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Quantum entanglement between the two-mode fields and atomic entropy squeezing in the system of a moving atom interacting with two-mode entangled coherent field*

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This paper investigates the entropy squeezing of a moving two-level atom interacting with the two-mode entangled coherent field via two-photon transition by using an entropic uncertainty relation and the degree of entanglement between the two-mode fields by using quantum relative entropy. The results obtained from numerical calculation indicate that the squeezed period, the duration of entropy squeezing and the maximal squeezing can be controlled by appropriately choosing the intensity of the light field, the atomic motion and the field-mode structure. The atomic motion leads to the periodic recovery of the initial maximal degree of entanglement between the two-mode fields. Moreover, there exists a corresponding relation between the time evolution properties of the atomic entropy squeezing and those of the entanglement between the two-mode fields.

Keywords: entropy squeezing, quantum relative entropy, atomic motion and field-mode structure, two-mode entangled light field

PACC: 4250, 0365

1. Introduction

The investigation of the squeezing of a two-level atom has attracted considerable attention in recent years. This is not only because it has potential applications in high-resolution spectroscopy,[1] high precision atomic fountain clocks,[2] high-precision spin polarization measurements,[3] the generation of quantum-controlled few-photon states,[4] the control of quantum noise,[5] and atomic spin polarization measurements,[6] but also because the generation of squeezed light[7] has been applied to quantum information theory, for example, in quantum teleportation,[8,9] cryptography,[10,11] and dense coding.[12] Most studies of atomic squeezing are 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 on atomic squeezing, in particular,[13] when the atomic inversion is zero. Several authors found an elegant entropic way of reformulating the HUR by using quantum entropy theory, and obtained an entropic uncertainty relation (EUR), which can be free from the triviality of the HUR.[14−16]

Quantum entanglement (QE) is one of the most striking features of quantum mechanics. In the last two decades, it has been recognized as a resource in quantum information processing.[17] Therefore, it is very important to quantify the entanglement to assess the efficacy of quantum information processing, to prepare and control quantum entangled states in well-controlled experimental conditions. QE can result from the interaction of an atom with a cavity mode field.[18−20] Recently, with the development of cavity quantum electrodynamics (QED) the interaction between a moving atom and the field has attracted much attention.[21−24] Research shows that the atomic motion can bring about the nonlinear effect of atomic populations,[21,22] and change the creation time of the Schrödinger cat state,[25] etc. Most experiments have involved a single cavity mode field interacting with one, two, or three atoms crossing it successively. It

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is worthwhile pointing out that unconditional quantum teleportation of an unknown coherent state has been realized experimentally by exploiting a two-mode squeezed vacuum state as an entanglement resource.[9] The realization of a more complex entanglement in cavity QED has been presented by involving two independent cavity modes in the experiment.[26,27] The multi-mode entanglement opens interesting perspectives for quantum information processing and nonlocality tests.[28,29] Liu *et al* have investigated the influences of atomic motion and the field-mode structure on QE in the system with a moving atom interacting with a two-mode field.[30] The results obtained can not only reveal the quantum features of the atom and the field but also have practical significance. In a recent paper[5] a moving two-level atom interacting with a coherent field has been studied. The authors studied the effects of the atomic motion and the field-mode structure on entropy squeezing and the relation between the squeezing and fidelity of the channel for atomic quantum states. Hence we, in the present paper, restrict ourselves solely to a discussion of the entropy squeezing of a moving atom interacting with the two-mode entangled coherent field, and the degree of the entanglement between the two-mode fields (DETMF) in the system.

This paper examines the influences of the atomic motion, field-mode structure and the intensity of the field. The relation between the atomic entropy squeezing and DETMF is also revealed. We find that the optimal atomic entropy squeezing and the duration of squeezing are determined by the intensity of the field, the atomic motion and the field-mode structure. The atomic motion leads to the periodic recovery of the initial maximal degree of entanglement between the two-mode fields. The evolution periods of atomic entropy squeezing and DETMF are controlled by atomic motion and the field-mode structure. When the atom inversion approaches zero, the time evolution of the atomic entropy squeezing is the opposite way to that of DETMF. The two-mode entangled coherent field in the system is a valuable resource for quantum information processing. The results obtained may be important for the experimental realization of the preparation of a squeezing atom and the control of entangled states in quantum information.

2. The model and state vector

The present cavity QED experiments[21] are equipped with an atomic beam passing along the axis of the rectangular or cylindrical cavity so that one can investigate the interaction of a moving atom with different field modes. The system considered here consists of a two-level atom in motion interacting with a quantized field via the two-photon transition processes. The effective Hamiltonian in the rotating-wave approximation is ($\hbar = 1$)[31]

$$H = \omega_1 a_1^+ a_1 + \omega_2 a_2^+ a_2 + \omega_0 \sigma_z + gf(z)\left(a_2 a_1 \sigma_+ + a_2^+ a_1^+ \sigma_-\right), \quad (1)$$

where σ_z and $\sigma_\pm$ are the atomic inversion and transition operators, respectively; a_j^+ (a_j) is the photon creation (annihilation) operator of the field mode with a frequency ω_j ($j = 1, 2$); ω_0 is the atomic transition frequency, g is the coupling constant between the atom and the two-mode entangled coherent fields; $f(z)$ denotes the shape function of the cavity field mode. We restrict our study to 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 involved in the usual way

$$f(z) \rightarrow f(vt), \quad (2)$$

where v denotes the speed of atomic motion. In order to make the later discussion convenient, a $\mathrm{TEM}_{\mathrm{mnp}}$ mode is defined as

$$f(z) = \sin\left(p\pi vt/L\right), \quad (3)$$

where p represents the number of half-wavelengths of the field mode inside a cavity with a length L. For simplicity, we consider the resonance case, in which $\omega_0 = \omega_1 + \omega_2$. We assume that the atom at the time $t = 0$ is in the excited state $|e\rangle$, and it enters the cavity then leaves the cavity after passing through p half-wavelengths of electric field. Using the standard techniques,[30,31] in the interaction picture and the two-dimensional atomic space we can write the time evolution Dyson operator as

$$U_I(t)=\begin{bmatrix} \cos(\sqrt{a_1a_2a_1^+a_2^+}g\theta(t)) & -\mathrm{i}a_1a_2\dfrac{\sin(\sqrt{a_1^+a_2^+a_1a_2}g\theta(t))}{\sqrt{a_1^+a_2^+a_1a_2}} \\ -\mathrm{i}a_1^+a_2^+\dfrac{\sin(\sqrt{a_1a_2a_1^+a_2^+}g\theta(t))}{\sqrt{a_1a_2a_1^+a_2^+}} & \cos(\sqrt{a_1^+a_2^+a_1a_2}g\theta(t)) \end{bmatrix}, \tag{4}$$

where

$$\theta(t)=\int_0^t f(vt')\mathrm{d}t'=\frac{L}{p\pi v}\left[1-\cos\frac{pv\pi t}{L}\right]. \tag{5}$$

We take the speed of the atom as $v=gL/\pi$ without losing generality, hence

$$\theta(t)=\left[1-\cos(pgt)\right]/(pg). \tag{6}$$

We consider that the field is initially in the two-mode entangled coherent state

$$\begin{aligned}|\Psi_{\mathrm{F}}(0)\rangle&=\alpha|\alpha_1\rangle|\alpha_2\rangle+\beta|-\alpha_1\rangle|-\alpha_2\rangle\\&=\sum_{n_1,n_2=0}^{\infty}F_{n_1,n_2}|n_1,n_2\rangle,\end{aligned} \tag{7}$$

$$\begin{aligned}&F_{n_1,n_2}=\mathrm{e}^{\frac{-\left(m^2+n^2\right)}{2}}\frac{\alpha n^{n_1}m^{n_2}+\beta(-n)^{n_1}(-m)^{n_2}}{\sqrt{n_1!n_2!}},\\&\alpha_1=m\mathrm{e}^{\mathrm{i}\varphi_1},\qquad\alpha_2=n\mathrm{e}^{\mathrm{i}\varphi_2},\end{aligned} \tag{8}$$

for $|\alpha_i\rangle$ and $|-\alpha_i\rangle$ are coherent states of the ith mode field, and they are π out of phase with respect to each other. The φ_i is the direction angle of the excitation of ith mode, in this paper we suppose $\varphi_i=0$. m and n denote the intensity of the two-mode fields. α and β represent the parameters of entanglement between the two-mode entangled coherent states and satisfy $\alpha^2+\beta^2=1$, $\alpha,\beta\in[0,1]$.

Then the initial state vector of the system is

$$|\Psi_{\mathrm{AF}}(0)\rangle=|\Psi_{\mathrm{A}}(0)\rangle\otimes|\Psi_{\mathrm{F}}(0)\rangle. \tag{9}$$

Along with time evolution, the state vector of the system at any time $t>0$ is given by

$$|\Psi_{\mathrm{AF}}(t)\rangle=U_I(t)|\Psi_{\mathrm{AF}}(0)\rangle=|C\rangle|e\rangle+|D\rangle|g\rangle \tag{10}$$

with

$$|C\rangle=\sum_{n_1,n_2=0}^{\infty}F_{n_1,n_2}\left[\cos\gamma(n_1,n_2,t)|n_1,n_2\rangle\right], \tag{11}$$

$$\begin{aligned}|D\rangle=&\sum_{n_1,n_2=0}^{\infty}F_{n_1,n_2}[(-\mathrm{i})\sin\gamma(n_1,n_2,t)\\&\times|n_1+1,n_2+1\rangle],\end{aligned} \tag{12}$$

where $\gamma(n_1,n_2,t)=\sqrt{(n_1+1)(n_2+1)}g\theta(t)$. The atomic reduced density operator for the system is given by

$$\begin{aligned}\rho_A(t)&=\mathrm{Tr}_{\mathrm{F}}|\Psi_{\mathrm{AF}}(t)\rangle\langle\Psi_{\mathrm{AF}}(t)|\\&=\begin{bmatrix}\rho_{11}&\rho_{12}\\\rho_{21}&\rho_{22}\end{bmatrix}=\begin{bmatrix}|C\rangle\langle C|&|C\rangle\langle D|\\|D\rangle\langle C|&|D\rangle\langle D|\end{bmatrix}.\end{aligned} \tag{13}$$

And the field reduced density operator for the system is given by

$$\begin{aligned}\rho_{\mathrm{F}}(t)&=\mathrm{Tr}_A|\Psi_{\mathrm{AF}}(t)\rangle\langle\Psi_{\mathrm{AF}}(t)|\\&=|C\rangle\langle C|+|D\rangle\langle D|.\end{aligned} \tag{14}$$

3. The atomic entropy squeezing

Following the work by Fang *et al* in Ref.[13], we can express the entropy squeezing of the two-level atom by using the quantum information entropy theory. The information entropy of the Pauli operators $S_\alpha(\alpha=x,y,z)$ for a two-level atom system 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 $P_i(S_\alpha)=\langle\Psi_{\alpha i}|\rho|\Psi_{\alpha i}\rangle$ $(i=1,2)$, which are the probability distributions for two possible measurements of an operator S_α. $H(S_x)$, $H(S_y)$, and $H(S_z)$ satisfy

$$H(S_x)+H(S_y)\geq 2\ln 2-H(S_z), \tag{16}$$

which may also be rewritten as

$$\delta H(S_x)\,\delta H(S_y)\geq\frac{4}{\delta H(S_z)}, \tag{17}$$

where $\delta H(S_\alpha)=\exp[H(S_\alpha)]$. The squeezing of the atom is determined by using the EUR (Eq.(17)) named entropy squeezing. The fluctuation in the 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:

$$E(S_\alpha)=\delta H(S_\alpha)-\frac{2}{\sqrt{|\delta H(S_z)|}}<0,\quad(\alpha\equiv x,\,y). \tag{18}$$

By using $\rho_A(t)$(Eq.(13)), we can obtain the information entropies of the atomic operators S_x, S_y and S_z as follows:

$$H\left(S_x\right)=-\left[\frac{1}{2}+\mathrm{Re}\left(\rho_{12}\left(t\right)\right)\right]\ln\left[\frac{1}{2}+\mathrm{Re}\left(\rho_{12}\left(t\right)\right)\right]-\left[\frac{1}{2}-\mathrm{Re}\left(\rho_{12}\left(t\right)\right)\right]\ln\left[\frac{1}{2}-\mathrm{Re}\left(\rho_{12}\left(t\right)\right)\right], \tag{19a}$$

$$H\left(S_y\right)=-\left[\frac{1}{2}+\mathrm{Im}\left(\rho_{12}\left(t\right)\right)\right]\ln\left[\frac{1}{2}+\mathrm{Im}\left(\rho_{12}\left(t\right)\right)\right]-\left[\frac{1}{2}-\mathrm{Im}\left(\rho_{12}\left(t\right)\right)\right]\ln\left[\frac{1}{2}-\mathrm{Im}\left(\rho_{12}\left(t\right)\right)\right], \tag{19b}$$

$$H\left(S_z\right)=-\rho_{22}\left(t\right)\ln\rho_{22}\left(t\right)-\rho_{11}\left(t\right)\ln\rho_{11}\left(t\right), \tag{19c}$$

where $\rho_{ij}\left(t\right)$ is given by Eqs.(11)–(13).

In the following, we will investigate the atomic entropy squeezing for the system under consideration. From Eqs.(11), (13) and (19a) for the component S_x we can prove entropy squeezing

$$E(S_x)=2\left(1-\frac{1}{\sqrt{\left|\delta H\left(S_z\right)\right|}}\right)\geq 0, \tag{20}$$

where $\dfrac{1}{\sqrt{\left|\delta H\left(S_z\right)\right|}}\leq 1$. This means that $E(S_x)$ cannot exhibit entropy squeezing. This corresponds to the result obtained in Ref.[16]. Thus we focus the attention on the discussion of $E(S_y)$ (the entropy squeezing of the component S_y) by a numerical calculation method.

In Figs.1(a)–1(d) we show the influence of the atomic motion and the field-mode structure parameter on the time evolution of $E(S_y)$ with $m=n=4$ and $\alpha=0.707$. Firstly, the atomic motion is neglected (as shown in Fig.1(a)). We can see that $E(S_y)$ exhibits a quite periodic evolution: it evolves in a way following a sine wave with a period of π except at the initial stage of time. It shows entropy squeezing in every period of the evolution of $E(S_y)$ in the scaled time. Figures 1(b)–1(d) illustrate the time evolution of $E(S_y)$ when the atom is moving at a speed $v=gL/\pi$, and the field-mode structure parameters are $p=1$, $p=2$ and $p=5$, respectively. In Fig.1(b)($p=1$), the range of entropy squeezing time increases more distinctly than that in Fig.1(a), but the value of maximal squeezing remains the same. From Figs.1(c) and 1(d) one can observe that the duration of entropy squeezing decreases and the degree of squeezing weakens as p increases. When p is big enough, only the entropy squeezing remains at the time when the atomic inversion exhibits rapid oscillation (revival-collapse phenomenon) (shown in Fig.2(d)).

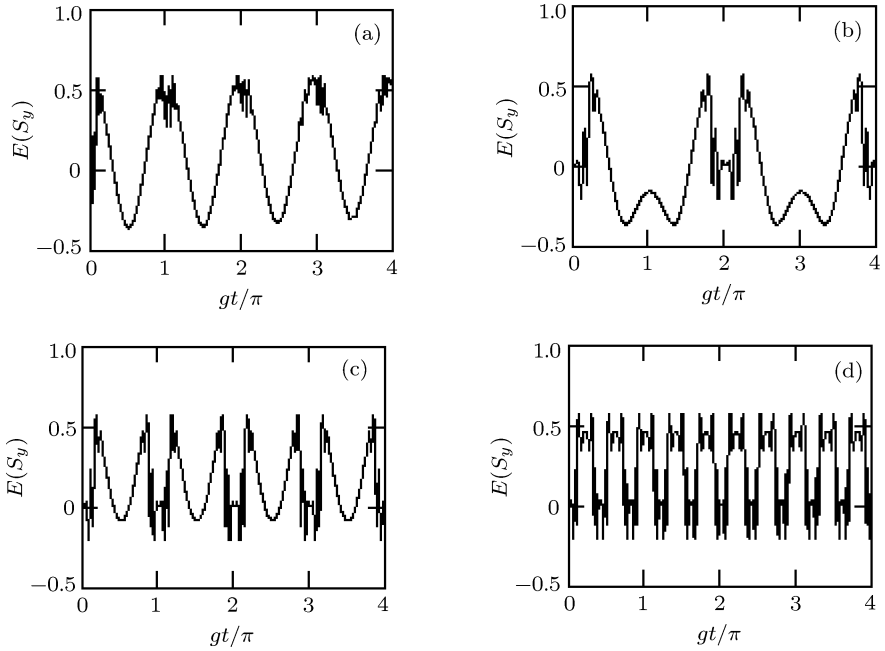


Fig.1. The time evolution of the information entropy squeezing factors $E(S_y)$. The field is in a two-mode entangled coherent state with $\alpha=0.707$, $m=n=4$: (a) the atomic motion neglected; (b) the atom moving at a speed $v=gL/\pi$ and $p=1$; (c) the atom moving at a speed $v=gL/\pi$ and p=2; (d) the atom moving at a speed $v=gL/\pi$ and $p=5$.

We can conclude that atomic motion causes the curve of the evolution of $E(S_y)$ to change. The period of the entropy squeezing and the duration of the information entropy squeezing are determined by the field-mode structure. These results are different from those in Ref.[5].

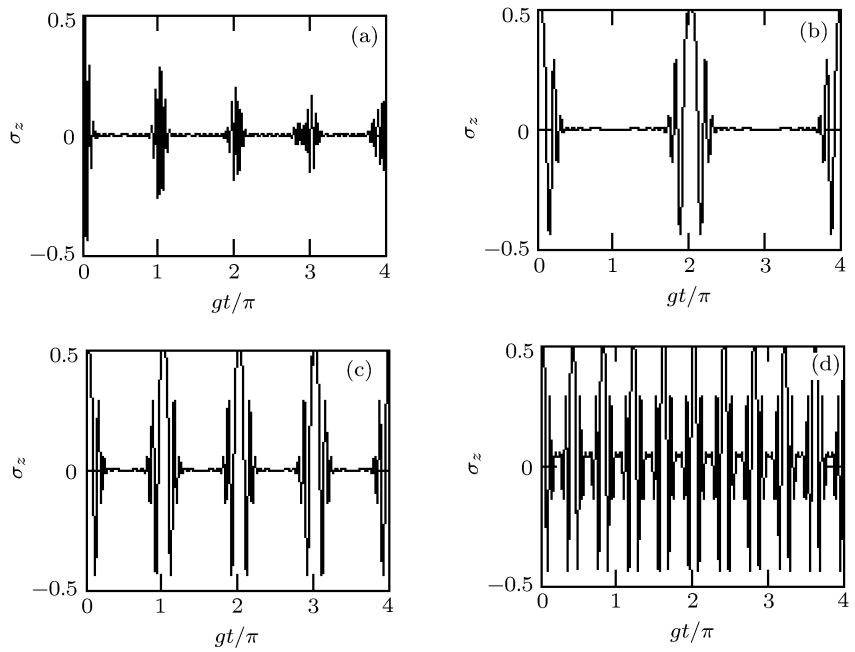


Fig.2. The time evolution of the atomic inversion; the field is in a two-mode entangled coherent state with $\alpha = 0.707$, $m = n = 4$. (a) The atomic motion neglected; (b) the atom moving at a speed $v = gL/\pi$ and $p = 1$; (c) the atom moving at a speed $v = gL/\pi$ and $p = 2$; (d) the atom moving at a speed $v = gL/\pi$ and $p = 5$.

Figure 3 presents the numerical results of the time evolution of $E(S_y)$ for different intensities of the two-mode entangled field with $p = 1$, $\alpha = 0.707$. Compared with Fig.1(b), it can be seen that $E(S_y)$ is strongly dependent on the light field intensity. The atomic entropy squeezing time increases and the degree of squeezing extends as the intensity of the field increases. But the period of the entropy squeezing evolution remains invariant. Additionally, when only α changes, the behaviours of the time evolution of $E(S_y)$ is similar to that of $\alpha = 0.707$. Thus the initial DETMF does not have an influence on the atomic entropy squeezing.

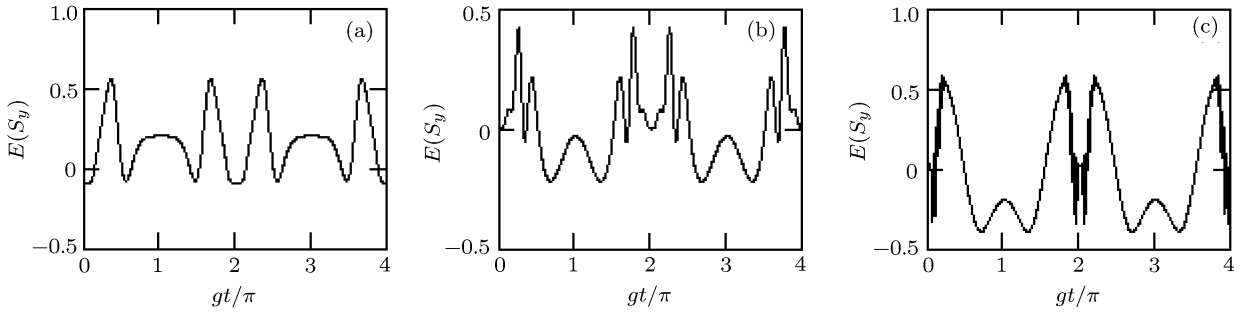


Fig.3. The time evolution of the information entropy squeezing factors; the atom is in motion and $p = 1$, the field is in an entangled coherent state with $\alpha = 0.707$: (a) $m = n = 1$; (b) $m = n = 2$; (c) $m = n = 8$.

4. Entanglement between the two-mode fields

The Hamiltonian given by Eq.(1) leads to the entanglement between the two-mode entangled coherent field and the atom, so that the state of the two-mode entangled coherent field may evolve into a mixed state. In this case, DETMF can be measured by the quantum relative entropy of the entanglement. The quantum relative entropy of entanglement plays an

important role in information,[32] which tells us the amount of entanglement in the state with its distance from the disentangled state. Following the conception given in Ref.[32] and the result in Ref.[33], we obtain

$$\mathrm{Er}(t) = -\sum_n a_{n,n}\mathrm{lb}a_{n,n} - S_\mathrm{F}, \tag{21}$$

where $a_{n,n} = \langle n,n|\,\rho_\mathrm{F}\,|n,n\rangle$, ρ_F is expressed by Eq.(14), S_F is the field reduced entropy of the system, which is defined as

$$S_\mathrm{F} = -\lambda^+\mathrm{lb}\lambda^+ - \lambda^-\mathrm{lb}\lambda^-, \tag{22}$$

where λ^+ and λ^- are the eigenvalues of the two-mode coherent field reduced density operator given by Eq.(14).

The time evolution of the quantum relative entropy of entanglement $\mathrm{Er}(t)$ given by Eq.(21) reflects the time evolution of DETMF. Figure 4 gives the numerical results of $\mathrm{Er}(t)$, in which the values of the parameter are the same as those in Fig.1. Comparing the plots in Figs.4 and 1, we find with interest that the period of the time evolution of DETMF is the same as that of the entropy squeezing of $E(S_y)$. If the atomic motion is neglected (shown in Fig.4(a)), the DETMF achieves its maximum value when $E(S_y)$ reaches the maximal squeezing. The time evolution of DETMF carries out a damping oscillation, which means that the two-mode field cannot recover its initial maximal entangled state periodically. If the atom is moving at a speed $v = gL/\pi$ (shown in Figs.4(b)–4(d)), both the maximum and the minimum value of DETMF remain invariant with respect to different field-mode structure parameters. The maximum values of DETMF, which are the same as the initial maximal degree of the entanglement, appear at the time $t = 2k\pi/pg(k = 0,\ 1,\ldots)$. That is to say, when the atom is in motion, the initial maximal entangled state can be recovered periodically. When the atom inversion approaches zero as shown in Fig.2, the time evolution of the DETMF is just the opposite to $E(S_y)$, that is, the maximum values and the minimum values of $\mathrm{Er}(t)$ correspond to the minimum values and the maximum values of $E(S_y)$ respectively. When the field-mode structure $p = 1$ (Fig.4(b)), the two-mode light field can be in a high degree of entanglement for a rather long scaled time. This reflects the control of atomic motion and field-mode structure on the DETMF, which can play an important role in enhancing and controlling entanglement. So it has a realizable meaning and is feasible in quantum information.

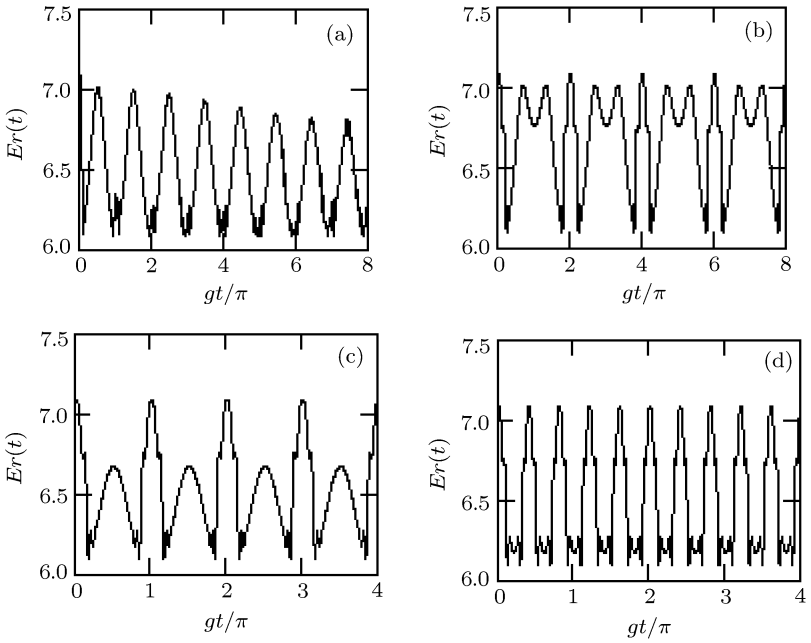


Fig.4. The time evolution of the relative entropy of the entanglement $\mathrm{Er}(t)$; the field is initially in a two-mode entangled coherent state with $\alpha = 0.707$, $m = n = 4$: (a) the atomic motion neglected; (b) the atom moving at a speed $v = gL/\pi$ and $p = 1$; (c) the atom moving at a speed $v = gL/\pi$ and $p = 2$; (d) the atom moving at a speed $v = gL/\pi$ and $p = 5$.

Physically, when $t = 2k\pi/pg(k = 0,\ 1,\ldots)$, the state vector evolves $|\Psi_\mathrm{AF}(t)\rangle = |C\rangle\,|e\rangle$, therefore the atom and the two-mode field are in the disentangled state, and the two-mode field is in the maximal entangled state. This is consistent with Ref.[33]. When the atom inversion exhibits rapid oscillation (shown

in Fig.2), which means that the rate of interchange energy between the atom and the two-mode field is fast, $E(S_y)$ manifests rapid oscillation while DETMF shows its rapid change. From Figs.1 and 4, we can see that atomic entropy squeezing not only is an accurate measure of the atom squeezing but also has some properties corresponding to the entanglement of the two-mode field.

So the time evolution of DETMF and atomic entropy squeezing can be controlled by changing the above parameters. Our results are important for the experimental realization and the control of atomic squeezing and maximal entangled states.

5. Conclusions

We have investigated the entropy squeezing of a moving two-level atom interacting with the two-mode entangled coherent field via two-photon transition by using EUR, and the entanglement of the two-mode light field in the system by using quantum relative entropy. From the above analysis, it is clearly noted that the atomic motion and the field-mode structure parameter have a notable influence on the atomic squeezing and DETMF. Therefore, we can draw the following conclusions. (1) The period of the atomic entropy squeezing is the same as that of the DETMF. They are determined by choosing atomic motion and the field-mode structure. (2) The maximal atomic entropy squeezing and the duration of squeezing are determined by the intensity of the field, atomic motion and the field-mode structure. (3) The initial high degree of DETMF can be recovered periodically when the atom is in motion. (4) When the atom inversion approaches zero, the evolution of the atomic entropy squeezing is in the opposite direction to that of DETMF. Our results show that we can prepare and control atomic squeezing and DETMF by choosing the parameters of atomic motion and field-mode structure. The system of the two-mode entangled coherent field interacting with a moving atom via a two-photon process is a valuable resource of quantum information. We believe that these results will also be useful in the research of the properties of interaction between the atom and the field.

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