Strong Correlation of Fluorescence Photons without Quantum Interference *

HU Xiang-Ming(胡响明)**, WANG Fei(王飞)

Department of Physics, Huazhong Normal University, Wuhan 430079

(Received 10 October 2006)

It has been predicted that a driven three-level V atom can emit strongly correlated fluorescence photons in the presence of quantum interference. Here we examine the effects of quantum interference on the intensity correlation of fluorescence photons emitted from a driven three-level Λ atom. Unexpectedly, strong correlation occurs without quantum interference. The quantum interference tends to reduce the correlation function to a normal level. The essential difference between these two cases is traced to the different effects of quantum interference on coherent population trapping (CPT). For the V atom, quantum interference and coherent excitation combine to lead to CPT. For the Λ atom, however, the quantum interference tends to spoil CPT while the coherent excitation induces the effect.

PACS: 42. 50. Ct, 32. 50. +d, 32. 80. Qk

Atomic coherence and quantum interference have led to many novel effects such as coherent population trapping (CPT),[1,2] electromagnetically induced transparency,[3,4] lasing without population inversion,[5,6] a variety of novel nonlinear optical processes,[7,8] and modification of spontaneous emission.[9,10] Recently, Swain *et al.* have suggested that a three-level atom can emit strongly correlated fluorescence photons in the presence of quantum interference.[11] The intensity correlation takes values of the order of hundreds and thousands, whereas the corresponding maximum in the absence of quantum interference is at a 'normal' level (values of the order of unity). We note that the quantum interference arises from the coupling of two transitions with parallel dipole moments to the same vacuum modes.[12,13] The parallel moments are difficult to find in realistic systems because this requires that the near-degenerate states have the same quantum numbers J and m_J. In order to overcome this difficulty, one has to turn to the equivalent realization in the dressed states representation.[14,15] In spite of this, the conditions are still very stringent. A metastable state is required for the additional coherent transition. Ficek and Swain showed that the extremely strong correlation is obtained by using a dc field to couple the decaying state to the metastable state.[16] It seems that the strong correlation occurs only in the presence of quantum interference.

Here we show that it is not always the case. We show that strong correlation occurs without quantum interference. In particular, we consider a three-level Λ atom, two metastable states of which are non-degenerate but closely spaced. The two transitions between the excited state and two metastable states have perpendicular dipole moments. A strong coherent field is applied to both the transitions. The fluorescence photons exhibit strong correlation. As a comparison, when quantum interference is assumed to be existent, the correlation becomes normal. The mechanisms for different systems are compared. We note that the extremely strong correlations are associated with but do not exactly occur at CPT. For these two systems quantum interferences play completely different roles. For the V system, CPT occurs only when quantum interference and coherent excitation combine to take effect. For the Λ system, CPT is induced simply by coherent excitation but the quantum interference tends to destroy the coherent effect.

The three-level Λ system is shown in Fig. 1. The two metastable states are not degenerate but closely spaced to each other. A single laser field of frequency ω is coupled to both the transitions $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$. It is obvious that conditions for CPT cannot be exactly satisfied. The master equation for the reduced density operator ρ is derived in an appropriate rotating frame and in the dipole approximation as[17]

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] + \mathcal{L}_1\rho + \mathcal{L}_2\rho + \mathcal{L}_{12}\rho, \tag{1}$$

where

$$H = -\hbar\Delta_1\sigma_{11} - \hbar\Delta_2\sigma_{22} - \hbar(\Omega_1\sigma_{13} + \Omega_2\sigma_{23} + \text{H.c.}), \tag{2}$$

is the system Hamiltonian, and

$$\mathcal{L}_1\rho = \frac{\gamma_1}{2}(2\sigma_{13}\rho\sigma_{31} - \sigma_{33}\rho - \rho\sigma_{33}), \tag{3}$$

and

$$\mathcal{L}_2\rho = \frac{\gamma_2}{2}(2\sigma_{23}\rho\sigma_{32} - \sigma_{33}\rho - \rho\sigma_{33}), \tag{4}$$

describe the spontaneous decays from state $|3\rangle$ to $|1\rangle$ and $|2\rangle$ with rates γ_1 and γ_2, respectively. For comparison, we include quantum interference in the present system

$$\mathcal{L}_{12}\rho = \beta\sqrt{\gamma_1\gamma_2}(\sigma_{13}\rho\sigma_{32} + \sigma_{23}\rho\sigma_{31}), \tag{5}$$

* Supported by the National Natural Science Foundation of China under Grant Nos 60378008 and 10574052.

** Email: xmhu@phy.ccnu.edu.cn

©2007 Chinese Physical Society and IOP Publishing Ltd

which arises the coupling of the two transitions $|1\rangle - |3\rangle$ and $|2\rangle - |3\rangle$ to the same vacuum when the two dipole moments are not perpendicular to each other. The parameter β accounts for the mutual orientation of the two dipole moments; $\beta = 0$ is for the perpendicular dipole moments and $\beta = \pm 1$ for parallel or antiparallel dipole moments; $\sigma_{kl} = |k\rangle\langle l|$ are the atomic projection operators for $k = l$ and the flip operators for $k \neq l$ $(k, l = 1, 2, 3)$; $2\Omega_1 = \boldsymbol{\mu}_1 \cdot \boldsymbol{E}/\hbar$ and $2\Omega_2 = \boldsymbol{\mu}_2 \cdot \boldsymbol{E}/\hbar$ are the Rabi frequencies, where $\boldsymbol{E}$ is the field amplitude, $\boldsymbol{\mu}_1$ and $\boldsymbol{\mu}_2$ are the atomic dipole moments. $\Delta_1 = \omega_{31} - \omega$ and $\Delta_2 = \omega_{32} - \omega = \Delta_1 - \omega_{21}$ are the atom-field detunings, where ω_{31} and ω_{32} are the atomic resonance transition frequencies, and ω_{21} is the level spacing between the two metastable states. The set of equations for the density matrix elements are derived as follows:

$$d\rho_{11}/dt = \gamma_1\rho_{33} + i\Omega_1\rho_{31} - i\Omega_1\rho_{13}, \tag{6}$$

$$d\rho_{33}/dt = -(\gamma_1 + \gamma_2)\rho_{33} + i\Omega_1\rho_{13} - i\Omega_1\rho_{31} + i\Omega_2\rho_{23} - i\Omega_2\rho_{32}, \tag{7}$$

$$d\rho_{12}/dt = i\omega_{21}\rho_{12} + \beta\sqrt{\gamma_1\gamma_2}\rho_{33} - i\Omega_2\rho_{13} + i\Omega_1\rho_{32}, \tag{8}$$

$$d\rho_{13}/dt = -\left[\frac{1}{2}(\gamma_1 + \gamma_2) - i\Delta_1\right]\rho_{13} - i\Omega_2\rho_{12} + i\Omega_1(\rho_{33} - \rho_{11}), \tag{9}$$

$$d\rho_{23}/dt = -\left[\frac{1}{2}(\gamma_1 + \gamma_2) - i\Delta_2\right]\rho_{23} - i\Omega_1\rho_{21} + i\Omega_2(\rho_{33} - \rho_{22}). \tag{10}$$

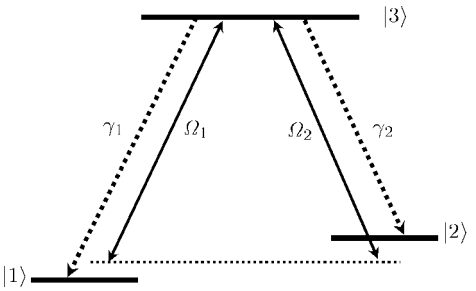


Fig. 1. The three-level Λ system. Here $|i\rangle$ $(i = 1, 2, 3)$ represents the atomic levels, γ_j are the decay rates and Ω_j are the Rabi frequencies $(j = 1, 2)$.

The normalized intensity-intensity correlation function is given by

$$g_2(\tau) = \lim_{t\to\infty} \frac{\langle E^{(-)}(t)E^{(-)}(t+\tau)E^{(+)}(t+\tau)E^{(+)}(t)\rangle}{\langle E^{(-)}(t)E^{(+)}(t)\rangle\langle E^{(-)}(t+\tau)E^{(+)}(t+\tau)\rangle}. \tag{11}$$

For the present system, we have $E^{(+)}(t) \propto D(t) = \boldsymbol{\mu}_1\sigma_{13}(t) + \boldsymbol{\mu}_2\sigma_{23}(t)$ and $E^{(-)}(t) = D^{\dagger}(t)$. By relating the field operators to the atomic operators, we can write the correlation function in the form

$$g_2(\tau) = \lim_{t\to\infty} \frac{\langle D^{\dagger}(t)\sigma_{33}(t+\tau)D(t)\rangle}{(|\boldsymbol{\mu}_1|^2 + |\boldsymbol{\mu}_2|^2)\langle\sigma_{33}(t)\rangle\langle\sigma_{33}(t+\tau)\rangle}. \tag{12}$$

By quantum regression theorem,[18] the correlation functions $\langle D^{\dagger}(t)\sigma_{kl}(t+\tau)D^{\dagger}(t)\rangle$ follow exactly the same set of equations with respect to the time τ for the density matrix elements $\rho_{lk}(\tau)$ under the initial conditions $\rho_{lk}(0)\langle\sigma_{33}(t)\rangle$, where $\rho_{lk}(0) = 0$ except for

$$\rho_{11}(0) = \frac{\gamma_1}{\gamma_1 + \gamma_2}, \tag{13}$$

$$\rho_{22}(0) = \frac{\gamma_2}{\gamma_1 + \gamma_2}, \tag{14}$$

$$\rho_{12}(0) = \rho_{21}(0) = \frac{\beta\sqrt{\gamma_1\gamma_2}}{\gamma_1 + \gamma_2}. \tag{15}$$

Thus we express the normalized intensity-intensity correlation function as

$$g_2(\tau) = \frac{\rho_{33}(\tau)}{\rho_{33}}\Big|_{\rho_{lk}(0)}, \tag{16}$$

where ρ_{33} and $\rho_{33}(\tau)$ are the steady and transient state population at the level 3, respectively.

In the following numerical calculation we scale the Rabi frequencies, the detunings and the decay rates in the units of γ_1, and the time is in units of γ_1^{-1}. The intensity correlation function $g_2(\tau)$ is plotted in Fig. 2 for (a_1) $\beta = 0$, $\omega_{21} = 1$, (a_2) $\beta = 0$, $\omega_{21} = 2$, (b_1) $\beta = 1$, $\omega_{21} = 1$, (b_2) $\beta = 1$, $\omega_{21} = 2$. The parameters are chosen as $\gamma_2 = 1$, $\Omega_1 = \Omega_2 = 5$, and $\Delta = \omega_{12}/2$. In the absence of quantum interference, the correlation function takes its maximal values of 41.8 and 10.8 for $\omega_{21} = 1$ (a_1) and $\omega_{21} = 2$ (a_2), respectively. These maximal values increase with the decreasing level spacing ω_{21}. The condition for the large values of correlation function is in sharp contrast to the case of the three-level V system, where strong correlation occurs only in the presence of quantum interference. For the present system, once in the presence of quantum interference, the correlation function is smaller than the maximal value 2, as shown in (b_1) and (b_2) in Fig. 2, which is similar to the usual case of the two-level system.

The physical mechanisms can be understood by examining the effects of quantum interference in two different systems. It is well known that no CPT occurs for the V system in the absence of quantum interference. This is due to the decoherence between the two excited states. Only in the presence of quantum interference, CPT is possible. Nearly but not exactly at CPT (for example, one can take $\beta = 0.99$),[11] a strong correlation is obtained. On the other hand, it is well known that CPT appears for the Λ system just when coherent excitation is employed. For small two-photon detunings $\Delta_1 - \Delta_2 = \omega_{21} \ll \Omega_1 = \Omega_2$, the system is nearly at CPT. For the cases in Figs. $2(a_1)$ and $2(a_2)$, the excited state populations at the steady state are 9.896×10^{-3} and 3.834×10^{-2}, respectively, which are near but unequal to zero. In such cases, strong correlation occurs. In the presence of quantum interference, however, CPT is seriously destroyed. For the cases in Figs. $2(b_1)$ and $2(b_2)$, the excited state

populations at steady state reach 0.491 and 0.481, respectively. This was verified by Javanainen.[13] By comparison, the quantum interferences have different effects on CPT in the different systems. For the V system quantum interference leads to CPT while for the Λ system tends to spoil CPT. For this reason the three-level Λ atom emits strongly correlated fluorescence photons without quantum interference.

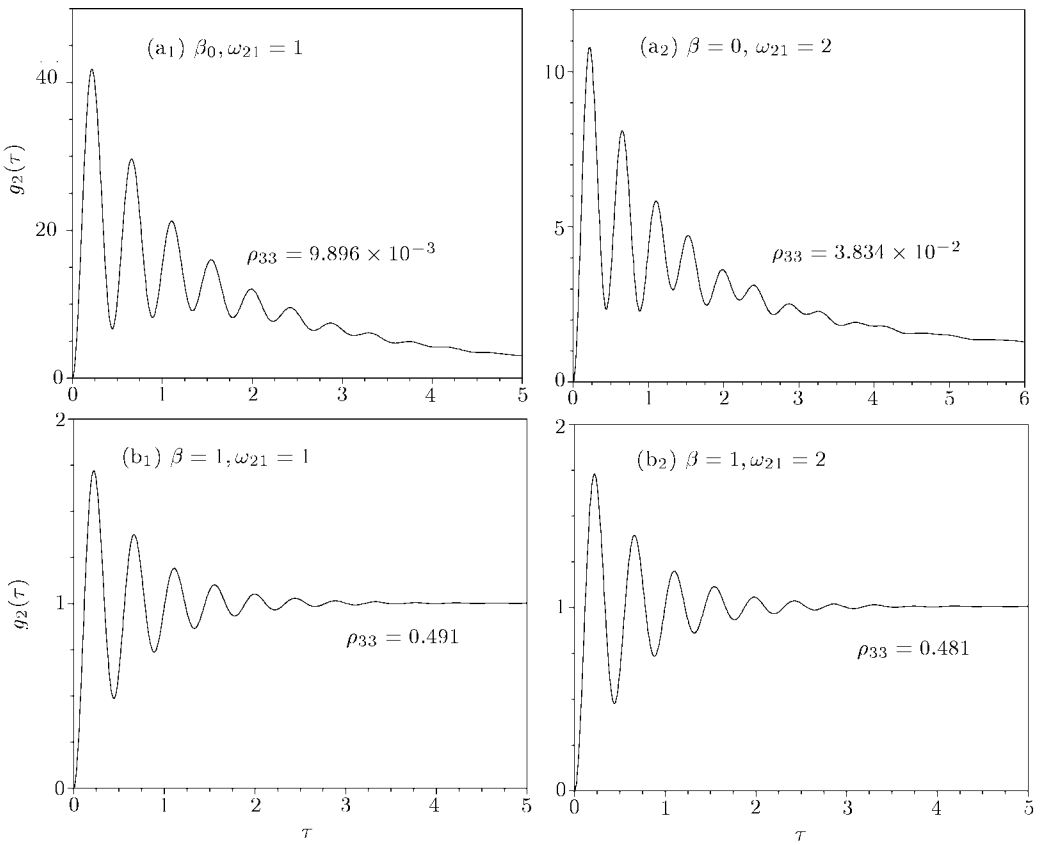


Fig. 2. Intensity correlation function $g_2(\tau)$ for (a$_1$) $\beta = 0$, $\omega_{21} = 1$, (a$_2$) $\beta = 0$, $\omega_{21} = 2$, (b$_1$) $\beta = 1$, $\omega_{21} = 1$, (b$_2$) $\beta = 1$, $\omega_{21} = 2$. Other parameters are shown in the text. The steady state populations ρ_{33} for the various cases are shown.

In conclusion, we have shown that fluorescence photons emitted from a driven three-level Λ system exhibit strong correlation without quantum interference. This is in sharp contrast to the case of the V system, where strong correlation appears only in the presence of quantum interference. The physical mechanisms responsible for the essential difference lie in the fact that the quantum interferences have different effects on CPT in the two systems. For the V system, it is quantum interference that leads to CPT. For the Λ system, however, CPT is induced simply by the coherent excitation but quantum interference tends to destroy CPT.

References

[1] Arimondo E 1996 *Prog. Opt.* ed Wolf E (Amsterdam: Elsevier) vol 35 p 257
[2] Gao J Y et al 2000 *Phys. Rev.* A **61** 023401
[3] Harris S E 1997 *Phys. Today* **50**(7) 36
Marangos J P 1998 *J. Mod. Opt.* **45** 471
[4] Tu X H et al 2003 *Chin. Phys. Lett.* **20** 1954
Zuo Z C et al 2005 *Chin. Phys. Lett.* **22** 1664
Xiao F et al 2003 *Chin. Phys. Lett.* **20** 1257
[5] Kocharovskaya O 1992 *Phys. Rep.* **219** 175
Scully M O 1992 *Phys. Rep.* **219** 191
[6] Mandel P 1994 *Contemp. Phys.* **34** 235
Mompart J and Corbalan R 2000 *J. Opt.* B **2** R7
[7] Schmidt H and Imamoglu A 1996 *Opt. Lett.* **21** 1936
Wang H, Goorsky D and Xiao M *Phys. Rev. Lett.* **87** 073601
Wu J H et al 2005 *Phys. Rev. Lett.* **95** 057401
[8] Wu Y and Deng L 2004 *Phys. Rev. Lett.* **93** 143904
Yang X X, Wu X and Wu Y 2005 *Chin. Phys. Lett.* **22** 2816
[9] Zhu S Y and Scully M O 1996 *Phys. Rev. Lett.* **76** 388
Zhang H Z, Tang S H and He J 2002 *Phys. Rev.* A **65** 063802
[10] Hu X M, Shi W X, Xu Q, Guo H J, Li J Y and Li X X 2006 *Phys. Lett.* A **352** 543
Hu X M, Xu Q, Li J Y, Li X X, Shi W X and Zhang X 2006 *Opt. Commun.* **260** 196
[11] Swain S, Zhou P and Fick Z 2000 *Phys. Rev.* A **61** 043410
[12] Cardimona D A, Raymer M G and Stroud C R Jr 1982 *J. Phys.* B **15** 55
[13] Javanainen J 1992 *Europhys. Lett.* **17** 407
[14] Fleischhauer M, Keitel C H, Narducci L M, Scully M O, Zhu S Y and Zubairy M S 1992 *Opt. Commun.* **94** 599
[15] Hu X M and Peng J S 2000 *J. Phys.* B **33** 921
[16] Ficek Z and Swain S 2004 *Phys. Rev.* A **69** 023401
[17] Scully M O and Zubairy M S 1997 *Quantum Opt.* (Cambridge: Cambridge University Press) p 250
[18] Lax M 1968 *Phys. Rev.* **172** 350