Physics Letters A 377 (2013) 200–205

Contents lists available at SciVerse ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Interference-assisted squeezing in fluorescence radiation

R. Arun

Department of Physics, Faculty of Engineering & Technology, SRM University, Kattankulathur 603 203, Tamilnadu, India

A R T I C L E   I N F O

Article history:
Received 24 July 2012
Received in revised form 13 October 2012
Accepted 7 November 2012
Available online 9 November 2012
Communicated by P.R. Holland

Keywords:
Resonance fluorescence
Squeezing
Quantum interference

A B S T R A C T

The squeezing spectrum of the resonance fluorescence is studied for a coherently driven four-level atom in the Y-type configuration. It is found that the squeezing properties of the fluorescence radiation are modified significantly when quantum interference of the spontaneous decays channels is included. We show a considerable enhancement of steady-state squeezing in spectral components for strong and off-resonant driving fields. The squeezing may be increased in both the inner and outer sidebands of the spectrum depending upon the choice of parameters. We also show that the interference can degrade the spectral squeezing by increasing the decay rates of atomic transitions. An analytical description using dressed states is provided to explain the numerical results.

1. Introduction

Squeezing of the radiation field is one of the distinct features of the quantum theory of light [1,2]. Squeezed states of light, being nonclassical in origin [3], have a reduced variance in one of the quadrature components of the electric field. It is well known that the resonance fluorescence from a driven atomic system can serve as a source of squeezed radiation. Theoretical investigations on two-level and three-level atoms demonstrated squeezing either in the total variance of phase quadratures or in the frequency (spectral) components of the fluorescence radiation [4–11]. For a driven two-level atom, Walls and Zöller first predicted that squeezing can occur in the in-phase/out-of-phase quadrature component of the fluorescent light [4a]. The noise spectrum was shown to exhibit single- and two-mode squeezing in the weak- and strong-excitation regimes [5,6]. Some experimental evidences of squeezing have also been reported in the phase-dependent spectra of two-level atoms [7]. Unlike in two-level systems, two-photon coherences play a significant role in the dynamics of three-level atoms driven by coherent fields [8,9]. Dalton et al. examined the role of atomic coherences and studied the maximum squeezing that can be obtained in the fluorescence from three-level systems [9]. A detailed study by Gao et al. [10,11] has shown that ultranarrow squeezing peaks may appear in the spectrum of driven three-level atoms in Ξ- and V-type configurations. However, the role of two-photon coherence is seen to destroy the spectral-component squeezing in the fluorescent field [10].

One of the interesting developments in the study of resonance fluorescence is the possibility of modifying spectral properties of the atoms via quantum interferences in spontaneous decay channels. The interference in spontaneous emission occurs when the atomic transitions are coupled by same vacuum modes. The early work of Agarwal on this subject demonstrated population trapping and generation of quantum coherence between the excited states in a V-type atom [12]. Since the fluorescence properties of a driven atomic system result from its spontaneous emission, studying the influence of interference in such processes has become an important topic of research [13–18]. Much attention has been paid to study the fluorescence spectrum of driven atoms [13–15]. All these theoretical studies assume non-orthogonal dipole moments of the atomic transitions for the interference to exist in decay processes [12]. However, in real atomic systems, it is difficult to meet this condition. Different schemes were later proposed to bypass the condition of non-orthogonal dipole moments [19–21]. Experimentally, coherence between the ground states arising from spontaneous emissions has been reported using electron spin polarization states in quantum dots [20] and Zeeman sub-levels in atomic systems [21].

The squeezing characteristics of the emitted fluorescent light was also discussed extensively [16–18]. In a three-level V-type atom interacting with a coherent field, the interference is shown to enhance the spectral-component squeezing in the presence of standard/squeezed vacuum [16]. Li et al. studied the squeezing spectrum of a four-level atom in the Λ-type scheme and showed that unusual squeezing properties appear due to interference if the fluorescent field is detected on the slow decaying transition [17]. Further, Gonzalo et al. have examined a driven three-level atom

E-mail address: r.arun74@gmail.com.

0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2012.11.021

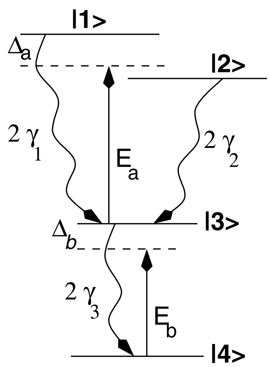

Fig. 1. The level scheme of the Y-type atom driven by coherent fields.

of the Λ configuration with particular attention to the squeezing in spectral components [18]. Recently, the effects of spontaneously generated interferences have been investigated in the context of enhancing self-Kerr nonlinearity [22], soliton formation [23], and preserving bi-partite entanglement [24].

In this Letter, we consider a four-level atom in the Y-type configuration interacting with two coherent fields (as shown in Fig. 1). The excited atomic states are assumed to be near degenerate and decay spontaneously via the same vacuum modes to the intermediate state. The atom in the intermediate state can make spontaneous transitions to the ground state. Since the cascade decays from the excited atomic states lead to an emission of the same pair of photons, quantum interference exists in decay processes. The role of the interference was investigated in the fluorescence spectrum of this system in Ref. [15]. In the present work, we study the squeezing spectrum and examine the interference effects on squeezing properties of the fluorescence fields.

The Letter is arranged as follows. In Section 2, we present the atomic density matrix equations, describing the interaction of a Y-type atom with two coherent fields, when the presence of quantum interference in decay channels is included. The formula for the squeezing spectrum is then derived using atomic correlation operators in Section 3. In Section 4, we analyze the numerical results of the squeezing spectrum and identify the origin of interference effects using the dressed-state picture. Finally, the main results are summarized in Section 5.

2. Driven Y-type atomic system and its density matrix equations

We consider a four-level atom in the Y-type configuration as shown in Fig. 1. In this scheme, the atom has two closely lying excited states $|1\rangle$ and $|2\rangle$ with energy separation $\hbar W_{12}$. It is assumed that the excited atomic states are coupled by common vacuum modes to decay spontaneously to the intermediate state $|3\rangle$ with rates $2\gamma_1$ and $2\gamma_2$. The atom in the intermediate state $|3\rangle$ is further allowed to undergo spontaneous emissions to the ground state $|4\rangle$ with decay rate $2\gamma_3$. The direct transitions between the excited states $|1\rangle \to |2\rangle$ and that between the excited and ground states $|1\rangle, |2\rangle \to |4\rangle$ of the atom are forbidden in the dipole approximation. We assume that the transition frequencies $(\omega_{13}, \omega_{23})$ of the upper transitions differ widely from that of the lower transition (ω_{34}). This leads to a situation in which the vacuum modes coupling the upper and lower atomic transitions are totally different. In addition to spontaneous decays, two coherent fields are applied on the atom as shown schematically in Fig. 1. The upper transitions $|1\rangle, |2\rangle \leftrightarrow |3\rangle$ are driven by a coherent field of frequency ω_a (amplitude E_a) and another field of frequency ω_b (amplitude E_b) couples the lower transition $|3\rangle \leftrightarrow |4\rangle$. The Rabi frequencies of the atom-field interaction are denoted as $\Omega_1 = \vec{\mu}_{13}.\vec{E}_a/\hbar$, $\Omega_2 = \vec{\mu}_{23}.\vec{E}_a/\hbar$, and $\Omega_3 = \vec{\mu}_{34}.\vec{E}_b/\hbar$ with $\vec{\mu}_{mn}$ being the dipole moment of the atomic transition from $|m\rangle$ to $|n\rangle$.

The system is studied in the interaction picture using time independent Hamiltonian

$$H_I = \hbar(\Delta_a + \Delta_b)A_{11} + \hbar(\Delta_a + \Delta_b - W_{12})A_{22} + \hbar\Delta_b A_{33} - \hbar(\Omega_1 A_{13} + \Omega_2 A_{23} + \text{H.c.}) - \hbar(\Omega_3 A_{34} + \text{H.c.}). \tag{1}$$

Here, the operators $A_{mn} = |m\rangle\langle n|$ represent the atomic population operators for $m = n$ and transition operators for $m \neq n$. To include decay processes in the dynamics, we use the master equation framework. With the inclusion of the decay terms, the time evolution of the density matrix elements in the interaction picture obeys [15]

$$\dot{\rho}_{11} = -2\gamma_1\rho_{11} + i\Omega_1(\rho_{31} - \rho_{13}) - p\sqrt{\gamma_1\gamma_2}(\rho_{12} + \rho_{21}), \tag{2}$$

$$\dot{\rho}_{22} = -2\gamma_2\rho_{22} + i\Omega_2(\rho_{32} - \rho_{23}) - p\sqrt{\gamma_1\gamma_2}(\rho_{12} + \rho_{21}), \tag{3}$$

$$\dot{\rho}_{33} = 2\gamma_1\rho_{11} + 2\gamma_2\rho_{22} - 2\gamma_3\rho_{33} + i\Omega_1(\rho_{13} - \rho_{31}) + i\Omega_2(\rho_{23} - \rho_{32}) + i\Omega_3(\rho_{43} - \rho_{34}) + 2p\sqrt{\gamma_1\gamma_2}(\rho_{12} + \rho_{21}), \tag{4}$$

$$\dot{\rho}_{12} = -(\gamma_1 + \gamma_2 + iW_{12})\rho_{12} + i\Omega_1\rho_{32} - i\Omega_2\rho_{13} - p\sqrt{\gamma_1\gamma_2}(\rho_{11} + \rho_{22}), \tag{5}$$

$$\dot{\rho}_{13} = -(\gamma_1 + \gamma_3 + i\Delta_a)\rho_{13} + i\Omega_1(\rho_{33} - \rho_{11}) - i\Omega_2\rho_{12} - i\Omega_3\rho_{14} - p\sqrt{\gamma_1\gamma_2}\rho_{23}, \tag{6}$$

$$\dot{\rho}_{23} = -\big[\gamma_2 + \gamma_3 + i(\Delta_a - W_{12})\big]\rho_{23} + i\Omega_2(\rho_{33} - \rho_{22}) - i\Omega_1\rho_{21} - i\Omega_3\rho_{24} - p\sqrt{\gamma_1\gamma_2}\rho_{13}, \tag{7}$$

$$\dot{\rho}_{34} = -(\gamma_3 + i\Delta_b)\rho_{34} + i\Omega_3(\rho_{44} - \rho_{33}) + i\Omega_1\rho_{14} + i\Omega_2\rho_{24}, \tag{8}$$

$$\dot{\rho}_{14} = -\big[\gamma_1 + i(\Delta_a + \Delta_b)\big]\rho_{14} + i\Omega_1\rho_{34} - i\Omega_3\rho_{13} - p\sqrt{\gamma_1\gamma_2}\rho_{24}, \tag{9}$$

$$\dot{\rho}_{24} = -\big[\gamma_2 + i(\Delta_a + \Delta_b - W_{12})\big]\rho_{24} + i\Omega_2\rho_{34} - i\Omega_3\rho_{23} - p\sqrt{\gamma_1\gamma_2}\rho_{14}. \tag{10}$$

Here, $\Delta_a = \omega_{13} - \omega_a$ corresponds to the detuning between the atomic frequency (ω_{13}) of the $|1\rangle \to |3\rangle$ transition and the frequency of the applied field E_a. Similarly, $\Delta_b = \omega_{34} - \omega_b$ denotes the detuning of the field acting on the lower transition. In writing Eqs. (2)–(10), we have assumed that the trace condition $\rho_{11} + \rho_{22} + \rho_{33} + \rho_{44} = 1$ is satisfied. The cross-coupling term $p \equiv \vec{\mu}_{13}.\vec{\mu}_{23}/|\vec{\mu}_{13}||\vec{\mu}_{23}|$ is referred to as the interference parameter. This term arises due to the quantum interference in spontaneous emission pathways. The effect of interference is to couple the populations and coherences as seen in Eqs. (2)–(10). It reflects the fact that population can be transferred between the excited states by the vacuum field. When $p = \pm 1$, the decays from the excited states $|1\rangle$ and $|2\rangle$ are coupled and the interference effects are maximal. If the atomic dipole moments are orthogonal $(p = 0)$, there is no interference effect in spontaneous emission.

For convenience in the calculation of the squeezing spectrum, we rewrite the density matrix equations (2)–(10) in a more compact matrix form by the definition

$$\hat{\Psi} = (\rho_{11}, \rho_{22}, \rho_{33}, \rho_{12}, \rho_{13}, \rho_{23}, \rho_{14}, \rho_{24}, \rho_{34}, \rho_{21}, \rho_{31}, \rho_{32}, \rho_{41}, \rho_{42}, \rho_{43})^T. \tag{11}$$

Substituting Eq. (11) into Eqs. (2)–(10), we get the matrix equation for the variables $\hat{\Psi}_j(t)$