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Electromagnetically-induced transparency in a multi-V-type system in cesium atomic vapour*

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Electromagnetically-induced transparency is observed in a three-level multi-V-type system in cesium vapour at room temperature. The absorption property is measured and the hyperfine structures of atomic states can be determined. The results of the experiment agree with the theoretical analysis.

Keywords: cesium atom, Electromagnetically-induced transparency, multi-V-type system
PACC: 3280, 3510W, 4225K

1. Introduction

Electromagnetically-induced transparency (EIT) in atomic systems has attracted great attention in recent years due to its applications in nonlinear optics and quantum optics. Many theoretical and experimental works have been focused on the phenomena related to atomic coherence, such as coherent population trapping and lasing without inversion[1,2] and EIT especially in Λ-type and cascade-type three-level rubidium atomic systems.[3,4] Clarke *et al.*[5] obtained EIT signals in cesium vapour and cold cesium atom cascade-type systems, respectively. A simple theoretical treatment of the EIT effect in a three-level Doppler-broadened medium was developed, which gave quite clear physical explanations to the experimental results, including the absorption and dispersion properties[6] and hyperfine spectroscopy.[7] The absorption of a weak probe beam at the resonance frequency can then be substantially reduced, while the enhancement of the index of refraction makes the group velocity in the EIT medium less than the velocity in vacuum.[8] As a result of this slowing of group velocity, the optical pulse that enters the EIT medium is spatially compressed,[9] which plays a very important role in quantum information storage.[10]

In real atomic systems, such as cesium atoms, the atomic states related to the coupling or probe field usually have many hyperfine levels which may contribute to the atomic coherence when the linewidth of the coupling or the probe field and the natural linewidth of the associated atomic transition are smaller than the separations between the hyperfine components. One cannot resolve these components simply due to the fact that the hyperfine structures are completely concealed by these broad linewidths of the coupling or the probe field. Yet the hyperfine components do contribute to the atomic coherence separately. In such a case, one is able to resolve the closely spaced hyperfine components as the probe frequency is scanned through the whole range of the hyperfine structures and the absorption of the probe beam is recorded. The hyperfine structures of excited states have been determined by EIT in a cascade rubidium atomic system.[7]

In this paper, we report on the three-level multi-V-type system EIT experiments of a weak probe laser beam passing through a cesium vapour. The hyperfine structures of $6P_{3/2}$ are determined. A theoretical model including all these hyperfine levels is presented. The experimental results are in agreement with theoretical calculations.

2. Theoretical treatment

The atomic system used in this experiment is a three-level multi-V-type cesium atomic system, and

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all the relevant hyperfine components are shown in Fig.1. We consider a closed V-type three-level system with a ground state $|1\rangle$ and two excited states $|2\rangle$ and $|3\rangle$ interacting with two laser fields. The transition $|1\rangle \rightarrow |2\rangle$ is coupled with the coupling or pumping field with frequency $\nu_{\rm c}$, and the other transition $|1\rangle \rightarrow |3\rangle$ is coupled with the probe field with frequency $\nu_{\rm p}$. The state $|1\rangle$ serves as a common state for the two transitions in the V-type system. The hyperfine level separation between F=3 and F=4 in $6S_{1/2}$ is about 9.19GHz and is irrelevant in this experiment, since it is much larger than the hyperfine separations in state $6P_{3/2}$. In this paper, one of the hyperfine F'=3,4 or 5 of $6P_{3/2}$ (serving as $|2\rangle$) and F=4 of $6S_{1/2}$ (serving as the common state $|1\rangle$) can be chosen to interact with pumping field, and another hyperfine of $6P_{3/2}$ (serving as the state $|3\rangle$) and F=4 of $6S_{1/2}$ can interact with probing field. Thus the EIT effect can be observed in different V-type systems.

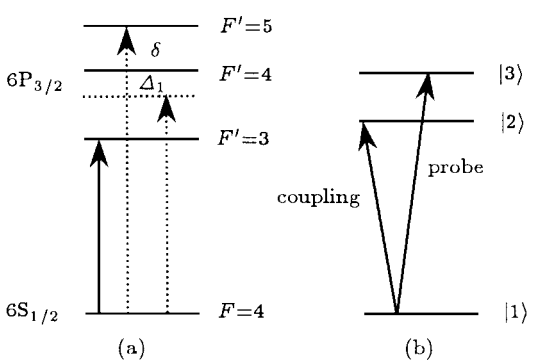


Fig.1. Relevant energy levels of the cesium atom: (a) the hyperfine levels of the cesium atom; (b) V-type three-level system.

We consider a closed three-level V-type system described by a semiclassical theory. The motion equations for the slowly varying off-diagonal matrix elements of the atomic density operator are

$$\dot{\rho}_{13} = [\mathrm{i}(\Delta_1 + \delta) - \gamma_{13}]\rho_{13} - \frac{\mathrm{i}\mu_{13}}{2}\varepsilon(\rho_{11} - \rho_{33}) + \frac{\mathrm{i}}{2}\Omega_{\rm c}\exp(-\mathrm{i}\Phi_{\rm c})\rho_{23},$$

$$\dot{\rho}_{23} = [\mathrm{i}(\Delta_2 - \Delta_1 + \delta) - \gamma_{23}]\rho_{23} + \frac{\mathrm{i}\Omega_{\rm c}}{2}\exp(\mathrm{i}\Phi_{\rm c})\rho_{13} - \frac{\mathrm{i}}{2}\mu_{13}\varepsilon\rho_{12}^{*},$$

$$\dot{\rho}_{12} = (\mathrm{i}\Delta_2 - \gamma_{12})\rho_{12} + \frac{\mathrm{i}}{2}\mu_{13}\varepsilon\rho_{23} - \frac{\mathrm{i}}{2}\Omega_{\rm c}\exp(-\mathrm{i}\Phi_{\rm c})(\rho_{11} - \rho_{22}).$$

Here γ_{13} and γ_{12} are the decay rates of two excited states $|2\rangle$ and $|3\rangle$ to the ground state $|1\rangle$, respectively, and γ_{13}= γ_{12}=γ, γ is about 5MH. γ_{23} is the nonradiative decay rate between two excited states, Δ_2 and Δ_1 are the detuning of probe and pump fields, $\Omega_{\rm c}$ is the Rabi frequency of pumping field, μ_{13} is the relevant dipole moment, and δ is the separation of the two hyperfine levels of $6P_{3/2}$. We assume that the probe field is weak enough and it does not significantly populate the upper level of the probe transition. Under these conditions, we solve the equations

$$\rho_{13} = \frac{\mu_{13}\varepsilon}{2Z}[(\Delta_2 - \Delta_1 + \delta)(\mathrm{i}\Delta_2 - \gamma) - \mathrm{i}/4\Omega_{\rm c}^2],$$

where

$$Z = [\mathrm{i}(\Delta_1 + \delta) - \gamma][\mathrm{i}(\Delta_2 - \Delta_1 + \delta)] \times [\mathrm{i}\Delta_2 - \gamma] + \Omega_{\rm c}^2(\mathrm{i}\Delta_2 - \gamma)/4.$$

The susceptibility of the atomic system can be written as

$$\chi = \frac{2N_0\mu_{13}}{\varepsilon}\rho_{13} = \frac{2N_0\mu_{13}^2}{\Omega_{\rm c}\hbar}\rho_{13},$$

where N_0 is the density of the atoms. The real and imaginary parts of the susceptibility lead to the dispersion and absorption characteristics of the atomic medium in the usual way.

We consider the pumping and probe laser passing through a Doppler-broadened atomic vapour in the same direction. In the case of $\nu_{\rm p} \approx \nu_{\rm c}$, the susceptibility of the atomic system takes the form given in Ref.[3].

When the laser line shape can be considered Lorentzian, the effect of the finite laser linewidth can be included in the decay rates, so that $\gamma \rightarrow \gamma + \Delta\nu_{\rm p} + \Delta\nu_{\rm c}$, where $\Delta\nu_{\rm p}$ and $\Delta\nu_{\rm c}$ are the linewidths of the probe and pumping field, respectively. The imaginary and real parts of χ are proportional to the absorption coefficient and dispersion properties, respectively, of the atomic medium for a weak probe beam. The theoretical results are shown in Fig.3 by the dashed line.

3. Experiments and results

The experimental set-up is shown in Fig.2. Both the pumping (DL1) and probe (DL2) lasers are New-Focus 6017 model external-cavity diode lasers that are temperature stabilized and can be tuned to the D_2 line of cesium atoms. The free-running linewidth of the lasers are less than 1MHz. These two laser beams are arranged to have orthogonal polarization and propagate in the same directions through a 3 cm

long cesium vapour cell which is kept at room temperature (~25°C). The weak probe beam is monitored by a avalanche photodiode (Hamamatsu Si APD, type S3884). The power of the pumping and probe beams are 10.1mW and 0.549mW, respectively, satisfying the condition $\Omega_c \gg \Omega_p$. The pumping beam is stabilized to transition from $6S_{1/2}(F=4)$ to $6P_{3/2}(F'=3)$ by the saturated absorption technique, and the probe laser is scanned across the transitions from the $6S_{1/2}$ $(F=4)$ to $6P_{3/2}$ hyperfine structures.

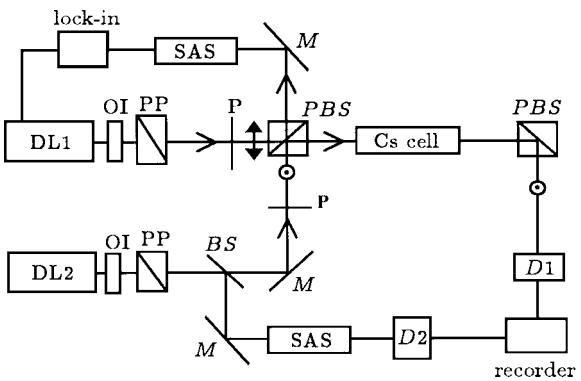


Fig.2. Experimental set-up: DL1 and DL2, diode lasers; M, completely reflecting mirror; P, polarizer; PP, prism pair; OI, optical isolator; PBS, cube polarization prism; SAS, saturated absorption spectroscopy device, $D1$ and $D2$, optical detectors; ⊙, the polarized direction of probe beam.

The results are shown in Fig.3 by the solid line. It is interesting to note that there are two absorption dips corresponding to the two hyperfine levels of the $6P_{3/2}$ ($F'=4$ and $F'=5$, respectively) (the transition from $F=4$ to $F'=2$ is the dipole forbidden transition). Because the pumping field exactly resonates with the $6S_{1/2}$ $F=4$ to $6P_{3/2}$ $F'=3$, while the probe field is scanned from $F=4$ to the $6P_{3/2}$ hyperfine structure, it makes two V-type systems ($F=4\rightarrow F'=4$ and $F=4\rightarrow F'=5$) as denoted in Fig.1, and there are two absorption dips in the absorption curve. These results agree with the theoretical result and Ref.[7]. Due to the fact that the laser beams have definite linewidths in the experiment, the linewidth of the experiment is greater than that of the theory. The absorption dips correspond to the two hyperfine levels of $6P_{3/2}$, therefore we can determine the hyperfine structure of the atom using the EIT effect. This method of spectroscopy is based on atomic coherence, and the resolution strongly depends on the natural decay rates of the related atomic states and the linewidths of both the probe and coupling fields. We also find the effects of the linewidth of the pumping field on the multi-V-type EIT. The result of the experiment shows that when the linewidth of the pumping light is decreased, the absorption dip is narrowed and the hyperfine structures can be more precisely determined. This agrees with the result of Ref.[11].

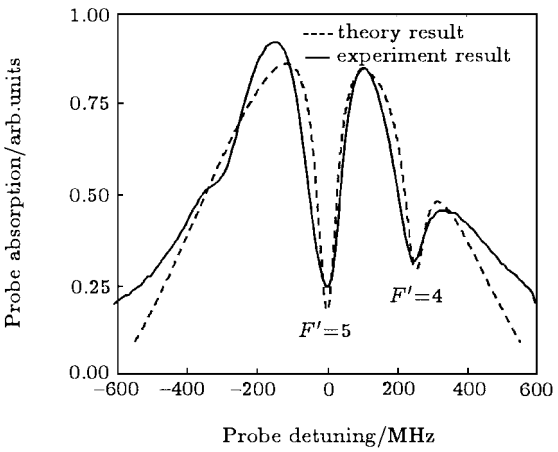


Fig.3. Absorption property of the cesium atom vapour versus probe detuning. The pumping frequency is stabilized at the transition from $6S_{1/2}$ $F=4$ to $6P_{3/2}$ $F'=3$, while the probe frequency is scanned over all the hyperfine structures of $6P_{3/2}$. The solid line shows the results of the experiment and the dashed line the results of the theory for $\gamma = 6.0$ MHz and δ=250MHz.

4. Conclusion

We have reported the experimental measurements of the absorption property of a weak probe in a multi-V-type system of cesium at room temperature. Two absorption dips were observed and the results of the experiments are in good agreement with the theoretical calculation. From the position of the absorption dips, the hyperfine structures of the atomic system are determined using atomic coherence, but the spectroscopic resolution strongly depends upon the natural decay rates of the related atomic states and linewidths of both the probe and coupling fields. So the linewidth of pumping light should be small, such that the hyperfine structures may be determined more precisely.

For a special V-type and cascade[7] atomic system, this method is proven to be another simple way for atomic spectroscopy which has high resolution. Our results show that one can use the atomic coherence as a useful property for atomic spectroscopy.

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