting Eqs. (8) and (9) into Eq. (4), we have the quantum state after $\hat{R}(\theta)$ operation on AQB1

$$\begin{aligned}|\psi_{SR(\theta)}\rangle &= A_R|e_1e_20\rangle + B_R|e_1g_20\rangle + C_R|e_1g_22\rangle \\ &\quad + D_R|g_1e_20\rangle + E_R|g_1g_20\rangle + F_R|g_1g_22\rangle, \end{aligned} \tag{10}$$

where six probability amplitudes are

$$\begin{aligned}&A_R = r_1\cos(\sqrt{2}gt)\cos\theta + r_3\cos(\sqrt{2}gt)\sin\theta, \\ &B_R = r_2\cos\theta + r_4\sin\theta, \\ &C_R = -\mathrm{i}r_1\sin(\sqrt{2}gt)\cos\theta - \mathrm{i}r_3\sin(\sqrt{2}gt)\sin\theta, \\ &D_R = -r_1\sin\theta + r_3\cos(\sqrt{2}gt)\cos\theta, \\ &E_R = -r_2\sin\theta + r_4\cos\theta, \\ &F_R = -\mathrm{i}r_1\sin(\sqrt{2}gt)\sin\theta - \mathrm{i}r_3\sin(\sqrt{2}gt)\cos\theta. \end{aligned} \tag{11, 12}$$

Then, let AQB1 pass through the detector M. If the measurement result is $|g_1\rangle$, the reduced density matrix of AQB2 inside the cavity is

$$\rho_{2R(\theta)}(t) = \begin{bmatrix} \rho_{22R} & \rho_{21R} \\ R_{12R} & \rho_{11R} \end{bmatrix}, \tag{13}$$

where the matrix elements are

$$\begin{aligned}&\rho_{22R} = |D_R|^2,\ \ \rho_{11R} = |E_R|^2 + |F_R|^2, \\ &\rho_{12R} = \rho_{21R}^* = E_RD_R^*. \end{aligned} \tag{14}$$

The subscript R means the rotation operation $\hat{R}(\theta)$ on AQB1.

3. Entropy squeezing of an AQB

According to Refs. [12] and [13], the information entropy of the Pauli operators S_α ($\alpha = x, y, z$) for an AQB is

$$H(S_\alpha) = -\sum_{i=1}^{2} P_i(S_\alpha) \ln P_i(S_\alpha), \quad \alpha = x, y, z, \tag{15}$$

where $P_i(S_\alpha) = \langle \psi_{\alpha i} | \rho | \psi_{\alpha i} \rangle$ ($i = 1, 2$) are the probability distributions for two possible measurement outcomes of operator S_α for an arbitrary quantum state ρ, $|\psi_{\alpha i}\rangle$ is the eigenstate of the operator S_α. $H(S_x)$, $H(S_y)$, and $H(S_z)$ satisfy the EUR

$$\delta H(S_x) \delta H(S_y) \geq \frac{4}{\delta H(S_z)}, \tag{16}$$

where $\delta H(S_\alpha) = \exp[H(S_\alpha)]$ is the entropy fluctuation. If the entropy fluctuation satisfies the following condition:

$$E(S_\alpha) = \delta H(S_\alpha) - \frac{2}{\sqrt{|\delta H(S_z)|}} < 0, \quad \alpha \equiv x \text{ or } y, \tag{17}$$

we say that entropy of the AQB is squeezed, and $E(S_\alpha)$ is called the entropy squeezing factor. When $E(S_\alpha) = -0.414$, it means optimal entropy squeezing, correspondingly that AQB is in the OESS and QN is minimal too. Previous work shows that when AQB is in the eigenstate of operator S_x as follows:[13]

$$|\phi\rangle = (|g\rangle + |e\rangle)/\sqrt{2}, \tag{18}$$

the S_x component of atomic operator has the optimal entropy squeezing, namely the OESS is the maximum coherent superposition state which is the physical resource of QC.

The expressions of information entropy of atomic operators S_α in three directions are[10]

$$\begin{aligned} H(S_x) &= -\left[\frac{1}{2} + \mathrm{Re}(\rho_{21})\right] \ln \left[\frac{1}{2} + \mathrm{Re}(\rho_{21})\right] \\ &\quad - \left[\frac{1}{2} - \mathrm{Re}(\rho_{21})\right] \ln \left[\frac{1}{2} - \mathrm{Re}(\rho_{21})\right], \end{aligned} \tag{19}$$

$$\begin{aligned} H(S_y) &= -\left[\frac{1}{2} + \mathrm{Im}(\rho_{21})\right] \ln \left[\frac{1}{2} + \mathrm{Im}(\rho_{21})\right] \\ &\quad - \left[\frac{1}{2} - \mathrm{Im}(\rho_{21})\right] \ln \left[\frac{1}{2} - \mathrm{Im}(\rho_{21})\right], \end{aligned} \tag{20}$$

$$H(S_z) = -\rho_{22} \ln \rho_{22} - \rho_{11} \ln \rho_{21}, \tag{21}$$

where ρ_{ij} are the density matrix elements of the AQB. Obviously, the information entropy and entropy squeezing properties of an AQB are determined by its density matrix elements.

4. Time evolution of the entropy squeezing factor

In principle, we may tune the whole system into different quantum states $|\psi_{S0}(t)\rangle$ or $|\psi_{SR(\theta)}(t)\rangle$ by changing the probability amplitudes A_0, B_0, C_0, D_0, E_0, F_0 or A_R, B_R, C_R, D_R, E_R, F_R. The reduced density matrix of the AQB2 inside the cavity can be correspondingly determined and the evolution of entropy squeezing factor is controlled. In this section, we manipulate AQB1 outside the cavity by changing the probability amplitudes above, and realize the evolution of entropy squeezing and preparation of OESS of AQB2. In the following, we discuss two cases, i.e., before and after operation on AQB1 outside the cavity.

4.1. Before operation on the AQB1 outside the cavity

In this subsection we discuss the entropy squeezing properties of AQB2 before operation on AQB1, and the schematic circuit diagram is shown in Fig. 2.

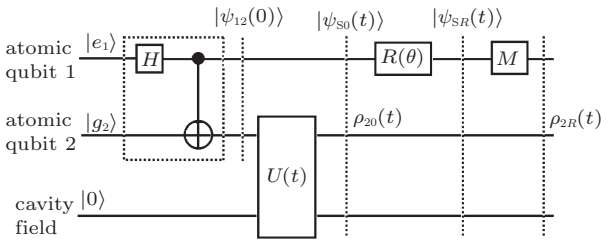


Fig. 2. Schematic circuit diagram. H and $U(t)$ represent Hadmard operation and unitary evolution.

We assume that the initial state of AQB1 and AQB2 is $|e_1 g_2\rangle$. By exerting the Hadamard (H) operation on AQB1 and CNOT operation between AQB1 and AQB2, we can prepare Bell state as follows:

$$|\psi_{12}(0)\rangle = \frac{1}{\sqrt{2}}(|g_1 e_2\rangle - |e_1 g_2\rangle), \tag{22}$$

which corresponds to the case of $r_1 = r_4 = 0$, $r_3 = -r_2 = 1/\sqrt{2}$ in Eq. (1). After AQB2 enters into the microwave cavity and undergoes the unitary evolution $U(t)$ as shown in Eq. (3), the quantum state of the whole system is

$$\begin{aligned} |\psi_{S0}(t)\rangle &= \frac{1}{\sqrt{2}}\{(|e_1 g_2\rangle - \cos(\sqrt{2}gt)\,|g_1 e_2\rangle)\,|0\rangle \\ &\quad - \mathrm{i}\sin(\sqrt{2}gt)\,|g_1 g_2\rangle\,|2\rangle\}. \end{aligned} \tag{23}$$

Correspondingly, AQB2 is in the state $\rho_{20}(t)$ as follows:

$$\rho_{20}(t) \equiv 1/2 \begin{bmatrix} \cos^2(\sqrt{2}gt) & 0 \\ 0 & 1 + \sin^2(\sqrt{2}gt) \end{bmatrix}. \tag{24}$$

Figures 3(a) and 3(b) show the time evolutions of squeezing factors $E(S_x)$ and $E(S_y)$ of AQB2 for reduced density operator $\rho_{20}(t)$. Both curves are oscillating with a period of $\pi/\sqrt{2}$ and have non-negative amplitudes, indicating that no squeezing effect exists for AQB2. These phenomena can be explained below.

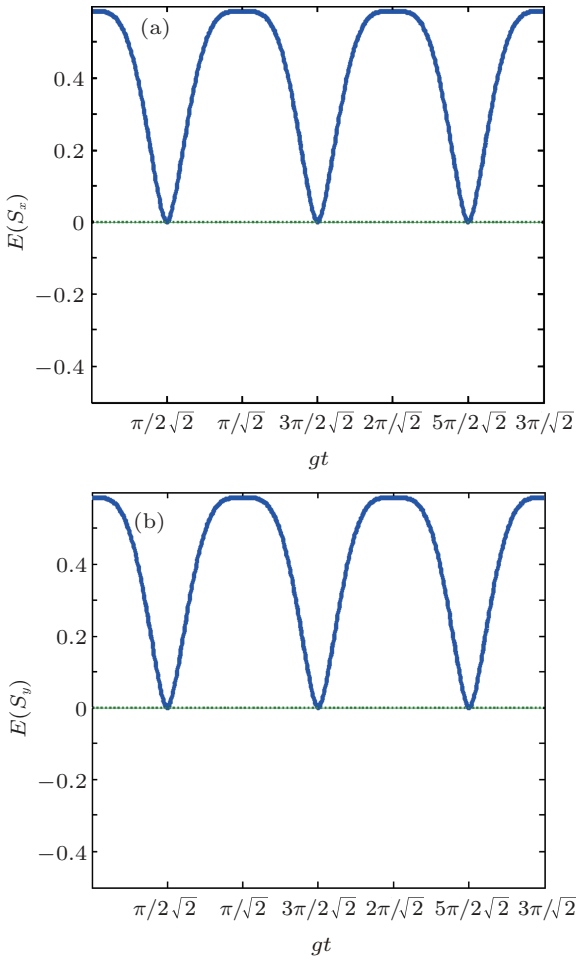


Fig. 3. (color online) Time evolutions of (a) $E(S_x)$ and (b) $E(S_y)$. The two AQBs are initially in $|\psi_{12}(0)\rangle$.

When $gt = (\sqrt{2}/2)n\pi$ $(n = 0, 1, 2\ldots)$, the quantum state of the whole system is

$$\left|\psi_{S0}\left(\frac{\sqrt{2}}{2}n\pi\right)\right\rangle = \frac{1}{\sqrt{2}}(|e_1 g_2\rangle \pm |g_1 e_2\rangle) \otimes |0\rangle\,. \quad (25)$$

It shows that two AQBs are in Bell states, leading to the maximum mixed state for the AQB2 as

$$\rho_{20}\left(\frac{\sqrt{2}}{2}n\pi\right) = \frac{1}{\sqrt{2}}(|g_2\rangle\langle g_2| + |e_2\rangle\langle e_2|), \quad (26)$$

so the $E(S_\alpha)(= 0.586)$ of AQB2 is maximal.

However, when $gt = [(2n+1)\pi/2\sqrt{2}]$ $(n = 0, 1, 2, \ldots)$, the state of the whole system is

$$\left|\psi^I_{S0}\left(\frac{2n+1}{2\sqrt{2}}\pi\right)\right\rangle = \frac{1}{\sqrt{2}}\{(i\,|g_1 2\rangle \pm |e_1 0\rangle) \otimes |g_2\rangle\}. \quad (27)$$

Here AQB2 is in the ground state and disentangled with its environment, that is,

$$\rho_{20}\left(\frac{2n+1}{2\sqrt{2}}\pi\right) = |g_2\rangle\langle g_2|\,, \quad (28)$$

which means that at these times AQB2 becomes a classical bit and $E(S_\alpha)$ is zero.

4.2. After operation on AQB1 outside the cavity

In the following, we discuss the case where we exert the rotation operation $\hat{R}(\theta)$ on AQB1 when AQB2 enters into the microwave cavity. The time evolution of entropy squeezing factor $E(S_x)$ for $\hat{R}(\theta)$ operation is depicted in Fig. 4.

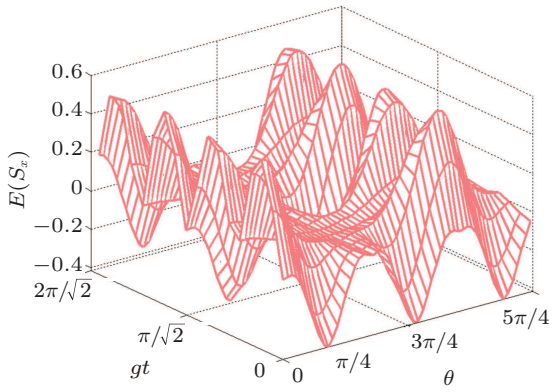


Fig. 4. (color online) Evolutions of the $E(S_x)$ with scaling time gt and rotation angle θ.

We find that there is no squeezing effect in the case of $\theta = n\pi/2$. In the case of $\theta = n\pi$, the rotation operation only changes the phase of AQB1 state, i.e., $\hat{R}(\pi)|\psi_{S0}(t)\rangle = -|\psi_{S0}(t)\rangle$, which is identical to that before performing the operation. In the case of $\theta = (2n+1)/\pi$, the rotation operations flip the quantum states $|e\rangle$ and $|g\rangle$ into each other. Inserting it into Eqs. (13) and (14), we can obtain that the quantum state of AQB2 is always in $|g_2\rangle$ and therefore $E(S_x) \equiv 0$ at arbitrary time. In the other cases except $\theta = n\pi/2$ there will be entropy squeezing effect for AQB2.

In the following, we pay our attention mainly to the case of optimal entropy squeezing. For the rotation operation $\hat{R}((2n+1)\pi/4)$ on AQB1, we depict the entropy squeezing factors $E(S_x)$ and $E(S_y)$ against the scaling time gt in Figs. 5(a) and 5(b). When $gt = n\pi/\sqrt{2}$ $(n = 0, 1, 2, \ldots)$, $E(S_x) = -0.414$, indicating that the optimal entropy squeezing for S_x is present. However, there is no entropy squeezing effect for S_y as $E(S_y) \geq 0$.

Mathematically, setting $r_1 = r_4 = 0$, $r_3 = -r_2 = 1/\sqrt{2}$, and substituting them into Eqs. (11) and (12), we have the probability amplitudes as follows:

$$A_R = -B_R = D_R = E_R = \frac{1}{2}, \quad F_R = 0. \quad (29)$$

Inserting D_R, E_R, and F_R into Eq. (13), the density matrix of the AQB2 is

$$\rho_{2R(\pi/4)}\left(\frac{\pi}{\sqrt{2}}\right) = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad (30)$$

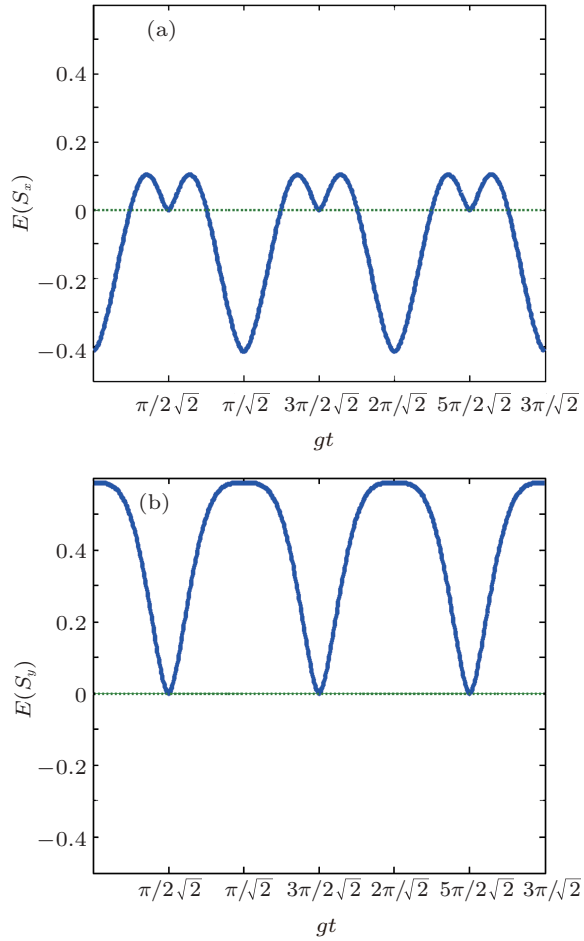


Fig. 5. (color online) Time evolutions of $E(S_x)$ and $E(S_y)$ in the case of $\hat{R}(\pi/4)$. The two AQBs are initially in the state $|\psi_{12}(0)\rangle$.

namely

$$\left|\psi_{2R(\pi/4)}\left(\frac{\pi}{\sqrt{2}}\right)\right\rangle = \frac{1}{\sqrt{2}}(|e_2\rangle + |g_2\rangle). \tag{31}$$

So far, we have prepared the AQB2 into OESS which is the maximum coherent superposition state. Physically, the $\hat{R}(\pi/4)$ operation turns the eigenstates $|g_1\rangle$ and $|e_1\rangle$ of AQB1 into superposition states with the same amplitude as follows:

$$\hat{R}(\pi/4)\,|g_1\rangle = \frac{1}{\sqrt{2}}(|g_1\rangle + |e_1\rangle), \tag{32}$$

$$\hat{R}(\pi/4)\,|e_1\rangle = \frac{1}{\sqrt{2}}(|g_1\rangle - |e_1\rangle). \tag{33}$$

The $\hat{R}(\pi/4)$ operation converts the state of the whole system at time $gt = \pi/\sqrt{2}$ into

$$\left|\psi_{SR(\pi/4)}\left(\frac{\pi}{\sqrt{2}}\right)\right\rangle = \frac{1}{\sqrt{2}}\{(|e_1e_2\rangle - |e_1g_2\rangle + |g_1e_2\rangle + |g_1g_2\rangle)\otimes|0\rangle\}. \tag{34}$$

It shows that two AQBs are separated from the cavity field, but entangled with strong coherence. Whichever AQB1 is in $|g_1\rangle$ or $|e_1\rangle$, AQB2 will restore to its maximum coherent superposition state, which is the physical reason for the occurrence of OESS.

5. Conclusions

In this paper, we study the entropy squeezing properties of AQB by controlling its external environment, that is, the microwave cavity field and AQB entangled with it, and draw the conclusions below.

(i) When there is no operation performed on AQB1 outside the cavity, AQB2 inside the cavity is always in a disentangled mixed state or a classical state, without squeezing effect.

(ii) In the case where the initial states for two AQBs are in Bell states, i) when $\hat{R}(n\pi/2)$ operations are performed on AQB1 outside the cavity, AQB2 inside the cavity is decoherent without entropy squeezing; ii) except the case of $\hat{R}(n\pi/2)$, there will be entropy squeezing effect for AQB2; iii) when $\hat{R}((2n+1)\pi/4)$ operation is performed on AQB1 outside the cavity, AQB2 inside the cavity shows the optimal entropy squeezing with a period of $\pi/\sqrt{2}$. Its OESS is prepared and the maximum coherent superposition state is restored.

Our conclusions show that with the appropriate rotation and measurement operations on AQB1 outside the cavity, we can control the entropy squeezing properties of AQB2 and prepare its OESS by adjusting the interaction time between AQB2 and the cavity field. Our study theoretically may provide an alternative way of inhibiting decoherence of single AQB in the QN environment, and establish a better foundation for investigating entropy squeezing properties of AQB in the more complicated environment.

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