Generation of Multi-atom Dicke States with Quasi-unit Probability through the Detection of Cavity Decay

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Abstract

We propose a scheme to create universal Dicke states of \( n \) largely detuned atoms through detecting the leaky photons from an optical cavity. The generation of entangled states in our scheme has quasi-unit success probability, so it has potential practicability based on current or near coming laboratory cavity QED technology.

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Entanglement plays an important role in the fields of quantum theory and quantum information processing (QIP). It is not only used to test quantum mechanics against local hidden variable theory [1], but also holds the keys of the applications of QIP including computation [2], communication [3], and cryptography [4]. There are many theoretical and practical schemes to entangle two particles or multi-particles, such as spontaneous parametric down converters [5], linear ion trap [6], atomic ensembles [7], and cavity QED [8]. Among them, the schemes based on cavity QED attract persistent interest in the experimental realization because long-lived states in high-Q cavities provide a promising tool for creating entanglement and superposition, and also possible for implementation of quantum computing [9]. Entangled states for two-level atoms in cavity QED have been observed for [8, 10] in experiment to date.

One of the main obstacles for the implementation of quantum information in cavity QED, including preparation of multi-atom entanglement, is the decoherence of the atoms and cavity fields. As potential solutions, largely detuned atoms in the cavities [11] and dissipation-assisted conditional quantum evolution via the detection of cavity decay [12] have been proposed to date. On the one hand, when the atoms have large detuning with the cavity modes, the atomic populations in the excited states are very small and thus atomic spontaneous emission (described by the rate $\gamma_s$) can be neglected. In other words, the atomic excited states can be eliminated due to large detuning and atoms evolve only in their ground state space. On the other hand, cavity decay is also considered as a useful ingredient, not a destructive factor, since the idea was proposed by Plenio and Knight [13].

Recently, Hong and Lee proposed a scheme to generate two-atom entangled state in a cavity quasideterministicly [14]. In their paper, two three-level atoms should couple resonantly with two different polarized cavity modes. Therefore, the atomic spontaneous emission is a significant reason to decrease the success probability, especially when the trials have been done for several times. Here, we propose an extended and improved scheme to generate Dicke states [15] of arbitrary n among N trapped largely detuned atoms with quasi-unit probability. Furthermore, we extend our conclusion to generate a non-trivial subset of Dicke states of the n atoms step by step. The Dicke states are defined as $|n, m\rangle_{\text{Dicke}} = C(n, m) (s_1)^m (s_0)^{n-m} \otimes_{j=1}^{n} |e\rangle_j$ [15]. Here, the collective operators $s_k$ ($k = 0, 1$) are defined as $s_k = \sum_{j=1}^{n} |k\rangle_{jj} \langle e|$, and the normalization coefficient $C(n, m) = 1/\sqrt{n!m!(n-m)!}$. The multi-atom Dicke states and the GHZ states in general
belong to different classes of entangled states, and Dicke states are relatively more immune to the influence of noise [16]. Dicke states have many interesting applications in QIP and in high-precision measurements [17].

In the current practical cavity QED system, optical cavity always has a finite quality factor, and the coherent coupling rate $g(r)$ between the atom and the cavity mode changes fast if the atoms pass the cavity within a predefined time. So now we take into account N atom are trapped in a bimodal cavity as showed in fig. 1a, and the trapping time has been demonstrated up to several seconds [18, 19]. The two cavity modes have different polarization $L$ (left-circularly polarized) and $R$ (right-circularly polarized). The cavity photons leaked out through the mirror, can be detected by two single-photon detectors $D_0$ and $D_1$ without failure, and $D_0$ ($D_1$) is triggered by $L$ ($R$) photon due to the quarter-wave plate (QWP). The trapped atoms have the identical five-level configuration, as depicted in fig. 1b, the ground states $|0\rangle$, $|1\rangle$, $|2\rangle$ and the excited state $|e\rangle$, $|r\rangle$. The configuration can be obtained in $^{87}\text{Rb}$. For example, the states $|0\rangle$, $|1\rangle$, and $|2\rangle$, are respectively $|F = 2, m = -1\rangle$, $|F = 2, m = 1\rangle$, $|F = 1, m = -1\rangle$ of $5^2S_{1/2}$; $|e\rangle$ and $|r\rangle$ are respectively $|F = 1, m = 0\rangle$, $|F = 1, m = -1\rangle$ of $5^2P_{1/2}$. Atomic transition $|0\rangle \leftrightarrow |e\rangle$ ($|1\rangle \leftrightarrow |e\rangle$) is coupled with cavity mode $a_L$ ($a_R$). The two $\pi$-polarized classical laser pulses $\varepsilon_1$ and $\varepsilon_2$ are used to transfer the occupation of the state $|0\rangle$ to $|2\rangle$ with Rabi frequencies $\Omega_1(t)$ and $\Omega_2(t)$ respectively.

The $n$ atoms, expected to entangle together, can be arbitrarily chosen from $N$ trapped atoms. We first completely transfer the occupations of the state $|0\rangle$ of the other ($N-n$) atoms to those of the state $|2\rangle$. Then the ($N-n$) atoms are beyond systemic state evolution space (cavity + $n$ atoms). Before study the system evolution dynamics, we do some consideration. The separation between any two atoms is large enough compared with the wavelength of the fields in interest so that the dipole-dipole interaction among atoms can be neglected. This assumption is feasible because cavity length is always much larger than the wavelength of cavity modes. We neglect spontaneous emission of the atoms. Subject to no decay being recorded in the detectors, under the rotating wave approximation, the system conditionally evolves according to a non-Hermitian Hamiltonian which is given by (in units of $\hbar = 1$)

$$H_1 = \sum_{i=1}^{n} \left( \omega_e |e\rangle_{ii} \langle e| + \omega_0 |0\rangle_{ii} \langle 0| + \omega_1 |1\rangle_{ii} \langle 1| \right) + \left( \omega_L - \frac{iK_L}{2} \right) a_L^\dagger a_L + \left( \omega_R - \frac{iK_R}{2} \right) a_R^\dagger a_R + \sum_{i=1}^{n} \left( g_L |e\rangle_{ii} \langle 0| a_L + g_R |e\rangle_{ii} \langle 1| a_R + H.c. \right),$$

(1)
FIG. 1: (a) Schematic setup to realize multi-atom entangled state in a leaky optical cavity. QWP is a quarter-wave plate, PBS is a polarization beamsplitter, and $D_0$ and $D_1$ are two single-photon detectors. (b) The energy level diagram of atoms. The states $|0\rangle$, $|1\rangle$ and $|2\rangle$ are the hyperfine states in the ground-state manifold, respectively; $|e\rangle$ and $|r\rangle$ are the excited state. Atomic transition $|0\rangle \leftrightarrow |e\rangle$ ($|1\rangle \leftrightarrow |e\rangle$) is coupled with the cavity mode $a_L$ ($a_R$).

where $\omega_e$ ($\omega_0$, $\omega_1$) is the atomic energy in the atomic state $|e\rangle$ ($|0\rangle$, $|1\rangle$); $\omega_{\mu=L,R}$ is the frequency for the cavity mode $a_{\mu}$; $g_{\mu}$ (assumed real) is the single-photon coherent coupling rate with the cavity mode $a_{\mu}$; $\kappa_L = \omega/Q_L$ and $\kappa_R = \omega/Q_R$ denote the rate of decay of the cavity mode fields $a_L$ and $a_R$, respectively, and $H.c.$ stands for the Hermitian conjugate. Then the interaction Hamiltonian in the interaction picture can be written as

$$H_2 = \sum_{i=1}^{n} (g_L |e\rangle_{ii} \langle 0| a_L + g_R |e\rangle_{ii} \langle 1| a_R + H.c. - \left(\Delta_L + \frac{i\kappa_L}{2}\right) a_L^\dagger a_L - \left(\Delta_R + \frac{i\kappa_R}{2}\right) a_R^\dagger a_R.$$  

(2)

Here, the detuning $\Delta_L$ ($\Delta_R$) is defined as $\omega_e - \omega_0 - \omega_L$ ($\omega_e - \omega_1 - \omega_R$), and our scheme works in the strongly detuned limit $\Delta_{\mu} \gg g_{\mu'}$.

Expressing the state of the total system in the form of $|\text{atoms}\rangle |\text{cavity}\rangle$, the initial state of the system is prepared as $|0_1 0_2 \cdots 0_n\rangle |L\rangle$, which means all atoms are in the ground state $|0\rangle$ and the cavity fields have a $L$ polarized photon. The temporal evolution of the system is spanned by the $2n+1$ basis states: $\{ |0_1 0_2 \cdots 0_n\rangle |L\rangle$, $|e_1 0_2 \cdots 0_n\rangle |vac\rangle$, $|0_1 0_2 \cdots e_n\rangle |vac\rangle$, $|1_1 0_2 \cdots 0_n\rangle |R\rangle$, $\cdots$, $|0_1 0_2 \cdots 1_n\rangle |R\rangle \}$. Since the initial atomic state is symmetrical and the atoms are indistinguishable in the evolution state space, the basis states reduce to $\{ |\phi_0\rangle = |0_1 0_2 \cdots 0_n\rangle |L\rangle$, $|\phi_1\rangle = \frac{1}{\sqrt{n}} (|1_1 0_2 \cdots 0_n\rangle + \cdots + |0_1 0_2 \cdots 1_n\rangle) |R\rangle$, $\cdots$, $|\phi_n\rangle = \frac{1}{\sqrt{n}} (|0_1 0_2 \cdots e_n\rangle + \cdots + |0_1 0_2 \cdots 1_n\rangle) |R\rangle$ \}$. 

4
\[ |\phi_2\rangle = \frac{1}{\sqrt{n}} (|e_10_2 \cdots 0_n\rangle + \cdots + |0_10_2 \cdots e_n\rangle)|\text{vac}\rangle. \]  

The state of the system at arbitrary time is described by

\[ |\Psi (t)\rangle = c_0 (t) |\phi_0\rangle + c_1 (t) |\phi_1\rangle + c_2 (t) |\phi_2\rangle. \quad (3) \]

According to Schrödinger equation \(i\partial_t |\Phi (t)\rangle = H_2 |\Phi (t)\rangle\), we have

\[
\begin{align*}
 idc_0 (t) /dt &= - \left( \Delta_L + \frac{i\kappa_L}{2} \right) c_0 (t) + \sqrt{n}g_L c_2 (t), \\
 idc_1 (t) /dt &= - \left( \Delta_R + \frac{i\kappa_R}{2} \right) c_1 (t) + g_R c_2 (t), \\
 idc_2 (t) /dt &= \sqrt{n}g_L c_0 (t) + g_R c_1 (t).  
\end{align*}
\]

Then we utilize the transformation \(\lambda_{\nu=0,1,2} (t) = c_\nu (t) e^{-i\Delta_L t}\), therefore, eqs. (4) can be written as

\[
\begin{align*}
 d\lambda_0 (t) /dt &= - \frac{\kappa_L}{2} \lambda_0 - i\sqrt{n}g_L \lambda_2 (t), \\
 d\lambda_1 (t) /dt &= - i \left( \Delta_L - \Delta_R - \frac{i\kappa_R}{2} \right) \lambda_1 (t) - ig_R \lambda_2 (t), \\
 d\lambda_2 (t) /dt &= - i\sqrt{n}g_L \lambda_0 (t) - ig_R \lambda_1 (t) - i\Delta_L \lambda_2 (t). 
\end{align*}
\]

Assuming \(g_R = g_L = g\), \(\kappa_L = \kappa_R = \kappa\), \(\Delta_L, \Delta_R \gg g\), and \(|\Delta_L - \Delta_R| \ll g\), the atomic population in the excited state \(|e\rangle\) is very small, and we can put \(d\lambda_2 (t) /dt = 0 \quad \text{[20]}\) so that eqs. (3) and (5) reduce to

\[
\begin{align*}
 |\Psi (t)\rangle &= \lambda_0 (t) |\phi_0\rangle + \lambda_1 (t) |\phi_1\rangle, \\
 d\lambda_0 (t) /dt &= \left( \frac{ing^2}{\Delta_L} - \frac{\kappa}{2} \right) \lambda_0 (t) + i\sqrt{n}g^2 \Delta_L \lambda_1 (t), \\
 d\lambda_1 (t) /dt &= i\sqrt{n}g^2 \Delta_L \lambda_0 (t) + \left[ \frac{ig^2}{\Delta_L} - i(\Delta_L - \Delta_R) - \frac{\kappa}{2} \right] \lambda_1 (t). 
\end{align*}
\]

Here we neglect the common phase \(e^{i\Delta_L t}\). The solutions of eqs. (6) are

\[
\begin{align*}
 \lambda_0 (t) &= e^{-\kappa t/2} e^{\frac{\omega_0 t}{2}} \left[ \cos \left( \frac{\Omega_1 t}{2} \right) + i \frac{2ng^2 - \Delta_L \Omega_0}{\Delta_L \Omega_1} \sin \left( \frac{\Omega_1 t}{2} \right) \right], \\
 \lambda_1 (t) &= ie^{-\kappa t/2} e^{\frac{\omega_0 t}{2}} \frac{\Delta_L^2 \Omega_1^2 - (\Delta_L \Omega_0 - 2ng^2)^2}{2\sqrt{n}g^2 \Delta_L \Omega_1} \sin \left( \frac{\Omega_1 t}{2} \right), 
\end{align*}
\]

where \(\Omega_0 = \frac{(n+1)g^2}{\Delta_L} - (\Delta_L - \Delta_R), \Omega_1 = \sqrt{\left[ \frac{(n+1)g^2}{\Delta_R} + (\Delta_L - \Delta_R)^2 + 2(n - 1)(\Delta_L - \Delta_R) \frac{g^2}{\Delta_L} \right]}\). When \(n = 1\) and \(\kappa = 0\), it is the result of ref \([20]\). In order to obtain multi-atom entangled
state, we consider the case of \( n > 1 \). If we have

\[
\Delta_L - \Delta_R = (1 - n) g^2 / \Delta_L
\]

and thus

\[
\Omega_0 = 2ng^2 / \Delta_L,
\]

\[
\Omega_1 = 2\sqrt{n}g^2 / \Delta_L,
\]

Then eqs. (7) reduce to a laconic expression

\[
\lambda_0 (t) = e^{-\kappa t/2} e^{i \frac{\Omega_0 t}{2}} \cos \left( \frac{\Omega_1 t}{2} \right),
\]

\[
\lambda_1 (t) = e^{-\kappa t/2} i e^{i \frac{\Omega_0 t}{2}} \sin \left( \frac{\Omega_1 t}{2} \right).
\]

The factor \( e^{-\kappa t/2} \) describes the leakage of cavity photons.

Assume the detector \( D_0 \) or \( D_1 \) has a response at time \( t = t_r \leq T \) (Here, \( T \) is a waiting time of two detectors), and then this coherent time evolution \( |\Psi (t)\rangle \) governed by \( H_2 \) is immediately interrupted by a corresponding quantum jump operator \[ \sqrt{n}g^2 / \Delta_L \]

| \[] \]

\[ b_0 (= a_L) \) or \( b_1 (= a_R), \) respectively. After the detector \( D_k \) responses, the state of system can be written as

\[
|\Psi (t_r)\rangle^{D_k} = \frac{b_k |\Psi (t_r)\rangle}{||b_k |\Psi (t_r)\rangle||}
\]

In the case that \( D_1 \) responses, after tracing out the cavity modes part, we can see that the \( n \) atoms are prepared in the entangled state \( |\varphi\rangle_{ent} = \frac{1}{\sqrt{n}} (|1,0_2 \cdots 0_n\rangle + \cdots + |0_1,0_2 \cdots 1_n\rangle). \) \( |\varphi\rangle_{ent} \) is right a W state \[ \[16 \] \] of \( n \) particles, which is a special case (\( m = 1 \)) of Dicke states \( |n,m\rangle_{Dicke}. \) Notice that if we let \( \sqrt{n}g_L = g_R \) in eqs. (4) and (5), the original multi-atom model reduces to a symmetric three-level system in the ref. \[ \[20 \] \]. In this case, two-photon resonant condition \( \Delta_L = \Delta_R \) should be met in order to generate \( |\varphi\rangle_{ent}. \) But the condition of \( \sqrt{n}g_L = g_R \) is not always satisfied in actual system because \( g_L / g_R \) has a determinate relation for two given atomic transitions. Obviously, the state of the \( n \) atoms relapses to their initial state \( |0_1,0_2 \cdots 0_n\rangle \) if \( D_0 \) is triggered. With the reinjection of a new left-circularly polarized photon into the cavity, the same process is repeated until the entangled state is prepared. Similar to the ref. \[ \[14 \] \], we can make the experiment automatically repeat itself through replacing the detector \( D_0 \) by a path directed back to the cavity, so that the left-circularly polarized photon can be automatically fed back to the cavity. Therefore, \( |\varphi\rangle_{ent} \)
can be produced with near unit probability. Furthermore, if we reinject a new left-circularly polarized photon into the cavity after a W state of n atoms is achieved, we can prepare Dicke state $|n,2\rangle_{\text{Dicke}}$. Moreover, if the same process is repeated, universal n-qubit Dicke states $|n,m\rangle_{\text{Dicke}}$ can be prepared step by step [22].

Now we turn to analyze the efficiency of the scheme. In the absence of spontaneous emission of the atoms, From eqs. (10), one can know that the probability of photons decay from cavity is $P_{\text{decay}}(t) = 1 - |e^{-\kappa t/2}|^2$, and in the time interval $dt_r$, the probability that the detector $D_1$ is triggered is $|\sin \left(\frac{\Omega_1 t}{2}\right)|^2 \cdot \left(\frac{dp_{\text{decay}}(t_r)}{dt_r}\right) dt_r$. Noticeably, a left- or right-circularly polarized photon will finally leak out due to the factor $e^{-\kappa t/2}$ in eqs. (10). In fact, in the case of $\kappa T \gg 1$, we consider one of detectors should response with the time $T$, so that the probability of the detector $D_1$ is triggered, i.e., the success probability $p_{\text{suc}}$ of entangled state $|\varphi\rangle_{\text{ent}}$ being prepared, can be roughly calculated as

$$p_{\text{suc}} \approx \int_0^T \left|\sin \left(\frac{\Omega_1 t}{2}\right)|^2 \cdot \left(\frac{dp_{\text{decay}}(t_r)}{dt_r}\right) dt_r\right|^2 \approx \frac{2ng^4}{\Delta_L^2 (\kappa^2 + \Omega_1^2)}.$$  

In order to get the maximum of $p_{\text{suc}}$, we find that it is corresponds to the minimum of $\Omega_1$, that is, $(\Delta_L - \Delta_R) = -\frac{(n-1)g^2}{\Delta_L}$. Especially take notice that this condition agrees with eqs. (8, 9). So we have

$$p_{\text{suc}} = \frac{2ng^4}{\Delta_L^2 \kappa^2 + 4ng^4}. \quad (13)$$

As showed in fig. 2, we can find, for a given $\Delta_L$, iff $\kappa \ll g$, $p_{\text{suc}}(g, \kappa)$ reaches near 50%.

We consider a set of practical parameters. $g = 2\pi \times 16$ MHz and $\kappa = 2\pi \times 1.4$ MHz are given in Rempe’s group [18]. We also choose $T = 0.5 \mu s$ (Commonly, the coherence time of atomic internal states in a high-Q cavity is much larger than the order of $T$ [23]), $\Delta_L = 20g$, and $n = 3$. After a trial, $p_{\text{suc}} = \frac{2ng^4}{\Delta_L^2 \kappa^2 + 4ng^4} \approx 0.36$. The probability is not very high, but it increases to quasi-unit after several trials. For instance, the total success probability is more than 99% after ten trials.

In addition, the atoms always has spontaneous emission when they are in the excited states. However, the occupation of the excited states is very small since the atomic transitions are largely detuned with cavity modes in our scheme. Our numerical simulation shows the occupation is less than 3% based on above practical parameters. Therefore, atomic spontaneous emission is an inappreciable ingredient in our scheme.
FIG. 2: The success probability $p_{suc}$ computed numerically as a function $g/\kappa$ and $n$. Other parameter: $\Delta_L = 20g$.

F-P cavity has a general mode function described by $\chi(\vec{r}) = \sin(kz) \exp[-(x^2 + y^2)/w_0^2]$ \cite{24}, and $g(r) = g_0 \chi(\vec{r})$, where $w_0$ and $k = 2\pi/\lambda$ are, respectively, the width and the wave vector of the Gaussian cavity mode, and $\vec{r}(x, y, z)$ describes the atomic locations; $z$ is assumed to be along the axis of the cavity. In the above description we have assumed the coupling rate $g_{L,R}(r) = g$, which means all atoms are addressed on some certain locations. An obviously best case is: $\sin(k_{L,R}z) = 1$ and $x = y = 0$. Apparently, these conditions still remain a challenge based on current cavity QED technology. We also note our scheme requires an efficient source of single photons \cite{25} and their injection into an optical cavity. However, as a theoretical design, our scheme is still potentially feasible in the near future technology, for all these obstacles are now under active investigations \cite{19, 26} and may be overcame in the near future.

In conclusion, we have presented a scheme to prepare multi-atom entangled state in an optical cavity. Based on current and near future cavity QED technology, considering and using the dissipation of the system, we design a scheme based on measurements to leaky photons, to generate universal Dicke states $|n, m\rangle_{\text{Dicke}}$ of $n$ atoms. In principle, although the preparation is probabilistic in one trial, the probability of success reaches close to unit after several trials. Obviously, our scheme has ultra-high fidelity, since non-ideal single-photon detectors, absorption by cavity mirrors and atomic spontaneous emission just decrease the
success probability, not the fidelity of states.

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