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Dependence of electromagnetically induced transparency on temperature*

Xiao Feng(肖 峰), Guo Rui-Min(郭瑞民), Li Lu-Ming(李路明),
Yang Dong-Hai(杨东海), and Chen Xu-Zong(陈徐宗)†

Key Laboratory of Quantum Information and Measurement, Ministry of Education of China, Department of Electronics, Peking University, Beijing 100871, *China*

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We performed an experimental study on the dependence of the linewidth of electromagetically induced transparency (EIT) on the temperature of medium in a Λ-type configuration using caesium vapour. We found that the transparent window is narrowed in the EIT whose two ground levels are composed of two hyperfine levels, and broadened in the case when the two ground levels are degenerated Zeeman sublevels, as the temperature of vapour cell is increased. The explanation for the phenomena is given qualitatively.

Keywords: electromagnetically induced transparency, Λ-type configuration, Zeeman sublevel
PACC: 4250, 3510W, 4225

1. Introduction

Electromagnetically induced transparency (EIT) is a quantum interference which eliminates the absorption effect of a medium on a propagating weak probe light field in resonance with an atomic transition, with a strong coupling light field on another linked transition.[1] Since 1991, when Boller *et al* observed the EIT phenomenon with high-power pulsed lasers in neutral strontium atomic vapour,[2] a great deal of theoretical and experimental work has followed. Among them, all the three types of EIT, including Λ-, V-, and cascade- type, have been well studied under many kinds of conditions and media.[3−6] In recent years, great progress has been made in respect of the potential applications. In particular, in 1999, the speed of light was slowed to 17m/s by Hau *et al.* [7] Two years later, storage of light was realized in cooled atomic cloud of sodium and in the vapour of ^{87}Rb respectively by Hau [8] and Lukin,[9] based on the mechanism of EIT. These important experiments, together with the high-resolution spectroscopy, high-precision magnetometers,[10−14] need a narrow EIT linewidth. Under this impetus, the dependence of EIT linewidth on the experimental parameters such as atomic relaxation, Doppler broadening, laser linewidth and laser intensity, etc., has attracted a great deal of interest recently. Experimentally, the EIT linewidth has been studied in several papers:[12,15] for example, how the laser intensity influences the EIT linewidth is now well known. Also there has been some theoretical work on the EIT linewidth carried out in recent years.[16,17]

However, to the best of our knowledge, no experiments have been reported on the dependence of EIT linewidth on the temperature of medium. The solution to this problem would not only be helpful to an understanding of the physical mechanism of EIT, but is also very important for its applications, such as the experiment of stopping light where the temperature needs to be carefully considered. In this paper, we perform two experiments in a caesium vapour cell, using hyperfine levels and Zeeman sublevels as the two ground states for a Λ-type EIT system, respectively. We have found an interesting phenomenon: namely, that when the temperature of the vapour cell increases, the EIT linewidth can be broadened or narrowed. A qualitative explanation for this is given.

2.Experiments and results

The experiments are carried out in the same

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†E-mail: xzchen@ele.pku.edu.cn

setup, with one caesium vapour cell used. A resistance wire that is made into a solenoid is employed to heat the cylindrical vapour cell. In order to avoid an additional magnetic field to the vapour cell by the solenoid, we use bifilar winding with opposite directions. An asbestos cloth is placed between the resistance wire and the vapour cell, which results in a uniform heating, and a thermometer is used to monitor the temperature of the vapour cell.

The diagram of the relevant levels we use in the first experiment of the EIT, whose two ground states are composed of two hyperfine levels, is shown in Fig.1. We employ the transition of $6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=4 for coupling, and $6S_{1/2}$, F=4 $\rightarrow$ $6P_{3/2}$, F=4 for probe. In the setup shown in Fig.2, DL1 serving as the coupling is a Toptical diode laser with an external cavity, and DL2, a New Focus laser, serves as the probe. Both the linewidths of the two lasers are less than 1 MHz. We put these two laser beams together in the same directions of propagation by PBS3, with their linear polarization being orthogonal. QWP1 turns the two overlapped beams to left circular and right circular polarization respectively, and QWP2 restores the two circularly polarized beams to linear ones. Only the weak probe beam is monitored by a photodiode after passing through a 7cm caesium vapour cell. The vapour cell is covered with a solenoid of resistance wire and an asbestos cloth that are used to change the temperature, and then the whole is shielded by μ metal to protect from the earth magnetic field. By the saturated absorption technique, DL1 is locked to the transition from $6S_{1/2}$, F=3 to $6P_{3/2}$, F=4, and DL2 is used to scan the transition from $6S_{1/2}$, F=4 to $6P_{3/2}$, F=3,4,5. The intensities of the coupling and probe laser beams are 3 and 0.8mW, respectively.

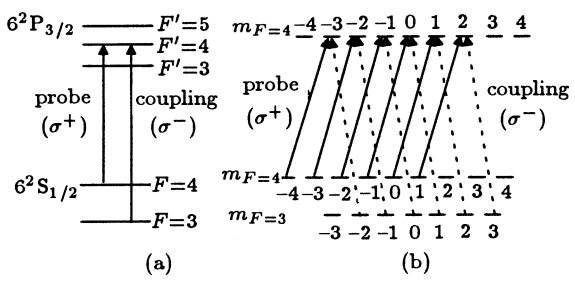


Fig.1. Relevant energy levels of the caesium atom for the first experiment. (a) The hyperfine levels $6S_{1/2}$, F=3 and $6S_{1/2}$, F=4 serve as two ground states, and the $6P_{3/2}$, F=4 serves as the common state in the Λ-type EIT configuration. (b) The details of couplings among the Zeeman sublevels with the laser polarization used in the experiment when EIT occurs.

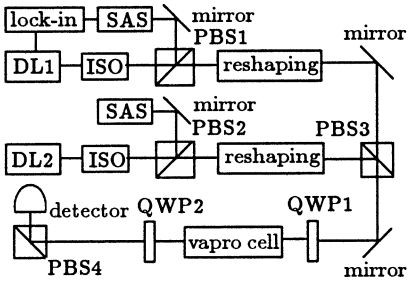


Fig.2. Experimental setup for the two experiments. DL1 and DL2 are diode lasers with an external cavity for each; ISO is optical isolator; an anamorphic prism is used for reshaping; the vapour cell is shield by μ metal; the detector is a photodiode.

Figure 3 shows the results we obtained in the experiment. The EIT linewidth decreases from 5.28 to 3.39 MHz, corresponding to the temperature of the caesium vapour cell increasing from 24 to 60°C. Among the data, an error occurs at 56°C, which leads to an abnormal point. The origin that the EIT linewidth has a narrower tendency versus the temperature of the caesium vapour cell will be discussed later in this paper.

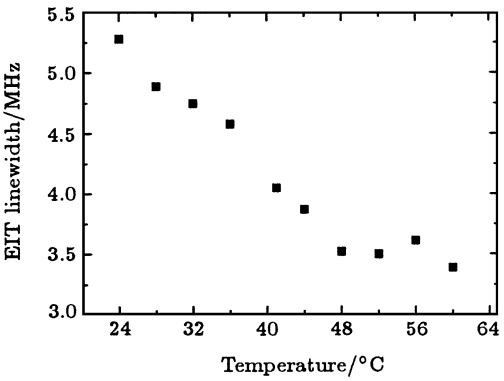


Fig.3. EIT linewidth versus the temperature of the caesium vapour cell. A decreasing tendency of EIT linewidth versus temperature is clearly visible. There is an abnormal point in the figure, which we consider as an error.

The schematic of energy levels for the second experiment of the EIT, whose two ground states consist of degenerated Zeeman sublevels, is shown in Fig.4. In this case, we employ a coupling laser with right circular polarization and a probe laser with left circular polarization to couple the same transition $6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=2. The same experimental setup and even the same optical collimation as that in the first experiment are used, as shown in Fig.2, where DL1 is locked to the transition of $6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=2, and DL2 scan over the transition of $6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=2. The seven ground states and the five common states in the EIT system are degenerated due to the

caesium vapour cell being shielded by μ metal, so that EIT occurs when the probe frequency is resonant with the transition of $6S_{1/2}$, F=3 $\rightarrow$ $6P_{3/2}$, F=2. It is important to mention that, in this experiment, when we obtain the data, we have to turn off the power supply to the resistance wire that otherwise would generate a weak magnetic field on the vapour cell, because the EIT system with degenerated ground states is very sensitive to the magnetic field. The power of the coupling and probe laser beam is 1.49 and 0.13mW, respectively.

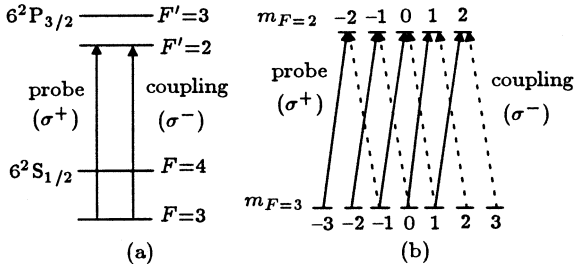


Fig.4. Relevant energy levels of the caesium atom for the second experiment. (a)The hyperfine level $6S_{1/2}$, F=3 serves as two ground states, and $6P_{3/2}$, F=4 serves as the common state in the Λ-type EIT configuration. (b) Detail of couplings among the Zeeman sublevels with the laser polarization as used in the experiment when EIT occurs.

The results are shown in Fig.5. It is surprising that in this case the EIT linewidth has a different behaviour versus the temperature of the vapour cell. The EIT linewidth increases from 4.8 to 11.2 MHz, when the temperature of the caesium vapour cell changes from 32 to 48°C; this has an opposite tendency to the case of the first experiment.

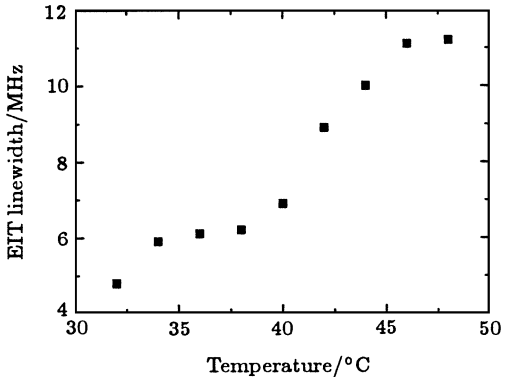


Fig.5. EIT linewidth versus the temperature of the caesium vapour cell. An increasing tendency of EIT linewidth versus temperature is clearly visible.

3. Discussion and conclusion

The EIT linewidth depends on many parameters, such as the linewidth of coupling laser, coupling intensity, collimation between the coupling and probe light when they pass through the vapour cell, temperature of vapour, atomic density, with or without buffer gas in the vapour, etc. As we know, the collision of atoms that results in dephasing when EIT occurs, depends on the temperature of vapour. In other words, the collision will increase the decay of atomic levels and broaden the transparent window of EIT. From this point of view, the higher the temperature, the wider the EIT linewidth, if the other parameters are kept unchanged. However, there lies a trick in it. That is, with increasing temperature of the cell, the atomic density in the vapour will increase at the same time. This process contributes to the narrower EIT linewidth, because more atoms take part in the coherence when EIT occurs. So, there are two contradictory effects on the EIT linewidth simultaneously, as a result of the increase of the temperature of the vapour cell. One is the collision that broadens the EIT linewidth, the other is the atomic density that narrows it. The variation of the EIT linewidth versus the temperature of the vapour cell we observe in experiments depends on which effect is larger in the process of heating.

In our cases, the EIT linewidth narrows when heating the caesium vapour cell in the first experiment, where the two ground states for the Λ-type EIT configuration consist of two hyperfine levels. It is demonstrated that the atomic density of vapour plays a leading role in the EIT linewidth compared with the collision. In contrast, as intuitively shown in Fig.5, the EIT linewidth broadens in the second experiment, where the two ground states consist of degenerated Zeeman sublevels. It is identified that in this case the collision of atoms is dominant between the two factors that affect the EIT linewidth. The opposite behaviours of these two EITs can be explained qualitatively as follows. In the first experiment, the splitting of the two ground states is relatively large, which is about 9.19 GHz, from $6S_{1/2}$, F=3 to $6S_{1/2}$, F=4. Nevertheless, in the second experiment, the splitting of the two ground states is degenerated. This will lead to different decay between the two ground states in these two EIT configurations. In our situation, the decay between the two ground states in the second configuration (as shown in Fig.4) is more sensitive to the collision than in the first configuration (as shown in Fig.1), because the splitting of the second configuration is smaller than that of the first one. In other words, the decay between the two ground states in the

second configuration is larger than that in the first one owing to the collision. That is the reason why the atomic density of vapour plays a leading role in the EIT linewidth in the first configuration, instead of the collision, and why the collision is the dominant effect on the EIT linewidth in the latter configuration, compared with the atomic density of vapour.

In conclusion, we have found different behaviours of the EIT linewidth when increasing the temperature of the caesium vapour cell in two different Λ-type EIT configurations, and further that there are two contradictory effects on the EIT linewidth when the temperature of vapour cell is increased. These two contradictory effects can lead to a different behaviour of EIT linewidth versus the temperature, corresponding to the different EIT configuration of energy levels. This is important in many experiments such as light slowing, because we have to control the temperature of the medium to obtain a narrow EIT linewidth. On the other hand, our experiments further our understanding of the mechanism of the EIT phenomenon.

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