Absorption spectrum of a V-type three-level atom driven by a coherent field

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We examine the absorption of a weak probe beam by a laser driven V-type atom with a pair of closely lying excited levels, where both the driving and probe lasers interact simultaneously with the two transitions. The effects of quantum interference among decay channels on the absorption spectra are also investigated. We introduce dipole moments in the dressed-state representation and the Hamiltonian in terms of the dressed states describing the interaction between the probe and the atom. In the degenerate case, features similar to that of a driven two-level atomic system are found due to some dark transitions in the spontaneous emission and the fact that the probe beam only detects certain transitions. In the nondegenerate case, the absorption spectrum is strongly influenced by the degree of quantum interference, resulting in different line shapes for emission peaks, absorption peaks, and dispersionlike profiles. The effect of probe polarization on the absorption spectrum is also investigated.

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I. INTRODUCTION

The absorption properties of a weak probe beam in a two-level atom driven by an intense pump field has been calculated by Mollow [1] in 1972 and observed a few years later [2]. The dispersionlike behavior and the possibility of amplification of the probe field can be demonstrated and be understood in terms of dressed states [3]. In the Autler-Townes effect, the transition from one of the two levels connected by the strong field to a third level is probed [4]. The absorption spectra exhibit two absorption components, known as the Autler-Townes components. This Autler-Townes absorption doublet can also be related to the dressed states. Various experiments in gases [5] and in solid-state systems [6] have confirmed the presence of such effects.

In recent years, absorption, stimulated emission, and spontaneous emission processes subject to quantum interference resulting from different transition processes have been of considerable interest. A good example studied intensively is the basic V system consisting of two close levels coupled by the same vacuum modes to another lower state. In this system, quantum interference results from the cross coupling between two indistinguishable decay channels. The interference effects associated with this model lead to many remarkable phenomena, including quantum-beat effect [7], population trapping in a degenerate system [8], very narrow absorption and fluorescence spectra [9–11], fluorescence quenching in the free space [12], phase-dependent line shapes [13], lasing without inversion [14,10,15], and others [16,17].

An interesting experimental demonstration of such quantum interference was reported in sodium dimers by Xia and co-workers [18]. In this experiment, the fluorescent intensity as a function of the detuning of the driving field exhibited two-peak or three-peak features according to parallel or anti-parallel dipole moments. However, in a later paper it was reported that a repeat of the experiment had failed to observe the same features [19]. A detailed theoretical investigation of the experimental system showed that the number of peaks in the spectrum depends on the excitation processes [20]. This theoretical work demonstrated that Xia's experiment could be explained by the complex excitation process, which is composed of a two-step one-photon process and a one-step two-photon process. Even though the main theoretical effect predicted by Ref. [12] was not observed in Xia's experiment, this experiment nevertheless showed some interesting effects induced by the quantum interference between correlated decay transitions. The difficulty with this kind of experiment stems from the fact that the very existence of the vacuum-induced interference relies on the stringent condition that the dipole matrix moments for the two close states decaying to a common final state must be nonorthogonal. Several new methods to bypass this strict condition have been proposed [21,22]. For example, the two levels are mixed by applying static and electromagnetic fields so that the relevant dipole moments become nonorthogonal [21]. In a later paper [22], Agarwal demonstrated that the anisotropy of the vacuum of the electromagnetic field could lead to quantum interference among the decay channels of closely lying states even if the dipole matrix elements were orthogonal.

The absorption properties of the V system in the absence of any pump field have been investigated by several authors [10,23]. Here, the existence of quantum interference may lead to ultranarrow spectral lines, transparency, amplification without inversion, and reverse-saturated absorption. In addition, the absorption spectra of a probe beam for this system driven by a single coherent field have been studied by Menon and Agarwal [16] under the condition that the coherent field only drives *one* transition and a probe detects *another* transition. It was demonstrated that quantum interference leads to gain features instead of the usual absorption features in the Autler-Townes effect. In a later work, Ficek *et al.* [24]

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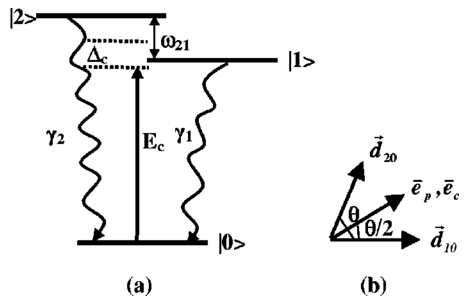

FIG. 1. (a) Energy scheme used in this paper. (b) The arrangement of field polarizations and dipole moments. θ is the angle between the two dipole moments. The polarization directions for both the probe and driving fields parallel to the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$.

showed that the gain of the probe is due to an unexpected amplification on a completely inverted, nondecaying transition. Similar absorption spectroscopy has also been studied in Ref. [15] where a strong field acts on *one* of the two transitions of the V-type system. In a more recent paper, Akram *et al.* [25] investigated the effect of quantum interference on the population distribution of the V-type atom driven by two lasers. The absorption properties of the weaker laser under the influence of the stronger laser were considered under different coupling configurations.

In this paper, the weak probe absorption in the same V-type atom is investigated under the condition that *both the driving field and the probe field interact simultaneously with two different arms of the* V system. Both degenerate and nondegenerate systems will be considered with or without the presence of quantum interference among decay channels. It is found that interestingly this model exhibits complex features. While most of the times it is similar to a laser-driven two-level system studied by Mollow [1], in some special cases, a nondecaying state among the dressed states may lead to surprising absorption and emission features. The outline of the paper is as follows. In Sec. II, we describe the model and the basic density-matrix equations. By utilizing the quantum-regression theorem, the steady-state probe absorption spectrum is obtained. In Sec. III, we introduce the dipole moments in the dressed-state representation and the Hamiltonian in terms of the dressed states describing the interaction between the probe and the atom. In Sec. IV, we analyze the absorption spectra in the degenerate V system and show that features similar to a driven two-level atomic system are found due to some dark transitions between the dressed states. In Sec. V, the absorption spectra in the nondegenerate V system are investigated in detail. Different line shapes, such as emission peaks, absorption peaks, and dispersionlike peaks can be exhibited for different degrees of quantum interference. In Sec. VI, we consider the absorption properties of this system when the probe polarization is tuned to a special direction. It is shown that the probe polarization can dramatically modify the structure of the absorption spectra. Finally, we give a summary.

II. THE ATOMIC MODEL AND SOLUTION FOR THE ABSORPTION

The atomic system considered in this paper is displayed in Fig. 1(a). We study a closed V-type three-level atom, where two close excited states $|1\rangle$ and $|2\rangle$ separated in frequency by ω_{21} decay to the ground state $|0\rangle$ with rates γ_1 and γ_2, respectively. $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$ are the dipole moments of the atomic transition from $|0\rangle$ to $|1\rangle$ and $|2\rangle$, respectively. It is seen that the cross coupling between the two transitions $|1\rangle - |0\rangle$ and $|2\rangle - |0\rangle$ gives rise to quantum-interference effect. The degree of quantum interference can be denoted by $p = \cos\theta$, where θ is the angle between the spontaneous emission dipole moments for the two decay channels $|1\rangle - |0\rangle$ and $|2\rangle - |0\rangle$. When $\theta \neq 90°$, interference between two spontaneous emission paths can arise. Maximal quantum interference is seen when the dipole moments are parallel or antiparallel, i.e., $p = \pm 1$. On the other hand, the system exhibits no interference effect when $p = 0$. We study the case where the two upper levels are coupled by a strong coherent field E_c with frequency ω_c. In the interaction picture, the resultant master equation for the reduced density operator ρ takes the form [10,16]

$$\dot{\rho}_{11} = -\gamma_1\rho_{11} - \frac{p}{2}\sqrt{\gamma_1\gamma_2}(\rho_{12}+\rho_{21}) + i\Omega_1(\rho_{10}-\rho_{01}), \tag{1}$$

$$\dot{\rho}_{22} = -\gamma_2\rho_{22} - \frac{p}{2}\sqrt{\gamma_1\gamma_2}(\rho_{12}+\rho_{21}) + i\Omega_2(\rho_{20}-\rho_{02}), \tag{2}$$

$$\dot{\rho}_{21} = -\frac{1}{2}(\gamma_1+\gamma_2+i2\omega_{21})\rho_{21} - \frac{p}{2}\sqrt{\gamma_1\gamma_2}(\rho_{11}+\rho_{22}) + i\Omega_1\rho_{20} - i\Omega_2\rho_{01}, \tag{3}$$

$$\dot{\rho}_{10} = -\left[\frac{\gamma_1}{2} + i\left(\Delta_c - \frac{\omega_{21}}{2}\right)\right]\rho_{10} - \frac{p}{2}\sqrt{\gamma_1\gamma_2}\rho_{20} + i\Omega_2\rho_{12} + i\Omega_1(\rho_{11}-\rho_{00}), \tag{4}$$

$$\dot{\rho}_{20} = -\left[\frac{\gamma_2}{2} + i\left(\Delta_c + \frac{\omega_{21}}{2}\right)\right]\rho_{20} - \frac{p}{2}\sqrt{\gamma_1\gamma_2}\rho_{10} + i\Omega_1\rho_{21} + i\Omega_2(\rho_{22}-\rho_{00}), \tag{5}$$

$$\rho_{00} + \rho_{11} + \rho_{22} = 1, \quad \rho_{ij}^* = \rho_{ji}. \tag{6}$$

In the above equations, $\Omega_i = E_c \mathbf{e}_c \cdot \mathbf{d}_{i0}$ ($i = 1,2$) denotes the Rabi frequencies of the driving field, E_c is the laser-field amplitude, Δ_c is the detuning between the frequency of the driving laser and the average atomic transition frequency $\omega_0 = (\omega_1 + \omega_2)/2$. The steady-state absorption spectrum $A(\Delta_p)$ for a weak, frequency-tunable probe beam is propor-

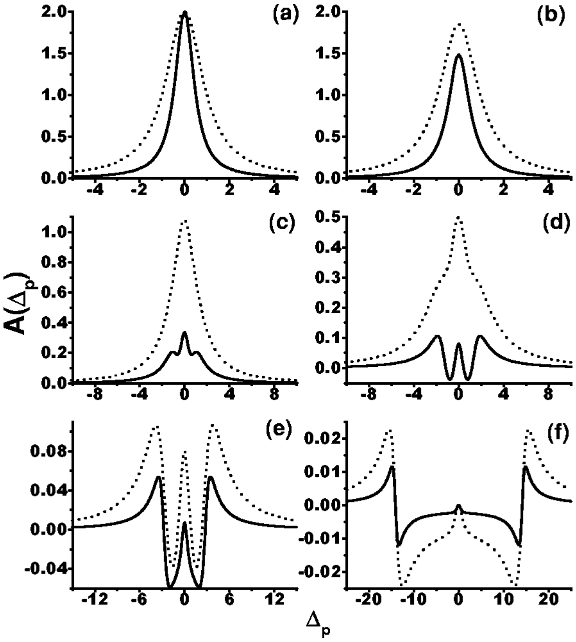

FIG. 2. Absorption spectra in the case of degenerate excited levels driven by a field with detuning $\Delta_c=0$. The atomic parameters employed are $\gamma_2=\gamma_1=1$; $\omega_{21}=0$. For the solid line, $p=0$. For the dashed line, $p=1$. (a) $\Omega_1=\Omega_2=\Omega=0$; (b) $\Omega_1=\Omega_2=\Omega=0.1$; (c) $\Omega_1=\Omega_2=\Omega=0.3$; (d) $\Omega_1=\Omega_2=\Omega=0.5$; (e) $\Omega_1=\Omega_2=\Omega=1$; (f) $\Omega_1=\Omega_2=\Omega=5$.

tional to the Fourier transform of the stationary average value of the two-time commutator of the atomic dipole operators [26]

$$A(\Delta_p)=\mathrm{Re}\int_0^\infty \lim_{t\to\infty}\langle[D(t+\tau),D^+(t)]\rangle e^{i(\Delta_p-\Delta_c)\tau}d\tau \quad (7)$$

where, Δ_p is the detuning between the probe frequency and the average atomic transition frequency $\omega_0=(\omega_1+\omega_2)/2$, and $D(t)=d_{10}|0\rangle\langle 1|+d_{20}|0\rangle\langle 2|$ is the component of the atomic polarization operator in the direction of the probe field polarization vector $\mathbf{e}_p$. We also have $d_{i0}=\mathbf{d}_{i0}\cdot\mathbf{e}_p$.

In order to evaluate the absorption spectra, we write the density matrix equations in the form

$$\frac{d}{dt}\Psi=L\Psi+I, \quad (8)$$

where

$$\Psi=(\rho_{11},\rho_{22},\rho_{21},\rho_{12},\rho_{10},\rho_{01},\rho_{20},\rho_{02})^T. \quad (9)$$

The matrix $\mathbf{L}$ has the form

$$\begin{pmatrix}
-\gamma_1 & 0 & -\frac{\gamma_{12}}{2} & -\frac{\gamma_{12}}{2} & i\Omega_1 & -i\Omega_1 & 0 & 0\\
0 & -\gamma_2 & -\frac{\gamma_{12}}{2} & -\frac{\gamma_{12}}{2} & 0 & 0 & i\Omega_2 & -i\Omega_2\\
-\frac{\gamma_{12}}{2} & -\frac{\gamma_{12}}{2} & -\frac{\gamma_1+\gamma_2+2i\omega_{21}}{2} & 0 & 0 & -i\Omega_2 & i\Omega_1 & 0\\
-\frac{\gamma_{12}}{2} & -\frac{\gamma_{12}}{2} & 0 & -\frac{\gamma_1+\gamma_2-2i\omega_{21}}{2} & i\Omega_2 & 0 & 0 & -i\Omega_1\\
2i\Omega_1 & i\Omega_1 & 0 & i\Omega_2 & -\left[\frac{\gamma_1}{2}+i\left(\Delta_c-\frac{\omega_{21}}{2}\right)\right] & 0 & -\frac{\gamma_{12}}{2} & 0\\
-2i\Omega_1 & -i\Omega_1 & -i\Omega_2 & 0 & 0 & -\left[\frac{\gamma_1}{2}-i\left(\Delta_c-\frac{\omega_{21}}{2}\right)\right] & 0 & -\frac{\gamma_{12}}{2}\\
i\Omega_2 & 2i\Omega_2 & i\Omega_1 & 0 & -\frac{\gamma_{12}}{2} & 0 & -\left[\frac{\gamma_2}{2}+i\left(\Delta_c+\frac{\omega_{21}}{2}\right)\right] & 0\\
-i\Omega_2 & -2i\Omega_2 & 0 & -i\Omega_1 & 0 & -\frac{\gamma_{12}}{2} & 0 & -\left[\frac{\gamma_2}{2}-i\left(\Delta_c+\frac{\omega_{21}}{2}\right)\right]
\end{pmatrix}, \quad (10)$$

where we have defined γ_{12} as $p\sqrt{\gamma_1\gamma_2}$. The matrix I can be written as

$$I=(0,0,0,0,-i\Omega_1,i\Omega_1,-i\Omega_2,i\Omega_2)^T. \tag{11}$$

Following the same procedure as described in Refs. [1,23,26], the steady-state probe absorption spectrum is obtained by using the quantum regression theorem. The result is

$$\begin{aligned}A(\Delta_p)=\mathrm{Re}\{&d_{10}^2[M_{55}(\overline{\rho_{00}}-\overline{\rho_{11}})+M_{51}\overline{\rho_{01}}\\&+M_{54}\overline{\rho_{02}}-M_{57}\overline{\rho_{21}}]+d_{20}^2[M_{77}(\overline{\rho_{00}}-\overline{\rho_{22}})+M_{72}\overline{\rho_{02}}\\&+M_{73}\overline{\rho_{01}}-M_{75}\overline{\rho_{12}}]+d_{10}d_{20}^*[M_{57}(\overline{\rho_{00}}-\overline{\rho_{22}})\\&+M_{52}\overline{\rho_{02}}+M_{53}\overline{\rho_{01}}-M_{55}\overline{\rho_{12}}]\\&+d_{10}^*d_{20}[M_{75}(\overline{\rho_{00}}-\overline{\rho_{11}})\\&+M_{71}\overline{\rho_{01}}+M_{74}\overline{\rho_{02}}-M_{77}\overline{\rho_{21}}]\},\end{aligned} \tag{12}$$

where $M_{ij}=[(z-L)^{-1}|_{z=i(\Delta_p-\Delta_c)}]_{ij}$, $\overline{\rho_{ii}}$ is the steady-state population of level $|i\rangle$ $(i=0,1,2)$, and $\overline{\rho_{ij}}$ $(i\neq j)$ are the steady-state atomic coherences.

Expression (12) is our basic result for the discussions to be followed. In order to study the steady-state behavior of this system, we set $\dot{\rho}_{ij}=0$ in Eq. (8) so that we obtain a 8×8 matrix equation. The steady-state populations and coherences can be obtained by solving numerically the matrix equation. All the absorption spectra presented in the following sections are obtained in this way.

III. DRESSED-ATOM MODEL

In the present and the following two sections, we align the polarization directions for both the driving field $\mathbf{e}_c$ and probe field $\mathbf{e}_p$ along the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$, as shown in Fig. 1(b). This arrangement of polarization implies that both the driving and probe fields interact with the two transitions with the same weights. We also assume the Rabi frequencies of the driving field are real. From the relation $\gamma_1/\gamma_2=(|\mathbf{d}_{10}|/|\mathbf{d}_{20}|)^2$, we arrive at the following relations: $\Omega_1/\Omega_2=\sqrt{\gamma_1/\gamma_2}$ and $d_{i0}=|\mathbf{d}_{i0}|\cos(\theta/2)=\sqrt{(1+p)/2}|\mathbf{d}_{i0}|$.

The Hamiltonian describing the interaction between the atom and the driving laser with frequency ω_c in the rotating frame is of the form

$$\begin{aligned}H_c=&\left(\Delta_c-\frac{\omega_{21}}{2}\right)|1\rangle\langle 1|+\left(\Delta_c+\frac{\omega_{21}}{2}\right)|2\rangle\langle 2|\\&+[(\Omega_1|1\rangle\langle 0|+\Omega_2|2\rangle\langle 0|)+\mathrm{H.c.}].\end{aligned} \tag{13}$$

Assuming the magnitudes of both dipole moments to be identical and the detuning of the coupling laser to be zero, we have $\gamma_1=\gamma_2=\gamma$ and $\Omega_1=\Omega_2=\Omega$. In this situation, the dressed states, as defined by the eigenvalue equation, $H_c|\alpha\rangle=\lambda_\alpha|\alpha\rangle$, are of the form [9]

$$\begin{aligned}|a,N\rangle=&\frac{1}{2}[-(1-\epsilon)|2,N-1\rangle-(1+\epsilon)|1,N-1\rangle\\&+4\eta|0,N\rangle],\\|b,N\rangle=&-2\eta|2,N-1\rangle+2\eta|1,N-1\rangle+\epsilon|0,N\rangle,\\|c,N\rangle=&\frac{1}{2}[(1+\epsilon)|2,N-1\rangle+(1-\epsilon)|1,N-1\rangle+4\eta|0,N\rangle],\end{aligned} \tag{14}$$

where

$$\Omega_R=\sqrt{\omega_{21}^2+8\Omega^2},\quad \eta=\frac{\Omega}{\Omega_R},\quad \epsilon=\frac{\omega_{21}}{\Omega_R}. \tag{15}$$

The eigenvalues according to above eigenstates are

$$\lambda_a=N\omega_c-\frac{1}{2}\Omega_R,\quad \lambda_b=N\omega_c,\quad \lambda_c=N\omega_c+\frac{1}{2}\Omega_R. \tag{16}$$

The dressed states expressed by Eq. (14) form an infinite ladder of nondegenerate three-state manifolds. Adjacent manifolds are separated by $\omega_0=(\omega_1+\omega_2)/2$. Inside a manifold, the states $|c\rangle$ and $|a\rangle$ are separated by $\frac{1}{2}\Omega_R$ and $-\frac{1}{2}\Omega_R$ from the state $|b\rangle$, respectively.

The atomic dipole moment in the dressed-state picture has matrix elements

$$\begin{aligned}\langle a,N+1|\mathbf{d}|a,N\rangle&=-\eta(1-\epsilon)\mathbf{d}_{20}-\eta(1+\epsilon)\mathbf{d}_{10},\\\langle a,N+1|\mathbf{d}|b,N\rangle&=-\tfrac{1}{2}\epsilon(1-\epsilon)\mathbf{d}_{20}-\tfrac{1}{2}\epsilon(1+\epsilon)\mathbf{d}_{10},\\\langle a,N+1|\mathbf{d}|c,N\rangle&=-\eta(1-\epsilon)\mathbf{d}_{20}-\eta(1+\epsilon)\mathbf{d}_{10},\\\langle b,N+1|\mathbf{d}|a,N\rangle&=-4\eta^2\mathbf{d}_{20}+4\eta^2\mathbf{d}_{10},\\\langle b,N+1|\mathbf{d}|b,N\rangle&=-2\eta\epsilon\mathbf{d}_{20}+2\eta\epsilon\mathbf{d}_{10},\\\langle b,N+1|\mathbf{d}|c,N\rangle&=-4\eta^2\mathbf{d}_{20}+4\eta^2\mathbf{d}_{10},\\\langle c,N+1|\mathbf{d}|a,N\rangle&=\eta(1+\epsilon)\mathbf{d}_{20}+\eta(1-\epsilon)\mathbf{d}_{10},\\\langle c,N+1|\mathbf{d}|b,N\rangle&=\tfrac{1}{2}\epsilon(1+\epsilon)\mathbf{d}_{20}+\tfrac{1}{2}\epsilon(1-\epsilon)\mathbf{d}_{10},\\\langle c,N+1|\mathbf{d}|c,N\rangle&=\eta(1+\epsilon)\mathbf{d}_{20}+\eta(1-\epsilon)\mathbf{d}_{10}.\end{aligned} \tag{17}$$

The above equations indicate that some of the matrix elements can be zero if $\mathbf{d}_{10}=\mathbf{d}_{20}$ or $\epsilon=0$. It is to be noted that when $\mathbf{d}_{10}=\mathbf{d}_{20}$, we get $p=1$ and accordingly the quantum interference is maximal [27].

It is to be noted that the interaction of the atom with the vacuum field allows *spontaneous emission* to occur from state $|i,N+1\rangle$ to state $|j,N\rangle$ only if $\langle i,N+1|\mathbf{d}|j,N\rangle\neq 0$. This is due to the fact that Hamiltonian H_V describing spontaneous emission from $|i,N+1\rangle$ to state $|j,N\rangle$ is [8]

$$H_V=\sum_{k,s}\hbar g_{ks}a_{ks}|i,N+1\rangle\langle j,N|+\mathrm{c.c.}, \tag{18}$$

$$g_{ks}=(2\pi ck/L^3\hbar)^{1/2}\langle i,N+1|\mathbf{d}|j,N\rangle\cdot\mathbf{e}_{ks}.$$

Here a_{ks} represents the annihilation operator for photon in mode $\mathbf{k}s$ and $\mathbf{e}_{ks}$ is its polarization vector. From the above equations, it is explicit that the Hamiltonian H_V would be zero if $\langle i,N+1|\mathbf{d}|j,N\rangle=0$. It will be demonstrated in following sections that we can directly predict the steady-state population in the dressed states by using the dipole moments introduced in Eqs. (17). Under a certain condition, trapping state can be found due to dark transitions from this state to the states in the lower manifold. However, the dark transition in the spontaneous emission does not imply that a probe beam is unable to detect this transition. In a recent paper, Ficek, Swain, and Akram have shown that the gain of a probe beam, predicted for the same V system [16], is due to an unexpected amplification on a completely inverted dark transition. Moreover, we are able to ascertain the transitions that can be detected by the probe beam from the interaction Hamiltonian between the atom and the probe field. If the direction of probe polarization is aligned parallel to the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$, the interaction Hamiltonian of the probe beam with the atom is given by

$$\begin{aligned}H_p&=\tfrac{1}{2}\mathbf{d}_{10}\cdot\mathbf{E}_p(e^{-i\omega_p t}|1\rangle\langle 0|+\text{H.c.})\\&\quad+\tfrac{1}{2}\mathbf{d}_{20}\cdot\mathbf{E}_p(e^{-i\omega_p t}|2\rangle\langle 0|+\text{H.c.})\\&=\tfrac{1}{2}\mathbf{d}_{10}\cdot\mathbf{E}_p[e^{-i\omega_p t}(|1\rangle+|2\rangle)\langle 0|+\text{H.c.}].\end{aligned}\tag{19}$$

From Eqs. (14), the superposition $|1\rangle+|2\rangle$ in the above equation can be written as

$$|1\rangle+|2\rangle=|c\rangle-|a\rangle.\tag{20}$$

The above equation indicates that the probe field can only be coupled to such transitions where the final states are either $|a\rangle$ or $|c\rangle$, but not $|b\rangle$. Besides, it is to be noted that the polarization direction of the probe determines the transitions that can be detected. As the polarization direction changes, different transitions can be probed with different weights. In fact, it is possible to have the state $|b\rangle$ as the final state by tuning the probe polarization. In the following two sections, we first study the case where the polarization direction for the probe field is parallel to the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$. Then, in order to show the contrasting effects of the probe polarization, the case resulting from different arrangement of the probe polarization will be studied in Sec. VI. The coupled transition to the probe field is altogether independent of the quantum-interference factor p (however, the coupling strength does depend on the factor of p). On the other hand, the dipole moments between dressed states are strongly dependent on p. Hence, the detected transition and the allowed spontaneous transitions may not be the same. This unusual phenomenon is certainly due to the effects of quantum interference.

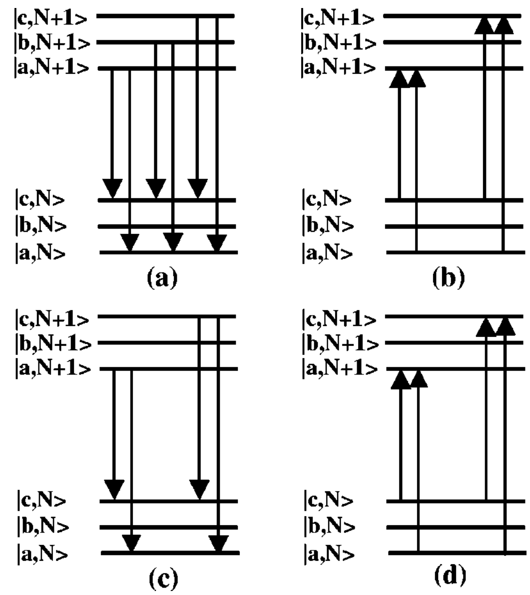

FIG. 3. Allowed spontaneous transitions [(a) and (c)] and detected transitions by the probe [(b) and (d)] between dressed states of two neighboring manifolds. The atomic parameters are $\gamma_2=\gamma_1=\gamma$; $\omega_{21}=0$. $\Delta_c=0$ and $\Omega_1=\Omega_2=\Omega$. For (a) and (b), $p=0$; for (c) and (d), $p=1$.

IV. THE CASE OF THE DEGENERATE EXCITED LEVELS

We first consider the case of the degenerate excited levels where $\omega_{21}=0$. When $p=0$, i.e., the quantum interference among the decay channels vanishes, the V system serves as two independent sets of two-level systems. Since both the coupling and probe beams interact with the two transitions $|1\rangle-|0\rangle$ and $|2\rangle-|0\rangle$ with the same weight, the pump-probe absorption spectrum is the sum of two independent Mollow-like absorption spectra of a driven two-level atom [1,2]. When $p=1$, both the resonance florescence [9] and absorption spectrum in the absence of driving field [10] of the V-type atom exhibit the features of a single transition but with a linewidth of $\gamma_1+\gamma_2$. Similar conclusions can be drawn from the absorption spectra shown in Fig. 2, where it is seen that the absorption spectra are similar to the conventional Mollow case. In the following discussion, we shall show that the dark (nondecaying) transitions between the dressed states are the source of such phenomenon.

In the case of degenerate excited levels, we have $\omega_{21}=0$ and hence $\epsilon=0$. The atomic dipole moment expressed by Eq. (17) has the following matrix elements:

$$\langle i,N+1|\mathbf{d}|b,N\rangle=0.\tag{21}$$

In Fig. 3(a), the allowed transitions between the dressed states are indicated by solid arrows. From Eq. (21), it is seen that the state $|b,N\rangle$ in a given manifold is not coupled to the states of the manifold above. Therefore, the state $|b,N\rangle$ cannot be populated by spontaneous emission from states $|i,N+1\rangle$ $(i=a,b,c)$ of a higher manifold. Furthermore, even if there is initially some population in state $|b,N\rangle$, it would have decayed to $|a,N-1\rangle$ or $|c,N-1\rangle$. Consequently, the population of $|b,N\rangle$ is zero under the steady-state condition. This conclusion is easily verified from the master equation in the dressed-states basis, the steady-state solutions of which have been presented in Ref. [9]. It is to be noted that Eq. (21) is not affected by the presence of quantum interference between the atomic transitions and thus the population of state $|b,N\rangle$ is zero, independent of the value of p.

In this case, the bare state $|0\rangle$ can be expressed in terms of dressed states

$$|0\rangle=\frac{1}{\sqrt{2}}|a\rangle+\frac{1}{\sqrt{2}}|c\rangle. \tag{22}$$

Upon substituting Eqs. (20) and (22) into Eq. (19), one can easily find that the interaction Hamiltonian of the probe beam and atom consists only of the transitions between the dressed states $|a\rangle$ and $|c\rangle$. In Fig. 3(b), we show the allowed transitions that the probe beam will detect.

Due to the zero population in state $|b,N\rangle$ and the fact that the absorption of a weak probe involves only the states $|a,N\rangle$ and $|c,N\rangle$, the absorption spectra of the weak probe resemble the Mollow spectrum of a driven two-level atom. In Fig. 2, we display the absorption spectra under the resonance driving condition, i.e., $\Delta_c=0$, for both $p=0$ and $p=1$. As expected, for case of $p=0$, the set of curves depicting the evolvement of the absorption spectra with the Rabi frequency of the driving field is similar to the case of driven two-level system [2]. However, the dispersionlike absorption on the sides of the spectra occurs at around $\sqrt{8}\Omega$ from the line center, instead of Ω as in the original Mollow case. This can be easily explained by the eigenvalues of the dressed states expressed by Eq. (16).

When the quantum interference is maximal, i.e., $p=1$, we have the following relations:

$$\langle b,N+1|\mathbf{d}|i,N\rangle=0,\ \ \langle i,N+1|\mathbf{d}|b,N\rangle=0. \tag{23}$$

It is seen that the dressed state $|b,N\rangle$ is totally decoupled from other states. There are four allowed transitions between the dressed states, as shown in Fig. 3(c), which is the same as original Mollow case of a driven two-level system. Therefore, from the view of the transitions between the dressed states, the absorption spectra under maximal interference are similar to the Mollow case. In addition, from Eq. (17) it is seen that the magnitudes of dipole moments between dressed states $|a\rangle$ and $|c\rangle$ attain maximal values when $\mathbf{d}_{20}$ is parallel to $\mathbf{d}_{10}$, namely, when $p=1$. As a result, the linewidth of the spectral lines is broadened by the presence of the quantum interference. For example, the linewidths of the central peak for $p=1$ in Figs. 2(a) and 2(b) are clearly larger than those for $p=0$.

In Fig. 4, we present the absorption spectra for the case of nonzero detuning of the driving field. When the detuning of the driving field is comparable to or larger than the natural linewidth, the spectra consist of one absorption component and one emission component at the Rabi sidebands and a small dispersionlike component at $\Delta_p=\Delta_c$. All these features are similar to the driven two-level system and the origins of this phenomenon have been well understood. In short, quantum interference just acts to broaden the linewidths in the absorption spectra.

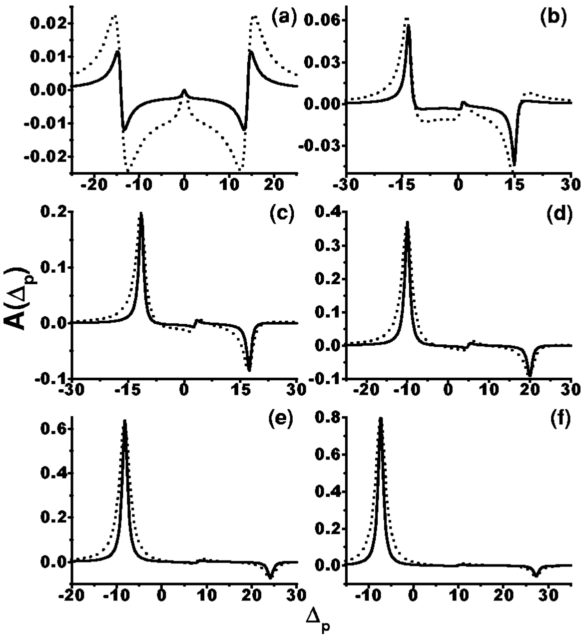

FIG. 4. Absorption spectra in the case of degenerate excited levels driven by a field with detuning $\Delta_c\neq 0$. The parameters employed are $\gamma_2=\gamma_1=1$; $\omega_{21}=0$; $\Omega_1=\Omega_2=\Omega=5$. For the solid line, $p=0$. For the dashed line, $p=0.99$. (a) $\Delta_c=0$; (b) $\Delta_c=1$; (c) $\Delta_c=3$; (d) $\Delta_c=5$; (e) $\Delta_c=8$; (f) $\Delta_c=10$.

V. THE CASE OF THE NONDEGENERATE EXCITED LEVELS

For the nondegenerate case, we study the absorption spectra with a resonant driving field, i.e., $\Delta_c=0$. Under this condition, the dressed states and their eigenvalues as well as the dipole moments between dressed states as expressed by Eqs. (14)–(17) are still valid. We plot in Fig. 5 the absorption spectra with a nonzero splitting of the excited doublet and different degrees of quantum interference. In Fig. 5(a), one finds that for $p=0$, the spectrum exhibits two dispersionlike

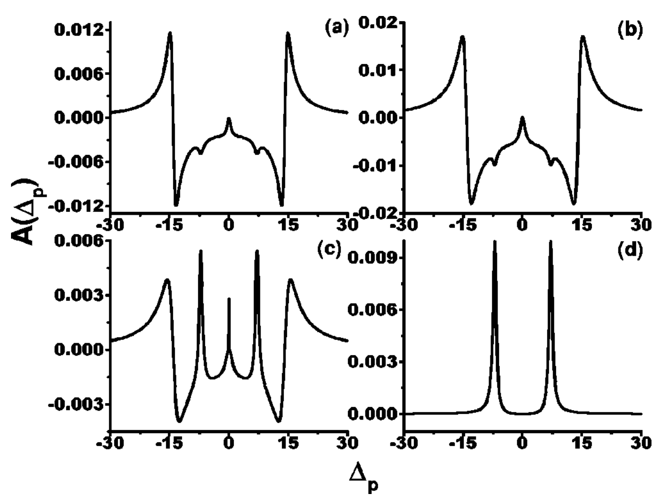

FIG. 5. Absorption spectra in the case of nondegenerate excited levels. The parameters employed are $\omega_{21}=1$; $\gamma_2=\gamma_1=1$; $\Omega_1=\Omega_2=\Omega=5$, $\Delta_c=0$. (a) $p=0$; (b) $p=0.5$; (c) $p=0.999$; (d) $p=1$.

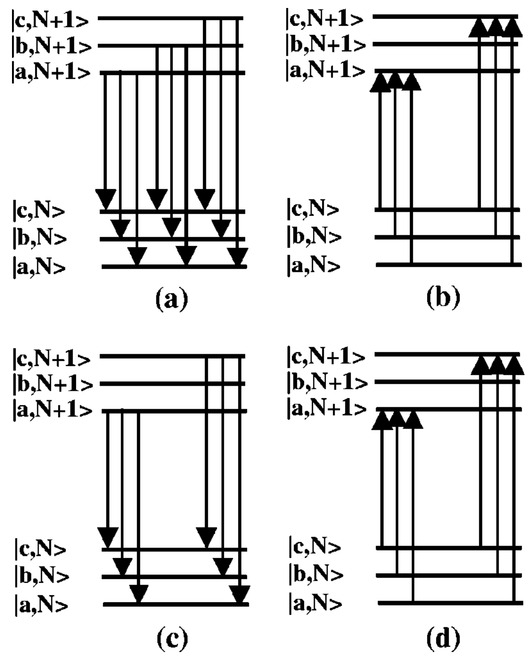

FIG. 6. Same as Fig. 3, but with $\omega_{21}\neq 0$. For (a) and (b), $p=0$; for (c) and (d), $p=1$.

lines in the far sidebands (the same as in the degenerate case) and two emission peaks in the near sidebands. When p increases, i.e., when quantum interference effect becomes more obvious, the two emission peaks evolve into absorption peaks, as seen in Figs. 5(c) and 5(d). Finally, the two dispersionlike lines disappear when the quantum interference is maximal, leaving only two absorption peaks located at $\pm\Omega_R/2$.

The above features can be understood in terms of the dipole moments between the dressed states and the interaction Hamiltonian described in Sec. III. We first consider the case when $p=0$. Under this condition, we see immediately that all the dipole matrix elements in Eq. (17) are nonzero. Therefore, the spontaneous emission can occur, in principle, for all possible transitions between the manifolds $N+1$ and N, as shown in Fig. 6(a). However, since ϵ is small when $\omega_{21}\ll\Omega_R$, the matrix elements $\langle i,N+1|\mathbf{d}|b,N\rangle$ have smaller values compared to other elements. It is thus expected that in the steady state the population of state $|b\rangle$, ρ_{bb}, is less than the populations in the states $|a\rangle$ or $|c\rangle$ (this conclusion can also be drawn from the analytical expression for ρ_{bb} derived in Ref. [9]). Therefore, it is possible to realize a population inversion between $|b,N\rangle$ and $|a,N+1\rangle$ or $|c,N+1\rangle$. When a probe beam detects the absorption properties of the driven three-level atom, the probe field is coupled to those transitions where the final state is either $|a,N\rangle$ or $|c,N\rangle$, as shown in Fig. 6(b). The transitions $|b,N\rangle-|i,N+1\rangle$ $(i=a,c)$ appear as emission peaks at the frequency $\pm\frac{1}{2}\Omega_R$ in the absorption spectra of the probe due to the population inversion. On the other hand, the transitions $|j,N\rangle-|i,N+1\rangle$ $(i,j=a,c)$ give rise to the conventional Mollow-like absorption spectra around the frequencies 0 and $\pm\Omega_R$.

We next consider the case when $p=1$. In this case, the absorption spectrum is dramatically modified by quantum interference. Because $\theta=0$, we have $\mathbf{d}_{10}=\mathbf{d}_{20}$. As a result, the following equations can be obtained;

$$\langle b,N+1|\mathbf{d}|i,N\rangle=0, \quad (i=a,b,c). \tag{24}$$

It is seen that the state $|b,N+1\rangle$ in a given manifold is not coupled to the states $|i,N\rangle$ of the manifold below, as shown in Fig. 6(c). As a result, this state is unable to lose its population by spontaneous emission. Consequently, the entire population is trapped in the dressed state $|b\rangle$, a conclusion which can also be easily proven by numerical calculation or by analytical expression of ρ_{bb} obtained in Ref. [9]. Due to this trapping state, fluorescence quenching has been predicted [9]. It is worth emphasizing that the florescence-quenching effect predicted by Zhu and Scully [12] can also be understood in terms of such dipole moments between the dressed states. When a probe beam detects such a trapping system, the detected transitions are $|i,N\rangle-|j,N+1\rangle$, where, $i=a,b,c$ and $j=a,c$. In Fig. 6(d), we show the detected transitions between the dressed states by the probe beam, which are the same as Fig. 6(b). However, because $\rho_{aa}=\rho_{cc}=0$, only two transitions are seen to dominate the absorption behavior, namely, the transitions $|b,N\rangle-|a,N+1\rangle$ and $|b,N\rangle-|c,N+1\rangle$. The other transitions, such as $|a,N\rangle-|c,N+1\rangle$, will not be visible in the absorption spectra because of zero population in both of the states $|a,N\rangle$ and $|c,N\rangle$. Since $\rho_{bb}-\rho_{ii}=1$, $(i=a,c)$, these two transitions give rise to two absorption peaks at the frequencies $\pm\Omega_R/2$, as shown in Fig. 5(d).

When p deviates from the maximal value of 1, the quantum interference is not complete for rendering $\rho_{bb}=1$. Subsequently $\rho_{aa}=\rho_{cc}\neq 0$. The situation is similar to the case of $p=0$, where there are two dispersionlike lines at the frequencies $\pm\Omega_R$. Around the frequencies $\pm\Omega_R/2$, either emission Lorentzian profiles [as in Fig. 5(b)] or absorption Lorentzian profiles [as in Fig. 5(c)] can appear, depending on the population difference between ρ_{bb} and ρ_{aa}.

The above properties of absorption are not restricted by the requirement that ω_{21} is comparable to or less than γ. In Fig. 7, we consider the case where $\omega_{21}=5\gamma$. Apparently, similar features can be found in Figs. 7 and 5. In Fig. 8, we show the absorption spectra with various Rabi frequencies of the driving field under the condition that $p=1$. It is seen that the splitting of the two absorptive Lorentzians becomes symmetrically larger with an increase in the Rabi frequency of the driving field, but the absorption magnitude becomes smaller. Here again, quantum interference has the dramatic effect to cause two absorption resonances to evolve into two other absorption resonances. As such phenomena occur only under maximal quantum interference, it is a useful indicator of the existence of such quantum interference in decay channels.

VI. PROBE POLARIZATION ON THE ABSORPTION SPECTRUM

In the preceding two sections, the absorption spectra have been studied under the assumption that the polarization direction of probe field is parallel to the direction bisecting the

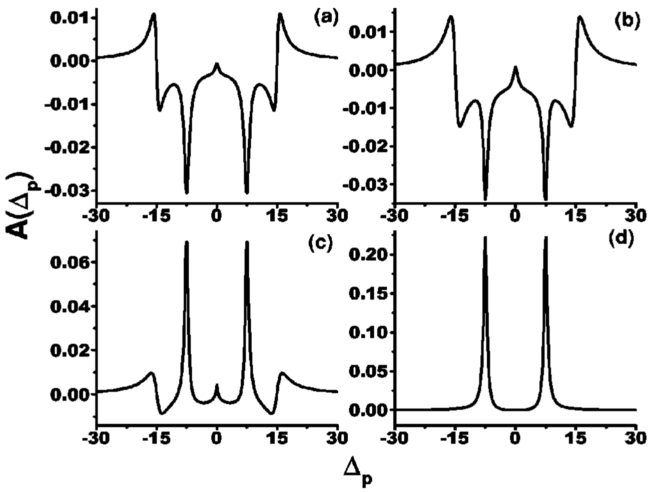

FIG. 7. Absorption spectra in the case of nondegenerate excited levels. The parameters employed are $\omega_{21}=5;\ \gamma_2=\gamma_1=1;\ \Omega_1=\Omega_2=\Omega=5,\ \Delta_c=0$. (a) $p=0$; (b) $p=0.5$; (c) $p=0.9$; (d) $p=1$.

angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$. Under this condition, Eq. (20) is satisfied and it forbids the final state of the transitions that the probe couples to be the state $|b\rangle$. As a result, the absorption spectra can be easily understood in terms of Figs. 3(b), 3(d) and Figs. 6(b), 6(d), which depict the allowed transitions that the probe detects. However, as the direction of probe polarization is tuned, the absorption spectra exhibit new features since the allowed transitions have been altered. In this section, another case is investigated to illustrate the effects of probe polarization on absorption spectra.

Consider the case that the polarization direction of the coupling laser is the same as that employed in the preceding three sections, but the direction of probe polarization is parallel to $\mathbf{d}_{10}$, we reach the following equations: $d_{10}=|\mathbf{d}_{10}|$ and $d_{20}=|\mathbf{d}_{20}|\cos(\theta)=p|\mathbf{d}_{20}|$. Substituting these two equations into Eq. (12) we obtain the absorption spectra for this case.

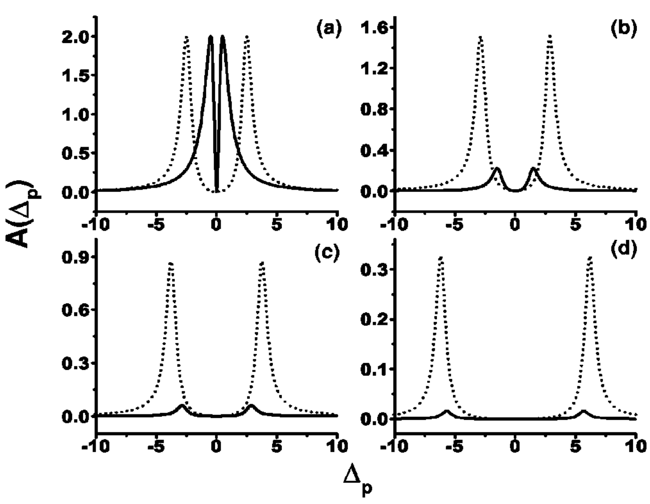

FIG. 8. Absorption spectra in the case of nondegenerate excited levels. The parameters employed are $p=1;\ \gamma_2=\gamma_1=1;\ \Delta_c=0$. For the solid line, $\omega_{21}=1$. For the dashed line, $\omega_{21}=5$. (a) $\Omega_1=\Omega_2=\Omega=0$; (b) $\Omega_1=\Omega_2=\Omega=1$; (c) $\Omega_1=\Omega_2=\Omega=2$; (d) $\Omega_1=\Omega_2=\Omega=4$.

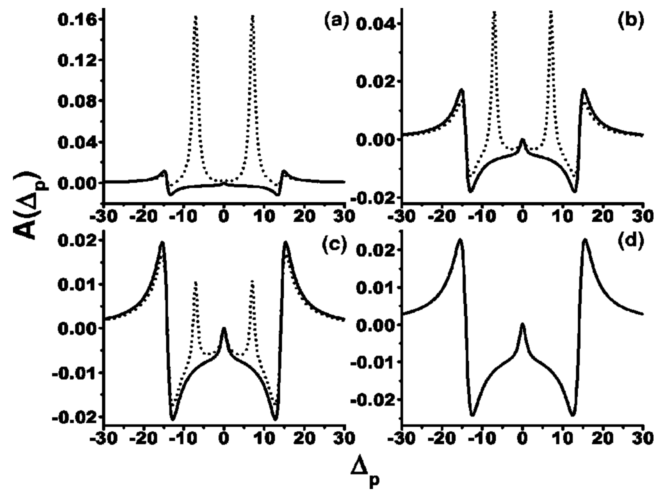

FIG. 9. Absorption spectra in the case of degenerate excited levels. The solid lines are according to the case where the probe polarization is parallel to the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$, while the dotted lines are according to the case where the probe polarization is parallel to $\mathbf{d}_{10}$. The parameters employed are $\gamma_2=\gamma_1=1;\ \omega_{21}=0;\ \Omega_1=\Omega_2=\Omega=5,\ \Delta_c=0$. (a) $p=0$; (b) $p=0.5$; (c) $p=0.7$; (d) $p=1$.

Typical spectra of a degenerate case are shown in Fig. 9. Compared to the spectra studied in the previous case, we see that as θ is far from 0, there are two absorptive profiles symmetrically located at the frequencies $\pm\Omega_R/2$ except the Mollow-like spectra at around the frequencies $\pm\Omega_R$ and 0. This is due to the fact that the transitions from $|a\rangle$ and $|c\rangle$ to $|b\rangle$ have become possible under this condition. Owing to the zero population of $|b\rangle$, these transitions give rise to two absorptive profiles. As p is equal to 1, these two peaks disappear because the zero θ makes no distinctions between this case and the one studied in Sec. IV.

The absorption spectra in the nondegenerate case are depicted in Fig. 10 where the same parameters as used in Fig. 7 are

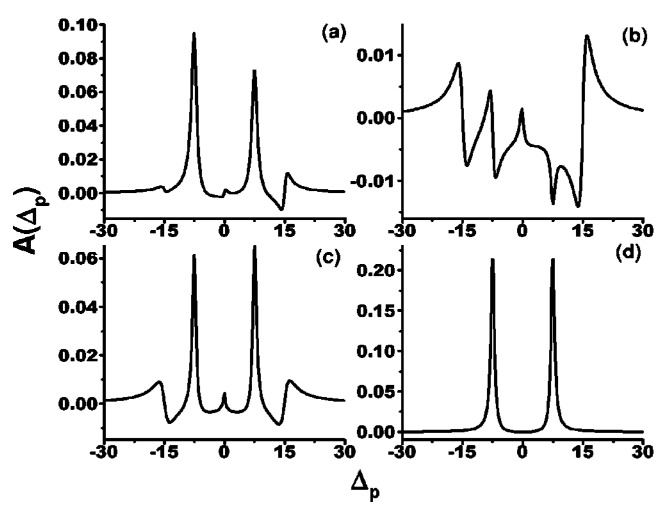

FIG. 10. Absorption spectra in the case of nondegenerate excited levels under the condition that the direction of probe polarization is parallel to $\mathbf{d}_{10}$. The parameters employed are the same as those in Fig. 7.

employed. Here, because the probe detects the transitions $|0\rangle-|1\rangle$ and $|0\rangle-|2\rangle$ with different weights, the absorption spectra exhibit asymmetry characteristics. Comparing Fig. 10(a) with Fig. 7(a), we see that the two emission peaks at frequencies $\pm\Omega_R/2$ become two absorption peaks. Obviously, the transitions from $|a\rangle$ and $|c\rangle$ to $|b\rangle$ produce these two absorption peaks. In contrast, when the direction of the probe polarization is parallel to the direction bisecting the angle subtended by $\mathbf{d}_{10}$ and $\mathbf{d}_{20}$, the state $|b\rangle$ cannot be the final state in the transitions that the probe detects and thus these two absorptive profiles do not appear.

It is to be noted that the probe polarization plays an important role only when θ is far from 0, namely, p is far from 1, which means the effect of quantum interference is not obvious. As the quantum interference becomes maximal, the probe polarization will not affect the structure of absorption spectra.

VII. CONCLUSION

We have investigated the absorption spectra for a weak probe in a V-type atom in the presence of a strong driving field. The effects of quantum interference among decay channels were also taken into account. Two distinct cases, according to the degenerate and nondegenerate excited levels, were studied. It is pointed out that the absorption spectra can be explained by introducing dipole moments and the Hamiltonian in terms of dressed states. Due to some dark transitions of spontaneous emission between dressed states, the population may be trapped or emptied in certain dressed state. In these processes, the effects of quantum interference play important roles. As a result, population inversion or noninversion between dressed states may take place. For the degenerate case, Mollow-like absorption spectra were exhibited, which can be understood by the fact that one of the three dressed states has zero population and does not involve in the absorption process. Furthermore, quantum interference only influences the linewidth of absorption lines but not the spectral structure. While in the nondegenerate case, the absorption spectrum is strongly dependent on the effect of quantum interference. In the absence of quantum interference, the absorption spectra exhibit Mollow-like spectra plus two emission peaks. When quantum interference is maximal, only two absorptive Lorentzian lines exist. It is interesting to note that under the influence of maximal quantum interference, the driving field can cause two absorption resonances to evolve into two other absorption resonances. Furthermore, the probe polarization has dominative effects on the absorption spectrum. By tuning the probe polarization, we can obtain different absorption spectra, which are in turn manifestations of different detected transitions.

The present paper has studied the properties of the dressed state of the V system with and without quantum interference between the decay channels when a strong coupling laser interacts simultaneously with the two transitions. In Ref. [9], the case of V system with near maximal quantum interference under a strong coupling field has been studied. However, that paper [9] was mainly a study of the fluorescence properties. There the resonance fluorescence is attributed to the spontaneous transitions between different dressed states in adjacent manifolds. The effect of quantum interference may suppress or cancel some possible dressed-state transitions. This also leads to possible fluorescence suppression in other similar four-level schemes [12], in which the core part consists of the three-level model driven by a coupling laser. Compared with the fluorescence, the absorption spectrum of a weak probe in the driven V system manifests more interesting effects since the detected transitions in the dressed picture by the probe can be controlled by means of the probe polarization. This detected transition can even be a dark transition in the spontaneous decay [24]. Nevertheless, the previous works [16,15,24] only investigated the absorption properties of the V system under the condition that the coupling laser only drive one-arm transition. In particular, when quantum interference is maximal or near maximal, it is difficult to realize experimentally the condition for one-arm driving. Very few papers have studied the absorption spectrum of the V system driven by a coupling laser interacting with both transitions. Only in Ref. [25], the authors studied the case where the coupling laser is coupled to both atomic transitions. However, most of the results of this paper, except those for the nondegenerate case under maximal quantum interference, are not obtained in Ref. [25].

The present paper hereby demonstrates that the correlation between decay channels will modify the population of the dressed states. This is typically induced by some dark transitions between the dressed states. As a probe detects the absorption property of this laser-driven system, the detected transitions can be controlled by probe polarization. Various spectra features, such as absorption and emission peaks or Mollow-like structure, can be obtained as the probe polarization is tuned.

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