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Investigation on spontaneously generated coherence

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Abstract: Spontaneously Generated Coherence(SGC) refers to a kind of quantum coherence induced by the process of spontaneous emission. It can greatly affect the dynamics of a quantum system, and accounts for a variety of important phenomena. Many efforts have been devoted to this topic, aiming to investigate the essence of quantum coherence and advanced technologies. However, the existence of SGC needs rigorous requirements which can hardly been fulfilled in atoms placed in a free space. Therefore we must give particular considerations to investigate this coherence experimentally. In this paper, a few interesting phenomena related to SGC are summarized, such as gain without inversion, coherent population trapping, phase sensitive spectra, and modifications of absorption, emission, and refraction. We also review the investigations on the realization of SGC, such as modifying the vacuum, coupling levels with static fields, simulating SGC with coherence induced by coherent fields, and studying SGC in special materials.

Key words: atomic coherence; spontaneously generated coherence; quantum optics

1　Introduction

When a multi-level atom decays from two close-lying upper levels (a common upper level) to a common lower level (two close-lying lower levels), the emission of one of the two decaying channels affects the other, *vice versa*. Quantum interference arises between the decay processes. As a result, coherence can be generated between the two close-lying levels. The coherence is generated by spontaneous emission, so it is named as Spontaneously Generated Coherence (SGC) or Decay Induced Coherence (DIC). Because spontaneous emission is brought about by the coupling of atoms to the vacuum of electromagnetic fields, SGC is also called Vacuum Induced Coherence (VIC).

SGC was first proposed by Agarwal in 1974[1]. It was showed that population trapping and generation of quantum coherences in the excited states can be achieved in a degenerate V system. SGC can significantly affect the properties of quantum systems, and lead to a number of interesting phenomena, such as amplification without and with inversion[2-15], phase dependent gain and absorption[16-27], dark lines in emission spectra[28-30], cancellation and suppression of spontaneous emission[31-36], narrow spectral lines[37-43], splitting[44,45] and squeezing[46-48] of spontaneous emis-

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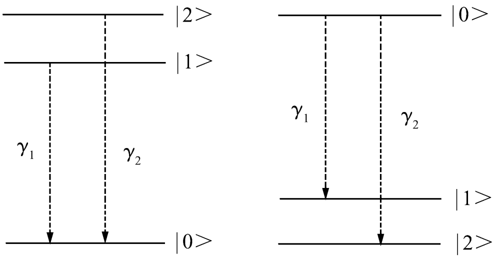
sion, enhancing superfluorescence[49], coherent population trapping[50-56] and transferring[57], modification of absorption and refraction[58-69], Kerr nonlinearity[70-72], optical bistability[73,74], and photon-photon correlation[75-77]. Spontaneous emission had once been viewed as merely a resource of decoherence, while SGC is a kind of quantum coherence built by spontaneous emission. The study of SGC modified the way we look at matter-radiation interactions, and is obviously important to the fundamental understandings of quantum optics. Meanwhile, the aforementioned phenomena induced by SGC are also useful to applied physics, such as quantum information and computing, high-refraction material, and teleportation.

Although SGC attracts many interests, the very existence of SGC requires two stringent conditions: (1) the dipole moments of the two decay channels are non-orthogonal; (2) the close-lying levels are near-degenerate. These conditions are very difficult to meet, if not impossible, as a result, we can hardly directly investigate SGC in atomic systems. Progresses have been made to bypass the rigorous requirements, examples are modifying the vacuum[78-81], diving atoms with low frequency fields[82-84], coupling relevant levels with DC fields[85-88] and magnetic fields[89], simulating SGC with coherence generated by microwave fields[90,91] and laser fields[92-98]. Fano interference in semiconductor quantum wells has been viewed as a substitute of SGC[99,100]. Efforts have also been made to find SGC in special media, such as quantum dots[101] and left handed materials[102].

In this paper, we summarize a few remarkable features related to SGC, and investigations on the realization of SGC. The paper is organized as follows: in Section 2, we describe the basic understanding of SGC; in Section 3, we summarize a few phenomena induced by SGC; in Section 4, we review the progresses of investigations on the realization of SGC; Section 5 is a summary of the paper.

2 Understanding of SGC

There are two basic schemes of SGC: V-type, and Λ-type. V-type SGC refers to the case that two close-lying upper levels decay to a common lower level (Fig. 1 (a)); and Λ-type SGC refers to the case that a common upper level decays to two close-lying lower levels (Fig. 1 (b)). SGC comes about when the two channels are coupled by one vacuum mode.



(a) V-type (b) Λ-type

Fig. 1 Basic schemes of SGC.

We can understand the physics of SGC in the scheme of [28], which is a V-type (Fig. 2). This system comprises three levels with the two upper levels $|a_1\rangle$ and $|a_2\rangle$ decaying to the common lower level $|b\rangle$. The evolution of the state vector obeys the Schrödinger equation, and can be written as

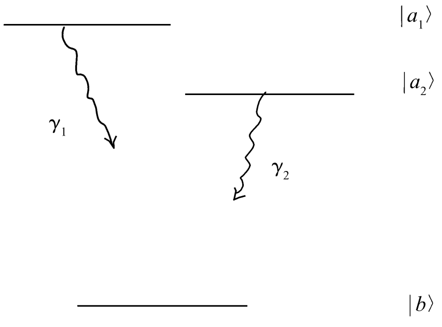


Fig. 2 Three-level scheme of [28].

$$|\psi(t)\rangle = A^{(1)}(t)|a_1\rangle|0\rangle + A^{(2)}(t)|a_2\rangle|0\rangle + \sum_k B_k(t)b_k^+|0\rangle|b\rangle, \quad (1)$$

where b^+ is the creation operator for the kth vacuum mode, k stands for both momentum and polarization of the vacuum modes. When the two dipole moments of the two transitions are parallel or anti-parallel to each other, the amplitudes of the possibilities obey the following equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}A^{(1)}(t) = -\frac{\gamma_1}{2}A^{(1)}(t) - \frac{\sqrt{\gamma_1\gamma_2}}{2}A^{(2)}(t)\mathrm{e}^{\mathrm{i}\omega_{12}t}, \tag{2a}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}A^{(2)}(t) = -\frac{\gamma_2}{2}A^{(2)}(t) - \frac{\sqrt{\gamma_1\gamma_2}}{2}A^{(1)}(t)\mathrm{e}^{-\mathrm{i}\omega_{12}t}, \tag{2b}$$

where ω_{12} is the energy space between the two upper levels and γ_1, γ_2 are the corresponding rates of decay. The effects of SGC are the cross-interference between the two levels $|a_1\rangle$ and $|a_2\rangle$. The coefficients of the interference are $\frac{\sqrt{\gamma_1\gamma_2}}{2}\mathrm{e}^{\mathrm{i}\omega_{12}t}$ and $\frac{\sqrt{\gamma_1\gamma_2}}{2}\mathrm{e}^{-\mathrm{i}\omega_{12}t}$. It is obvious that the effects of SGC are significant only when ω_{12} is small.

The physics of Λ-type SGC can be analyzed in the similar way. There are also detailed discussions on the two basic types of SGC[103]. With the above basic understanding, the study of SGC has been extended to various configurations, such as laser coupled multi-level systems. SGC has also been investigated in the equal-spaced Ladder type systems[104].

3 Phenomena related to SGC

3.1 Gain without and with inversion

Gain without inversion is one of the earliest studies related to SGC. In 1989, Harris investigated a four-level system (see Fig. 3), in which the upper levels are purely lifetime broadened and decay to an identical continuum[2]. They showed that SGC between the upper levels would lead to reduction of the absorption and that the stimulated emission was unaffected. Then laser amplification might be obtained without inversion. Following this work, Imamoǧlu presented an equivalent three-level atomic system, where the upper two levels have the same J and m_J quantum numbers and decay radiatively to a single level[3]. After that, Harris and Macklin discussed the effect of the transient response of the systems in which gain without inversion might be obtained[4].

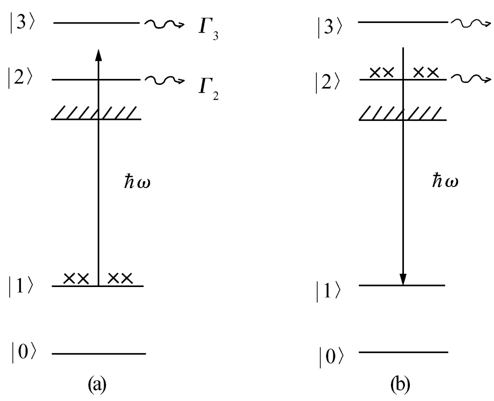


Fig. 3　Energy-level diagram of [2] (a) Atoms in $|1\rangle$ at $t=0$ absorb probe radiation and decay to an energy-conserving ion and electron (b) Atoms in level $|2\rangle$ at $t=0$ both auto-ionize and are stimulated to level $|1\rangle$ thereby producing gain at the probe frequency. Levels $|1\rangle$, $|2\rangle$, and $|3\rangle$ may be pumped by electrons or photons from level $|0\rangle$.

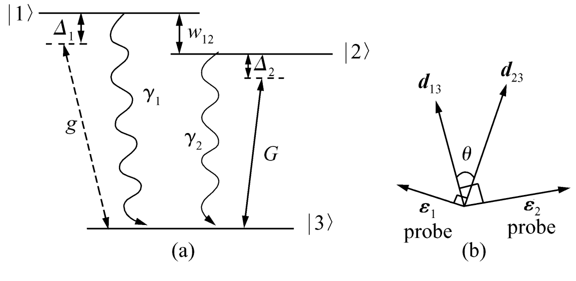


Fig. 4　Schematic configurations of [5] (a) Three-level V system (b) The arrangement of field polarizations and dipole moments.

The effect of SGC on gain without inversion can be clearly seen in [5]. The authors investigated a three-level atomic system which was coupled by a weak probe field g and a strong coupling field G (Fig. 4). They calculated the absorption spectrum of the probe field g. The typical results is shown in

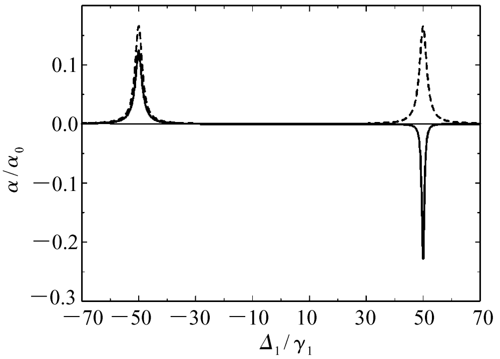


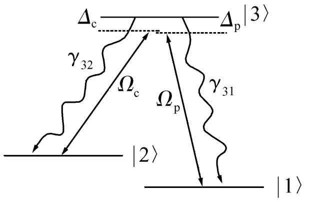
Fig. 5 Effect of SGC on probe absorption. The dashed curve is the result in the absence of SGC(θ = 90°); the solid curve is the result when SGC is present(θ = 15°).

Fig. 5. When θ = 90°(Fig. 4(b)), there is no SGC between the levels $|1\rangle$ and $|2\rangle$(see Fig. 4(a)), and the absorption is shown in Fig. 5 by dotted line. The two absorption peaks correspond to the Autler-Townes splitting induced by the coupling filed G. When θ = 15°(see Fig. 4(b)), there is SGC between the levels $|1\rangle$ and $|2\rangle$. The absorption spectrum is shown in Fig. 5 as the solid line, and a gain component arises. By comparing the solid line and the dotted line, we can see the effect of SGC. They also explained the phenomenon with the quasi-trapping states. There have been more detailed investigations on gain without inversion in the three-level V-type system with SGC[6-8]. The study on this topic has also been extended to three-level Λ systems[9-11], and four-level systems[12,13].

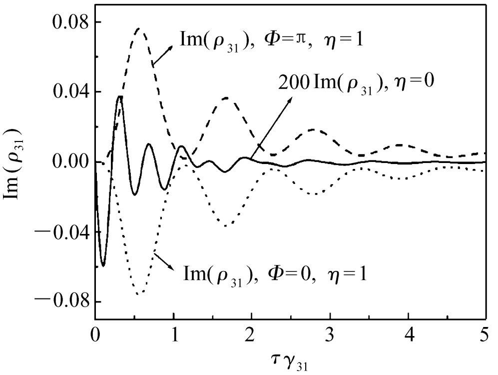
SGC is also useful to achieve gain with inversion. Wu *et al.* investigated the features of a four level system with a doublet of close-lying levels[14], and found that population trapping at excited levels and probe gain with inversion can be achieved with weak incoherent pumping. There existed population inversion in their system, but the inversion is achieved by SGC. Moreover, Xu *et al.* showed that owing to the effects of SGC, both probe gains with and without population inversion might be achieved with very weak incoherent pumping[15].

3.2 Phase dependent spectrum

With the presence of SGC, quantum systems can be phase sensitive. That is to say, we can modulate the features of absorption, gain, and dispersion with relative phase of applied laser fields. There is a series of works on this topic. Wu and Gao investigated the effect SGC in a three-level Λ system[16], and found that SGC contributed to inversionless gain. The profile of inversionless gain can be modulated by changing the relative phase between the applied two fields. A typical work is done by Xu *et al.*[17]. They investigated the effect of SGC on transient process in a three-level Λ system(see Fig. 6(a)) where SGC might exist between the two lower levels $|1\rangle$ and $|2\rangle$. They calculated the gain profile of the probe field Ω_p with different parameters. The typical result is shown in Fig. 6(b). When $\eta = 0$, which means the absence of SGC, the line shape is shown by solid lines. The probe field shows oscillatory behavior versus time, and exhibits periodic amplification and absorption. When $\eta = 1$, which means the presence of SGC, the system exhibits different features with



(a) Three-level Λ-type atomic system



(b) Time evolution of the gain-absorption coefficient for not considering SGC(η=0) and considering SGC(η=1)

Fig. 6 Energy levels and results of [17].

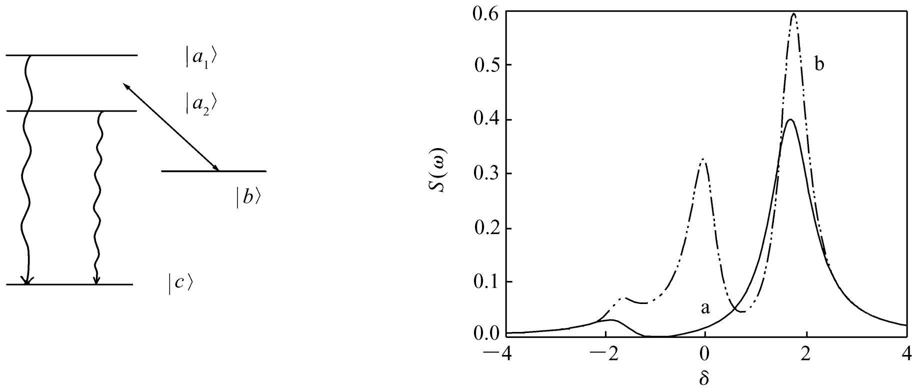
different values of the relative phase Φ between the two laser fields Ω_p and Ω_c. With $\Phi = 0$, the transient gain disappears, only leaves the oscillating absorption (see dotted curve). With $\Phi = \pi$, the transient absorption disappears, only leaves the oscillating gain. There are more detailed studies on the phase dependent inversionless gain in three-level Λ systems[18,19].

In three-level V systems, the profile of gain can also be phase sensitive. Wu *et al.* investigated such a system, which was driven by a strong coherent field and a weak field[20]. They found that due to SGC, probe gain could be achieved and modulated at different probe detunings just by tuning the relative phase between the probe and coherent field to different regions. After that, Xu *et al.* examined the transient response in a similar system[24] and showed the phase sensitivity induced by SGC. The study on this topic has been extended to various systems, such as closed four-level systems[21,22,26], open three-level Λ systems[23,27], and open three-level Ladder systems[25].

3.3 Control of spontaneous emission

Spontaneous emission is one of the most fundamental phenomena resulting from the interaction between radiation and matter. It is a resource of quantum noise of optical devices, and also a main drawback of high frequency lasing since the spontaneous emission rate is typically proportional to the frequency cubed (ω^3). Hence, there are many studies on how to prevent spontaneous emission. Controlling of the spectra of spontaneous emission is also a topic of great interest because it has potential applications in applied optics such as high-precision spectroscopy and magnetometry. Among the methods of modifying spontaneous emission, using the effects of SGC is an efficient way. With the presence of SGC, spontaneous emission can be altered almost at will, such as cancellation, narrowing, splitting, quenching, and squeezing[28-49].

After the early works on spontaneous emission in systems with SGC[28-30], Zhu and Scully investigated a four-level system (see Fig. 7 (a)), and showed spectral line elimination and spontaneous emission cancellation[31]. SGC arises due to the spontaneous emission from the two upper levels $|a_1\rangle$ and $|a_2\rangle$ to the lower level $|c\rangle$. The two upper levels are coupled to a fourth level by a laser field. The representative spectrum of the spontaneous emission is shown in Fig. 7(b). The dot-dashed line is the result when SGC is not considered, while the solid line is the result when SGC is considered. We can see that spectral line is eliminated owing to the effect of SGC. More details of such a system can be found in their later works[33,40].

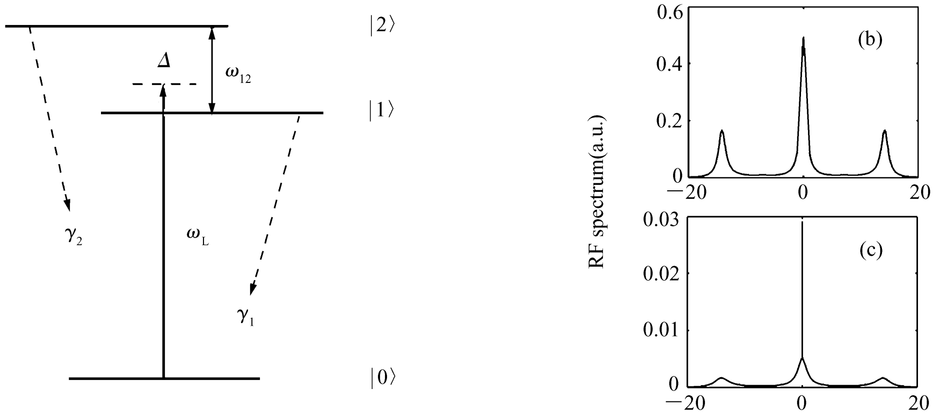


(a) Four-level atomic system

(b) Spontaneous spectrum

Fig. 7 Energy levels and results of [31].

Zhou and Swain proposed the narrowing of spontaneous emission in a three-level system[37]. The configuration is shown in Fig. 8 (a), which comprises three levels coupled by a monochromatic laser field. They calculated the resonance fluorescence spectrum at different parameters. Fig. 8 (b) and (c) are part of their results. The former is the spectrum neglecting the SGC between the upper levels |1⟩ and |2⟩, while the latter is the spectrum considering SGC. An ultra narrow peak arises in the middle due to the effect of SGC. The authors extended their work, and analyzed more details, such as the effect of the laser field, in the year of 1997[38].



(a) Three-level system coupled by a monochromatic laser field

(b),(c) Resonance fluorescence spectrum without and with the presence of SGC

Fig. 8 Energy levels and results of [37].

In systems with SGC, spontaneous emission can also be modified via relative phases of the applied laser fields. Paspalakis and Knight analyzed a four-level system with SGC[39], and used the phase difference of two lasers with equal frequencies for the control of spontaneous emission. They got interesting results such as extreme spectral narrowing and selective and total cancellation of fluorescence decay. With the presence of SGC, we can achieve many other interesting features, such as narrowing spontaneous emission without intensity reduction[41], enhancing superfluorescence [49], simultaneous narrowing of the central peak and side bands[43], squeezing[46-48] and splitting[45] of resonance fluorescence. The study of spontaneous emission has also been extended to systems where SGC exists among more than two levels[42].

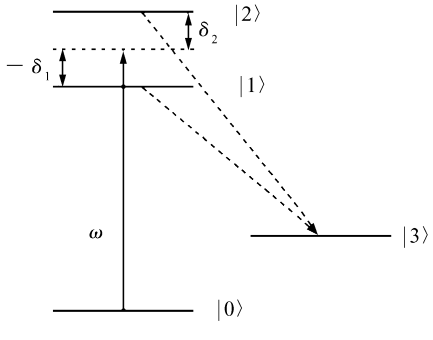
The control of spontaneous emission has once been experimentally verified[32]. The authors carried out the experiment in sodium dimmers, and observed complete depression of spontaneous emission with the population trapped at upper levels. Although there was a report about the failure of repeating this experiment[36], the conflicts were mainly about the experimental conditions, such as the transition properties. The physical process is logical, and has been intensively analyzed[34,35,44].

3.4 Coherent population trapping and transferring

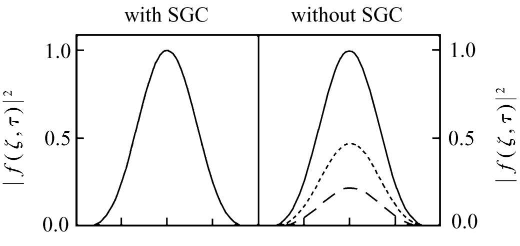
Coherent Population Trapping (CPT) states are the stationary states of the Hamiltonian which remain non-evolving in the presence of the radiative relaxation of the system. They are responsible for many quantum phenomena, such as the aforementioned cancellation of spontaneous emission and gain without inversion. In systems with SGC, the interesting features related to CPT have attracted much attention. In 1992, Hegerfeldt and Plenio investigated the dynamics of a three-level V system, and showed that populations might be trapped into the excited levels with the presence of SGC[50]. Then Luo and Xu showed stable non-lasing population inversion in both a three-level ladder system and a three level V system[51]. In 1997, Huang *et al.* investigated two types of four-level configurations and discussed the condition of trapping the population into two closing lying levels[52]. In 2005, Berman analyzed the effect of SGC on the CPT properties in a three level V system driven by an optical field[53], and showed that the response of the system depends critically on whether or not SGC is present. CPT can also be achieved due to double-dark states in systems where SGC exists among three levels[54]. Kozlov *et al.* investigated CPT together with lasing without inversion and quenching of spontaneous emission systematically[55]. Yang *et al.* analyzed the effect of SGC on CPT of moving atoms[56]. SGC can also affect the process of coherent population transfer[57].

3.5 Modification of absorption and dispersion

SGC has significant effects on the properties of atomic systems, therefore, can modify the absorption and dispersion dramatically. In 1992, Fleischhauer *et al.* investigated various atomic systems that are appropriate for high index of refraction with low absorption[58]. In 1997, Zhou and Swain examined the absorption of a weak probe beam for a three-level system[59], and showed that SGC could result in very narrow resonances, transparency, and even gain without inversion. In 1999, Menon and Agarwal investigated the effects of SGC on the pump-probe response of a three-level Λ system[60]. They calculated the profiles of refraction and absorption under the conditions that SGC is present and absent. SGC preserved the feature of electromagnetically induced transparency, and brings about quantitative changes in the line profiles. Paspalakis *et al.* investigated a four-level system (see Fig. 9(a)), and showed a typical effect of SGC on the absorption[61]. SGC arises when the two upper levels $|1\rangle$ and $|2\rangle$ decays to the level $|3\rangle$, and can lead to the lossless propagation of the laser pulse. A representative result is shown in Fig. 9(b). When there is SGC between the two upper levels, the shape and intensity preserves in the propagation (see the left line shape). When there is no SGC, the laser pulse is attenuated as it propagates in the medium, and the profile varies from the solid line to the dotted line and dashed line (see the right lines). Following this work, the authors extended their study to a three-level system, and gave more details[62].



(a) Four-level system



(b) Propagation of the laser pulse

Fig. 9 Energy levels and results of [61].

The effect of SGC on steady-state absorption has also been extensively studied in different systems, such as three-level V system[63], four-level Y system[64,69]. Dong and Tang calculated the absorption spectrum in a laser driven V system, where both the driving field and probe lasers interacts simultaneously with the two transitions. They found that the absorption features were strongly influenced by the degree of SGC[63]. Hou *et al.* investigated the one-photon and two-photon absorption in a four level Y system[64]. They showed that SGC could lead to probe gain without incoherent pumping, and suppress the two-photon transparency. They also considered the influence of the relative phase between the laser fields. The absorption properties of an alternative Y configuration were considered by Dutta *et al.*[69]. SGC can affect the dispersion of quantum systems, so one can obtain the control of group velocity of light in systems with SGC. Superluminal and slow lights can be achieved in three-level Λ system[65,67,68] and four-level tripod systems[66].

3.6 Other interesting phenomena

The effects related to SGC are not limited to the above examples. SGC can also induce other interesting phenomena. Niu and Gong studied the enhancement of nonlinearity based on SGC[70]. They considered general three-level systems including Λ, Ladder, and V types. It was found that Kerr nonlinearity depends critically on the presence of SGC, and that large nonlinearity can be realized with proper parameters. After that work, Niu *et al.* focused on a V-type three-level atomic system, and showed control of Kerr nonlinearity by manipulating the effect of SGC[71]. Yan *et al.* investigated the enhancement of the self-Kerr nonlinearity in a four-level Y-type atom with SGC existing between the two highest levels[72]. They examined the phase sensitivity of self-Kerr nonlinearity, and provided exact analytical explanations.

Optical bistability is an interesting phenomenon which can be obtained with SGC. Antón and Calderón studied the behavior of a V-type three-level atomic system in a ring cavity driven by a coherent field[73]. With the presence of SGC, they predicted that optical bistability could be realized with a considerable decrease in the threshold intensity and the cooperative parameter. Joshi *et al.* examined a three-level V-type system driven by a probe field and a coupling field[74]. They investigated the effects of SGC on optical bistability and discussed the possibility of obtaining optical multistability in the system by controlling SGC and coupling field strength.

SGC can also affects the photon correlations in atomic system. Swain *et al.* investigated two-time intensity correlation functions of the fluorescence field emitted from a three level V-type system[75]. They showed that the correlation depended on the intensity of the driving field. Switching between anti correlation and large correlation is demonstrated theoretically. Raymond Ooi studied the effect of SGC on two-photon correlation in a double cascade scheme[76], and showed that SGC leads to shifts of correlation profile. Correlation was suggested to be a probe of SGC[77], because SGC can significantly affect the two-time photon-photon correlations.

4 Realization of SGC

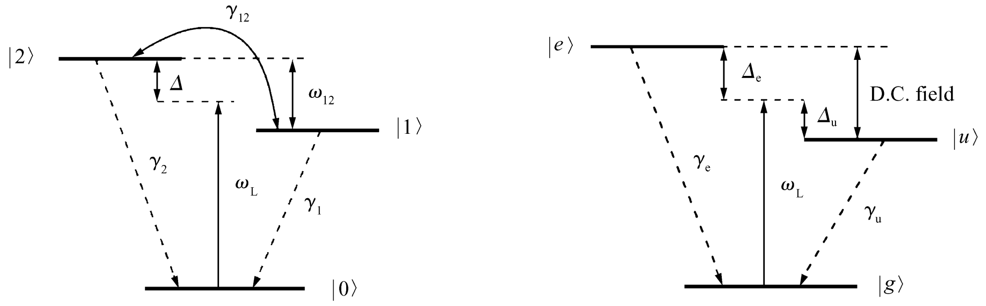
The existence of SGC requires two conditions: the close-lying levels are near-degenerate providing that the corresponding dipole moments are not orthogonal. These two conditions are very difficult to implement in atoms. For example, as Berman mentioned[53], in a three-level Λ-type atomic system, SGC between the two ground-state sublevels $|F=1, m_{\mathrm{f}}=0\rangle$ and $|F=0, m_{\mathrm{f}}=1\rangle$ can be generated by the spontaneous emission from the excited state $F=1, m_{\mathrm{f}}=0\rangle$. But the effect of SGC is normally negligible in this case since the hyperfine separations are usually much greater than the excited-decay rate and any Rabi frequencies. As a result, SGC can hardly be realized in atomic systems and there are very few experimental investigations on SGC. There have been many efforts on finding an approach by which the two rigorous requirements can be overcome. We summarize the examples as follows.

4.1 Modifying the vacuum

SGC arises when different decay channels are coupled by one vacuum mode, so the dipole moments need to be non-orthogonal for atoms in the free space. But this requirement is not necessary when the vacuum is properly modified. Patnaik and Agarwal reported the realization of SGC in a cavity[78]. They let the atoms with orthogonal dipoles interact with the vacuum of a preselected polarized cavity mode, and discussed the requirements of producing SGC. In 2000, Agarwal theoretically demonstrated how the anisotropy of the vacuum of the electromagnetic field could lead to SGC[79]. Their key result was that SGC could be given by the scalar formed from the antinormally ordered electric field correlation tensor for the anisotropic vacuum and the dipole matrix elements for the transitions. Then in 2001, Li *et al*. studied SGC of an atom embedded in a multilayer dielectric medium[80]. They showed how the spatial anisotropy of the medium could induce SGC in the situations of a dielectric plate cavity and a dielectric wave-guide. Owing to the intrinsic quenching of spontaneous emission of atomic dipoles oriented parallel to metallic surfaces, the effect of SGC can be enhanced when atoms are placed near plasmonic nanostructures[81].

4.2 Driving atoms with low frequency fields, DC fields, magnetic fields, mirowave fields, and laser fields

When atoms are driven by fields, quantum interference may arise and induce phenomena which can be interpreted as SGC. Evers and Keitel suggested driving two-level atoms with a low-frequency field[82]. The intense field allowed for additional decay channels with the exchange of one or more low-frequency photons during an atomic transition. Moreover, when the frequency of the field was lower than the total decay width of the atomic transition, interference came about between different decay channels. The study in such a system was then extended[83,84].



(a) Three-level V-type configuration with SGC between the upper levels

(b) Three-level V-type configuration with the upper levels coupled by a DC field

Fig. 10　Schematic diagrams of [86].

The requirements of SGC can be bypassed by directly coupling different levels with DC field. Berman analyzed the suppression of spontaneous emission in systems with SGC, and suggested the phenomenon could be achieved by coupling upper levels with a DC field[85]. Ficek and Swain gave a good example of this method[86]. They investigated the properties of a three-level V-type configuration with SGC between the upper levels (see Fig. 10(a)). The upper levels $|1\rangle$ and $|2\rangle$ were coupled to the lower level $|0\rangle$ by a monochromatic field ω_L, and decayed to $|0\rangle$ with rates γ_1 and γ_2. The Hamiltonian could be written as

$$H = (\Delta - \omega_{12})A_{11} + \Delta A_{22} + [\Omega_1 A_{10} + \Omega_2 A_{20} + H.c.], \tag{3}$$

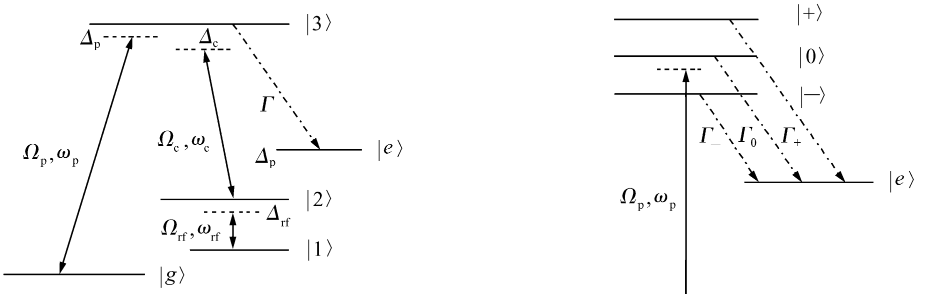
Assuming $\gamma_1 = \gamma_2$, they transformed the Hamiltonian to

$$H = \Delta_1 (A_{ss} + A_{aa}) - \frac{1}{2}\omega_{12}(A_{sa} + A_{as}) + \sqrt{2}\Omega(A_{s0} + A_{0s}), \tag{4}$$

where $|s\rangle = (|1\rangle + |2\rangle)/\sqrt{2}$, $|a\rangle = (|1\rangle - |2\rangle)/\sqrt{2}$. After the transformation, the Hamiltonian was similar to that of the DC coupled system. In this way, they showed that systems with SGC could be simulated with systems coupled by DC fields. Then

Joshi and Xiao extended the study to optical storage[87]. The absorption spectra of a similar system were investigated[88], and depression of absorption and narrow resonance were theoretically demonstrated.

We can also couple levels with static magnetic fields or microwave fields to simulate SGC[89]. This quantum coherence can lead to phenomena which can be interpreted with the concept of SGC. For example, Li *et al.* investigated the spontaneous emission spectra of a five-level system[90], where a hyperfine transition was driven by a microwave field (see Fig. 11(a)). They showed a few interesting phenomena in this system, such as spectral-line narrowing, enhancement, suppression, and spontaneous emission quenching. In the dressed-stated representation, the five level system turns to the case of Fig. 11(b). The aforementioned phenomena can be explained with the effects of SGC between the three dressed levels $|+\rangle$, $|0\rangle$, and $|-\rangle$. We can found another work studying SGC with a microwave field in a four-level Y system[91]. Again SGC between the dressed levels were responsible for interesting spectral features.



(a) Five-level system, levels $|1\rangle$ and $|2\rangle$ are coupled by a microwave field

(b) Corresponding dressed-state description

Fig. 11 Energy levels of [90].

Simulating SGC with coherence generated by laser field is also a good choice. In 1998, Patnaik and Agarwal investigated quantum beats in two-photon correlations of a four-level cascade system[92], and suggested that the use of ac Stark splitting can overcome the requirements of SGC. In 2000, Hu and Peng discussed the realization of SGC in dressed state level of three-level Λ and V systems[93]. Control of spontaneous emission has been studied in different four-level levels[94-96], where interesting phenomena were attributed to SGC between dressed levels. Inspired by these works, we experimentally investigated the effects of SGC in four-level Λ and V systems[97,98]. The four-level Λ system we considered is shown in Fig. 12. The two excited close-lying levels $|2\rangle$ and $|3\rangle$ separated in frequency by ω_{23} decay to the ground state $|1\rangle$ with rates γ_2 and γ_3, respectively. The coupling field ω_c simultaneously drives the transitions of $|4\rangle$ to $|2\rangle$ and $|4\rangle$ to $|3\rangle$ with Rabi frequencies Ω_c. The probe field ω_p probes the absorption from the ground state $|1\rangle$ to the excited states $|2\rangle$ and $|3\rangle$ with the corresponding Rabi

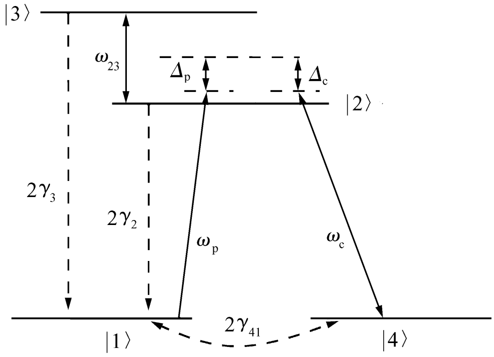
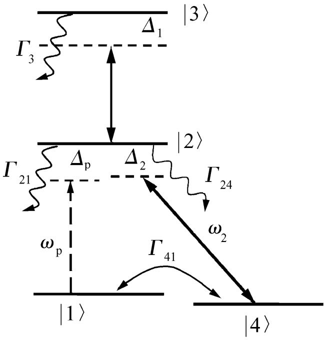
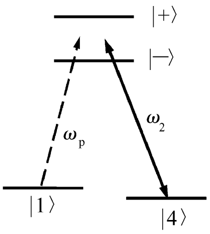


Fig. 12 Schematic diagram of the four-level Λ-type in [97].

frequencies of Ω_p. We found a few interesting features of the absorption spectrum owing to SGC between the levels $|2\rangle$ and $|3\rangle$, such as double transparency windows and a controllable narrow absorption peak. We proposed an experimental approachable energy scheme which consists of four levels interacting with two coupling fields (see Fig. 13(a)). In the dressed-state picture of ω_1, the system turns out to be a four-level system with two upper levels $|+\rangle$ and $|-\rangle$ (see Fig. 13(b)). Then we found the system (see Fig. 13(a)) 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 Λ-type system with two close-lying upper levels (see Fig. 12). In this way, we experimentally verified the prediction in dressed states. After this work, we made the second investigation on the effect of SGC in a four-level V system, where the absorption features were sensitive to the Rabi frequencies of the driving field[98]. We took similar steps and got satisfying results.



(a) Schematic diagram of the experimental approachable atomic system



(b) Corresponding dressed-state representation

Fig. 13 Energy levels of [97].

4.3 Fano interference in asymmetric quantum wells

In asymmetric quantum wells, Fano interference may arise between different states when they tunnel to a continuum of energies. There is a great similarity between such interference and SGC. Wu *et al.* investigated a system of quantum wells as shown in Fig. 14[99].

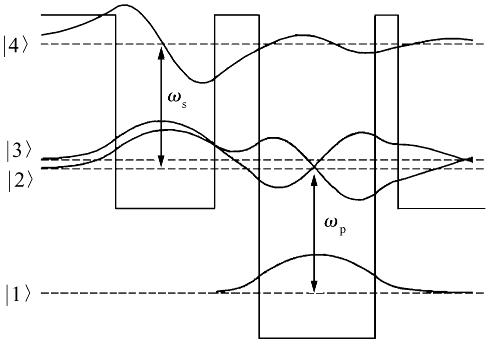


Fig. 14 Conduction subbands of the asymmetric double quantum well.

The ground and first excited states that one would observe, respectively, in the shallow and deep wells when isolated mix to create two new states $|2\rangle$ and $|3\rangle$. Tunneling to a continuum of energies take place from states $|2\rangle$ and $|3\rangle$ through the thin barrier on the right. Using the Fano interference between the two states, they demonstrated an efficient mechanism for ultra fast and broad band all-optical switching. Then in 2007, Li analyzed the controllability of optical bistability in a similar system[100].

Except the above solutions, people are still trying to find SGC in special media. For example, there was an experimental evidence of SGC in quantum dots[101], and the effect of SGC can be greatly enhanced in left-handed materials[102].

5 Summary

SGC can significantly affect the properties of quantum systems and lead to a lot of interesting phenomena. The study of SGC is of great importance in both fundamental researches and applied physics. But due to the stringent conditions, the realization of SGC needs more consideration. We review a few investigations on SGC, including the related phenomena and the efforts made to overcome the requirements. Specifically, it is convenient to simulate SGC with coherence with coherent fields such as laser fields and microwave fields and many theoretical results can be verified in this way. For practical use, we believe that the SGC in condensed matter is more meaningful, because the properties such as transition energy, dipoles, and symmetries can be controlled flexibly by modifying the structures.

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