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Entropy squeezing of the field interacting with a nearly degenerate V-type three-level atom*

Zhou Qing-Chun(周青春)[a)b)] and Zhu Shi-Ning(祝世宁)[a)†]

[a)] *State Key Laboratory of Solid State Microstructure, Nanjing University, Nanjing* 210093, *China*

[b)] *Department of Mathematics and Physics, Jiangsu University of Science and Technology, Zhenjiang* 212003, *China*

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The position- and momentum-entopic squeezing properties of the optical field in the system of a nearly degenerate three-level atom interacting with a single-mode field are investigated. Calculation results indicate that when the field is initially in the vacuum state, it may lead to squeezing of the position entropy or the momentum entropy of the field if the atom is prepared properly. The effects of initial atomic state and the splitting of the excited levels of the atom on field entropies are discussed in this case. When the initial field is in a coherent state, we find that position-entropy squeezing of the field is present even if the atom is prepared in the ground state. By comparing the variance squeezing and entropy squeezing of the field we confirm that entropy is more sensitive than variance in measuring quantum fluctuations.

Keywords: field entropy, V-type three-level atom, squeezed state
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1. Introduction

The squeezing effect of an optical field has been an attractive subject in quantum optics. Since Yuen[1] proposed the concept of the squeezed state in 1976, squeezed light, due to its potential applications in optical information technology, has been studied extensively, and important achievements in both theory and experiment have been made.[2−13] It has been shown that the squeezing of light can be realized through interaction of an optical field and atoms, so investigation of field squeezing in an atom–field interaction system is significant. In many theoretical studies of field squeezing in the past, the Heisenberg uncertainty relation is used to judge the presence of squeezing in one of the quadratures of the field according to whether its variance is less than the corresponding vacuum limit. In many situations, however, variance tends to overestimate quantum fluctuations, because it involves only statistical moment of the second order and does not include higher-order moments. A more proper measure of fluctuations is the information entropy of the system. Recently, Fang *et al*,[3,4] starting from the entropy uncertainty relation,[5] put forward the concept of entropy squeezing, and made possible the highly sensitive measurement of the field squeezing effect. In this paper, we investigate the entropy squeezing effect of the field in the system composed of a nearly degenerate V-type three-level atom interacting with a single-mode field.

2. Model and state vector

Consider a system in which a single-mode optical field interacts with a V-type three-level atom having a ground level $|a\rangle$ and two closely lying excited levels $|b\rangle$ and $|c\rangle$, as indicated in Fig.1. In the rotating wave approximation and the interaction picture, the Hamiltonian for the system can be written as

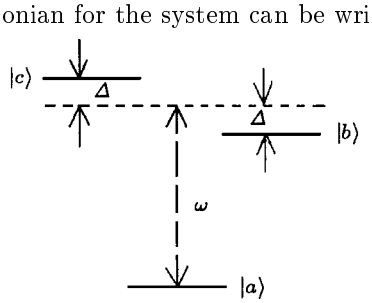


Fig.1. Energy structure of the three-level atom.

$$V_{\rm I} = g(\mathrm{e}^{-\mathrm{i}\Delta t}|b\rangle\langle a|a + \mathrm{e}^{\mathrm{i}\Delta t}a^{+}|a\rangle\langle b|) + g(\mathrm{e}^{\mathrm{i}\Delta t}|c\rangle\langle a|a + e^{-\mathrm{i}\Delta t}a^{+}|a\rangle\langle c|), \quad (1)$$

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†Corresponding author. E-mail: zhusn@nju.edu.cn

where $a(a^+)$ is the annihilation (creation) operator of the field, $|i\rangle\langle j|$ $(i,j=a,b,c)$ is the atomic-transition operator from $|j\rangle$ to $|i\rangle$, Δ is the detuning of the field, g is the coupling constant between the field and the transition $|a\rangle \leftrightarrow |b\rangle$ or $|a\rangle \leftrightarrow |c\rangle$, and $\hbar$ is taken to be unity. We assume the atom is initially prepared in the superposition of states $|a\rangle$, $|b\rangle$ and $|c\rangle$:

$$|\psi_{\rm a}(0)\rangle = c_0|a\rangle + c_1|b\rangle + c_2|c\rangle,$$

$$(|c_0|^2 + |c_1|^2 + |c_2|^2 = 1), \tag{2}$$

and the initial field is in an arbitrary state which can be expanded in terms of Fock states as

$$|\psi_{\rm f}(0)\rangle = \sum_{n=0}^{\infty} F_n|n\rangle. \tag{3}$$

The state vector for the atom–field system at time $t=0$ (when the interaction begins) is then

$$|\Psi(0)\rangle = \sum_n F_n\,[c_0|a,n\rangle + c_1|b,n\rangle + c_2|c,n\rangle], \tag{4}$$

where the first index in the kets on the right-hand side denotes the atomic state and the second indicates photon number. By inspecting the Hamiltonian (1), we may write the state vector of the system at time t as

$$\begin{aligned}|\Psi(t)\rangle = &\sum_{n=0}^{\infty}[C_{a,n}(t)|a,n+1\rangle + C_{b,n}(t)|b,n\rangle \\ &+ C_{c,n}(t)|c,n\rangle] + D(t)|a,0\rangle.\end{aligned} \tag{5}$$

From the Schrödinger equation

$$\mathrm{i}\frac{\partial}{\partial t}|\Psi(t)\rangle = V_{\rm I}|\Psi(t)\rangle, \tag{6}$$

we obtain

$$\begin{aligned}\mathrm{i}\dot{C}_{a,n}(t) =& g\sqrt{n+1}[\mathrm{e}^{\mathrm{i}\Delta t}C_{b,n}(t) + \mathrm{e}^{-\mathrm{i}\Delta t}C_{c,n}(t)],\\ \mathrm{i}\dot{C}_{b,n}(t) =& g\sqrt{n+1}\mathrm{e}^{-\mathrm{i}\Delta t}C_{a,n}(t),\\ \mathrm{i}\dot{C}_{c,n}(t) =& g\sqrt{n+1}\mathrm{e}^{\mathrm{i}\Delta t}C_{a,n}(t),\\ \mathrm{i}\dot{D}(t) =& 0.\end{aligned} \tag{7}$$

The initial conditions can be expressed as

$$\begin{aligned}C_{a,n}(0) =& F_{n+1}c_0,\\ C_{b,n}(0) =& F_n c_1,\\ C_{c,n}(0) =& F_n c_2,\\ D(0) =& F_0 c_0.\end{aligned} \tag{8}$$

Eqs.(7) and (8) can be solved to obtain

$$\begin{aligned}C_{b,n}(t) =& \sum_{i=1}^{3} A_{i,n}\exp[\mathrm{i}(\lambda_{i,n}-\Delta)t],\\ C_{c,n}(t) =& \frac{1}{g^2(n+1)}\sum_{i=1}^{3}[\lambda_{i,n}(\lambda_{i,n}-\Delta) - g^2(n+1)\\ &\times A_{i,n}\exp[\mathrm{i}(\lambda_{i,n}+\Delta)t],\\ C_{a,n}(t) =& \frac{1}{g\sqrt{n+1}}\sum_{i=1}^{3}(\Delta-\lambda_{i,n})A_{i,n}\exp(\mathrm{i}\lambda_{i,n}t),\\ D(t) =& F_0 c_0,\end{aligned} \tag{9}$$

where

$$\begin{aligned}A_{1,n} =& \frac{1}{(\lambda_{1,n}-\lambda_{2,n})(\lambda_{1,n}-\lambda_{3,n})}\\ &\times\{[g^2(n+1)+(\Delta-\lambda_{2,n})(\Delta-\lambda_{3,n})]F_n c_1\\ &+ g^2(n+1)F_n c_2\\ &+ g\sqrt{n+1}(\lambda_{2,n}+\lambda_{3,n}-\Delta)F_{n+1}c_0\},\\ A_{2,n} =& \frac{1}{(\lambda_{1,n}-\lambda_{2,n})(\lambda_{3,n}-\lambda_{2,n})}\\ &\times\{[g^2(n+1)+(\Delta-\lambda_{1,n})(\Delta-\lambda_{3,n})]F_n c_1\\ &+ g^2(n+1)F_n c_2\\ &+ g\sqrt{n+1}(\lambda_{1,n}+\lambda_{3,n}-\Delta)F_{n+1}c_0\},\\ A_{3,n} =& \frac{1}{(\lambda_{1,n}-\lambda_{3,n})(\lambda_{2,n}-\lambda_{3,n})}\\ &\times\{[g^2+(\Delta-\lambda_{1,n})(\Delta-\lambda_{2,n})]F_n c_1\\ &+ g^2(n+1)F_n c_2\\ &+ g\sqrt{n+1}(\lambda_{1,n}+\lambda_{2,n}-\Delta)F_{n+1}c_0\},\\ \lambda_{1,n} =& 0,\\ \lambda_{2,n} =& \sqrt{2g^2(n+1)+\Delta^2},\\ \lambda_{3,n} =& -\sqrt{2g^2(n+1)+\Delta^2}.\end{aligned} \tag{10}$$

The reduced density operator for the field is

$$\rho_{\rm f}(t) = {\rm Tr}_{\rm a}(|\Psi(t)\rangle\langle\Psi(t)|), \tag{11}$$

where $\mathrm{Tr_a}$ means the trace is taken over atomic variables. In the position representation and the momentum representation, the expressions for the Fock state $|n\rangle$ of the field are

$$\begin{aligned}\langle x|n\rangle =& \left[\frac{\exp(-x^2)}{\sqrt{\pi}2^n n!}\right]^{1/2} H_n(x),\\ \langle p|n\rangle =& \frac{1}{\mathrm{i}^n}\left[\frac{\exp(-p^2)}{\sqrt{\pi}2^n n!}\right]^{1/2} H_n(p),\end{aligned} \tag{12}$$

respectively, where $H_n(x)$ and $H_n(p)$ are Hermite polynomials.

3. Field entropy squeezing

The position entropy and momentum entropy of the field are defined as[6,7]

$$S_x(t) = -\int_{-\infty}^{\infty} \langle x|\rho_{\rm f}|x\rangle \ln\langle x|\rho_{\rm f}|x\rangle {\rm d}x,$$
$$S_p(t) = -\int_{-\infty}^{\infty} \langle p|\rho_{\rm f}|p\rangle \ln\langle p|\rho_{\rm f}|p\rangle {\rm d}p, \qquad (13)$$

where the density matrix element can be obtained from Eqs.(11) and (12),

$$\langle x|\rho_{\rm f}|x\rangle = \left|\sum_{n=0}^{\infty} C_{a,n}\langle x|n+1\rangle + D\langle x|0\rangle\right|^2 + \left|\sum_{n=0}^{\infty} C_{b,n}\langle x|n\rangle\right|^2 + \left|\sum_{n=0}^{\infty} C_{c,n}\langle x|n\rangle\right|^2. \qquad (14)$$

We obtain $\langle p|\rho_{\rm f}|p\rangle$by replacing x with p in (14). The entropy uncertainty relation of position and momentum is

$$\exp[S_x(t)]\exp[S_p(t)] \geq \pi {\rm e}. \qquad (15)$$

We here introduce two quantities

$$\delta_x(t) = \exp[S_x(t)] - \sqrt{\pi {\rm e}},$$
$$\delta_p(t) = \exp[S_p(t)] - \sqrt{\pi {\rm e}}. \qquad (16)$$

When $\delta_x < 0$ ($\delta_p < 0$), the position (momentum) or $x(p)$ component of the field is squeezed.

3.1. The field initially in the vacuum state

In this situation, $F_n = \delta_{n,0}$ in Eqs.(4)–(10), and Eq.(14) reduces to

$$\langle x|\rho_{\rm f}|x\rangle = \frac{\exp(-x^2)}{\sqrt{\pi}}|\sqrt{2}xC_{a,0}(t) + D(t)|^2 + \frac{\exp(-x^2)}{\sqrt{\pi}}[|C_{b,0}(t)|^2 + |C_{c,0}(t)|^2], \qquad (17a)$$

$$\langle p|\rho_{\rm f}|p\rangle = \frac{\exp(-x^2)}{\sqrt{\pi}}|-{\rm i}\sqrt{2}pC_{a,0}(t) + D(t)|^2 + \frac{\exp(-x^2)}{\sqrt{\pi}}[|C_{b,0}(t)|^2 + |C_{c,0}(t)|^2], \qquad (17b)$$

where

$$C_{a,0}(t) = \frac{g\Delta}{\Omega_0^2}[(c_1 - c_2)(1 - \cos\Omega_0 t) - {\rm i}\,(c_1 + c_2)\Omega_0 \sin\Omega_0 t],$$
$$C_{b,0}(t) = \left\{\left(\frac{g}{\Omega_0}\right)^2 (c_1 - c_2) + \frac{(g^2 + \Delta^2)c_1 + g^2 c_2}{\Omega_0^2}\cos\Omega_0 t + {\rm i}\frac{\Delta c_1}{\Omega_0}\sin\Omega_0 t\right\}{\rm e}^{{\rm i}\Delta t},$$
$$C_{c,0}(t) = \left\{\left(\frac{g}{\Omega_0}\right)^2 (c_2 - c_1) + \left(\frac{1}{\Omega_0}\right)^2 [g^2 c_1 + (g^2 + \Delta^2)c_2]\cos\Omega_0 t - {\rm i}\frac{\Delta c_2}{\Omega_0}\sin\Omega_0 t\right\}{\rm e}^{{\rm i}\Delta t} \qquad (18)$$

with $\Omega_0 = \sqrt{2g^2 + \Delta^2}$. Substituting Eqs.(17a), (17b) and (18) into (13) and (16), we obtain the position and momentum entropies of the field. It is obvious that both $\delta_x(t)$ and $\delta_p(t)$ are periodic functions of time. In the following we consider three cases for the initial atomic state.

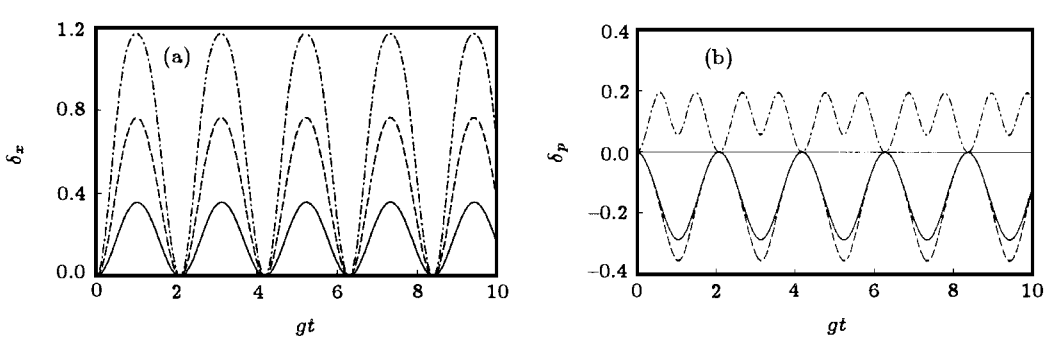


Fig.2. δ_x and δ_p of the field for $c_0 = \cos\frac{\theta}{2}$, $c_1 = c_2 = \frac{1}{\sqrt{2}}\sin\frac{\theta}{2}$, Δ/g=0.5 and different θ (solid line: $\theta = \pi/4$; dashed line: $\theta = 2\pi/5$; dash-dotted line: θ=$3\pi/5$).

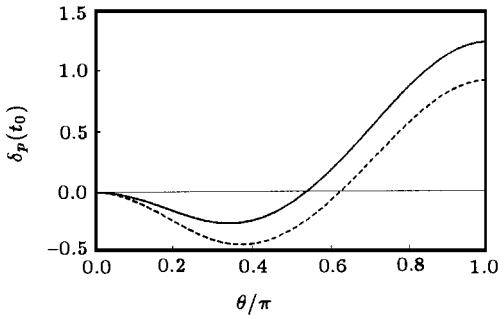


Fig.3. $\delta_p(t_0)$ as a function of θ for $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = c_2 = \dfrac{1}{\sqrt{2}}\sin\dfrac{\theta}{2}$ (solid line: Δ/g=1, dashed line: Δ/g=0).

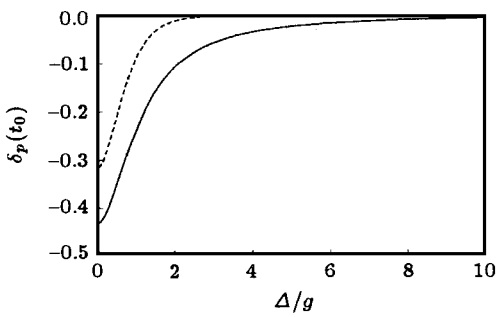


Fig.4. $\delta_p(t_0)$ as a function of Δ for $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = c_2 = \dfrac{1}{\sqrt{2}}\sin\dfrac{\theta}{2}$ (solid line: $\theta = 2\pi/5$, dashed line: $\theta = \pi/2$).

3.1.1. $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = c_2 = \dfrac{1}{\sqrt{2}}\sin\dfrac{\theta}{2}$

The evolutions of $\delta_x(t)$ and $\delta_p(t)$ are presented in Fig.2. Both their periods are $\tau = \pi/\sqrt{2g^2+\Delta^2}$, but the momentum component of entropy can be squeezed while the position component cannot. The squeezing depth is determined by the population distribution angle θ and the detuning Δ. The maximum squeezing of momentum component occurs at $t_0 = (2m+1)\tau/2$, where m=0, 1, 2.... Figure 3 displays $\delta_p(t_0)$ as a function of θ for two given values of detuning, and Fig.4 illustrates variation of $\delta_p(t_0)$ with detuning for given θ. Entropy squeezing reaches its maximum at $\theta = 0.374\pi$ and Δ=0 (i.e. the atom is degenerate). The amount of maximal squeezing is about 15%. For $\theta = 0$, the atom is initially in the ground state, and no entropy squeezing exists in either component since $\delta_p(t) = \delta_x(t) = 0$. We will see entropy squeezing is possible for an initial atomic ground state and an initial coherent field in Section 3.1.3.

3.1.2. $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = -c_2 = \dfrac{1}{\sqrt{2}}\sin\dfrac{\theta}{2}$

The time-evolutions of $\delta_p(t)$ and $\delta_x(t)$ in this case are periodic with a period $\tau = 2\pi/\Omega_0$, twice that for the case of 3.1.1, as shown in Fig.5. Contrary to Fig.2, the position component of the field now exhibits squeezing while the momentum component does not. If the atom is degenerate, i.e. $\Delta = 0$, $\delta_p(t)$ and $\delta_x(t)$ are always null, indicating that there is no squeezing. We also see that the entropy squeezing depth in Fig.5(a) is smaller than that in Fig.2 (b) for the same parameters Δ and θ. The maximal entropy squeezing takes place at $\Delta \approx 1.5g$, rather than $\Delta = 0$ as in 3.1.1. Variation of $\delta_x(t_0)$ with θ takes a shape similar to $\delta_p(t_0)$ in Fig.3, and the maximal squeezing remains 15%.

3.1.3. $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = \mathrm{e}^{\mathrm{i}\phi}\sin\dfrac{\theta}{2}$, $c_2 = 0$

Time-evolution periods in this case are $\tau = 2\pi/\sqrt{2g^2+\Delta^2}$ for $\Delta \neq 0$ and $\pi/\sqrt{2}g$ for $\Delta = 0$. The effects of initial atomic state on field entropy squeezing are shown in Fig.6. Both components of the field may display entropy squeezing in a certain range of θ, and the maximal squeezing takes place at time $t_0 = (m+1/2)\tau$ for the position component and $t_0 \approx (m+1/2)\tau/2$ for the momentum component. From Fig.6 we see the squeezing of either component of the field is intermittent. Squeezing duration and squeezing depth vary with Δ and θ. The influence of ϕ on $\delta_x(t)$ for $\theta = \pi/4$ and $\Delta = 2g$ is illustrated in Fig.7. It also affects the shape of the evolution curve besides the squeezing depth and squeezing time.

We have mentioned that if the atom is initially in the ground state, there is no entropy squeezing for the field. Calculations also show that when the initial atomic state is an arbitrary superposition of the two upper energy states, field entropy squeezing never occurs. In both cases, either D or $C_{a,0}$ in Eqs.(17a) and (17b) is null, so we come to the conclusion that the field squeezing is due to the interference of the zero-photon and one-photon field states.

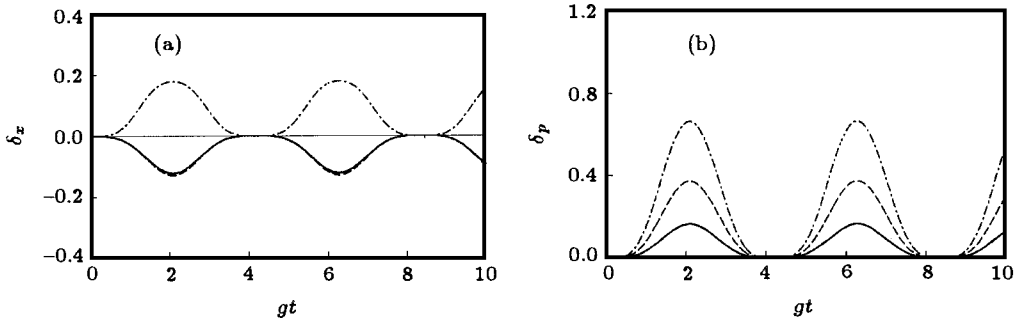


Fig.5. δ_x and δ_p of the field for $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = -c_2 = \dfrac{1}{\sqrt{2}}\sin\dfrac{\theta}{2}$, Δ/g=0.5 and different θ (solid line: $\theta = \pi/4$; dashed line: $\theta = 2\pi/5$; dash-dotted line: $\theta = 3\pi/5$).

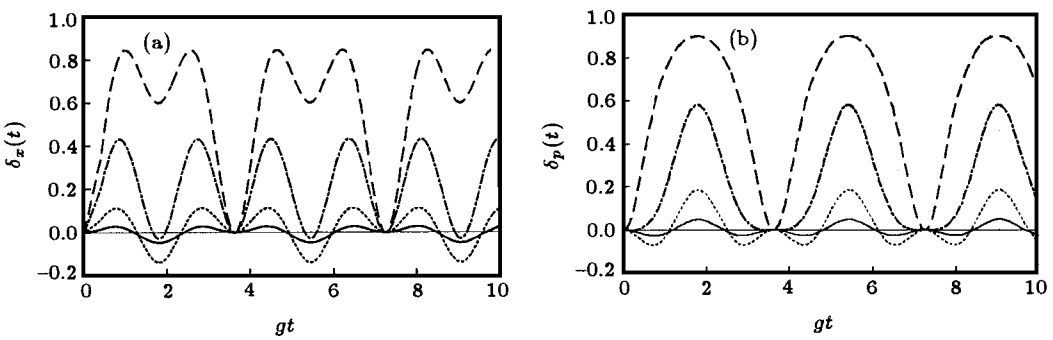


Fig.6. Time evolution of δ_x and δ_p for $c_0 = \cos\dfrac{\theta}{2}$, $c_1 = \mathrm{e}^{\mathrm{i}\phi}\sin\dfrac{\theta}{2}$, $c_2 = 0$, Δ/g=0, ϕ=0 and different θ (solid line: θ=$\pi/8$; dotted line: $\theta = \pi/4$; dash-dotted line: $\theta = \pi/2$; dashed line: $\theta = \pi$).

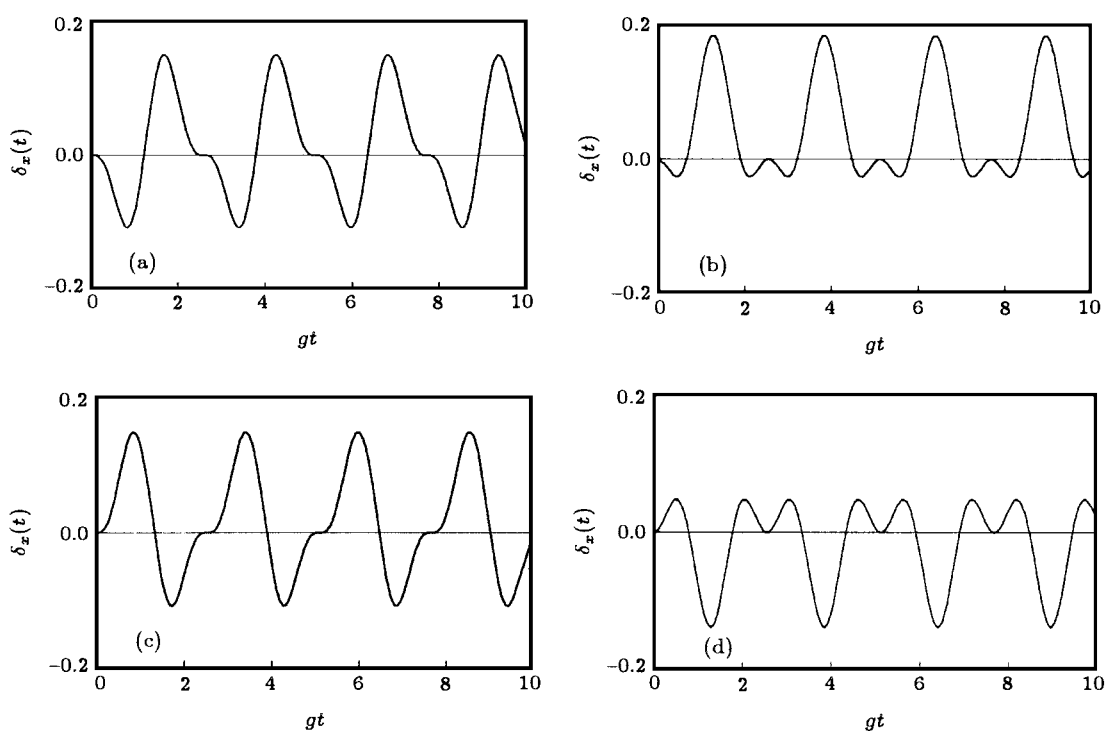


Fig.7. $\delta_x(t)$ for $\theta = \pi/4$, Δ/g=2, and different $\phi(c_0 = \cos\dfrac{\theta}{2}$, $c_1 = \mathrm{e}^{\mathrm{i}\phi}\sin\dfrac{\theta}{2}$, $c_2 = 0)$, $\phi = \pi/4$ (a), $\pi/2$ (b), $3\pi/2$ (c), π (d).

3.2. The field is initially in the coherent state

$$F_n = \exp[-\bar{n}/2]\frac{\bar{n}^{n/2}}{\sqrt{n!}}, \tag{19}$$

where $\bar{n}$ is the initial mean photon number of the field, and we have chosen the phase of the coherent state to be zero for simplicity. Here, we only consider the case where the atom is in the ground state at $t = 0$. In order to compare the entropy squeezing and the variance squeezing of position component, we write down the variance of the quadrature operator $x = (a + a^+)/\sqrt{2}$:

$$\begin{aligned}(\Delta_{\rm f}x)^2 =&\langle x^2\rangle - \langle x\rangle^2\\ =&\frac{1}{2}\sum_{n=0}^{\infty}[\langle n|\rho_{\rm f}|n\rangle(1+2n)\\ &+\langle n|\rho_{\rm f}|n-2\rangle\sqrt{n(n-1)}\\ &+\langle n|\rho|n+2\rangle\sqrt{(n+1)(n+2)}]\\ &+\frac{1}{2}\Big[\sum_{n=0}^{\infty}\langle n|\rho_{\rm f}|n-1\rangle\sqrt{n}\\ &+\langle n|\rho_{\rm f}|n+1\rangle\sqrt{n+1}\Big]^2. \end{aligned}\tag{20}$$

The matrix element in (20) is given by

$$\begin{aligned}\langle n|\rho_{\rm f}|m\rangle =&C_{b,n}C^*_{b,m} + C_{c,n}C^*_{c,m}\\ &+(C_{a,n}+F_0\delta_{n,0})(C^*_{a,m}+F_0\delta_{m,0}),\end{aligned}\tag{21}$$

where

$$\begin{aligned}C_{a,n}(t) =&\frac{F_n}{\Omega_n^2}[\Delta^2 + 2g^2(n+1)\cos\Omega_n t],\\ C_{b,n}(t) =&\frac{F_n g(n+1)}{\Omega_n^2}\\ &\times[\Delta(1-\cos\Omega_n t) - {\rm i}\Omega_n\sin\Omega_n t]{\rm e}^{-{\rm i}\Delta t},\\ C_{c,n}(t) =&-\frac{F_n g(n+1)}{\Omega_n^2}\\ &\times[\Delta(1-\cos\Omega_n t) + {\rm i}\Omega_n\sin\Omega_n t]{\rm e}^{{\rm i}\Delta t}.\end{aligned}\tag{22}$$

with $\Omega_n = \sqrt{2g^2(n+1)+\Delta^2}$in the above equations. Based on equations (20)–(22), $(\Delta_{\rm f}x)^2$can be evaluated. The result is presented in Fig.8. If $(\Delta_{\rm f}x)^2 - 1/2 < 0$, the position component of the field is squeezed. The position-entropy squeezing can be seen from Fig.8. Comparison of (a) and (b) in Fig.8 indicates that, when $0 < gt < 1.37$, both exhibit squeezing, but $\Delta_{\rm f}x$ does not show while $\delta_x(t)$ still shows field squeezing during $1.37 < gt < 2.04$ and $4.01 < gt < 4.86$. The difference comes from the fact that $\Delta_{\rm f}x$ includes only the second-order statistical moment of the density matrix while $\delta_x(t)$ includes more. Thus we come to the conclusion that entropy is more sensitive to the field squeezing effect and entropy realizes the highly sensitive measure of squeezing. It is easily seen that $\delta_x(t)$ also exhibits squeezing if $\Delta_{\rm f}x$ shows squeezing at the same time.[4,6]

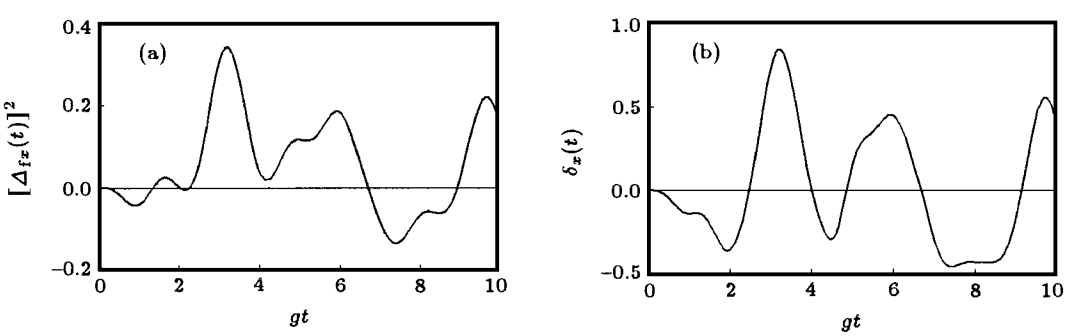


Fig.8. Variance in the x component (a) and evolution of δ_x (b) for a field initially in a coherent state and the atom initially in the ground state (Δ=0, $\bar{n}$=0.5).

4. Conclusions

We studied the squeezing of the field in the system of a V-type three-level atom interacting with a single-mode field by considering the field position and momentum entropies. We found that the field may be squeezed during the evolution of the system if the field is in the vacuum state or coherent state. The squeezing duration and depth of the position and momentum entropies depend strongly on the initial atomic state and the energy splitting of the excited levels of the V-type three-level atom. The squeezing is due to the interference of zero-photon and one-photon field states. We confirmed that entropy is more suitable and accurate than variance in measuring quantum fluctuations for an initial coherent cavity field interacting with a three-level atom.

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