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Superpositions and Entanglement of Mesoscopic High-order Squeezed Vacuum States in Cavity QED

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Abstract We propose a scheme for generating the superpositions and the entanglement between the mesoscopic high-order squeezed vacuum states by considering the multi-photon interaction of N two-level atoms in a cavity with high quality factor, assisted by a strong driving field. In terms of specific choices of the cavity detuning, many multiparty entangled states between the atoms and the mesoscopic high-order squeezed vacuum states and among the high-order squeezed vacuum states of the cavity modes can be generated, including the macroscopic "Schrödinger cats" of the mesoscopic high-order squeezed vacuum states, the entanged states of the macroscopic "Schrödinger cats", and so on. Our scheme is achievable within the current techniques in the cavity QED.

Keywords Multiparty entanglement · Cavity QED · Multi-photon interaction

It is known that the study on the transition between the microscopic and macroscopic worlds in quantum measurement theory leads to extensive studies of mesoscopic quantum states [1–7]. The coherent states and then a lot of superpositions and entangled states have been prepared in cavity QED [1–5] and in trapped ions system [6, 7]. In contrast, although many studies have been made for the preparation of the squeezed single- or multi-mode vacuum states [8–13] in the nonlinear optical fields, only few attention has been paid on the study of superpositions and the entanglement of the squeezed vacuum state [14, 15]: Kitagawa and Yamamoto have investigated the maximal entanglement of two-mode squeezed state via swapping with number-phase measurement and Alexanian has proposed a scheme for realizing the atom-field entangled and stead states by two-photon processes in cavity QED without the classical driving field. Recently, a scheme [16, 17] for squeezed vacuum measurements without homodyning has been proposed by Wenger et al., following the theoretical proposal presented by Fiurášck and Cerf [18]. However, there are few researches on superpositions and entanglement of high-order mesoscopic squeezed vacuum states.

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In this paper, we propose a scheme for generating the macroscopic superpositions and entanglement between mesoscopic high-order squeezed vacuum states by considering the multi-photon interaction between N two-level atoms and a multi-mode cavity with high quality factor, which is assisted by a strong driving field. We show how to prepare the macroscopic "Schrödinger cats" of the microscopic high-order squeezed vacuum states as well as many multiparty mesoscopic entangled states by virtue of a detuned cavity and the resonant classical field. Moreover, we can also obtain a series of macroscopic entangled states between the usual coherent states and the high-order squeezed vacuum states using the combination of the one-photon interaction Hamiltonian with the multi-photon interaction Hamiltonian.

Consider a spatially narrow bunch of N identical two-level atoms in a multi-photon interaction with M modes of a high-quality cavity, driven additionally by an external classical field. The Hamiltonian can be expressed as (assuming $\hbar = 1$)

$$H_s = \omega_0 \sum_{j=1}^{N} S_{z,j} + \sum_{i=1}^{M} \omega_{ci} a_i^+ a_i + \sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij}(a_i^{+n} S_j^- + a_i^n S_j^+)$$
$$+ \Omega \sum_{j=1}^{N} (e^{-i\omega_L t} S_j^+ + e^{i\omega_L t} S_j^-), \tag{1}$$

where ω_0, ω_{ci}, and ω_L are the frequencies of the resonant transition between $|e\rangle$ and $|g\rangle$, the cavity modes, and the classical laser field, respectively. $S_{z,j} = \frac{1}{2}(|e\rangle\langle e| - |g\rangle\langle g|)$, $S_j^+ = |e\rangle\langle g|$, and $S_j^- = |g\rangle\langle e|$, a_i^+ and a_i are the creation and annihilation operators for the cavity mode, respectively, and g and Ω are the coupling constants of each atom to the cavity modes and to the driving field, respectively. In the rotating frame with respect to the driving field frequency ω_L, the Hamiltonian is given by

$$H_r = \sum_{j=1}^{N} \Delta S_{z,j} + \sum_{i=1}^{M} \delta_i a_i^+ a_i + \Omega \sum_{j=1}^{N} (S_j^+ + S_j^-) + \sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij}(a_i^{+n} S_j^- + a_i^n S_j^+), \tag{2}$$

where $\Delta = \omega_0 - \omega_L$ and $\delta_i = \omega_{ci} - \omega_L/n$. Assuming that $\Delta = 0$ is satisfied, in the interaction picture we have

$$H_i = e^{iH_{r0}t} H_{ri} e^{-iH_{r0}t}$$
$$= \frac{1}{2}\sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij} [|+\rangle_{jj}\langle +| - |-\rangle_{jj}\langle -| + e^{in\Omega t}|+\rangle_{jj}\langle -|$$
$$- e^{-in\Omega t}|-\rangle_{jj}\langle +|] a_i^n e^{-in\delta_i t} + H.c, \tag{3}$$

where

$$H_{r0} = \sum_{i=1}^{M} \delta_i a_i^+ a_i + \Omega \sum_{j=1}^{N} (S_j^+ + S_j^-), \tag{4}$$

and

$$H_{ri} = \sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij}(a_i^{+n} S_j^- + a_i^n S_j^+), \tag{5}$$

and $|\pm\rangle_j = (|g\rangle_j \pm |e\rangle_j)/\sqrt{2}$ and $S_{jx}|\pm\rangle_j = (S_j^+ + S_j^-)|\pm\rangle_j = \pm|\pm\rangle_j$. In the strong driving regime $\Omega \gg \delta_i, g_{ij}$,the effective Hamiltonian under the rotating-wave approximation is obtained as follows

$$\begin{aligned} H_{ieff} &= \frac{1}{2}\sum_{j=1}^{N}\sum_{i=1}^{M} g_i(|+\rangle_{jj}\langle+| - |-\rangle_{jj}\langle-|)(a_i^n e^{-in\delta_i t} + a_i^{+n} e^{in\delta_i t}) \\ &= \frac{1}{2}\sum_{j=1}^{N}\sum_{i=1}^{M} S_{jx} g_i(a_i^n e^{-in\delta_i t} + a_i^{+n} e^{in\delta_i t}). \end{aligned} \tag{6}$$

In what follows, we will produce the entangled states in different cases based on (6). In the case that $N = 1, M = 2$, (i.e., two quasi-resonant normal modes in the cavity), and the atom-field is initially in $|g\rangle|0\rangle_1|0\rangle_2$, the total state evolves as

$$\begin{aligned} |\psi_1\rangle &= e^{-iH_{ieff}t}|g\rangle|0\rangle_1|0\rangle_2 \\ &= e^{-iH_{ieff}t}\frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)|0\rangle_1|0\rangle_2 \\ &= \frac{1}{\sqrt{2}}[|+\rangle S(\xi_1)S(\xi_2) + |-\rangle S(-\xi_1)S(-\xi_2)]|0\rangle_1|0\rangle_2 \\ &= \frac{1}{\sqrt{2}}(|+\rangle|\xi_1\rangle|\xi_2\rangle + |-\rangle|-\xi_1\rangle|-\xi_2\rangle), \end{aligned} \tag{7}$$

where the squeezed operator is defined by $S(\xi_l) = e^{\frac{1}{2}(\xi_l^* a_l^n - \xi_l a_l^{+n})}$, $\xi_l = -\int_0^t i g_l e^{-i2\delta_l t'}dt' = g_l(e^{-in\delta t} - 1)/n\delta_l$, $(l = 1, 2)$ and $|\xi_l\rangle$ is the high-order squeezed vacuum state of the cavity mode. Equation (7) describes a three-party entangled state between one microscopic and two mesoscopic components. It can also be written as

$$|\psi_1\rangle = \frac{1}{2}[|g\rangle(|\xi_1\rangle|\xi_2\rangle + |-\xi_1\rangle|-\xi_2\rangle) + |e\rangle(|\xi_1\rangle|\xi_2\rangle - |-\xi_1\rangle|-\xi_2\rangle)]. \tag{8}$$

Returning to the Schrödinger picture, we rewrite (8) as,

$$\begin{aligned} |\psi_2\rangle = \frac{1}{2}\Big[&|g\rangle\left(e^{-in\Omega t}\left|\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|\xi_2 e^{-in\omega_{c2}t}\right\rangle + e^{in\Omega t}\left|-\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|-\xi_2 e^{-in\omega_{c2}t}\right\rangle\right) \\ &+ e^{-i\omega_L t}|e\rangle\left(e^{-in\Omega t}\left|\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|\xi_2 e^{-in\omega_{c2}t}\right\rangle - e^{in\Omega t}\left|-\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|-\xi_2 e^{-in\omega_{c2}t}\right\rangle\right)\Big]. \end{aligned} \tag{9}$$

Then our detection of the atom in the basis $\{|g\rangle, |e\rangle\}$ yields the macroscopic entangled high-order squeezed vacuum states

$$|\psi_3\rangle_\pm = \frac{1}{\sqrt{2}}\Big[e^{-in\Omega t}\left|\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|\xi_2 e^{-in\omega_{c2}t}\right\rangle \pm e^{in\Omega t}\left|-\xi_1 e^{-in\omega_{c1}t}\right\rangle\left|-\xi_2 e^{-in\omega_{c2}t}\right\rangle\Big], \tag{10}$$

respectively. Consider k same cavities as above. If the atom goes continuously through them before the measurement, we acquire macroscopic multi-party entangled mesoscopic high-order squeezed states by a detection of the atom

$$|\psi_4\rangle_\pm = \frac{1}{\sqrt{2^k}}\left[\prod_{j=1}^{2k} e^{-in\Omega t_j/2}\left|\xi_j e^{-in\omega_{cj}t_j}\right\rangle \pm (-1)^k \prod_{j=1}^{2k} e^{in\Omega t_j/2}\left|-\xi_j e^{-in\omega_{cj}t_j}\right\rangle\right], \tag{11}$$

where we have assumed that the same Ω and different interaction time t_j with respect to each cavities. It is noted that (11) describes a multi-party macroscopic entangled the mesoscopic high-order squeezed state involving $2k$ mesoscopic components, called as *generalized macroscopic GHZ state*.

Particularly in the case of $N = M = 1$, equation (7) is reduced to

$$|\psi_5\rangle = \frac{1}{\sqrt{2}}(|+\rangle_1 |\xi\rangle + |-\rangle_1 |-\xi\rangle), \tag{12}$$

with $\xi = g(e^{-in\delta t} - 1)/2\delta$, which is a "Schrödinger cat" state [19–21], made of high-order squeezed vacuum states. In the Schrödinger picture, we obtain

$$\begin{aligned} |\psi_6\rangle = \frac{1}{2}\Big[& |g\rangle_1 \left(e^{-in\Omega t} \left|\xi e^{-in\omega_c t}\right\rangle + e^{in\Omega t} \left|-\xi e^{-in\omega_c t}\right\rangle\right) \\ & + |e\rangle_1 e^{-i\omega_L t}\left(e^{-in\Omega t} \left|\xi e^{-in\omega_c t}\right\rangle - e^{in\Omega t} \left|-\xi e^{-in\omega_c t}\right\rangle\right)\Big], \end{aligned} \tag{13}$$

in which the detection of the atomic state $|g\rangle_1(|e\rangle_1)$ will create the *even* (*odd*) mesoscopic high-order squeezed vacuum states of the cavity field,

$$|\psi\rangle_{1eoc} = \frac{1}{\sqrt{2}}\left(e^{-in\Omega t} \left|\xi e^{-in\omega_c t}\right\rangle \pm e^{in\Omega t} \left|-\xi e^{-in\omega_c t}\right\rangle\right). \tag{14}$$

Alternatively, for the case of $N = 2, M = 1$, equation (6) yields the time evolution from initial state $|g\rangle_1|g\rangle_2|0\rangle$ to

$$\begin{aligned} |\psi\rangle_{2i} &= \frac{1}{2}(|+\rangle_1 |+\rangle_2 |2\xi\rangle + (|+\rangle_1 |-\rangle_2 + |-\rangle_1 |+\rangle_2) |0\rangle + |-\rangle_1 |-\rangle_2 |-2\xi\rangle) \\ &= \frac{1}{2}\{|g\rangle_1 |g\rangle_2 [|2\xi\rangle + 2|0\rangle + |-2\xi\rangle] + |g\rangle_1 |e\rangle_2 [|2\xi\rangle - |-2\xi\rangle] \\ &\quad + |e\rangle_1 |g\rangle_2 [|2\xi\rangle - |-2\xi\rangle] + |e\rangle_1 |e\rangle_2 [|2\xi\rangle - 2|0\rangle + |-2\xi\rangle]. \end{aligned} \tag{15}$$

In the Schrödinger picture, detecting the two atoms in the states $|g\rangle_1|g\rangle_2$, $|g\rangle_1|e\rangle_2(|e\rangle_1|g\rangle_2)$, and $|e\rangle_1|e\rangle_2$ will generate following states, respectively

$$\begin{aligned} |\psi\rangle_{2s1} &= \mathcal{N}_1\left(e^{-i2n\Omega t} \left|2\xi e^{-in\omega_c t}\right\rangle + 2|0\rangle + e^{i2n\Omega t} \left|-2\xi e^{-in\omega_c t}\right\rangle\right), \\ |\psi\rangle_{2s2} &= \mathcal{N}_2\left(e^{-i2n\Omega t} \left|2\xi e^{-in\omega_c t}\right\rangle - e^{i2n\Omega t} \left|-2\xi e^{-in\omega_c t}\right\rangle\right), \\ |\psi\rangle_{2s3} &= \mathcal{N}_3\left(e^{-i2n\Omega t} \left|2\xi e^{-in\omega_c t}\right\rangle - 2|0\rangle + e^{i2n\Omega t} \left|-2\xi e^{-in\omega_c t}\right\rangle\right). \end{aligned} \tag{16}$$

Extending to the case of $N = 2k+1, M = 1$ with initial state $\prod_i^{2k+1} |g\rangle_i$, we obtain straightforwardly

$$\begin{aligned} |\psi\rangle_{2k+1i} = \mathcal{N}_{2k+1}\Bigg[& \prod_{i=1,}^{2k+1} |+\rangle_i |(2k+1)\xi\rangle + \sum_{l\neq i}^{2k+1} \prod_{i=1,}^{2k+1} |+\rangle_i |-\rangle_l |(2kn-1)\xi\rangle \\ & + \cdots + \sum_{i\neq l}^{2k+1} \prod_{l=1,}^{2k+1} |+\rangle_i |-\rangle_l |-(2n-1)\xi\rangle + \prod_{l=1,}^{2k+1} |-\rangle_l |-(2k+1)\xi\rangle \Bigg]. \end{aligned} \tag{17}$$

In the Schrödinger picture, by measurements in the $\prod_i^{2k+1}|g\rangle_i|0\rangle$, we have

$$|\psi\rangle_{2k+1s} = \mathcal{N}_{2k+1}\sum_{j=-(k+1)}^{k} C_{2k+1}^{k-j} e^{-(2j+1)n\Omega t}\left|(2j+1)\xi e^{-in\omega_c t}\right\rangle, \tag{18}$$

where

$$C_{2n+1}^{k-j} = \frac{(2k+1)!}{(k-j)!(k+j+1)!}. \tag{19}$$

Equation (18) describes a macroscopic superposition state composing of $2(k+1)$-mesoscopic components without an Fock state $|0\rangle$. In fact, if in case of $N = 2k$, and $M = 1$ with the initial state $\prod_i^{2k}|g\rangle_i|0\rangle$ are considered, we can acquire

$$|\psi\rangle_{2ks} = \mathcal{N}_{2k}\sum_{j=-k}^{k} C_{2k}^{k-j} e^{-2jn\Omega t}\left|2j\xi e^{-in\omega_c t}\right\rangle, \tag{20}$$

in which the $(2k+1)$ mesoscopic component states involve the Fock state $|0\rangle$ and

$$C_{2k}^{k-j} = \frac{(2k)!}{(k-j)!(k+j)!}. \tag{21}$$

The states in (18) and (20) are usually called as bigger high-order macroscopic "Schrödinger cat" states. Based on (18) and (20), we can furthermore obtain the entangled state between two macroscopic "Schrödinger cats" through the same process as above.

In Ref. [4], the macroscopic superposition and entanglement of coherent states were studied under the one-photon interaction in a cavity, assisted by a classical field. If we have two cavities, in one of which the atom inside is governed by one-photon interaction as in (5) in Ref. [4], and in other of which (6) of the present paper works. Supposing that the system is initially in $|g\rangle|0\rangle_1|0\rangle_2$ and that the atom passes sequentially through the cavities for interaction time t_1 and t_2, respectively, we obtain in the interaction picture

$$|\psi\rangle' = \frac{1}{\sqrt{2}}(|+\rangle\,|\alpha\rangle_1\,|\xi\rangle_2 + |-\rangle\,|-\alpha\rangle_1\,|-\xi\rangle_2), \tag{22}$$

where $\alpha = g_{11}(e^{i\delta_1 t_1} - 1)/2\delta_1$ and $\xi = g_{12}(e^{-i2\delta_2 t_2} - 1)/2\delta_2$ and in which $|\alpha\rangle_1$ is a usual coherent state resulted from the displacement operator. In the Schrödinger picture, we have the following macroscopic entangled state between the coherent states and the mesoscopic high-order squeezed states after the detection in the basis $\{|g\rangle, |e\rangle\}$,

$$\begin{aligned}|\psi\rangle_{mBell} = \mathcal{N}_{1,2}^{\pm}\Big(&e^{-in\Omega(t_1+t_2)}\left|\alpha e^{-i\omega_{c1}t_1}\right\rangle_1\left|\xi e^{-in\omega_{c2}t_2}\right\rangle_2\\ &\pm e^{in\Omega(t_1+t_2)}\left|-\alpha e^{-i\omega_{c1}t_1}\right\rangle_1\left|-\xi e^{-in\omega_{c2}t_2}\right\rangle_2\Big),\end{aligned} \tag{23}$$

which are also called the *generalized marcoscopic Bell-states*.

Due to the classical laser as an external source, the cavity system under consideration is different from the usual ones because the anti-Jaynes-Cummings (JC) interactions can be present, which has been shown in [4]. In our model, when $\delta = \pm n\Omega$ and $|\delta| \gg g_i$, equation (3) will turn to the effective Hamiltonians of multi-photon JC and anti-JC interactions in the dressed basis $|\pm\rangle_j$,

$$H^{+}_{TJC} = \frac{1}{2}\sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij}[|+\rangle_{jj}\langle -|\, a_i^n + |-\rangle_{jj}\langle +|\, a_i^{+n}], \tag{24}$$

and

$$H^{-}_{TAJC} = \frac{1}{2}\sum_{j=1}^{N}\sum_{i=1}^{M} g_{ij}[|+\rangle_{jj}\langle -|\, a_i^{+n} + |-\rangle_{jj}\langle +|\, a_i^{n}], \tag{25}$$

which might be useful in quantum optics and quantum information processing. For example, based on (24), we can *deterministically* produce a generalized M-cavity-mode W-type entanglement state, being consisted of Fock state $|n\rangle$ and vacuum state $|0\rangle$ of the cavity modes

$$|W\rangle_M = \frac{1}{\sqrt{M}}\sum_{j=1}^{M}|n\rangle_j \prod_{i=1,i\neq j}^{M}|0\rangle_i \,. \tag{26}$$

The anti-JC interaction of (25) can be used to construct logic gates [22, 23] as done by blue-detuned laser in ion-trap system. It can also be applied to test the theoretical work for JC model in the absence of the rotating wave approximation [24].

Compared to the intensive study regarding the coherent states [1–7], the macroscopic "Schrödinger cats" and macroscopic entangled states [14, 15] from the usual squeezed vacuum states have a little been investigated. The nonclassical squeezed states of light has potential applications in optical communications and gravitational detection [8–13]. According to Refs. [25, 26], the use of entanglement of multi-trapped-ions can improve the signal-to-noise ratio and the detection sensitivity of quantum systems in spectroscopy and atomic clocks. So we argue that the macroscopic superpositions and entanglement of the high-order squeezed vacuum states generated by our schemes might also be useful in metrology.

Now we discuss the experimental feasibility of our proposal with current available cavity QED techniques. Both microwave and optical regimes may be used for implementation of our scheme [25–33]. For example, in the microwave regime, we assume that $\delta/2\pi = 1$ MHz, $\Omega/2\pi = 1$ GHz, and $g_{ij}/2\pi = 0.05$ MHz [29]. The lifetime of the circular Rydberg atom state with principle quantum 51 is about 30 ms, much longer than the cavity decay time T_{cav} (0.84 ms) in the case of multiphoton inside [34]. If we assume that the cavity size is $L = 27.5$ mm and the atomic velocity is 495 m/s [29], the interaction time of the atoms with the cavity mode is $T_i = 5.4 \times 10^{-2}$ ms, which is much shorter than T_{cav}, and then $T_{cav}/T_i = 15.65$, meaning that if the detection time T_d is equal to the interaction time T_i, we can sequentially manipulate about *five* atoms to realize the first part of our scheme in a single cavity. Furthermore, if the distance between neighbor cavities is half of the cavity size, we can carry out the multi-cavity part of our scheme with about *eight* cavities involved by detection on a single atom.

In summary, we have proposed a scheme for realizing the superpositions and entanglement of the mesoscopic high-order squeezed vacuum states, based on the multi-photon JC model, assisted by strongly-assisted driving classical field. As a byproduct, we also discussed how to create a series of macroscopic entangled states between the usual coherent states and the high-order squeezed vacuum states, and how to generate the generalized multi-mode W-type entanglement states consisting of $|n\rangle$ and $|0\rangle$ of the cavity modes. We have shown the feasibility to achieve our scheme with current techniques in cavity QED [30–34].

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