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# Effect of relaxation rate on population distribution, EIT and refraction in $\Lambda$ and $V$ systems*

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In the three-level $\Lambda$-type and $V$-type systems, we find that the same pump-effect parameter $R\left(=\dfrac{2|V_c|^2\gamma}{(\omega_{ac}-\omega_c)^2+\gamma^2}\right)$ determines the population distributions, while the probe field leads to population fluctuations near the absorption peaks. With the increasing of the relaxation rate $\gamma$, the population distributions are shifted and their fluctuation amplitudes decrease. At the same time the electromagnetically induced transparency window becomes a broadened absorption peak, and the dispersion at the zero probe detuning changes from positive to negative. Large population fluctuation and non-fluctuation observed in different systems are attributed to the different relaxation rates.

**Keywords:** relaxation rate, population distribution, pump-effect parameter
**PACC:** 4250

## 1. Introduction

The decay effect induced by spontaneous radiation was first investigated by Weisskopf and Wigner in the 1930s.[1,2] Using the perturbative method, they found that for a transition from level $|m\rangle$ to $|n\rangle$, the relaxation rate $\gamma_{mn}$ (or linewidth) equals the average of $\gamma_m$ and $\gamma_n$, i.e. $\gamma_{mn}=(\gamma_m+\gamma_n)/2$. Here $\gamma_m$ is the decay rate of level $|m\rangle$, and $\gamma_n$ of $|n\rangle$. In a following paper,[3] Weisskopf considered the atomic collision and added a Stark broadening term in the linewidth formula. About the same time, Heitler[4] pointed out that the interaction between atoms has two consequences. Firstly, the collisions with neighbouring atoms may induce a transition to the ground-level. If the number of effective collisions per second is $\eta$, the breadth of level $|i\rangle$ will increase $\eta$. The second effect is the shifting and splitting of the excited state such as Stark effect and resonance coupling, which cause no state change but lead to an effective broadening. This introduces a dephasing rate $\gamma_{\rm phase}$ in the linewidth. The collisions could be controlled by the buffer gas, resulting in constructive interference.[5] Generally $\eta \ll \gamma_{\rm phase}$, we can treat $\gamma_{\rm phase}$ as the main broadening effect.[6] So the relaxation rate becomes $\gamma_{mn}=(\gamma_m+\gamma_n)/2+\gamma_{\rm phase}$.

As an alterable term in $\gamma_{mn}$, the dephasing rate $\gamma_{\rm phase}$ varies in different media. In the electromagnetically induced transparency (EIT) experiments of alkali metal atomic gases,[7,8] it comes from atom collision, which increases with the gas temperature or density. Lukin *et al*[9] discussed the dependence of absorption and refraction upon relaxation rates in phase coherent media. Boyd *et al* considered[10] the four-wave parametric interaction in two extreme cases. The results for $\gamma_{\rm phase}=0$ are quite different from those for $\gamma_{\rm phase}\gg(\gamma_m+\gamma_n)/2$. Recently the interest in EIT has extended to solid state materials such as rare-earth-doped crystals for practicability.[11,12] Here $\gamma_{\rm phase}$ mainly comes from spin interaction and also increases with the temperature. By changing the media properties, we can always control $\gamma_{\rm phase}$ so as to change $\gamma_{mn}$.

In this work, by varying $\gamma_{\rm phase}$, we investigate the effect of relaxation rate on population distribution, EIT and refraction in $\Lambda$ and $V$ systems. We find that the same pump-effect parameter $R=$

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$\frac{2|V_c|^2\gamma}{(\omega_{ac}-\omega_c)^2+\gamma^2}$ determines the population distributions, while the probe field leads to population fluctuation near the absorption peaks. For given drive and probe Rabi frequencies, when we increase the relaxation rate $\gamma$, the population distributions are shifted and the amplitudes of population fluctuation are decreased. The EIT window becomes a broad absorption peak, and the dispersion at the zero probe detuning changes from positive to negative. The large population fluctuation and non-fluctuation in different systems are explained by different relaxation rates coming from the energy structures.

## 2. Theory

The energy structure of the three-level $\Lambda$ system is shown in Fig.1(a). A pump field with frequency $\omega_c$ is applied between states $|a\rangle$ and $|c\rangle$, and a probe field with frequency $\omega_p$ between states the $|a\rangle$ and $|b\rangle$. We consider the decay of atomic levels due to the spontaneous emission and the collisions. For simplicity we ignore the Doppler effect. In the rotating-wave approximation, the system is governed by the optical Bloch equations:

$$\dot{\rho}_{aa} = -\frac{\mathrm{i}}{\hbar}(V_{ba}\rho_{ab}-\rho_{ba}V_{ab}) - \frac{\mathrm{i}}{\hbar}(V_{ca}\rho_{ac}-\rho_{ca}V_{ac}) - (\Gamma_{ab}+\Gamma_{ac})\rho_{aa}, \quad (1)$$

$$\dot{\rho}_{bb} = \frac{\mathrm{i}}{\hbar}(V_{ba}\rho_{ab}-\rho_{ba}V_{ab}) + \Gamma_{ab}\rho_{aa} - \Gamma_{bc}\rho_{bb} + \Gamma_{cb}\rho_{cc}, \quad (2)$$

$$\dot{\rho}_{cc} = \frac{\mathrm{i}}{\hbar}(V_{ca}\rho_{ac}-\rho_{ca}V_{ac}) + \Gamma_{ac}\rho_{aa} - \Gamma_{cb}\rho_{cc} + \Gamma_{bc}\rho_{bb}, \quad (3)$$

$$\dot{\rho}_{ab} = -\frac{\mathrm{i}}{\hbar}[V_{ab}(\rho_{aa}-\rho_{bb}) - V_{ac}\rho_{cb}] - (\mathrm{i}\omega_{ab}+\gamma_{ab})\rho_{ab}, \quad (4)$$

$$\dot{\rho}_{ac} = -\frac{\mathrm{i}}{\hbar}[V_{ac}(\rho_{aa}-\rho_{cc}) - V_{ab}\rho_{bc}] - (\mathrm{i}\omega_{ac}+\gamma_{ac})\rho_{ac}, \quad (5)$$

$$\dot{\rho}_{bc} = \frac{\mathrm{i}}{\hbar}(V_{ba}\rho_{ac}-\rho_{ba}V_{ac}) - (\mathrm{i}\omega_{bc}+\gamma_{bc})\rho_{bc}, \quad (6)$$

$$\dot{\rho}_{ij} = \dot{\rho}^*_{ji}, \quad (7)$$

where $\omega_{ij}=\omega_i-\omega_j$ is the energy separation between the states $|i\rangle$ and $|j\rangle$. The interaction energy $V_{ai}$ of the transition $|a\rangle \leftrightarrow |i\rangle$ is $V_{ab}=\hbar V_p(\omega_p)\mathrm{e}^{-\mathrm{i}\omega_p t}$ or $V_{ac}=\hbar V_c(\omega_c)\mathrm{e}^{-\mathrm{i}\omega_c t}$, in which $V_p(\omega_p)$ and $V_c(\omega_c)$ are the probe and drive Rabi frequencies, respectively. $\Gamma_{ij}$ is the transition rate from the state $|i\rangle$ to $|j\rangle$. We set $\Gamma_{ab}=\Gamma_{ac}=\Gamma$ and $\Gamma_{bc}=\Gamma_0$. Assuming the collision-induced dephasing rate to be uniform for all $\gamma_{ij}$, the relaxation rates of off-diagonal elements can be written as $\gamma_{ab}=\gamma_{ac}=\gamma=(2\Gamma+\Gamma_0)/2+\gamma_{\mathrm{phase}}$ and $\gamma_{bc}=\gamma_0=\Gamma_0+\gamma_{\mathrm{phase}}$.

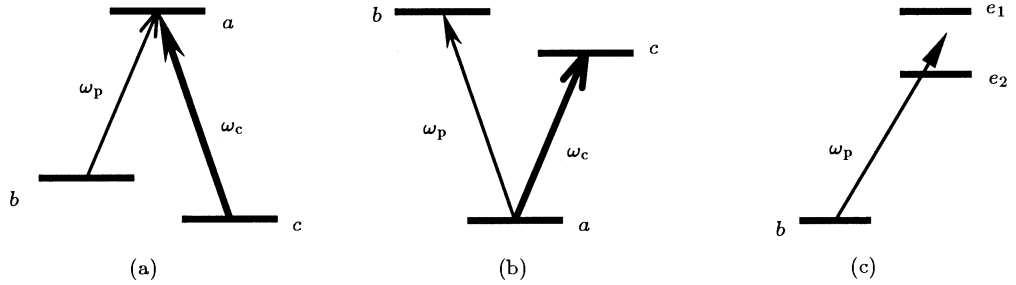



**Fig.1.** Energy structure of $\Lambda$ (a) and $V$ (b) systems. The pump field is applied between $|a\rangle$ and $|c\rangle$, and the probe field between $|a\rangle$ and $|b\rangle$. (c) is the energy structure of $\Lambda$ system in the picture of dressed state. The pump field combines state $|a\rangle$ and $|c\rangle$ into dressed states $|e_1\rangle$ and $|e_2\rangle$. The probe field is applied between $|b\rangle$ and $|e_1\rangle$, $|e_2\rangle$.

In view of the practical photonic processes, we can write the matrix elements as $\rho_{ab}=\rho_{ab}(\omega_p)\mathrm{e}^{-\mathrm{i}\omega_p t}$, $\rho_{ac}=\rho_{ac}(\omega_c)\mathrm{e}^{-\mathrm{i}\omega_c t}$, $\rho_{bc}=\rho_{bc}(\omega_c-\omega_p)\mathrm{e}^{-\mathrm{i}(\omega_c-\omega_p)t}$, $\rho_{aa}=\rho^{dc}_{aa}$, $\rho_{bb}=\rho^{dc}_{bb}$, $\rho_{cc}=\rho^{dc}_{cc}$. For a closed transition, $\rho_{aa}+\rho_{bb}+\rho_{cc}=1$. A set of linear equations of the Fourier amplitudes $\rho_{ij}(\omega_k)$ are obtained[13,14] in the steady state.

First we assume the probe field to be so weak that we can replace $V_p(\omega_p)$ with zero. These equations are solved and we get the population distribution as

$$\rho^{dc}_{aa} = \frac{\Gamma_0 R}{4\Gamma\Gamma_0+(\Gamma+3\Gamma_0)R}, \quad (8)$$

$$\rho^{dc}_{bb} = \frac{2\Gamma\Gamma_0+(\Gamma+\Gamma_0)R}{4\Gamma\Gamma_0+(\Gamma+3\Gamma_0)R}, \quad (9)$$

$$\rho^{dc}_{cc} = \frac{2\Gamma\Gamma_0+\Gamma_0 R}{4\Gamma\Gamma_0+(\Gamma+3\Gamma_0)R}, \quad (10)$$

where $R=\frac{2|V_c|^2\gamma}{(\omega_{ac}-\omega_c)^2+\gamma^2}$.

Then including a nonzero probe field, the system is modified. Population distribution is sensitive to the probe detuning and fluctuates around the Stark peaks. The susceptibility is $\chi(\omega_{\rm p}) \propto [\rho_{ab}(\omega_{\rm p})]/(V_{\rm p}/\gamma)$. Its real and imaginary parts represent the refraction and absorption of probe field, respectively.

For a three-level $V$ system as shown in Fig.1(b), all the equations and results are similar to those of the $\Lambda$ system. The difference lies in the decay rates. For example, in $V$ system $\gamma_{ab} = \gamma_{ac} = \gamma = (\Gamma + \Gamma_0)/2 + \gamma_{\rm phase}$ and $\gamma_{bc} = \gamma_0 = \Gamma + \Gamma_0 + \gamma_{\rm phase}$. When the probe field is zero, the population solution reads

$$\rho_{aa}^{dc} = \frac{\Gamma^2 + 2\Gamma\Gamma_0 + (\Gamma + \Gamma_0)R}{\Gamma^2 + 2\Gamma\Gamma_0 + (2\Gamma + 3\Gamma_0)R}, \qquad (11)$$

$$\rho_{bb}^{dc} = \frac{\Gamma_0 R}{\Gamma^2 + 2\Gamma\Gamma_0 + (2\Gamma + 3\Gamma_0)R}, \qquad (12)$$

$$\rho_{cc}^{dc} = \frac{(\Gamma + \Gamma_0)R}{\Gamma^2 + 2\Gamma\Gamma_0 + (2\Gamma + 3\Gamma_0)R}, \qquad (13)$$

where $R = \dfrac{2|V_{\rm c}|^2\gamma}{(\omega_{ca} - \omega_{\rm c})^2 + \gamma^2}$, which has the same form as that in the $\Lambda$ system. $R/\gamma = \dfrac{2|V_{\rm c}|^2}{(\omega_{ca} - \omega_{\rm c})^2 + \gamma^2}$ is defined as a pump-effect parameter existing in all systems. The numerator represents the strength of pump field. The first term in the denominator is the square of the pump detuning. The pump effect surely will decrease with increasing pump detuning. The second term in the denominator is the square of the relaxation rate. It also weakens the pump effect.

## 3. Results and discussion

In this section, numerical calculations are performed. First, the influence of pump effect on population distribution is considered. In the $\Lambda$ system, we set $\Gamma = 0.2$, $\Gamma_0 = 0.02$, $V_{\rm c} = 4.0$, $\omega_{ac} = \omega_{\rm c}$. Figure 2(a) shows the $\rho$–$R$ curve, which is plotted from Eqs.(8)–(10). When the pump effect is weak, the population of the two lower levels are both close to 0.5 and almost no atom stays in the state $|a\rangle$. When the pump effect is strong, the atoms in the state $|c\rangle$ are mostly pumped into $|b\rangle$. The remainder are equally distributed in the states $|a\rangle$ and $|c\rangle$ due to the strong coupling field between them. In the $V$ system we set $\Gamma = 0.18$, $\Gamma_0 = 0.02$, $V_{\rm c} = 4.0$, $\omega_{ca} = \omega_{\rm c}$. Following Eqs.(11)–(13) the $\rho$-$R$ curves are plotted in Fig.2(b). When the pump effect is weak, most atoms stay in the ground state $|a\rangle$, i.e. $\rho_{aa} \approx 1, \rho_{bb} \approx \rho_{cc} \approx 0$. When the pump effect is strong enough, half of the atoms in the ground state are excited into state $|c\rangle$, i.e. $\rho_{aa} \approx \rho_{cc} \approx 0.5, \rho_{bb} \approx 0$. We note that $\rho_{aa} = \rho_{cc}$ is a common feature in both systems when the pump effect is strong, because in the strong field the stimulated emission is far stronger than spontaneous emission. The competition of the stimulated emission and the stimulated absorption will erase any population difference between $|a\rangle$ and $|c\rangle$. Since the pump effect depends on the relaxation rate, the population distribution also changes with $\gamma$.

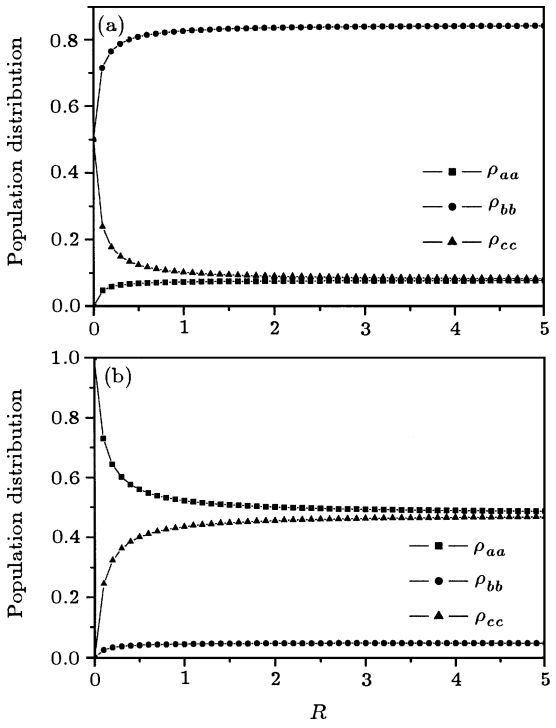



**Fig.2.** $\rho$–$R$ curves in $\Lambda$ and $V$ systems. (a) $\Lambda$ system, when pump effect is weak, $\rho_{aa} \approx 0$, $\rho_{bb} \approx \rho_{cc} \approx 0.5$; when pump effect is strong, $\rho_{aa} \approx \rho_{cc} \approx 0.1$, $\rho_{bb} \approx 0.8$. (b) $V$ system, when pump effect is weak, $\rho_{aa} \approx 1$, $\rho_{bb} \approx \rho_{cc} \approx 0$; when pump effect is strong, $\rho_{aa} \approx \rho_{cc} \approx 0.485$, $\rho_{bb} \approx 0.03$.

Applying the probe field $V_{\rm p} = V_{\rm c}/100$, we investigate the fluctuation of population distributions of the $\Lambda$ system by varying the relaxation rates $\gamma$ and $\gamma_0$. In Fig.3(a), we assume that there is no collision, i.e. $\gamma_{\rm phase} = 0$, $\gamma = (2\Gamma + \Gamma_0)/2 = 0.21$, $\gamma_0 = \Gamma_0 = 0.02$. The distribution is almost insensitive to the probe detuning $(\omega_{\rm p} - \omega_{ab})$. Only in the frequency regions around the absorption peaks, does there exist population fluctuation. Because the probe field excites the atoms from the state $|b\rangle$ to $|a\rangle$, then some of the excited atoms decay into the state $|c\rangle$, causing the population transfer. In Figs.3(b) and (c), we consider the collision effects. The collision induced state-change decay is ignored and only the dephasing rate $\gamma_{\rm phase}$ is

added into $\gamma$ and $\gamma_0$. In Fig.3(b) $\gamma_{\rm phase} = 0.29$, thus $\gamma = 0.5$, $\gamma_0 = 0.31$. The population fluctuation decreases compared with Fig.3(a). When we continue to increase $\gamma_{\rm phase}$ to 4.79, $\gamma = 5.0$, $\gamma_0 = 4.81$, the fluctuation disappears as shown in Fig.3(c). So the fluctuation amplitudes decrease with the relaxation rate. The fluctuation widths are about $\gamma$. In the $V$ system the probe field causes similar population fluctuation. But the amplitudes are far smaller than those in the $\Lambda$ system, for most atoms excited by the probe field finally decay back to the ground level without population transfer.

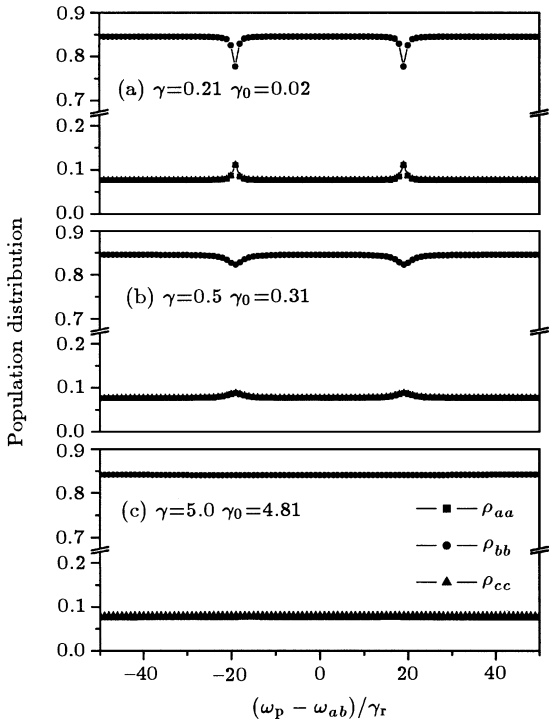



**Fig.3.** Population distribution in the $\Lambda$ system. Here $\gamma_{\rm r} = (2\Gamma + \Gamma_0)/2 = 0.21$ is the pure radiative decay rate. The main distribution consists of straight lines. Population fluctuations are observed near the absorption peaks. With the increasing of relaxation rate (a)$\gamma_{\rm phase} = 0$, $\gamma = 0.21$, $\gamma_0 = 0.02$; (b)$\gamma_{\rm phase} = 0.29$, $\gamma = 0.5$, $\gamma_0 = 0.31$; (c)$\gamma_{\rm phase} = 4.79$, $\gamma = 5.0$, $\gamma_0 = 4.81$, we find both shift of main distribution and decrease of fluctuation amplitudes.

We can explain the population fluctuation in view of the dressed state. Combining $|a\rangle$ and $|c\rangle$ with the pump field, we construct two dressed states $|e_1\rangle$ and $|e_2\rangle$ with frequencies $\omega_{e1} = \omega_a + V_{\rm c}$, and $\omega_{e2} = \omega_a - V_{\rm c}$. As shown in Fig.1(c), now the system contains $|b\rangle$, $|e_1\rangle$, $|e_2\rangle$ and the only external field is the probe field. Similar to the pump effect, there is a probe effect $R' = \dfrac{2|V_{\rm p}|^2\gamma}{(\omega_{\rm p} - \omega_{e1b})^2 + \gamma^2} + \dfrac{2|V_{\rm p}|^2\gamma}{(\omega_{\rm p} - \omega_{e2b})^2 + \gamma^2}$. When the effective probe detunings ($\omega_{\rm p} - \omega_{e1b}$ and $\omega_{\rm p} - \omega_{e2b}$) are both large, $R' \to 0$, the population distribution is stable. Only around the resonant frequencies does $R'$ become large, leading to a noticeable change of population distribution. This is the origin of population fluctuation. Since at resonance one of the probe detunings approaches to zero, $R'$ would be inversely proportional to the relaxation rate $\gamma$. When $\gamma$ is large, $R'$ is small and close to the value in the nonresonant region, so the fluctuation is small. When $\gamma$ is small, $R'$ is large, which results in a large fluctuation.

Both large-scale population fluctuation[15] and non-fluctuation distributions[16] have been observed in the degenerate two-level systems with Zeeman splitting. The difference is attributed to the different energy structures. In a two-level $F_e = 0 \leftrightarrow F_g = 1$ system driven by a parallel polarized field and probed by a transverse polarized field (with $\sigma_\pm$ components) as shown in Fig.4(a), $V_{\rm c} = 5.0\gamma$, $V_{\rm p} = V_{\rm c}/100$, and $\omega_{10} = 2.5\gamma$. The pump field resonant to $|0\rangle \leftrightarrow |e\rangle$ pumps most atoms into $|-1\rangle$ and $|1\rangle$. In the probe frequency region closer to $|-1\rangle \leftrightarrow |e\rangle$, some atoms in state $|-1\rangle$ will be excited into $|1\rangle$ so $\rho_{11} > \rho_{-1-1}$, while in the region closer to $|1\rangle \leftrightarrow |e\rangle$ the result of probe excitation is $\rho_{11} < \rho_{-1-1}$. The transition rate $\Gamma_{-11}$ is so small that the inequality of the states $|-1\rangle$ and $|1\rangle$ cannot be eliminated in the steady state. The population fluctuation is large as shown in Fig.4(b). Figure 5 exhibits another situation. For a two-level $F_e = 1 \leftrightarrow F_g = 0$ system driven and probed by two transverse polarized fields, $V_{\rm c} = 5.0\gamma$, $V_{\rm p} = V_{\rm c}/100$, $\omega_{10} = 2.5\gamma$. Since $\omega_{\rm c} = \omega_{0g}$, the pump field is not resonant to $|-1\rangle \leftrightarrow |g\rangle$ or $|1\rangle \leftrightarrow |g\rangle$. So most atoms concentrate in the state $|g\rangle$. When the probe field is resonant more atoms are excited into states $|-1\rangle$ or $|1\rangle$. Due to the large $\gamma$ they quickly decay back into $|g\rangle$. Hence the distribution is insensitive to the probe frequency. It is the difference of energy structures that makes the distinctness of population distribution in the two systems. If the atoms excited by probe field could only decay back, the fluctuation would be very small, as in the case shown in Fig.4 of Ref.[17]. If these atoms could decay into other levels and accumulate there, we would find obvious fluctuation.

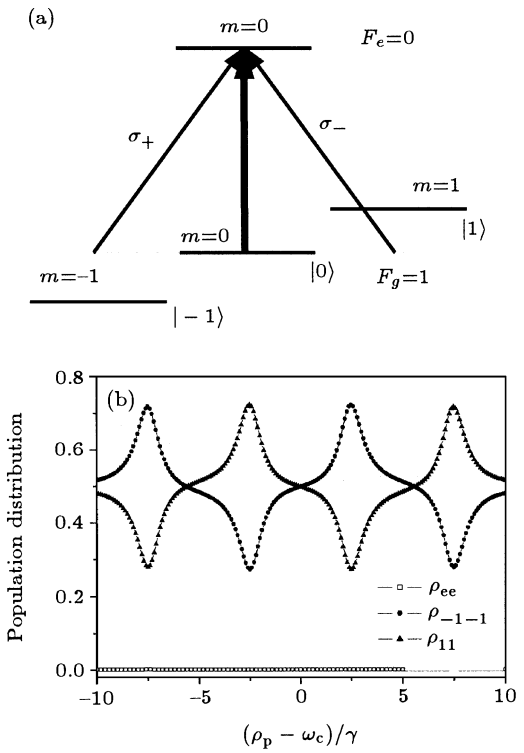



**Fig.4.** Energy structure and population distribution of the two-level $F_e = 0 \leftrightarrow F_g = 1$ system. $V_c = 5.0\gamma$, $V_p = V_c/100$, $\omega_{10} = 2.5\gamma$. The population fluctuation amplitude is very large. Cited from Ref.[14].

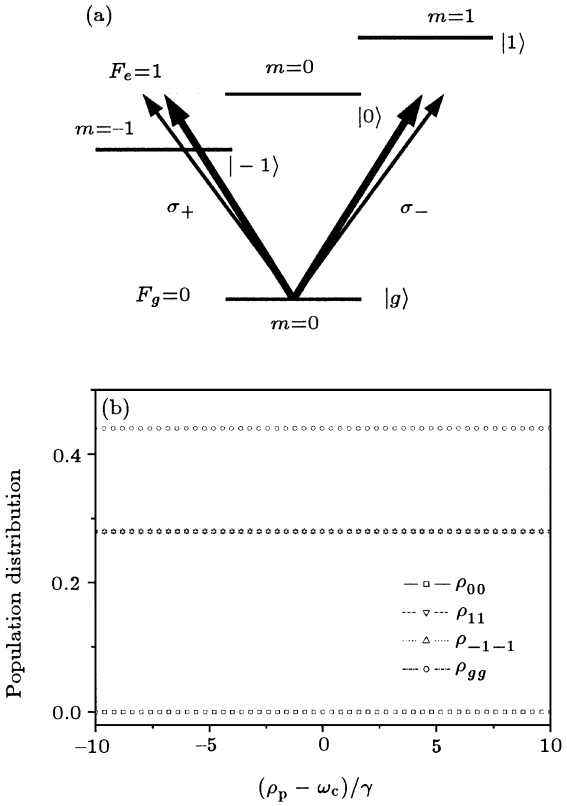



**Fig.5.** Energy structure and population distribution of the two-level $F_e = 1 \leftrightarrow F_g = 0$ system. $V_c = 5.0\gamma$, $V_p = V_c/100$, $\omega_{10} = 2.5\gamma$. The distribution is almost insensitive to the pump–probe detuning. Cited from Ref.[15].

The corresponding absorption and refraction spectra of $\Lambda$ system are depicted in Fig.6. The absorption spectrum is a typical EIT window with line width $\gamma$. Increasing $\gamma$, the absorption peaks become lower and wider. When $\gamma$ is large enough, the two peaks rise again and join together. In this process, the dispersion at zero probe detuning increases from zero. It changes to negative when $\gamma$ is large. In $V$ system we get similar results. Thus the relaxation rate $\gamma$ also decides the line features in both systems.

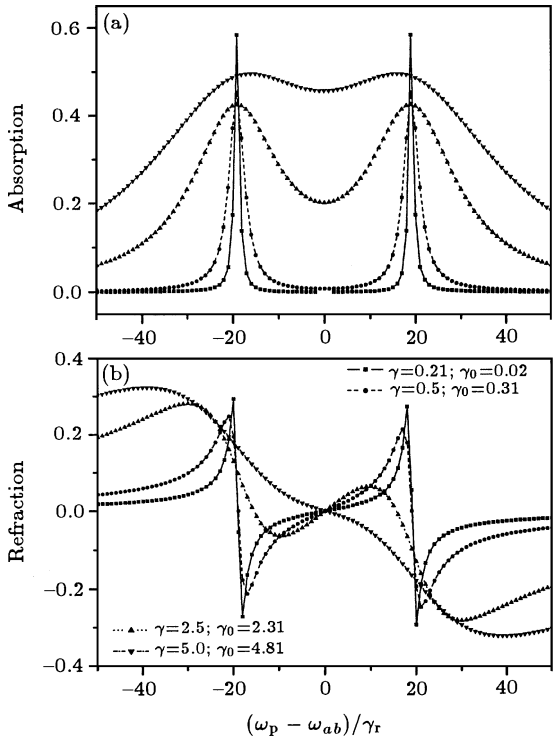



**Fig.6.** Absorption (a) and refraction (b) spectra of $\Lambda$ system. $V_c = 4.0\gamma_r$, $V_p = V_c/100$, $\omega_{bc} = 10\gamma_r$. With the increasing of relaxation rate, the EIT window changes to absorption peak, and dispersion changes from positive to negative at the probe detuning.

## 4. Summary

Generally, for a given system, the main population distributions are determined by the pump effect, while the population fluctuation is determined by the probe effect. Since both the pump and probe effects are influenced by the relaxation rate, this decides the main feature of the population distribution. At the same time the width of absorption peaks as well as dispersion sign are also determined by the relaxation rate. We can readily say that the relaxation rate plays a crucial role in all multilevel systems.

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