Single-atom entropy squeezing and quantum entanglement in Tavis–Cummings model with atomic motion*

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We examine the single-atom entropy squeezing and the atom–field entanglement in a system of two moving two-level atoms interacting with a single-mode coherent field in a lossless resonant cavity. Our numerical calculations indicate that the squeezing period, the squeezing time and the maximal squeezing can be controlled by appropriately choosing the atomic motion and the field-mode structure. The atomic motion leads to a periodical time evolution of entanglement between the two-atom and the field. Moreover, there exists corresponding relation between the time evolution properties of the atomic entropy squeezing and that of the entanglement between the two atoms and the field.

Keywords: atomic entropy squeezing, quantum reduced entropy, Tavis–Cummings model, atomic motion and field-mode structure

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1. Introduction

The investigation of the squeezing of a two-level atom and the light field has attracted considerable attention in recent years.[1−7] This is not only due to the fact that it has potential applications in high-resolution spectroscopy, the high precisions atomic fountain clocks, the high-accuracy spin polarization measurements, the generation of quantum controlled few-photon states, the control of quantum noise, the atomic spin polarization measurements, but also because the generation of squeezed light[8,9] has been applied to quantum information theory, for example in quantum teleportation,[10,11] cryptography,[12,13] and dense coding.[14] Most of the studies of atomic squeezing were based on the Heisenberg uncertainty relation (HUR), which is regarded as a standard limitation on measurements of quantum fluctuations. However, the HUR cannot give us sufficient information about atomic squeezing, in particular, when the atomic inversion is zero.[15] Several authors found an elegant entropic way of reformulating the HUR by using quantum entropy theory, and obtained an entropic uncertainty relation (EUR), which could be free from the triviality of the HUR.[7,16,17]

Quantum entanglement is one of the most striking features of quantum mechanics. It has been recognized as a resource in quantum information processing[19] and quantum computing.[20] Recently, a metropolitan quantum cryptography network for government administration was demonstrated.[21] This is a big step toward the actualization of practical large-scale quantum cryptography network. Consequently, the understanding of entangled states has become more and more important. There has been a lot of work on bipartite or multipartite entanglement, and the general theory of entanglement has blossomed enormously.[4,22,23] We have also paid attention to the relationship between the atomic squeezing and the entanglement.[24] Furthermore, the generation of entanglement and squeezing in circuit quantum electrodynamics was reported.[25,26]

The Tavis–Cummings model (TCM)[27] is a theoretical model consisting of many atoms coupled to a single-mode field in a lossless cavity. Since it can exhibit many nonclassical properties, it has received much attention. Up to now, the effects of the dipole–dipole interaction and phase-interrupting collisions between atoms,[28] the effect of the presence of a nonlinear medium[29] and amplitude–phase multistability in the TCM[30] have been studied. Very recently, more profound researches on the TCM have

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been made.[31−33]

In the present paper, we investigate the single-atom entropy squeezing in the two-atom TCM with atomic motion, and the degree of the entanglement between the two moving atoms and the single-mode coherent field (DEAF) in the system. The influences of the atomic motion, field-mode structure and the initial atomic state are examined. The relation between the atomic entropy squeezing and the DEAF is also revealed. The obtained results may be important for the experimental realization of the preparation of squeezing atom and the control of entangled state in quantum information. The rest of this paper is organized as follows. In Section 2, we introduce the model under consideration. In Section 3, the atomic entropy squeezing is discussed. In Section 4, the entanglement between the two moving atoms and the field is investigated. In the last section, some conclusions are drawn from the present study.

2. Model and state vector

Consider the TCM where two identical two-level atoms are in a single-mode cavity. The two atoms are moving along the z-axis of the cavity at the same speed v simultaneity. For simplicity, we ignore the dipole–dipole interaction of the atoms. The Hamiltonian of the TCM in the dipole approximation and rotating-wave approximation in the Schrödinger picture is[31]

$$H = H_0 + V, \tag{1}$$

where H_0 is the Hamiltonian for the two bare atoms and the cavity field ($\hbar = 1$),

$$H_0 = \omega a^+ a + \frac{1}{2}\omega\left(\sigma_{z1} + \sigma_{z2}\right), \tag{2}$$

and V is the Hamiltonian for the interaction between the atoms and the cavity field,

$$V = gf\left(z\right)\sum_{i=1}^{2}\left(a^+\sigma_i^- + \sigma_i^+ a\right) \tag{3}$$

with $a^+\left(a\right)$ being the photon creation (annihilation) operator for the cavity field mode, σ_{zi} and $\sigma_i^{\pm}$ being the pseudo-spin operators of the ith atom. We consider the resonance case, in which frequencies of the atomic transition and the cavity field are both ω. g is the coupling constant between the atoms and the cavity field mode, $f(z)$ denotes a shape function of cavity field mode. We restrict our study to the atomic motion along the z-axis so that the z-dependence of the field-mode function should be taken into account. The atomic motion can be incorporated in the usual way, i.e.

$$f(z) \ \rightarrow \ f(vt), \tag{4}$$

where v denotes the atomic motion speed. To be specific, we define the $\mathrm{TEM}_{\mathrm{mnp}}$ mode for transererse electric and magnatic as

$$f(z) = \sin\left(p\pi vt/L\right), \tag{5}$$

where p represents the number of half-wavelengths of the field mode inside a cavity with length L. Here we assume that the two atoms at time $t = 0$ enter the cavity and leave the cavity after passing through p half-wavelengths of electric field.

In the interaction picture, the Schrödinger equation for the system is

$$\mathrm{i}\frac{\partial}{\partial t}\left|\Psi\left(t\right)\right\rangle = V\left|\Psi\left(t\right)\right\rangle. \tag{6}$$

Since $[V(t), V(t')] = 0$, the time evolution operator can be written as

$$U(t) = \exp\left[-\mathrm{i}\int_0^t V(t')\mathrm{d}t'\right] = \exp\left[-\mathrm{i}\tilde{V}F(t)\right], \tag{7}$$

where $\tilde{V} = g\sum_{i=1}^{2}\left(a^+\sigma_i^- + \sigma_i^+ a\right)$ is the Hamiltonian for the interaction between the atoms and the cavity field when the atoms are motionless, and

$$F(t) = \int_0^t f(vt')\mathrm{d}t' = \frac{L}{p\pi v}\left[1 - \cos\frac{pv\pi t}{L}\right]. \tag{8}$$

For a particular choice of the atomic motion velocity $v = gL/\pi$, $F\left(t\right)$ becomes

$$F(t) = \left[1 - \cos(pgt)\right]/(pg). \tag{9}$$

We assume that the two atoms are initially in the superposition state

$$\left|\Psi_{\mathrm{A}}\left(0\right)\right\rangle = \cos\frac{\theta}{2}\left|g_1, g_2\right\rangle - \sin\frac{\theta}{2}\,\mathrm{e}^{\,\mathrm{i}\varphi}\left|e_1, e_2\right\rangle, \tag{10}$$

where $0 \leq \theta \leq \pi$ denotes the atomic distribution, and $0 \leq \varphi \leq 2\pi$ is the phase of the atom dipole (in this paper $\varphi = \pi$). And the cavity field is in the coherent state

$$\left|\alpha\right\rangle = \sum_{n=0}^{\infty} F_n\left|n\right\rangle,$$

where

$$F_n = \exp\left(-\frac{\left|\alpha\right|^2}{2}\right)\cdot\frac{\alpha^n}{\sqrt{n!}}, \tag{11}$$

$\alpha = \sqrt{\bar{n}}\exp\left(\mathrm{i}\beta\right)$, with $\bar{n}$ and β representing the initial average photon number (the intensity of the cavity

field) and the phase of the coherent field, respectively (therein, we suppose $\beta = 0$). Then the initial state vector of the system is

$$|\Psi(0)\rangle = |\Psi_{\rm A}(0)\rangle \otimes |\alpha\rangle . \tag{12}$$

The state vector of the system at any time $t > 0$ can be expressed as

$$\begin{aligned} |\Psi(t)\rangle &= U(t)\,|\Psi(0)\rangle \\ &= \sum_{n=0}^{\infty} F_n[D_{1,n-2}(t)\,|u_1, n-2\rangle \\ &\quad + D_{2,n-1}(t)|u_2, n-1\rangle + D_{3,n}(t)|u_3, n\rangle \\ &\quad + C_{1,n}(t)|u_1, n\rangle + C_{2,n+1}(t)|u_2, n+1\rangle \\ &\quad + C_{3,n+2}|u_3, n+2\rangle, \end{aligned} \tag{13}$$

where $|u_1\rangle = |e_1, e_2\rangle$, $|u_2\rangle = (|g_1, e_2\rangle + |e_1, g_2\rangle)/\sqrt{2}$ and $|u_3\rangle = |g_1, g_2\rangle$ are three swap-symmetry wave functions of the two identical atoms, which are used as the base vectors. The coefficients of Eq. (13) are

$$\begin{aligned} D_{1,n-2}(t) &= \frac{\sqrt{n(n-1)}}{2n-1} \\ &\quad \times \cos\frac{\theta}{2}\left[\cos\left(\sqrt{4n-2}gF(t)\right) - 1\right], \\ D_{2,n-1}(t) &= -\frac{{\rm i}\sqrt{n}}{\sqrt{2n-1}}\cos\frac{\theta}{2}\sin\left(\sqrt{4n-2}gF(t)\right), \\ D_{3,n}(t) &= \frac{1}{2n-1}\cos\frac{\theta}{2} \\ &\quad \times \left[n\cos\left(\sqrt{4n-2}gF(t)\right) + n - 1\right], \\ C_{1,n}(t) &= -\frac{1}{2n+3}\sin\frac{\theta}{2}\,{\rm e}^{{\rm i}\varphi}[(n+1) \\ &\quad \times \cos(\sqrt{4n+6}gF(t)) + n + 2], \\ C_{2,n+1}(t) &= -\frac{{\rm i}\sqrt{n+1}}{2n+3}\sin\frac{\theta}{2}\,{\rm e}^{{\rm i}\varphi}\sin\left(\sqrt{4n+6}gF(t)\right), \\ C_{3,n+2}(t) &= -\frac{\sqrt{(n+2)(n+1)}}{2n+3}\sin\frac{\theta}{2}\,{\rm e}^{{\rm i}\varphi} \\ &\quad \times \left[\cos\left(\sqrt{4n+6}gF(t)\right) - 1\right]. \end{aligned} \tag{14}$$

The atomic reduced density operator for the system is given by

$$\begin{aligned} \rho_{\rm A}(t) &= {\rm Tr}_{\rm F}\,|\Psi(t)\rangle\langle\Psi(t)| \\ &= \begin{bmatrix} \rho_{11} & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & \rho_{22} & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & \rho_{33} & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & \rho_{44} \end{bmatrix}, \end{aligned} \tag{15}$$

where

$$\begin{aligned} \rho_{11} &= \sum_{n=0}^{\infty} |(F_{n+2}D_{1,n}(t) + F_nC_{1,n}(t))|^2, \\ \rho_{22} = \rho_{23} = \rho_{33} = \rho_{32} &= \sum_{n=0}^{\infty} \left|\frac{1}{\sqrt{2}}\left(F_{n+1}D_{2,n}(t) + F_{n-1}C_{2,n}(t)\right)\right|^2, \\ \rho_{44} &= \sum_{n=0}^{\infty} |(F_nD_{3,n}(t) + F_{n-2}C_{3,n}(t))|^2, \\ \rho_{12} = \rho_{13} = \rho_{21}^* = \rho_{31}^* &= \sum_{n=0}^{\infty} \frac{1}{\sqrt{2}}\left(F_{n+2}D_{1,n}(t) + F_nC_{1,n}(t)\right)\left(F_{n+1}D_{2,n}^*(t) + F_{n-1}C_{2,n}^*(t)\right), \\ \rho_{14} = \rho_{41}^* &= \sum_{n=0}^{\infty} \left(F_{n+2}D_{1,n}(t) + F_nC_{1,n}(t)\right)\left(F_nD_{3,n}^*(t) + F_{n-2}C_{3,n}^*(t)\right), \\ \rho_{42} = \rho_{43} = \rho_{24}^* = \rho_{34}^* &= \sum_{n=0}^{\infty} \frac{1}{\sqrt{2}}\left(F_nD_{3,n}(t) + F_{n-2}C_{3,n}(t)\right)\left(F_{n+1}D_{2,n}^*(t) + F_{n-1}C_{2,n}^*(t)\right). \end{aligned} \tag{16}$$

3. Atomic entropy squeezing

Following the work by Fang *et al.* in Refs. [15] and [16] we can express the entropy squeezing of a two-level atom by using the quantum information entropy theory. The information entropies of the Pauli operators S_α ($\alpha = x, y, z$) for a two-level atom system are

$$H(S_\alpha) = -\sum_{i=1}^{2} P_i(S_\alpha)\ln P_i(S_\alpha), \quad \alpha = x, y, z, \tag{17}$$

where $P_i(S_\alpha) = \langle\Psi_{\alpha i}|\,\rho\,|\Psi_{\alpha i}\rangle$ ($i = 1, 2$), which are the probability distributions for two possible measurements of an operator S_α. $H(S_x)$, $H(S_y)$, $H(S_z)$ sat-

isfy

$$H(S_x) + H(S_y) \geq 2\ln 2 - H(S_z), \tag{18}$$

which may also be rewritten as

$$\delta H(S_x)\,\delta H(S_y) \geq \frac{4}{\delta H(S_z)}, \tag{19}$$

where $\delta H(S_\alpha) = \exp[H(S_\alpha)]$. The squeezing of the atom is determined by using the EUR (Eq. (19)) named entropy squeezing. The fluctuation in component S_α ($\alpha \equiv x,\, y$) of the atomic dipole is said to be squeezed in entropy if the information entropy $H(S_\alpha)$ satisfies the following condition:

$$E(S_\alpha) = \delta H(S_\alpha) - \frac{2}{\sqrt{|\delta H(S_z)|}} < 0, \quad (\alpha \equiv x,\, y). \tag{20}$$

Now we are in a position to calculate the single-atom entropy squeezing, for instance, for the first atom. We assume that A_1 and A_2 denote the first atom and the second atom respectively. The density matrix of the first atom can be obtained to be

$$\rho_{A_1} = \mathrm{Tr}_{A_2 F}\,|\Psi(t)\rangle\langle\Psi(t)| = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix}, \tag{21}$$

where

$$\begin{aligned}
q_{11} &= \sum_{n=0}^{\infty}\left[|F_{n+2}D_{1,n}(t) + F_nC_{1,n}(t)|^2 + \frac{1}{2}|F_{n+1}D_{2.n}(t) + F_{n-1}C_{2,n}(t)|^2\right],\\
q_{12} &= \sum_{n=0}^{\infty}\frac{1}{\sqrt{2}}[(F_{n+2}D_{1,n}(t) + F_nC_{1,n}(t))\left(F_{n+1}D^*_{2,n}(t) + F_{n-1}C^*_{2,n}(t)\right) + (F_{n+1}D_{2n}(t)\\
&\quad + F_{n-1}C_{2n}(t))\left(F_nD^*_{3,n}(t) + F_{n-2}C^*_{3,n}(t)\right),\\
q_{22} &= 1 - q_{11},\\
q_{21} &= q^*_{12}.
\end{aligned} \tag{22}$$

By using the reduced atomic density operator ρ_{A1}, we can obtain the information entropies of the atomic operators S_x, S_y, S_z for the first atom as follows:

$$H(S_x) = -\left[\frac{1}{2} + \mathrm{Re}(q_{12}(t))\right]\ln\left[\frac{1}{2} + \mathrm{Re}(q_{12}(t))\right] - \left[\frac{1}{2} - \mathrm{Re}(q_{12}(t))\right]\ln\left[\frac{1}{2} - \mathrm{Re}(q_{12}(t))\right], \tag{23a}$$

$$H(S_y) = -\left[\frac{1}{2} + \mathrm{Im}(q_{12}(t))\right]\ln\left[\frac{1}{2} + \mathrm{Im}(q_{12}(t))\right] - \left[\frac{1}{2} - \mathrm{Im}(q_{12}(t))\right]\ln\left[\frac{1}{2} - \mathrm{Im}(q_{12}(t))\right], \tag{23b}$$

$$H(S_z) = -q_{22}(t)\ln q_{22}(t) - q_{11}(t)\ln q_{11}(t). \tag{23c}$$

In the following, we will investigate the atomic entropy squeezing in the system. From Eqs. (14)–(23) we can prove for the component S_x entropy squeezing

$$E(S_x) = 2\left(1 - \frac{1}{\sqrt{|\delta H(S_z)|}}\right) \geq 0, \tag{24}$$

where $1/\sqrt{|\delta H(S_z)|} \leq 1$. This means that $E(S_x)$ cannot exhibit squeezing in the entropy. Thus we focus our attention on the discussion of $E(S_y)$ (the entropy squeezing of component S_y) by numerical calculation method.

In Figs. 1(a)–1(d) we show the influences of the atomic motion and the field mode structure parameter on the time evolution of $E(S_y)$ with $\theta = 0$, $\varphi = \pi$ and $\bar{n} = 36$. When the atomic motion is neglected as shown in Fig. 1 (a), $E(S_y)$ cannot exhibit squeezing except at initial stage of time. To compare with this, Figs. 1(b)–1(d) illustrate the time evolution of $E(S_y)$ when the atoms are moving at a speed $v = gL/\pi$, and the field mode structure parameters are $p = 1$, $p = 2$ and $p = 5$, respectively. It can be seen that as a result of the atomic motion, they exhibit periodical time evolutions and have the same peak values in every period, which is quite different from that of Fig. 1(a). Furthermore, component S_y is squeezed periodically, and the squeezing time becomes longer and the period shortens with the increase of p. When p is big enough, the moving atom may exhibit long time entropy squeezing effect, which is shown in Fig. 1(d).

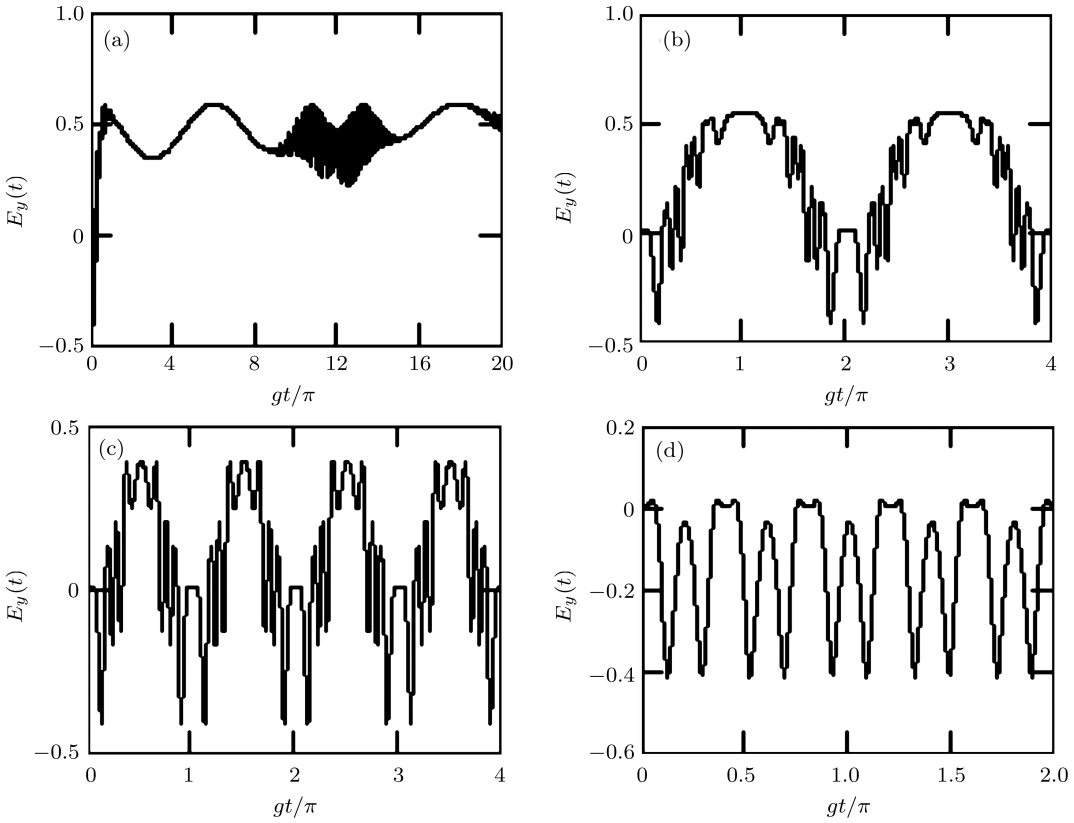


Fig. 1. Time evolution of information entropy squeezing factors $E(S_y)$ at $\theta = 0$, $\varphi = \pi$, and $\bar{n} = 36$, where panel (a) is for the atomic motion neglected; panels (b)–(d) are for the atoms moving at speed $v = gL/\pi$, and panel (b) is for $p = 1$; panel (c) is for $p = 2$; panel (d) is for $p = 5$.

We can conclude that atomic motion leads to the periodic time evolution of the atomic entropy squeezing The period of the entropy squeezing and the squeezing time of information entropy are determined by the field mode structure. These results are different from those in Ref. [6], and correspond to the results obtained in Ref. [7].

Figure 2 presents the numerical results of the time evolution of $E(S_y)$ for different initial states of the two atoms with $p = 1$, $\varphi = \pi$, and $\bar{n} = 36$. From Fig. 2(b), we can see when the two atoms are initially in a maximal entangled state (namely $\theta = \pi/2$), $E(S_y)$ cannot exhibit entropy squeezing. But for initially disentangled states ($\theta = 0$ or $\theta = \pi$), $E(S_y)$ exhibits the maximal entropy squeezing (Figs. 1(b) and 2(c)). While the two atoms are initially in usual entangled states (Fig. 2 (a)), $E(S_y)$ can exhibit some degree of entropy squeezing. The squeezing time and degree are dependent on the initial atomic state of the atoms. But the period of the time evolution of $E(S_y)$ keeps invariant.

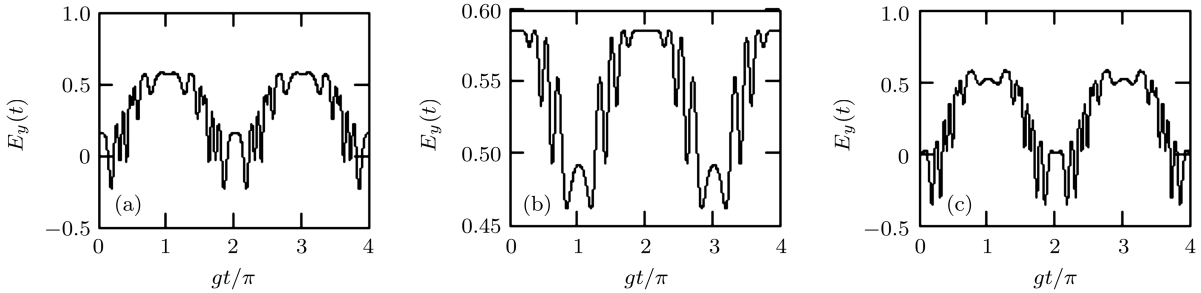


Fig. 2. Time evolutions of information entropy squeezing factor $E(S_y)$ with the two atoms moving at speed $v = gL/\pi$ and $p = 1$, $\varphi = \pi$, $\bar{n} = 36$, $\theta = \pi/8$ (a),$\pi/2$ (b), and π (c).

4. Entanglement between two moving two-level atoms and coherent field

According to the work by Phoenix and Knight,[34] we study the entanglement between the two atoms and a single-mode field by using the quantum reduced entropy. The time evolution of the two atomic (a single-mode field) reduced entropy reflects the time evolution of the DEAF. The higher the reduced entropy is, the greater the DEAF will be. The entropies of the two atoms and a single-mode field can be defined through their respective reduced density operators as

$$S_i\left(t\right) = -\mathrm{Tr}_i\left(\rho_i \ln \rho_i\right) \ , \quad (i = \mathrm{A \ or \ F}) \, . \tag{25}$$

Since we have assumed that the two atoms and the field are initially in a disentangled pure state, the total entropy of system $S\left(t\right)$ is zero. In terms of the triangle inequality of the entropy[35]

$$|S_{\mathrm{A}}(t) - S_{\mathrm{F}}(t)| \leq S(t) \leq |S_{\mathrm{A}}(t) + S_{\mathrm{F}}(t)| \, , \tag{26}$$

we can see that the reduced entropies of the two subsystems are identical. Consequently we only need to calculate the atomic reduced entropy $S_{\mathrm{A}}(t)$. It can be expressed as

$$S_{\mathrm{A}}\left(t\right) = -\mathrm{Tr}_{\mathrm{A}}\left[\rho_{\mathrm{A}}\left(t\right) \ln \rho_{\mathrm{A}}\left(t\right)\right] = -\sum_{i=1}^{4} \lambda_i \ln \lambda_i. \tag{27}$$

In the following we discuss the influences of the atomic motion and the field mode structure parameters on DEAF by using the above results.

Figure 3 shows the time evolution of reduced entropy $S_{\mathrm{A}}(t)$ of the entanglement with the same parameter values as those in Fig. 1. Comparing the plots in Fig. 3 and Fig. 1, it is interesting to find that the period of the time evolution of DEAF is the same as that of $E(S_y)$. If the atomic motion is neglected (shown in Fig. 3(a)), the time evolution of $S_{\mathrm{A}}(t)$ does not exhibit the periodicity and can maintain a relatively high value. If the two atoms are moving at a speed $v = gL/\pi$ (shown in Figs. 3(b)–3(d)), $S_{\mathrm{A}}(t)$ changes its orderliness, the two atoms and the field stay in the entangled state and in the disentangled state alternatively. And the DEAF becomes weaker obviously with

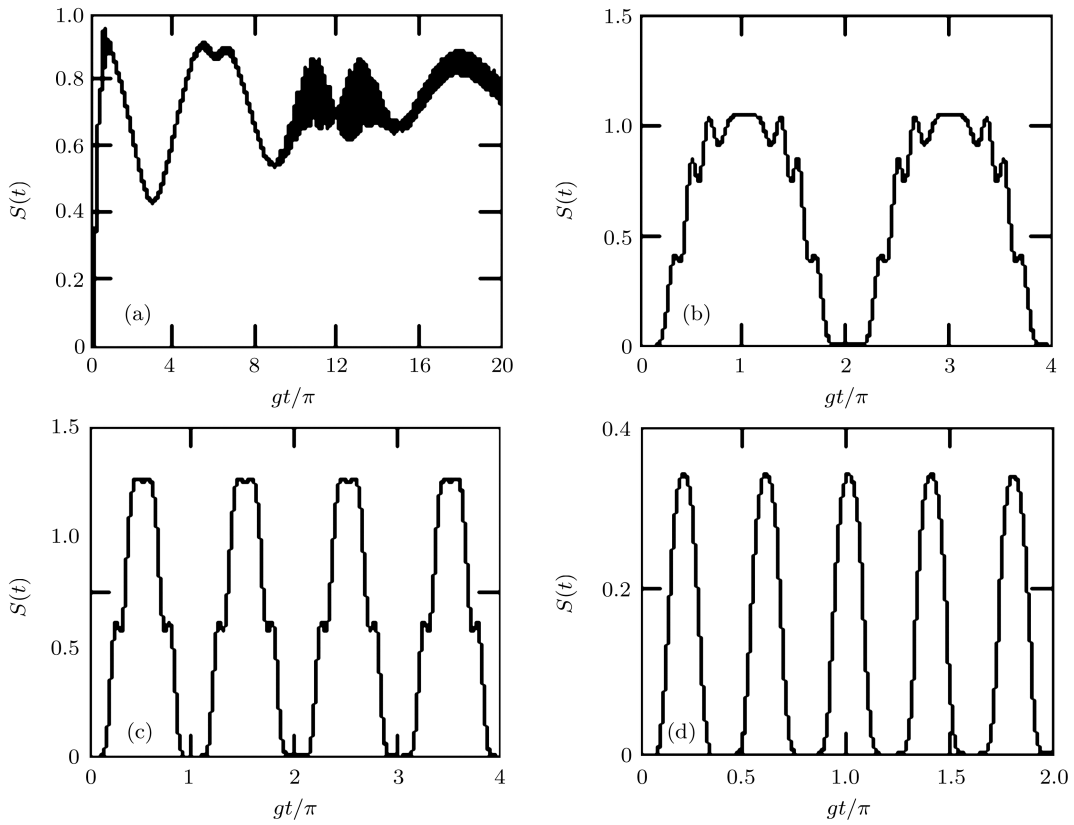


Fig. 3. Time evolutions of $S(t)$ for $\theta = 0$, $\varphi = \pi$, $\bar{n} = 36$, and $P = 1$ (b), 2 (c), and 5 (d). Panel (a) is for the atomic motion neglected; panels (b)–(d) are for the two atoms moving at speed $v = gL/\pi$.

the increase of p. That is to say, atomic motion works against DEAF and the bigger p can weaken the DEAF. It reflects the control of atomic motion and field mode structure of DEAF, which can play an important role in enhancing and controlling entanglement.

The two moving atoms and the single mode coherent field are in disentanglement at time $t = 2k\pi/pg(k = 0,\ 1, \cdots)$ when $E(S_y)$ takes its value of zero. Physically, at these points of the time, the state vector evolves into $|\Psi(t)\rangle = |u_3, n\rangle = |g_1, g_2\rangle \otimes |n\rangle$, therefore the two atoms and the cavity field are in the disentangled states. On the other hand, atomic motion leads the atoms–field interaction time to change. When the atoms are in motion, $gF(t)$ takes the place of gt. From Eq. (9) we can see $gF(t)$ is a function with a period of $2\pi/p$. The periodicity of $gF(t)$ leads $E(S_y)$ and $S_{\rm A}(t)$ to be periodical. So we can see that periods of $E(S_y)$ and $S_{\rm A}(t)$ decrease with the increase of p (see Figs. 1 and 3). This is similar to the result in Ref. [36]. It is also seen that the maximum values of $E(S_y)$ and $S_{\rm A}(t)$ always appear at the same time. So the time evolution of DEAF and the atomic entropy squeezing can be controlled by changing the above parameters. From Figs.1 and 3, we can see that atomic entropy squeezing not only is an accurate measure of atom squeezing but also has some properties corresponding to the entanglement between the two-atom and the field. Our results may be useful for the experimental realization and the control of the optimal atomic entropy squeezing and maximal entangled states.

5. Conclusions

We investigate the single-atom entropy squeezing for two moving two-level atoms interacting with a single-mode coherent field by using the EUR, and the DEAF in the system by using the quantum reduced entropy. From the above analysis, it is clearly noted that the atomic moving and the field mode structure parameter have a notable influence on the atomic squeezing and the DEAF. We can draw the following conclusions. (i) The period of the atomic entropy squeezing is the same as that of the DEAF. They are determined by choosing atomic motion and the field mode structure. (ii) The squeezing time and the squeezing degree are determined by the field mode structure and the initial atomic state. The atom in the two-atom Tavis–Cummings model with atomic motion may exhibit a long time entropy squeezing effect by appropriately choosing system parameters. (iii) The DEAF decreases as the field mode structure parameter increases. The atomic entropy squeezing has some properties corresponding to the DEAF, though their time evolutions are different in behaviour. Our results show that we can prepare and control atomic squeezing and DEAF by choosing parameters of atomic motion and field mode structure. We believe that these results will also be useful for investigating the properties of interaction between the atom and the field.

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