Is a rubidium cell with long decay time always useful for generating a non-classical photon pair?

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We experimentally find an interesting and unexpected thing: a rubidium cell with long decay time can not be used to generate a non-classical correlated photon pair via the D2 transition of $^{87}$Rb using four-wave mixing configuration [Opt. Express 16, 21708 (2008)]. In this work, we give a detail theoretical analysis on the EIT of hot $^{87}$Rb with different ground decay time, which shows a probable reason why a rubidium cell with long decay time is not a useful candidate for preparation of a non-classical photon pair via the D2 transition. The simulations agree well with the experimental results. We believe our find is very instructive to such kind of research.

It is well known that a rubidium cell with cell filled with buffer gas or wall paraffin coated can greatly decrease the decay between the ground states, and in most cases, the decrement of such decay can greatly improve the performance of the system. The cell with paraffin coated or buffer gas filled is extensively used in experiments of the generation of non-classical correlated photon pairs. In these works, a non-classical correlated photon pair is successfully generated using Raman scattering via the D1 transition of Rb in a cell filled with buffer gas. Very recently, we prepare non-classical correlated photon pairs using non-degenerate four-wave mixing in a rubidium cell. During the experiments, we find an interesting and unexpected thing: a normal rubidium cell is a good candidate for the generation of non-classical non-degenerate photon pairs using both the D1 and D2 transitions of $^{87}$Rb; On the contrary, we could not obtain the photon pairs via the D2 transition if a cell coated with paraffin or filled with buffer gas is used. We try the cells coated with paraffin, and filled with 30 Torr and 8 Torr’s neon respectively in experiments, we could observe the stimulated four-wave mixing in these cells, but can not obtain the correlated photon pairs.

We think this counter-intuitive result is very probably caused by the small split of the D2 transition of rubidium combined with the large Doppler broadening. Electromagnetically induced transparency (EIT) is the key part of this kind of experiments. However, this combination will make the EIT disappeared, if the decay between the ground states is ignorable. The disappearance of EIT makes it impossible to generate a coherence photon. Therefore no correlated photons can be obtained when a cell with ignorable decay between the ground states is used. Our theoretical analysis shows that the decay between the ground states can make the EIT reappear, which makes the generation of a correlated photon pair available. The experiment on the EIT effect of the D2 line of $^{87}$Rb with different kinds of cells supports our calculation. We believe our find is very instructive to such kind of research.

We show our theoretical analysis as follows. The energy level diagram of $^{87}$Rb is shown in Fig. 1(a). The figure shows that the excited levels of $^{87}$Rb are not singlets. The 5$P_{3/2}$ level has 4 sublevels, and the 5$P_{1/2}$ level has 2 sublevels. Two of the sublevels $F = 1$ and $F = 2$ can form a Λ structure for EIT with the ground states 5$S_{1/2}$. This structure can be simplified to a four-level structure as shown in Fig. 1(b), in which there are two Λ-type structures: $|1\rangle - |3\rangle - |2\rangle$ and $|1\rangle - |4\rangle - |2\rangle$ for EIT. If the energy difference between $|3\rangle$ and $|4\rangle$ is not large enough, these two paths will interfere with each other, and the property of the EIT will be changed, especially when the Doppler broadening is considered. We make a detail analysis by using the master equation. Considering a four level system with two fields $\omega_p$ and $\omega_c$ as shown in Fig. 1(b) we treat $\omega_p$ as the probe field, which is much weaker than the coupling field $\omega_c$. The effective Hamiltonian of the system can be written as

$$H_{\text{int}} = -\frac{\hbar}{2} \begin{pmatrix} 0 & 0 & \Omega_{p3} & \Omega_{p4} \\ 0 & 2(\Delta_p - \Delta_c) & \Omega_{c3} & \Omega_{c4} \\ \Omega_{p3} & \Omega_{c3} & 0 & 2\Delta_p \\ \Omega_{p4} & \Omega_{c4} & 0 & 2(\Delta_p - \omega_{x34}) \end{pmatrix},$$

where $\Delta_p = \omega_p - \omega_{31}$, $\Delta_c = \omega_c - \omega_{32}$, $\omega_{ij}$ is the frequency difference between levels $|i\rangle$ and $|j\rangle$. $\Omega_{pi} = \mu_i E_p / \hbar$ and $\Omega_{ci} = \mu_i E_c / \hbar$ are the Rabi frequencies of the fields with the corresponding transitions, $\mu_p$ is the transition electronic dipole moment of the $|i\rangle \rightarrow |j\rangle$ transition. Here we suppose all $\Omega_{pi}$ and $\Omega_{ci}$ are real. When a cell filled with buffer gas or coated with paraffin is used, the exchange of the atoms can be ignored, therefore the decay between the ground states is very small and can be ignored. The master equation for the atomic density operator can be written as
We numerically solve Eq. (2) to obtain the linear susceptibility $\chi(\omega_p)$ concerned with $\omega_p$, $\chi(\omega_p) \propto (\rho_{31}/\Omega_{p3} + \rho_{41}/\Omega_{p4})$. In the calculation, we suppose $\mu_{31} = \mu_{41} = \mu_{32} = -\mu_{42}$. The energy difference between $5P_{3/2}, F = 1$ and $5P_{3/2}, F = 2$ is 157 MHz, which is about 26 times $\Gamma_3 = \Gamma_{31} + \Gamma_{32}$ (about 6 MHz). Substituting the data $\Omega_{p3} = \Omega_{p4} = 0.001\Gamma_3$, $\Omega_{3} = -\Omega_{c4} = \Gamma_3$, $\Delta_c = 0$ to Eq. (2), we obtain $\text{Im}[\chi(\omega_p)]$ versus $\delta = \Delta_c - \Delta_c$ as shown in Fig. 2. This figure shows that the existence of level $|4\rangle$ will slightly affect the EIT spectrum: the EIT signal is not symmetric.

Following, we consider the effect of Doppler broadening. The distribution function of the frequency shift with respect to the center frequency $f_0$ can be simplified as

$$P(f) \propto \exp \left( -\frac{m\lambda_0^2(f - f_0)^2}{2kT} \right),$$

(3)

where $k$ is the Boltzmann constant, $T$ is the temperature, $f$ is the frequency, $m$ is the mass of $^{87}$Rb, and $\lambda_0$ is the wavelength of the corresponding transition. Substituted the data of $^{87}$Rb and $T = 320$ K into Eq. (3), the imaginary part of the susceptibility after Doppler integration is shown in Fig. 3. This figure clearly shows that the EIT signal has been ruined completely by the Doppler broadening. Instead of the transparency at $\delta = 0$, there is an enhanced absorptive peak. This absorptive peak is very small compared with the background, therefore we have not observed it in the experiment yet. The disappearance of the transparency window makes the atomic ensemble opaque to the photon. Therefore coherent photons can not be generated.

When a normal cell is used, the exchange of the atoms should be considered, the decay time between the ground state is short. The atoms leaving and entering the light beam can be considered as an effective decay between the ground states, the master equation for a normal cell can be denoted as

$$\frac{d\rho}{dt} = M - r\rho + \frac{r}{2}(\sigma_{11} + \sigma_{22}),$$

(4)

or

$$\frac{d\rho}{dt} = M + \gamma\left(2\dot{\sigma}_{12}\rho - \dot{\sigma}_{22}\rho - \rho\dot{\sigma}_{22}\right)$$

$$+ \frac{\gamma}{2}(2\dot{\sigma}_{21}\rho - \dot{\sigma}_{11}\rho - \rho\dot{\sigma}_{11}),$$

(5)

where $M$ is the right side of Eq. (2), $r$ is the exchange rate of atoms, $\gamma$ is the effective decay between the ground states caused by the exchange of atoms. Equation (4) gives a direct description of the atoms leaving and entering the field, and Eq. (5) shows the effective decay between the ground states caused by the exchange of atoms. Although these two descriptions are different, they show
The reason why the decay can enhance the EIT is that the decay makes the EIT signal reduced very quickly as the increment of detuning of the coupling. Therefore the interfere between the two EIT paths is small enough and the EIT can be preserved even the Doppler broadening exists. To support this point, we show the numerical result of the comparison of the EIT with and without the decay, which correspond to the cases in which the coupling is resonant with the $|2\rangle \rightarrow |3\rangle$ transition and is at the center of the $|2\rangle \rightarrow |3\rangle$ and $|2\rangle \rightarrow |4\rangle$ transitions. The results are shown in Fig. 5. Figure 5(a) shows that the decay does not affect the EIT too much when the coupling is resonant with a transition. Figure 5(b) shows that when the coupling is detuned from the transition, the interference of the two paths can cause a large absorptive peak at $\delta = 0$, which makes the disappearance of EIT after considering Doppler broadening. The existence of the decay between the ground states makes the absorptive peak weakened very quickly as the detuning of the coupling is increased, this makes the EIT preserved even Doppler broadening exists.

In the case of the D1 transition of the $^{87}\text{Rb}$, because the energy split of $5P_{1/2}$ is large enough, the EIT signal will always exists after integration of Doppler broadening. That is the reason why the work reported in Ref. [1, 2, 3, 4] can generate non-classical photon pairs successfully.

In conclusion, We make a detail theoretical analysis on the EIT at the D2 transition of the hot $^{87}\text{Rb}$, which shows the long decay time between the ground states will ruin the EIT. This analysis shows a probable reason why a rubidium cell with long decay time is not a useful candidate for preparation of a non-classical photon pair via the D2 transition. The simulations agree well with the experimental results. We believe our find can give a very useful instruction to such kind of research.

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