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Effect of spontaneously generated coherence on absorption in a V-type system: Investigation in dressed states

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We investigate the spectrum of a four-level V-type system. We show that spontaneously generated coherence between the two closely spaced excited levels produces interference effects in the absorption. As a result, more transparency windows appear comparing to the normal three-level V system. We can also control the number of the transparency windows to be two or three just by tuning the Rabi frequency of the coupling field. We present an equivalent system without the rigorous requirement of close-lying levels to observe the phenomena. We also experimentally demonstrate the corresponding features in a rubidium atomic beam.

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I. INTRODUCTION

Recently, there has been much interest in a variety of new effects which have their origin in the phenomenon of quantum coherence. Examples are electromagnetically induced transparency (EIT) [1–4], lasing without inversion [5–7], light storage [8–10], enhancing Kerr nonlinearity [11], suppression [12,13], quenching and narrowing [14–21], and phase control of spontaneous emission [22,23]. We can distinctly distinguish two main mechanisms of generating quantum coherence. The first one is by applied coherent fields, such as laser fields [1–4] and microwave fields [24], and the other one is by incoherent processes such as spontaneous emission [25]. Here we are particularly interested in the latter case.

The coherence generated by the process of spontaneous emission is named spontaneously generated coherence (SGC), vacuum induced coherence (VIC), or decay induced coherence and has been intensively studied in recent years. In a system with SGC, we can find coherent effect without preparing it. Such as in [26], SGC can lead to loss-free propagation of a single, short laser pulse through an absorbing medium without the requirement of a second coupling laser pulse, and in [15] SGC can give rise to ultrasharp spectral lines in the resonance fluorescence of an atom excited by a single mode laser field. This type of coherence has attracted much attention and lies at the heart of many novel quantum phenomena [11–23]. A nice review can also be found in [27].

However, the very existence of SGC requires close-lying levels subject to the conditions that these levels are near degenerate and the corresponding dipole matrix elements are not orthogonal. It is very difficult, if not impossible, to find such a system in real atoms. Therefore, it is difficult to realize SGC experimentally in atomic systems. So far, most works on SGC discuss theoretical aspects of the problem without touching the practical side. In order to observe the phenomena based on SGC, a few methods have been proposed to simulate this intriguing effect. SGC can be simulated by a dc field [28], a microwave field [29], or a laser field [30–32]. Nevertheless, most works of this type are theoretic and need experimental verification.

Applying the method of simulating SGC with a laser field, we reported an experimental investigation of the absorption features in a four-level Λ system with SGC [33]. We showed that double transparency windows and a controllable narrow absorption peak can be obtained with the presence of SGC.

In this paper, we investigate the effect of SGC on the absorption features of a V system. Our investigation begins with a standard three-level V system. When one of the two upper levels is replaced by a pair of close-lying levels with SGC, the line shape of absorption changes a lot comparing to the normal case and more transparency windows appear. We can also control the number of the transparency windows to be two or three just by tuning the Rabi frequency of the coupling field. We find an equivalent system in ^{85}Rb atoms and experimentally demonstrate the phenomena in a rubidium atomic beam.

II. THEORETICAL ANALYSIS

Figure 1(a) shows a standard three-level V system. It consists of one ground level and two excited levels. The excited levels $|2\rangle$ and $|e\rangle$ decay to the ground state $|1\rangle$ with rates γ_{21} and γ_{e1}, respectively. The coupling field ω_c drives the transition of $|1\rangle$ to $|2\rangle$ with Rabi frequency Ω_c. The probe field ω_p probes the absorption from the ground state $|1\rangle$ to the

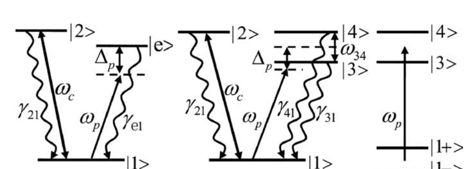

FIG. 1. (a) Schematic diagram of the three-level V system. (b) Schematic diagram of the four-level atomic system under consideration. (c) Corresponding dressed state representation of the four-level system.

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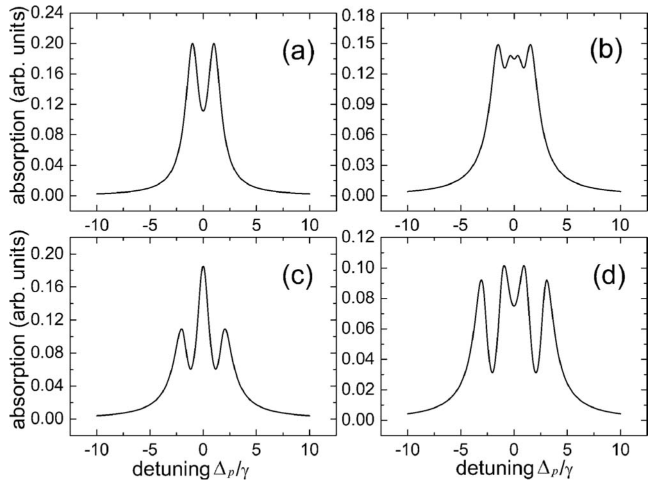

FIG. 2. (a) Standard V-type EIT. The Rabi frequency of the coupling field is $\Omega_c=\gamma$. (b)–(d) calculated absorption as a function of Δ_p with different Rabi frequencies of the coupling field. The Rabi frequencies are (b) $\Omega_c=0.6\gamma$, (c) $\Omega_c=\gamma$, and (d) $\Omega_c=2\gamma$. The other parameters are $\omega_{34}=2\gamma$, $\gamma_{21}=\gamma_{31}=\gamma_{41}=\gamma$.

excited state $|e\rangle$ with the corresponding Rabi frequency Ω_p. Figure 2(a) is the absorption spectrum of ω_p which shows a normal V-type EIT.

When the excited state $|e\rangle$ is replaced by a pair of close-lying levels $|3\rangle$ and $|4\rangle$, the system turns to be a four-level V configuration [see Fig. 1(b)]. It consists of one ground level and three excited levels. The excited level $|2\rangle$ decays to the ground state $|1\rangle$ with a rate γ_{21}. The two excited close-lying levels $|3\rangle$ and $|4\rangle$ are separated in frequency by ω_{34}. They decay to the ground state $|1\rangle$ with rates γ_{31} and γ_{41}, respectively. The probe field ω_p probes the absorption from the ground state $|1\rangle$ to the excited states $|3\rangle$ and $|4\rangle$ with the corresponding Rabi frequency Ω_p. The coupling field ω_c is tuned to be resonant with the transition of $|1\rangle$ to $|2\rangle$. The detuning of the probe field ω_p is defined as $\Delta_p=(\omega_{31}+\omega_{41})/2-\omega_p$. We assume $\gamma_{21}=\gamma_{31}=\gamma_{41}=\gamma$ and $\omega_{34}=2\gamma$. The SGC effect arises between the states $|3\rangle$ and $|4\rangle$ and is denoted by $\gamma_{34}=\sqrt{\gamma_{31}\gamma_{41}}/2=\gamma/2$.

By the standard approach of density-matrix equations, we calculate the absorption from $|1\rangle$ to $|3\rangle$ and $|4\rangle$ in the four-level system with SGC [see Fig. 1(b)]. Owing to the effects of SGC, the absorption spectrum changes dramatically. When Ω_c is relatively small, which means $\Omega_c<\omega_{34}/2$, the transparency becomes much weaker than the normal one, but the transparency window splits into three subwindows [see Fig. 2(b)]. In the case that Ω_c is comparable to $\omega_{34}/2$, we get two transparency windows with three absorption peaks and the peak in the middle is higher than the other two peaks [see Fig. 2(c)]. When $\Omega_c>\omega_{34}/2$, we get three transparency windows again [see Fig. 2(d)].

The origin of the line shapes can be easily seen in the dressed state representation of the coupling field ω_c [see Fig. 1(c)]. Due to the resonant coupling of the coupling field ω_c, the ground level $|1\rangle$ in Fig. 1(b) is split into two dressed sublevels, $|1+\rangle=(|1\rangle-|2\rangle)/\sqrt{2}$ and $|1-\rangle=(|1\rangle+|2\rangle)/\sqrt{2}$, whose energy separation is determined by $2\Omega_c$. There are four absorption peaks which can be attributed to the transitions from $|1-\rangle$ and $|1+\rangle$ to $|3\rangle$ and $|4\rangle$. In the case that the splitting between $|1-\rangle$ and $|1+\rangle$ is equal to that of $|3\rangle$ and $|4\rangle$, the transitions $|1-\rangle\rightarrow|3\rangle$ and $|1+\rangle\rightarrow|4\rangle$ are degenerate. As a result, the number of absorption peaks becomes three and the middle absorption peak is higher than the other two peaks. The effects of the coupling field and SGC induce destructive interferences between the transitions, so we see dips between the absorption peaks.

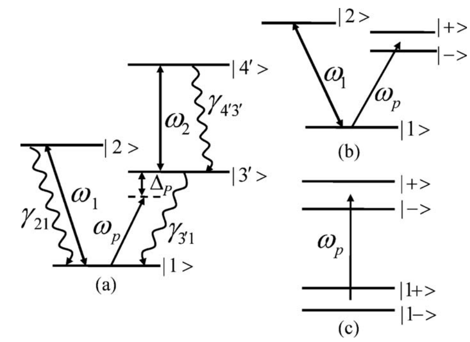

FIG. 3. (a) Schematic diagram of the experimental approachable atomic system under consideration. (b) Dressed state representation of ω_1. (c) Dressed state representation of ω_1 and ω_2.

We propose an experimental approachable scheme which consists of four levels interacting with two coupling fields [see Fig. 3(a)]. The ground level $|1\rangle$ interacts with the two excited levels $|2\rangle$ and $|3'\rangle$ by one of the coupling fields ω_1 and the probe field ω_p, respectively. The other coupling field ω_2 drives the transition of $|3'\rangle$ to $|4'\rangle$. We can analyze the system in the dressed state representation of ω_2. With the resonant coupling field ω_2, the level $|3'\rangle$ is split into two dressed sublevels, $|+\rangle=(|3'\rangle-|4'\rangle)/\sqrt{2}$ and $|-\rangle=(|3'\rangle+|4'\rangle)/\sqrt{2}$ [see Fig. 3(b)]. Similar to the case in [30] and [33], there exists an SGC effect between the states $|+\rangle$ and $|-\rangle$. The collaborate effects of SGC and the coupling field provide different absorption channels. Interference arising from these channels induces unusual spectral characteristics of absorption such as multitransparency windows. This system is obviously equivalent to the system with SGC [see Fig. 1(b)].

In the dressed state representation of both of the coupling fields ω_1 and ω_2, the system turns out to be a four-level case [see Fig. 3(c)] similar to that in Fig. 1(c). There are four transitions from the levels $|1+\rangle=(|1\rangle-|2\rangle)/\sqrt{2}$ and $|1-\rangle=(|1\rangle+|2\rangle)/\sqrt{2}$ to the levels $|+\rangle=(|3'\rangle-|4'\rangle)/\sqrt{2}$ and $|-\rangle=(|3'\rangle+|4'\rangle)/\sqrt{2}$. The space between the lower levels $|1+\rangle$ and $|1-\rangle$ is determined by the Rabi frequency of the coupling field ω_1, while the space between the upper levels $|+\rangle$ and $|-\rangle$ is determined by the Rabi frequency of the coupling field ω_2. By tuning these two Rabi frequencies, we can modify the spaces between the upper levels and between the lower levels, so that we can control the degeneracy of the transition $|1+\rangle$ to $|+\rangle$ and the transition $|1-\rangle$ to $|-\rangle$. In this way, we can switch the absorption spectrum of ω_p to be a three-peak structure and a four-peak structure.

We find the system proposed above in the hyperfine levels of ^{85}Rb [see Fig. 4(a)]. The ground state $|1\rangle$ is presented by $5S_{1/2}$, $F=3$. The excited levels $|2\rangle$, $|3'\rangle$, and $|4'\rangle$ are provided by $5P_{3/2}$, $F=4$; $5P_{1/2}$, $F=3$; and $5D_{3/2}$, $F=4$, respectively.

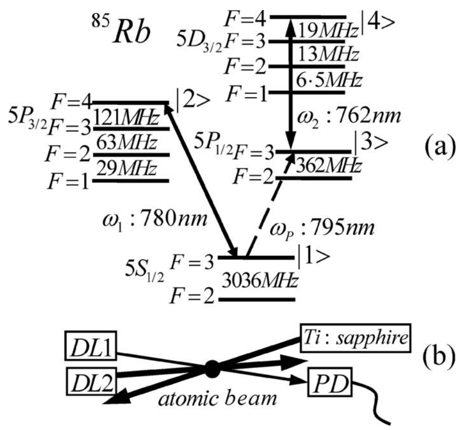

FIG. 4. (a) Energy-level scheme for ^{85}Rb. (b) Experimental setup. ω_p and ω_1 are generated by DL1 and DL2, respectively. PD is a photon diode detector.

The decay rates in Fig. 3(a) denote the radiative width of the excited states. It is reasonable to calculate them by the lifetimes of the excited states [34,35]. We get the following results: $\gamma_{21}=\gamma_{3'1}=6.0$ MHz and $\gamma_{4'3'}=0.8$ MHz.

III. EXPERIMENTAL SETUP

Our experimental setup is shown in Fig. 4(b). We carry out the experiment in a collimated rubidium atomic beam whose diameter is estimated to be 4 mm. The probe beam ω_p is provided by an extended cavity diode laser. It runs at the wavelength of 795 nm with the linewidth being 1 MHz. One of the two coupling fields ω_1 is provided by another extended cavity diode laser with the same linewidth. It runs at the wavelength of 780 nm and is frequency locked to the transition of $5S_{1/2}$, $F=3$ to $5P_{3/2}$, $F=4$. A Ti:sapphire ring cavity laser (Coherent 899 ring cavity laser system) with the linewidth of 0.5 MHz serves as the other coupling field ω_2. It works at the wavelength of 762 nm. The three laser beams are adjusted carefully to be orthogonal with the atomic beam.

The Doppler broadening in our atomic beam is much smaller than that in a rubidium cell which is about 600 MHz. But there remains a residual Doppler broadening, which is estimated to be 6–10 MHz, owing to the angular divergence of the atomic beam. To minimize the effect of this residual broadening, we make the coupling beam ω_2 propagate in the opposite direction of the other two beams. The three laser beams are nearly collinear with the angles smaller than 2° between each other. The small angles prevent the beam of the Ti:sapphire ring cavity laser from entering the diode lasers. We can also avoid the illumination of the coupling field ω_2 on the detector [PD in Fig. 4(b)] in such a configuration. We use attenuators to control the intensities of the three beams. The probe field ω_p, whose diameter at the interaction section is 1 mm, is attenuated to 1 μW. The coupling field ω_1, whose diameter at the interaction section is about 4 mm, is controlled to work at the power of 0–4 mW. The coupling field ω_2, whose diameter at the interaction section is about 6 mm, works at the power of 0–250 mW. We scan the probe beam near the transition of $5S_{1/2}$, $F=3$ to $5P_{1/2}$, $F=3$ at different Rabi frequencies of the two coupling fields, then record the absorption line shape. We show the experimental results of absorption in Fig. 5 with the solid lines. The horizontal axes are the detunings of the probe field to the transition of $5S_{1/2}$, $F=3$ to $5P_{1/2}$, $F=3$.

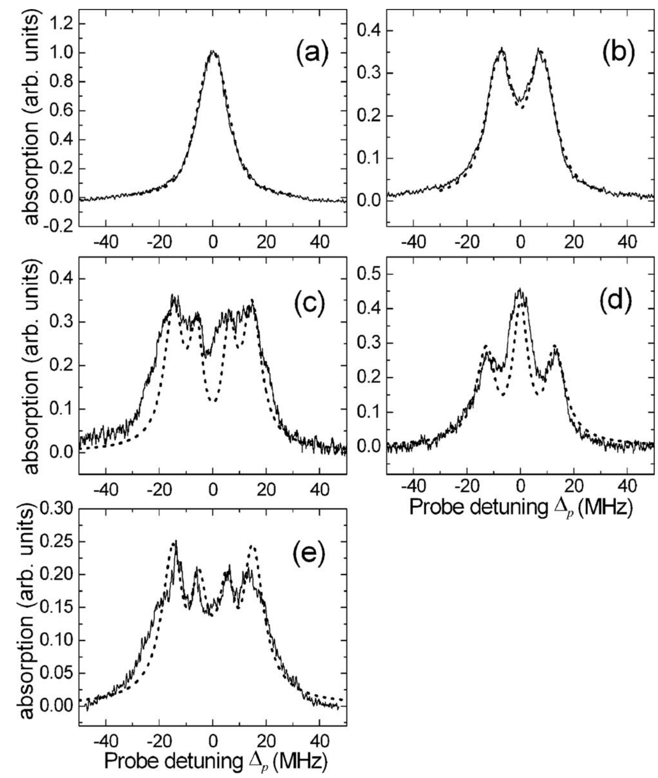

FIG. 5. Absorption spectra (arbitrary units) of the atomic beam for different Rabi frequencies of the two coupling fields. Solid curves are the experimental results; dotted curves are the theoretical simulation. (a) Without coupling field, (b) with coupling field ω_2 applied, $\Omega_c=6$ MHz. (b)–(d) With two coupling fields applied. The Rabi frequencies in megahertz are (c) $\Omega_1=4$, $\Omega_2=10$, (d) $\Omega_1=\Omega_2=6$, and (e) $\Omega_1=10$, $\Omega_2=4$.

IV. RESULTS AND DISCUSSIONS

When no coupling fields are applied, we get a standard absorption line shape of ^{85}Rb $5S_{1/2}, F=3 \rightarrow 5P_{1/2}, F=3$ [see Fig. 5(a)]. The full width at half maximum (FWHM), which is estimated to be 14 MHz, is broader than the 6 MHz natural width primarily because of residual Doppler broadening in the atomic beam and linewidth of the laser. When only the coupling field ω_1 is added, the line shape turns to be the case of V-type EIT [see Fig. 5(b)]. This is exactly what we predict in the three-level V system [see Fig. 2(a)].

In the case of applying two coupling fields, the line shape varies with the Rabi frequencies of the coupling fields Ω_1 and Ω_2. When $\Omega_1 < \Omega_2$, we see that the transparency becomes much weaker, but the transparency window splits into three subwindows [see Fig. 5(c)]. This situation is in accordance with the case of $\Omega_c < \omega_{34}/2$ in the system with SGC [see Fig. 2(b)]. Under the condition of $\Omega_1=\Omega_2$, we get two transparency windows and three absorption peaks. We see that the middle peak is much higher than the other two peaks on the sides [see Fig. 5(d)]. This situation corresponds to the case of $\Omega_c = \omega_{34}/2$ in the system with SGC [see Fig. 2(c)]. When $\Omega_1 > \Omega_2$, we get three transparency windows again [see Fig. 5(e)]. This situation corresponds to the case of $\Omega_c > \omega_{34}/2$ in the system with SGC [see Fig. 2(c)]. In this way, we demonstrate the absorption features predicted in the four-level V system with SGC [see Fig. 2].

The experimental results are in accordance with what we predict in the system with SGC. But they are not exactly the same. The main reason is that the theoretical results in the system with SGC are based on ideal atoms. In real atomic systems, Doppler broadening undoubtedly changes the absorption line shape. There are also effects from the linewidths of the lasers. We consider the residual Doppler broadening of the atomic beam in the one-dimensional case by neglecting the divergences of the three laser beams and make theoretical simulations including the above two effects. The calculated results are presented in dotted lines in Fig. 5.

The experimental results are in agreement with the theoretical simulations. But there are still differences between them, especially in the cases of two coupling fields. It is mainly because of the following five reasons. First, the separations between the hyperfine levels ^{85}Rb $5D_{3/2}, F=2,3,4$ are very small, so that there are effects induced by the levels ^{85}Rb $5D_{3/2}, F=2,3$. Second, we make the three laser beams propagate in small angles, so we cannot fully eliminate the Doppler effects. Third, we just consider a simple four-level system ignoring the magnetic sublevels. These reasons might make changes to the line shape. Fourth, the system is not closed. The upper level $5D_{3/2}$ decays to other levels such as $5P_{3/2}$, $6P_{1/2}$, and $6P_{3/2}$, for example. Fifth, the optical density is very small in the atomic beam. In the case of two coupling fields, the absorption becomes so weak that we have to average the results.

V. CONCLUSION

We have theoretically analyzed the absorption profile in a four-level V system. The SGC effect makes this system much different from a standard three-level system. In such a system with two close lying upper levels, the absorption line shape much depends on the relationship between the Rabi frequency of the coupling field and the separation between the two close lying levels. By tuning the Rabi frequency, we can control the transparency windows to be one, two, or three. We presented an equivalent four-level system without the rigorous requirement for SGC. We found this system in ^{85}Rb atoms and carried out the corresponding experiment in a rubidium atomic beam. We experimentally demonstrated the features of absorption predicted in the four-level V-type system with two close-lying upper levels. When only one coupling field is applied, there is only one transparency window. In the case of applying two coupling fields, when the Rabi frequencies of the two coupling fields are equal, there are two transparency windows with the middle absorption peak much higher than the other two peaks; when they are not equal, there are three transparency windows. In one word, we have demonstrated a few effects related to SGC in a four-level V system in the dressed states of ^{85}Rb atoms.

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