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Observation of spontaneously generated coherence on absorption in rubidium atomic beam

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ABSTRACT

We report the experimental observation of the effect of spontaneously generated coherence on absorption without the rigorous requirement of close-lying levels. The experiments are studied in both a four-level N-type and a four-level inverted-Y-type atomic system in a rubidium atomic beam. With the coupling and controlling field, the N-type system is equivalent to a system with three closely upper levels coupled to one lower level by the same vacuum modes. The quantum interference can induce two prominent and nearly transparent holes where the slope of the refractive index is very steep. This special situation could allow the simultaneous propagation of two weak pulses with different frequencies. When we tune the wavelength of the controlling field, the N-type system turns to be the inverted-Y atomic system. Under the two-photon resonance condition, the system is equivalent to a V-type system with two closely upper levels, and the interference can reduce one broad transparency window in the middle of the absorption spectrum. Besides we can control the number of the spontaneously decay channels by the detuning of the controlling field, thus the effect of spontaneously generated coherence can exist in three or two closely space levels.

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1. Introduction

Spontaneously generated coherence (SGC) refers to the interference of two or more decay channels with nonorthogonal electric-dipole transition matrix elements. It gives rise to a variety of novel quantum effects, such as lasing without inversion [1]; coherent population trapping [2] and transfer [3]; transparency of a short laser pulse [4]; cancellation and quenching [5]; narrowing [6] and squeezing [7] of spectrum of spontaneous emission; and phase sensitive line shapes [8]; quantum interference enhancement with left-handed materials [9] and plasmon-induced enhancement of quantum interference near metallic nanostructures [10].

However, it is very difficult to find a real atomic system with SGC to experimentally demonstrate these phenomena, for the existence of SGC requires two or more rigorous close-lying levels subject to the conditions that these levels are near degenerate and the corresponding dipole matrix elements are not orthogonal. The experiment in spontaneous emission from sodium dimers was reported few years ago [11]. However, another experiment [12] on a similar system failed to reproduce the same results. In order to observe the phenomena based on SGC in atomic systems without the near-degenerate levels, a few methods have been proposed to simulate this intriguing effect. Agarwal has suggested working in such situations where the vacuum of the electromagnetic field is anisotropic [13]. Ficek and Swain showed the simulation of SGC with the coupling of a DC field [14]. SGC has also been studied in dressed states of a microwave field [15], and a laser field [16]. But most works of this type are theoretic and have not been verified experimentally.

In this paper, we observe the effect of SGC on absorption spectrum without the rigorous requirement of close-lying levels. The experiments are studied in both a four-level N-type and a four-level inverted-Y system in a rubidium atomic beam. With a coupling field and a controlling field, the four-level N-type system is equivalent to a four-level system consists of three upper levels coupled by the same vacuum modes to the common ground level, which has been studied theoretically by Joshi et al.[17] and Antón et al. [18]. The presence of three possibilities of arriving at the ground state from the three excited levels can give rise to strong interference effects and can induce two prominent and nearly transparent windows where the slope of the refractive index is very steep, which has potential applications in the area of quantum memories [19] and slow light propagation and storage [20]. In a four-level inverted-Y system, under the two-photon resonance condition, there is a deep and broad transparency window due to the interference between the dressed levels, which is similar to the theoretical calculation of Ref [21]. And this system is similar to many other V-type systems with SGC [22], which can result in variety of novel quantum effects. And by changing the detuning of

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the controlling field, we can control the number of the decay channels, and the SGC effect can arises from two or three closely space levels.

The reasons we investigate the two types of systems together are as follows. First, we can study the two types in the same experimental setup and ^{85}Rb atom can be their concrete system. To switch the N-type system to inverted-Y system, we only need to change the wavelength of the controlling field, which is easy in our experimental setup. Second, we can observe the effect of SGC on absorption spectrum in both systems without the rigorous requirement of close-lying levels.

The paper is organized as follows. In Sec. 2, we give the level structure and laser coupling scheme for both systems and the schematic diagram of the experimental setup used in our experiment. In Sec. 3, we report the experiment of N-type system absorption with SGC. A theoretical calculation is given, and further more we give a dispersion spectrum which can be used in the area of slow light propagation. In Sec. 4, we present the experiment of inverted-Y system absorption with SGC. Then we give a theoretical calculation. In Section 5, we give a brief discussion and conclusions.

2. Schematic diagram of the experimental setup

We find both N-type and inverted-Y system in the hyperfine levels of ^{85}Rb. The level structure and laser coupling scheme for ^{85}Rb atoms used in our experiment are depicted in Fig. 1. The transition of $5S_{1/2}$, F=2→$5P_{1/2}$,F'=3 is coupled by the probe beam ω_p, which is provided by an extended cavity diode laser. And the laser runs at the wavelength of 795 nm and its linewidth is 1 MHz. The coupling field ω couples the transition of $5S_{1/2}$,F=3→$5P_{1/2}$,F'=3 and its Rabi frequency and detuning are Ω and Δ, respectively. The field$\omega$is provided by another extended cavity diode laser with the same linewidth and the wavelength. The controlling field ω' couples the transition of $5S_{1/2}$,F=3→$5P_{3/2}$,F'=4 for N-type system, or $5S_{1/2}$,F=3→$5D_{3/2}$,F'=4 for inverted-Y system. Its Rabi frequency and detuning are Ω' and Δ', respectively. It is provided by a coherent-899 Ti: sapphire laser working at the wavelength of 780 nm (N-type) or 762 nm (inverted-Y-type) with the linewidth of 0.5 MHz (In our experiment, it is easy to change the wavelength of coherent-899 Ti: sapphire laser). And the spontaneous decay rates of the states $5P_{1/2}$,F'=3, $5P_{3/2}$,F'=4 and $5D_{3/2}$,F'=4 are $2\pi*5.75$ MHz, $2\pi*6.06$ MHz and $2\pi*0.50$ MHz, respectively. The nonradiative decay rate between $5S_{1/2}$,F=2 and $5S_{1/2}$,F=3 is $2\pi*0.10$ MHz.

We carry out the experiment in a rubidium atomic beam to minimize the effect of Doppler broadening. The atom beam system is illustrated in Fig. 2(a). Rubidium sample is heated in a brass container to about 240 °C and jets rubidium atoms from the lower aperture. The atoms are collimated by the second aperture which is 20 cm above the lower one. The diameter of the two apertures is 2 mm.

A schematic for the experiment is shown in Fig. 2(b). The three laser beams are nearly collinear with the angles smaller than 2° between each other, which can avoid the illumination of the two coupling fields on the detector in such a configuration. In order to minimize the effect of the residual broadening, the three lasers are perpendicular to the atomic beam. And for N-type system we make these three laser beams propagate in the same direction, while, for inverted-Y system we make the controlling laser beam propagate in the opposite direction of the other two beams. In our experiment we can choose which line of the controlling field is used by half wave plate (λ/2WP 1) and polarization beam splitters (PBS). And we use other two half wave plate to make the polarization direction of the probe beam perpendicular to that of the coupling and controlling beams. The diameter at the interaction section of the probe field ω_p, coupling field ω and controlling field ω' are 1 mm, 4 mm and 6 mm, respectively. We scan the probe beam near the transition of $5S_{1/2}$,F=2→$5P_{1/2}$,F'=3 at different detuning of the two fields, and record the absorption line shape.

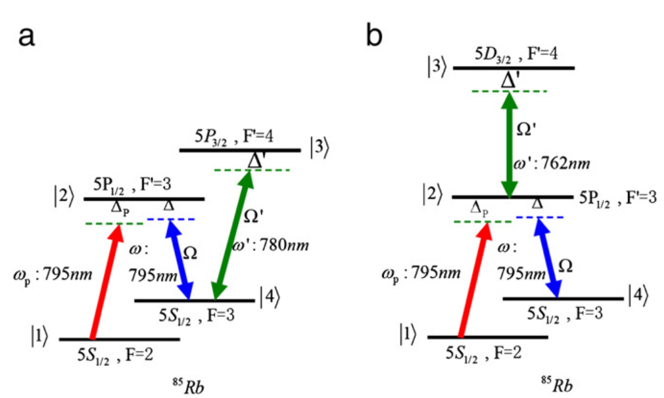

Fig. 1. Energy-level scheme for ^{85}Rb. (a) N-type atomic system; and (b) Inverted-Y atomic system.

3. N-type system

3.1. A Experiment

In this subsection, we study the N-type system [Fig. 1(a)] absorption spectrum. Fig.3 plots the measured absorption spectrum of the weak probe laser versus the probe frequency detuning of ω_P. The experimental data are plotted in solid blue lines, while the theoretical simulations are presented in dashed red lines. When no coupling field is applied, we get a standard absorption line shape of ^{85}Rb $5S_{1/2}$,F=2→$5P_{1/2}$,F'=3[see Fig. 3(a)]. The full width at half maximum (FWHM), which is estimated to be 12 MHz, is broader than the 6 MHz natural width primarily because of residual Doppler broadening in the atomic beam and the linewidth of the laser. When only the coupling field Ω is added, the line shape turns to be the case of electromagnetically induced transparency [see Fig. 3(b)]. In the case of applying both of the coupling and the controlling fields, the line shape varies with the detuning of the two coupling fields (Δ and Δ'). We note that two narrow windows appear, that is, the usual dark resonance obtained in a three-level system splits into two windows. Fig. 3(c) shows the absorption spectrum when both of the fields are on resonance ($\Delta\approx 0, \Delta'\approx 0$). We can observe the symmetric configuration with two transparency windows and three-equal-height absorption peaks. This situation is similar to the case of $\omega_{32}=\omega_{21}$ in the system with SGC [see Fig. 8(a) of Ref. [18]]. Fig. 3(d) shows the absorption spectrum observed with nonresonant lasers ($\Delta\approx\Delta'\neq 0$). The nonzero detuning of the two lasers leads to an asymmetrical configuration and the energy separation of the three peaks are unequal, which is similar to the special case of $\omega_{32}\neq\omega_{21}$ in the system with SGC [see Fig. 8(b) of Ref. [18]].

3.2. B Theory

From Fig. 3 we can see that our results are similar to the system studied by Antón et al [18], where the laser-driven four-level atom consist of three closely spaced upper levels decaying to a common lower level. The three upper levels are coupled by the same vacuum modes to the lower level leading to spontaneously generated coherence effects. The equality between our N-type system and that in Ref. [18] can be seen in the dressed state representation of the field ω and ω'.

In the fully dressed state picture of both driving fields ω and ω', levels $|2\rangle$,$|3\rangle$ and $|4\rangle$ in the bare state [see Fig. 4(a)] can be replaced by three new states $|+\rangle$,$|-\rangle$ and $|0\rangle$ [see Fig. 4(b)]. After the mathematical calculation, we obtain the following equations,

$$|i\rangle = \sin\varphi_i\cos\theta_i|2\rangle + \sin\varphi_i\sin\theta_i|3\rangle + \cos\varphi_i|4\rangle \quad (1)$$

Where $\tan\varphi_i = \sqrt{\frac{1}{A_i^2}+\frac{1}{B_i^2}}$, $\tan\theta_i = \frac{A_i}{B_i}$, $A_i = \frac{E_i}{\Omega}$, $B_i = \frac{\Delta-\Delta'-E_i}{\Omega'}$, and E_i is the eigenvalues of $|i\rangle$ ($i=0,+,-$). Thus the frequency separation of the three dressed levels are $E_+ - E_0$ and $E_0 - E_-$. And when we assume that the decay rate of $|3\rangle\rightarrow|2\rangle$ is zero, these two system are strictly equal.

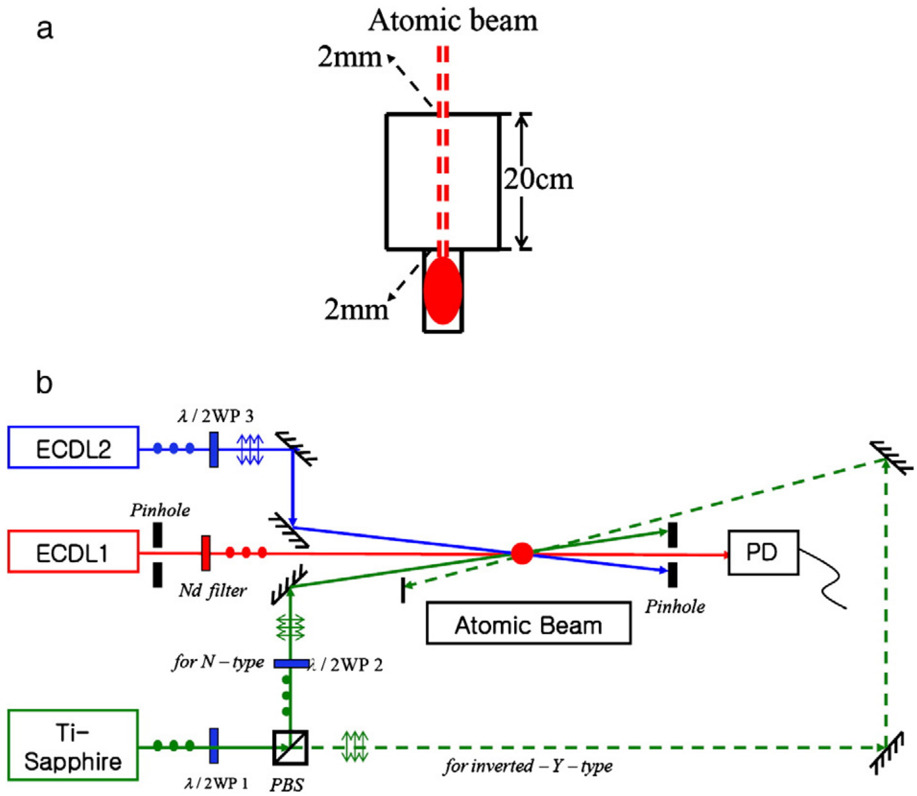

Fig. 2. (a) Illustration of the device generating atomic beam. (b) Schematic diagram of the experimental setup. ECDL: external cavity diode laser; Ti-Sapphire: coherent −899 Ti: sapphire laser; λ/2 WP: half wave plate; PD: photodiode detector; PBS: polarization beam splitters. The green solid line for N-type atomic system, while the green dotted line for inverted-Y atomic system.

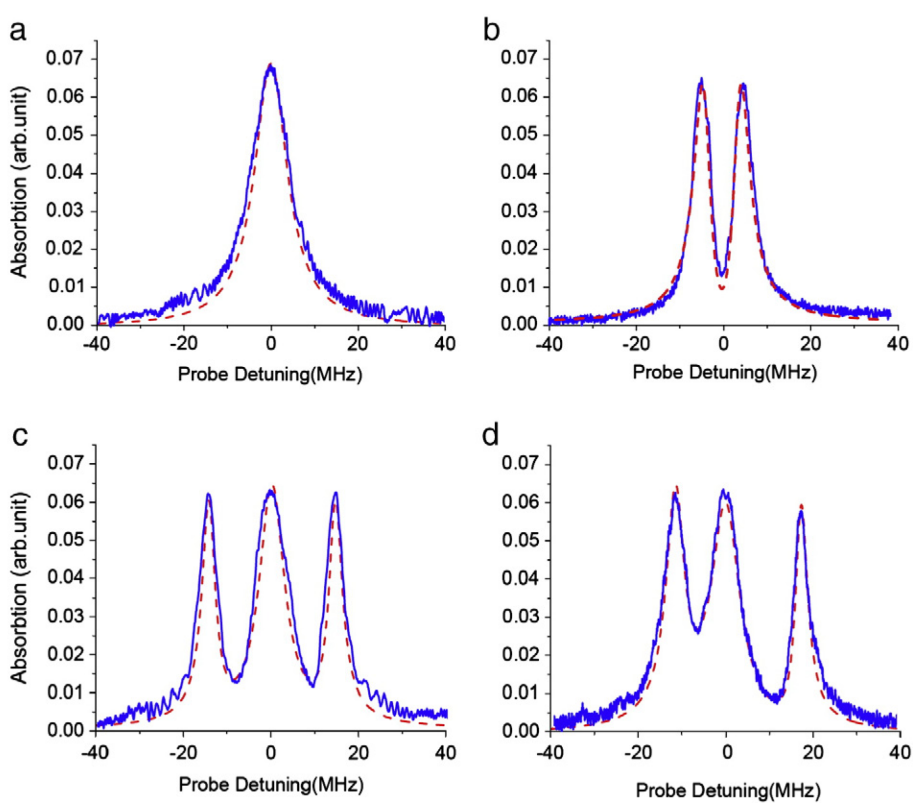

Fig. 3. Absorption spectrum (arbitrary units) of the N-type system for different Detuning of the two coupling fields. Solid blue curves are the experimental results; dotted red curves are the theoretical simulation. (a) Without coupling field. (b) With coupling field Ω applied. Parameters are $\Omega = 10MHz, \Delta \approx 0$. (c) and (d) with two coupling fields applied. Parameters are $\Omega = \Omega' = 10MHz$. (c) $\Delta \approx 0, \Delta' \approx 0$; (d) $\Delta \approx 6MHz$, $\Delta' \approx 6MHz$.

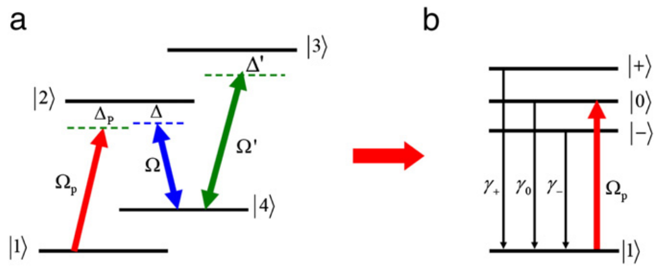

Fig. 4. (a) Schematic diagram of the four-level N system. (b) Dressed state representation of the four-level N system.

With the resonant coupling of these two fields ($\Delta = \Delta' = 0$), the frequencies of these three dressed sublevels $|+\rangle$, $|-\rangle$ and $|0\rangle$ relative to the level $|1\rangle$ are $\omega_{1\pm} = \omega_{21} \pm \sqrt{\Omega^2 + \Omega'^2}, \omega_{10} = \omega_{21}$, thus, the separation of $|+\rangle$ and $|0\rangle$, and that of $|0\rangle$ and $|-\rangle$ are equal ($\omega_{+0} = \omega_{0-} = \sqrt{\Omega^2 + \Omega'^2}$). And when$\Delta \neq 0, \Delta' \neq 0$, the separation of $|+\rangle$ and $|0\rangle$, and that of $|0\rangle$ and $|-\rangle$ are not equal. In both case, the SGC effect exists between these three dressed sublevels.

As we know, the slope of the real part of the susceptibility at the windows center is proportional to the group index. After calculation we arrive at the following result:

$$n_g \propto \mathrm{Re}\left[\frac{\partial \chi(\omega)}{\partial \omega}\right]_{\omega=\omega_{dark}} = \frac{2\gamma^2(3\omega_{dark} + \omega_{+0} - \omega_{0-})}{\omega_{dark}{}^2(2\omega_{dark} + \omega_{+0} - \omega_{0-})} \tag{2}$$

where,

$$\omega_{dark} = \frac{(\omega_{+0} - \omega_{0-}) \pm \sqrt{\omega_{+0}{}^2 + \omega_{0-}{}^2 + \omega_{+0}\omega_{0-}}}{3} \tag{3}$$

From Eq. (2), we can see that the group velocity of the probe pulse is very sensitive to the splitting of the closed dressed levels. As ω_{+0} or ω_{0-} decreases the slopes of the dispersive curve at the transparency windows become steeper, which leads to the lower group velocity. We can modify the energy separation by changing the detuning of the coupling field and the controlling field. Thus the steeper slopes of the dispersive curve at the transparency windows will be obtained.

We calculate the dispersion spectrum and the absorption from $|1\rangle$ to $|2\rangle$ in the four-level system. In the case of $\Delta = \Delta' = 0$, we obtain the result as show in Fig. 5(a), which is similar to Fig. 8(a) of Ref. [18]. We can obtain two transparency windows with three absorption peaks which have the same height. While, the dispersion curves present a very high slope at the center of the two transparency windows, which can make the group velocity be considerably slowed down. And this symmetrical spectrum can also lead to the same group velocity at two different frequencies, thus two weak pulses with different central frequencies can propagate with the same group velocity.

When $\Delta \neq 0, \Delta' \neq 0$, the separation of $|+\rangle$ and $|0\rangle$ and that of $|0\rangle$ and $|-\rangle$ are not equal any longer ($\omega_{+0} \neq \omega_{0-}$), we can obtain the result as shown in Fig. 5(b), which is similar to Fig. 8(b) of Ref. [18]. The configuration is asymmetric and the absorption spectrum can be made different at the two windows. By changing the detuning of the two fields, we can obtain different ω_{+0} and ω_{0-}. As ω_{+0} or ω_{0-} decrease, the dispersion slope becomes steeper and lower group velocity can occur. As we can see, one dispersion curve presents a much higher slope than the other one at their center of the transparency windows. Thus we can control the two weak pulses with different central frequencies propagating with different group velocities, which have potential applications in the area of all optical communication. For example, in Fig. 5(b), the ratio of velocities of the two pulse with different frequencies is 5.83. The ratio can become larger as one of the splitting decreases.

The result of the paper is demonstration of double transparency windows in absorption spectra. Similar results have been encountered in other four-level configurations tripod atoms [23]. The main difference is that in our case, the double transparency windows are generated via spontaneous coherence instead of the dynamically induced coherence. The advantage of spontaneously generated coherence over double EIT scheme is that we can obtain a large and positive slope of the dispersion and a great reduction of group velocity of a weak probe pulse.

4. Inverted-Y system

4.1. A. Experiment

In this section we will report the absorption spectrum of the inverted-Y system. The level structure and laser coupling scheme is depicted in Fig. 1 (b). Compared with the N-type system, the controlling field is coupled to the $5S_{1/2}$,F=3→$5D_{3/2}$,F'=4 transition. And the schematic for the experiment is shown in Fig. 2(b). In order to minimize the effect of the residual broadening, we make the controlling laser beam propagate in the opposite direction of the other two beams by the half wave plate (λ/2WP 1) and the polarization beam splitters (PBS).

Fig. 6 plots the measured absorption spectrum of the weak probe laser versus the probe frequency detuning of ω_P with both the coupling and the controlling field. The experimental data are plotted in solid blue lines, while the theoretical simulations are presented in dashed red lines. The detuning of the coupling and the controlling field will modulate the line shape of the absorption spectrum. When $\Delta = \Delta' = 0$, there is only one transparency window [see Fig. 6(a)]. Compared with applying only the coupling field [see Fig. 3(c)], we

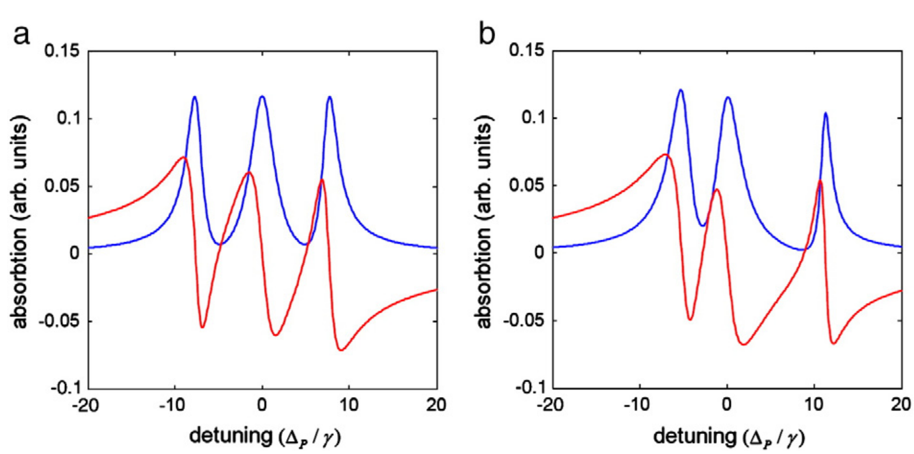

Fig. 5. Imaginary (red lines) and real (blue lines) parts of the probe susceptibility $A(\omega)$ as a function of ω. (a) $\Delta = 0, \Delta' = 0$ (b) $\Delta = 5\gamma, \Delta' = 5\gamma$. Other parameters are $\Omega = 5.8\gamma, \Omega' = 5\gamma$. (All variables are scaled by γ. And we take $\gamma = 1$, for simplicity.).

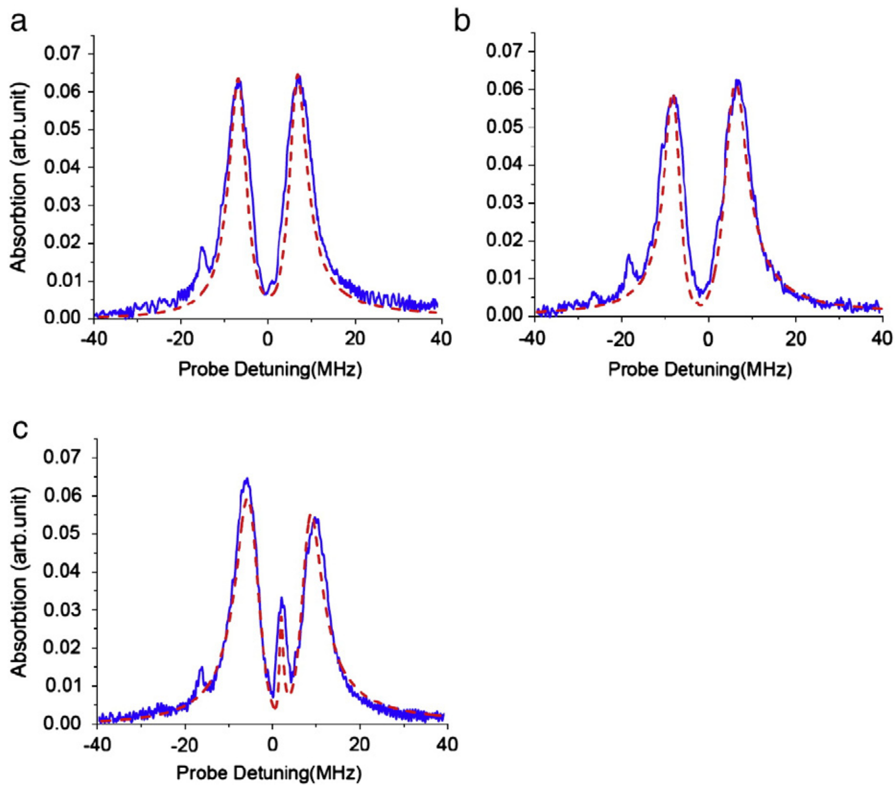

Fig. 6. Absorption spectrum (arbitrary units) of the inverted-Y system for different Detuning of the two coupling fields. Solid blue curves are the experimental results; dotted red curves are the theoretical simulation. Parameters are $\Omega=\Omega'=5MHz$. (a) $\Delta\approx 0$, $\Delta'\approx 0$. (b) $\Delta\approx 1MHz$, $\Delta'\approx -1MHz$. (b) $\Delta\approx 0$, $\Delta'\approx -3MHz$.

can see that the transparency window is broader when the controlling field is added. And when $\Delta=1MHz, \Delta'=-1MHz$ $(\Delta+\Delta'=0)$, there is still one broad transparency window, but the height of the two peaks are different [see Fig. 6(b)]. And when the condition of $\Delta+\Delta'=0$ is not satisfied, we can get two transparency windows with a narrow absorption peak in the middle [see Fig. 6(c)]. In the next section we will present the theoretical model to explain the results as shown in Fig. 6.

4.2. B. Theory

Consider a four-level system shown in Fig. 7(a). In the fully dressed state picture of both driving fields ω and ω', levels $|2\rangle$,$|3\rangle$ and $|4\rangle$ in the bare state can be replaced by three new dressed states $|+\rangle$,$|-\rangle$ and $|0\rangle$ [see Fig. 7(b)]. As we studied above, the SGC effect can exists between these three dressed sublevels. After the mathematical calculation, we can obtain the following equations,

$$|i\rangle = \cos\varphi_i \sin\theta_i|2\rangle + \sin\varphi_i|3\rangle + \cos\varphi_i \cos\theta_i|4\rangle \quad (4)$$

Where $\tan\varphi_i = \frac{E_i\Omega'}{\sqrt{E_i{}^2+\Omega^2(E_i-\Delta-\Delta')}}$, $\tan\theta_i = \frac{E_i}{\Omega}$, and E_i is the eigenvalues of $|i\rangle$ $(i=0,+,-)$.

Under the condition of $\Delta+\Delta'=0$, we can easily derive that the dressed level $|0\rangle$ is independent of level $|2\rangle$, which means that only two spontaneous transitions $|+\rangle\rightarrow|1\rangle$ and $|-\rangle\rightarrow|1\rangle$ can occur and no third spontaneous emission can take place. Thus the interference of the dressed levels only comes from the cross coupling between the decay channels $|+\rangle\rightarrow|1\rangle$ and $|-\rangle\rightarrow|1\rangle$, known as SGC. And this SGC effect can result in the transparency of the absorption spectrum, as we obtained in Fig. 6(a) and (b). The experiment results are similar to the theoretical calculation of Ref [21], which examined a weak probe beam for a V-type atom with a closely spaced doublet and demonstrated that quantum interference between the two excitation pathways can result in the transparency. So our system can be used to simulate the SGC in a V-type system.

And when $\Delta+\Delta'\neq 0$, the dressed level $|0\rangle$ is dependent of level $|2\rangle$, and all the three spontaneous transitions $|+\rangle\rightarrow|1\rangle$,$|0\rangle\rightarrow|1\rangle$ and $|-\rangle\rightarrow|1\rangle$ can occur. The interference of the dressed levels comes from the cross coupling between all the decay channels $|+\rangle\rightarrow|1\rangle$, $|0\rangle\rightarrow|1\rangle$ and $|-\rangle\rightarrow|1\rangle$. And the SGC effect can induce two transparency windows with a narrow absorption peak in the absorption spectrum, which is the case of Fig. 7(c).

In our experiment, under the two-photon resonance condition, the inverted-Y system is similar to many other V-type systems with SGC [22], which can result in variety of novel quantum effects, such as gain without inversion, transparency of a short laser pulse and ultranarrow spectral lines in resonance fluorescence. In Ref. [24], one can also simulate the V-type with SGC effect. The advantage of our experiment over theirs is that we can control the number of the decay channels by

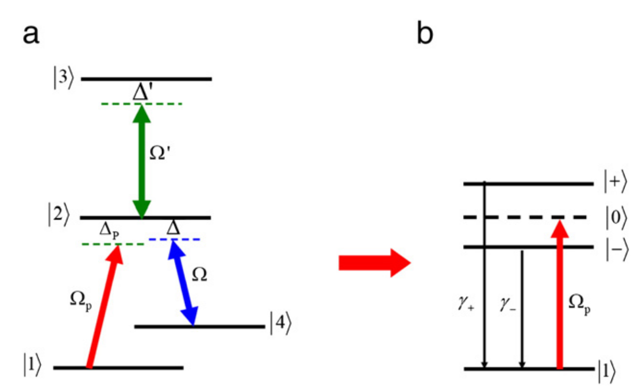

Fig. 7. (a) Schematic diagram of the four-level inverted-Y system. (b) Dressed state representation of the four-level inverted-Y system. When $\Delta+\Delta'=0$, only two spontaneous transitions $|+\rangle\rightarrow|1\rangle$ and $|-\rangle\rightarrow|1\rangle$ can occur.

changing the detuning of the controlling field, which means that the SGC effect can arises from two or three closely space levels.

5. Discussions and conclusion

The experimental results are in accordance with what we calculated in the system with SGC. But they are not exactly the same. There are three effects responsible for the differences. The first one is the decay rates of the states $5P_{3/2}$,F'=4→$5P_{1/2}$,F'=3, $5P_{1/2}$,F'=3→$5S_{1/2}$, F=3 and $5D_{3/2}$,F'=4→$5P_{1/2}$,F'=3. The second one is that the theoretical results in the system with SGC are based on ideal atoms. But in real atomic systems, the residual Doppler broadening undoubtedly broadens the absorption line shape. The last one is the effects from the linewidths of the lasers, which is another origin of the broadening. The theoretical simulations are made including the above effects and the results are presented in dashed red lines in Figs. 3 and 6.

The experimental results are in agreement with the theoretical simulations, but there are still differences between them. It is mainly because of the following four reasons. First, there are effects induced by the levels of $5D_{3/2}$,$F=2,3$, because of their small energy separations. Second, the three laser beams propagate in small angles, so there remains small Doppler effects. Third, we ignore the magnetic sublevels of the system, and only consider a simple four-level system. Fourth, the system is not closed, the upper level $5P_{3/2}$ decays to other levels such as $6P_{1/2}$ and $6P_{3/2}$, for example.

In conclusion, we have reported the experimental observation of the effect of spontaneously generated coherence on absorption without the rigorous requirement of close-lying levels. The experiments are studied in both a four-level N-type and a four-level inverted-Y system in a rubidium atomic beam. By coupling and controlling field, the bare state of the four-level N system is similar to the four-level system with three closely upper levels coupled to one lower level by the same vacuum modes with SGC. We experimentally demonstrated the features of absorption predicted in the four-level system with three close-lying upper levels. By changing the Rabi frequency and the detuning of the two lasers, we can control the splitting of the three dressed state, so as the position of the two transparency windows. The slope of the dispersive curve at the transparency windows can be the same, thus two laser pulses with different frequencies can propagate with the same slow group velocity; or, one can control the two laser pulses with different frequencies and different group velocities by changing the two coupling fields. As for the four-level inverted-Y system, under the condition of $\Delta+\Delta'=0$, it is equivalent to a V-type system with two closely upper levels. The SGC effect between the two decay channels can result in a deep and broad transparency window in absorption spectrum. And by the detuning of the controlling field, we can control the number of the spontaneously decay channels, thus the effect of spontaneously generated coherence can exist in three or two closely space levels.

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References

[1] S.E. Harris, Physical Review A 57 (1998) 4014;
S. Menon, G.S. Agarwal, Physical Review A 57 (1998) 4014.
[2] G.J. Yang, M. Xie, Z. Zhang, K. Wang, Physical Review A 77 (2008) 063825.
[3] X.H. Yang, S.Y. Zhu, Physical Review A 77 (2008) 063822.
[4] E. Paspalakis, N.J. Kylstra, P.L. Knight, Physical Review A 63 (2001) 043818;
D. Bortman-Arbiv, A.D. Wilson-Gordon, H. Friedmann, Physical Review A 63 (2001) 043818.
[5] S.Y. Zhu, M.O. Scully, Physical Review A 55 (1997) 4454;
H. Lee, P. Polynkin, M.O. Scully, S.Y. Zhu, Physical Review A 55 (1997) 4454.
[6] F.L. Li, S.Y. Zhu, Physical Review A 59 (1999) 2330;
C.H. Keitel, Physical Review Letters 83 (1999) 1307.
[7] M.A. Antón, O.G. Calderón, F. Carreño, Physical Review A 72 (2005) 023809;
I. Gonzalo, M.A. Antón, F. Carreño, O.G. Calderón, Physical Review A 72 (2005) 033809.
[8] E. Paspalakis, P.L. Knight, Physical Review A 62 (2000) 013811;
F. Ghafoor, S.Y. Zhu, M.S. Zubairy, Physical Review A 62 (2000) 013811.
[9] Y.P. Yang, J.P. Xu, H. Chen, S.Y. Zhu, Physical Review Letters 100 (2008) 043601.
[10] V. Yannopapas, E. Paspalakis, N.V. Vitanov, Physical Review Letters 103 (2009) 063602.
[11] H.R. Xia, C.Y. Ye, S.Y. Zhu, Physical Review Letters 77 (1996) 1032.
[12] L. Li, X. Wang, J. Yang, G. Lazarov, J. Qi, A.M. Lyyra, Physical Review Letters 84 (2000) 4016.
[13] G.S. Agarwal, Physical Review Letters 84 (2000) 5500.
[14] Z. Ficek, S. Swain, Physical Review A 69 (2004) 023401.
[15] Li Jia-Hua, Liu Ji-Bing, Chen Ai-Xi, Qi Chun-Chao, Physical Review A 74 (2006) 033816.
[16] J.H. Wu, A.J. Li, Ding Yue, Y.C. Zhao, J.Y. Gao, Physical Review A 72 (2005) 023802;
A.J. Li, J.Y. Gao, J.H. Wu, Lei Wang, Journal of Physics B 38 (2005) 3815.
[17] A. Joshi, W. Yang, M. Xiao, Physics Letters A 325 (2004) 30.
[18] M.A. Antón, O.G. Calderón, F. Carreño, Physical Review A 72 (2005) 023809.
[19] M. Fleischhauer, M.D. Lukin, Physical Review A 65 (2002) 022314;
A. Kalachev, S. Kröll, Physical Review A 74 (2006) 023814.
[20] Totsuka Kouki, Kobayashi Norihiko, Tomita Makoto, Physical Review Letters 98 (2007) 213904;
Praveen K. Vudyasetu, Ryan M. Camacho, John C. Howell, Physical Review Letters 100 (2008) 123903;
U. Schnorrberger, J.D. Thompson, S. Trotzky, R. Pugatch, N. Davidson, S. Kuhr, I. Bloch, Physical Review Letters 103 (2009) 033003.
[21] P. Zhou, S. Swain, Physical Review Letters 78 (1997) 832.
[22] S.Y. Zhu, R.C.F. Chan, C.P. Lee, Physical Review A 52 (1995) 710;
P. Zhou, S. Swain, Physical Review A 77 (1996) 3995;
E. Paspalakis, N.J. Kylstra, P.L. Knight, Physical Review A 61 (2000) 045802.
[23] B.S. Ham, P.R. Hemmer, Physical Review Letters 84 (2000) 4080;
E. Paspalakis, P.L. Knight, Journal of Optics B: Quantum and Semiclassical Optics 4 (2002) S372;
S. Rebic, D. Vitali, C. Ottaviani, P. Tombesi, M. Artoni, F. Cataliotti, R. Corbalán, Physical Review A 70 (2004) 032317;
D. Petrosyan, Y.P. Malakyan, Physical Review A 70 (2004) 023822.
[24] Z. Ficek, S. Swain, Physical Review Letters 69 (2004) 023401.