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Absorption spectroscopy of cold caesium atoms confined in a magneto-optical trap*

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Absorption spectra of cold caesium atoms confined in a magneto-optical trap are measured around D_2 line at 852nm with a weak probe beam. Absorption reduction dip due to electromagnetically induced transparency (EIT) effect induced by the cooling/trapping field in a V-type three-level system and a gain peak near the cycling transition are clearly observed. Several mechanisms mixed with EIT effect in a normal V-type three-level system are briefly discussed. A simple theoretical analysis based on a dressed-state model is presented for interpretation of the absorption spectra.

Keywords: absorption spectroscopy, caesium atoms, magneto-optical trap (MOT), V-type three-level system, electromagnetically induced transparency (EIT)

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1. Introduction

Because cold atoms are free from Doppler-broadening and allow much longer interaction time with external field compared with the case of thermal atomic vapour, they play more and more important roles in the fields of atomic physics, high-resolution spectroscopy, quantum optics and quantum metrology.[1−5] The magneto-optical trap (MOT)[6,7] has become a standard technique for creating cold neutral atomic samples in many laboratories for it is simple but powerful. To gain some dynamic information, measurements of absorption spectra of cold alkali atoms confined in a MOT have been performed by several groups.[8−11] For example, Grison *et al*,[8] Tobosa *et al*,[9] and Mitsunaga *et al*[10] measured the absorption spectra of cold caesium atoms in a MOT around 6 $^2S_{1/2}$ $F = 4 - 6^2P_{3/2}$ transitions of D_2 line (only $F = 4 - F' = 5$ cycling hyperfine transition in Refs.[8] and [9], but the whole three hyperfine transitions $F = 4 - F'$=3, 4 and 5 in Ref.[10]), and Zachorowski *et al*[11] measured the absorption spectra of cold ^{85}Rb atoms in a MOT around 5 $^2S_{1/2}$ $F = 3 - 5^2P_{3/2}$ F'=2, 3 and 4 transitions. Even after switching off the cooling/trapping beams of a MOT, measurements of pump–probe spectra of cold but free atoms also have been performed. For instance, the pump–probe spectra of cold alkali atoms released from a MOT around D_2 line were measured by Mitsunaga *et al*[10] and Chen *et al*[12] (caesium in Ref.[10], and ^{87}Rb in Ref.[12]). In all these cases probe absorption is strongly influenced by the cooling/trapping field or the pumping field.

Considering the atomic coherence induced by the pumping field, people have investigated experimentally the steady-state electromagnetically induced transparency (EIT) effects in the pump–probe spectra of cold alkali atoms with Λ-type[13−17] and ladder-type[15,18,19] three-level systems (^{85}Rb and ^{87}Rb in Ref.[13], ^{87}Rb in Refs.[14] and [15], sodium in Refs.[16,17], and caesium in Refs.[18,19]). One of the exciting points of EIT is that an optical pulse may have an extremely low group velocity[16] and even can be stored in an ultra-cold atomic sample.[17]

In this paper we present the absorption spectra of cold caesium atoms confined in a MOT around the D_2 line at 852 nm. Absorption reduction dips due

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to atomic coherence induced by the cooling/trapping field in a V-type three-level system are observed. In a normal V-type three-level system, several physical mechanisms such as absorption saturation and hyperfine optical pumping may be mixed with the EIT effect. A simple analysis is made in our case. Brief discussion based on a simple dressed-state model is also presented for interpretation of the obtained absorption spectra.

2. Vapour cell MOT of caesium atoms

Cold atomic sample is produced by a conventional vapour cell MOT.[7,20] A stainless steel vacuum chamber with a background pressure of about 5×10^{-7}Pa is connected with a caesium reservoir via a metal valve. A qradrupole magnetic field for MOT is generated by a pair of anti-Helmholtz coils with a typical gradient of 10^{-3}T/cm along the axis of the coils (corresponding to the current of 1.6A). A master-oscillator power-amplifier (MOPA) diode laser system (SDL, TC40-850) with a typical linewidth of about 500 kHz and a Bragg-distributed-reflector (DBR) diode laser (SDL, 5712-H1) with a typical linewidth of about 3 MHz are used for cooling/trapping and repumping laser sources, respectively. The frequency of both lasers is stabilized via the conventional locking technique based on saturation absorption spectroscopy. Typical frequency jitter for both lasers is about 1 MHz in a time scale of several seconds.

Relevant hyperfine levels of bare caesium atoms are schematically depicted in Fig.1, and the transitions for cooling/trapping field, repumping field and probe are also indicated by C, R and P, respectively.

Three circularly-polarized cooling/trapping laser beams with a spot diameter of about 15mm and a typical power of 16mW are guided by reflection mirrors to orthogonally intersect at the central point of the vacuum chamber and are retro-reflected back. A typical detuning of cooling/trapping field (Δ) is 15MHz below the cycling transition. The detuning can be easily controlled by an acousto-optical modulator (AOM, Crystal Technology Inc, Model 3080–122) with double-pass configuration. The repumping beam overlapped with one cooling/trapping beam is used to pump atoms on F=3 state back to the cycling transition. The repumping beam has a diameter of about 15mm and a typical power of 10mW. The schematic diagram of our MOT system is illustrated in Fig.2.

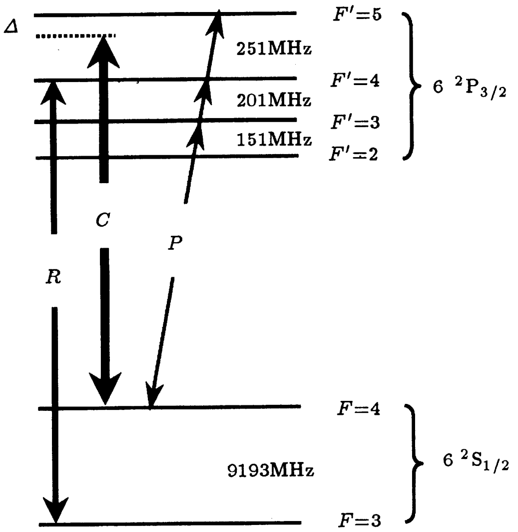

Fig.1. Schematic diagram of relevant hyperfine energy levels of bare caesium atoms. Cooling/trapping field (C), repumping field (R), and probe fields (P) are indicated by the arrows. Δ is the detuning of the cooling/trapping field to the cycling transition ($F = 4 - F'$=5).

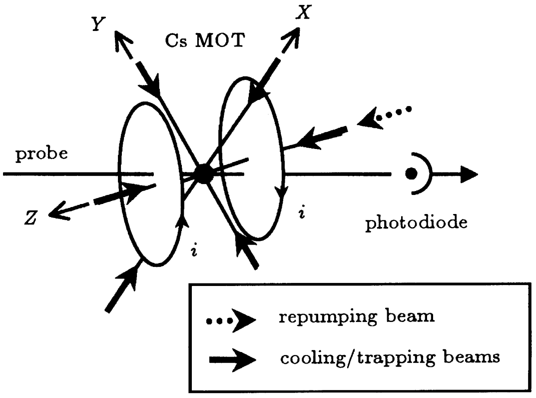

Fig.2. Schematic experimental setup of caesium magneto-optical trap (MOT). Three groups of the circularly-polarized cooling/trapping beams are mutually orthogonal. The quadrupole magnetic field is generated by a pair of the anti-Helmholtz coils with the same DC current intensity (i). The absorption spectra of the cold caesium atoms confined in the MOT are measured with the weak probe beam and the photodiode.

After three seconds loading, approximately 1×10^7 cold caesium atoms are captured in this vapour cell MOT. The measured temperature via time of flight is about 70μK, compared with the Doppler cooling limit T_D=125μK for caesium. The cold cloud has a typical size of about 1mm. Another DBR diode laser (SDL, 5712-H1) at 852nm is used for the probe (P in Fig.1). The probe beam is coupled into a polarization-maintaining optical fibre to gain a good transverse profile. After collimating, the linearly-polarized probe beam is sent through the cold cloud.

The angle between the probe beam and horizontal cooling/trapping beam is approximately 15°. Typical power for the probe is about 50μW. When we increase the probe power to a certain value, a dark spot inside the cloud can be clearly observed in the fluorescence image via a CCD camera. This indicates the pushing effect due to a relatively intense probe beam.

3. Absorption spectroscopy of cold caesium atoms confined in a MOT

During measurements of absorption spectra, we keep the cooling/trapping beams and the repumping beam on. The qradrupole magnetic field is also kept on. When the probe laser scans over $F = 4 - F'=3$, 4 and 5 transitions of D_2 line at 852nm, typical absorption spectra of the cold caesium cloud in the MOT are recorded as shown in Fig. 3(a) (lower curve). The saturation absorption spectra (SAS) of a caesium vapour cell are measured simultaneously for frequency calibration (upper curve in Fig.3(a)).

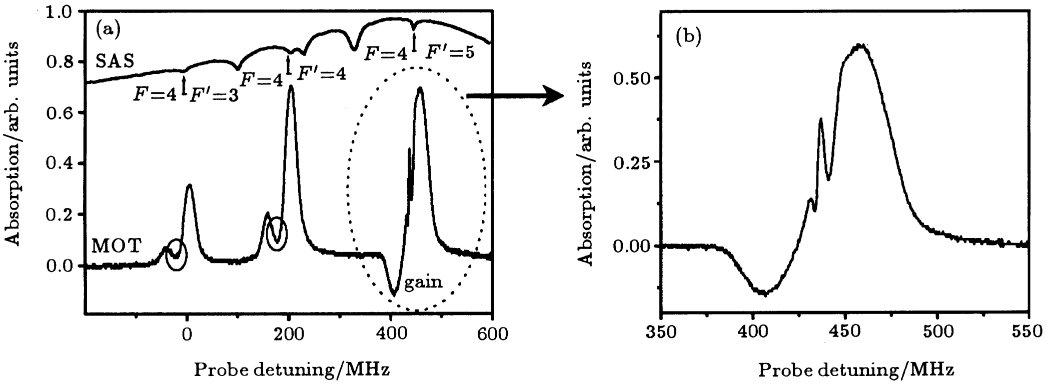

Fig.3. Typical absorption spectra of cold caesium atoms in the MOT as the probe scans over the $F = 4 - F'=3$, 4 and 5 hyperfine transitions of D_2 line (lower curve in (a)). The saturated absorption spectra (SAS) of a caesium vapour cell are presented for frequency calibration (upper curve in (a)). Two solid circles indicate the absorption reduction dips due to EIT effect in the V-type three-level system. A gain peak near the cycling transition is also observed. The part in the dashed circle is enlarged and shown as (b).

Because Doppler broadening dominates the absorption spectra of thermal atoms in the caesium vapour cell and the hyperfine splitting of 6 $^2P_{3/2}$ state is well below the Doppler broadening (about 500MHz), the signals of three hyperfine transitions ($F = 4 - F'=3$, 4, 5) and three crossovers are on the same Doppler background in the SAS. As expected in the case of cold atoms in the MOT, no Doppler background and no crossover are observed.. Absorption reduction dips can be clearly observed at the red side of $F = 4 - F'=3$ and $F = 4 - F'=4$ hyperfine transitions (indicated by solid circles in Fig.3(a)).

The signal corresponding to $F = 4 - F'=5$ cycling transition in the lower curve looks more complicated and is more or less similar to the results described in Refs.[8–10]. Zachorowski *et al*[11] reported roughly the same results in the absorption spectra of $F = 3 - F'=4$ hyperfine transition of the D_2 line in ^{85}Rb MOT. The peak on the right-hand side corresponds to the absorption of the cycling transition in the presence of the cooling/trapping field.[8,9] The gain peak is due to a three-photon Raman process.[8] Between these two components there is a dispersion-like structure (Fig.3(b)), which is due to Rayleigh resonance.[8]

4. Discussion

The absorption reduction dips indicated by solid circles in Fig.3(a) are due to the EIT effect in a V-type three-level system of cold caesium atoms. Considering the multi-three-level V-type system in Fig.1, we know that the common lower level is the F=4 hyperfine level of 6 $^2S_{1/2}$ ground state and one of the upper levels is the F'=5 hyperfine level of 6 $^2P_{3/2}$ excited state. The intense cooling/trapping field C couples F=4 and F'=5 levels with a red detuning Δ (Δ=15MHz in our experiment), while the weak probe field P couples F=4 and F'=3 or 4 level of the 6 $^2P_{3/2}$ excited state. Because the cold caesium cloud is very small (typical size is about 1mm in our case) and its centre is located at the zero point of net magnetic field, when we consider the light–atom interaction of these multi-three-level systems of cold atoms, we can ignore the magnetic field inside the region of cold cloud even though the qradrupole magnetic field actually exists.

Generally speaking, the EIT effect has rarely been observed in the V-type three-level configuration, because it is not pure but mixed with several effects.[21–23] Actually, the above-mentioned V-type three-level system is not ideal for practical multi-level atoms. The absorption saturation induced by the coupling field and the hyperfine optical pumping induced by both coupling and probe fields will take effect.[21] From the following simple analysis we can see that these two mechanisms will mix with absorption reduction due to EIT. As depicted in Fig.4(a), population in F=4 level will decrease due to the absorption saturation induced by the coupling field, so the probe absorption will be reduced. Figure 4(b) shows the hyperfine optical pumping induced by coupling and probe fields, which also will decrease the probe absorption. Adopting a coupling field exactly resonated with $F = 4 - F'$=5 cycling transition, we can apparently reduce the hyperfine optical pumping. In this case, Refs.[21, 23] reported observation of the EIT effect on a V-type three-level atomic system in vapour cell. In our case, even though the cooling/trapping field serves as the coupling field simultaneously, the population in the F=4 level still has big leakages in the relatively intense red-detuning coupling field. But the repumping field on $F = 3 - F'$=4 transition may avoid these population leakages. In this way the EIT effect in our V-type multi-three-level system of cold caesium atoms can be expected.

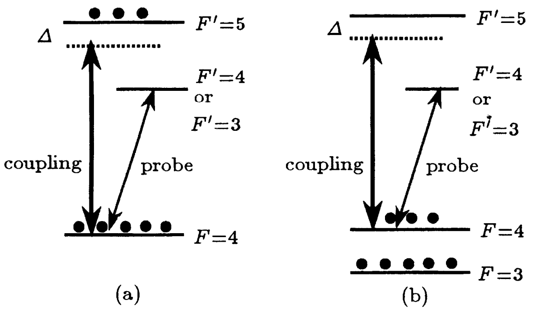

Fig.4. Two mechanisms involved in the V-type three-level system which may influence the atomic coherence induced by the coupling field: the saturation (a) and the hyperfine optical pumping (b). In our case the cooling/trapping field serves as the coupling field simultaneously.

To understand the absorption spectra of cold caesium atoms confined in the MOT and the EIT-induced absorption reduction, a simple dressed-atom model can be quoted as shown in Fig.5. The cold atomic sample coupled with the red-detuning coupling field (Fig.5(a)) can be described as in Fig.5(b) in a dressed-atom picture.[24] When $\Delta \sim \Gamma$, the coupling field will split F=4 and F'=5 levels into two dressed states ($|1(N-1)\rangle$ and $|2(N-1)\rangle$ for F=4, $|1(N)\rangle$ and $|2(N)\rangle$ for F'=5) with a frequency span of $\Omega = \sqrt{\Omega_\mathrm{C}^2 + \Delta^2}$; here Δ is the red detuning of the coupling field, Γ is the natural linewidth and Ω_C is the Rabi frequency of the coupling field.[24] F'=3 and 4 levels are weakly perturbed by the coupling field because of relatively far off-resonance. Also populations in four dressed states are qualitatively indicated in Fig.5(b) by solid circles. From this picture we can clearly see the asymmetrical Autler–Townes doublet in probe absorption around the $F = 4 - F'$=3 and 4 transitions, so the absorption reduction dips are expected. Concerning the cycling transition, the four dashed arrows near the right-hand side in Fig.5(b) indicate the probe resonant positions. From left to right, the first dashed arrow corresponds to the three-photon Raman gain peak in Fig.3 because of inversion of population. The fourth one corresponds to the absorption peak. The second and the third ones have the same frequency and they correspond to the middle dispersion-like structure (Rayleigh resonance) in Fig.3.

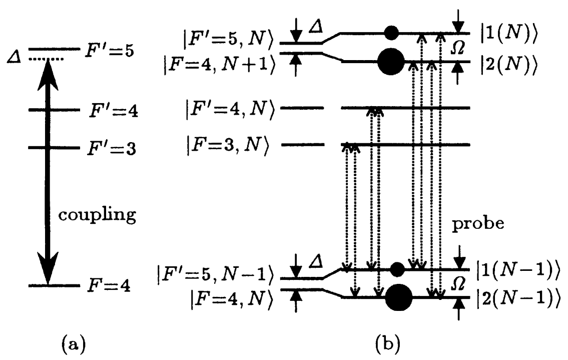

Fig.5. Relevant hyperfine levels of caesium bare atoms driven by the red-detuning coupling field (a). Dressed-atom levels (b). Δ is the red detuning of coupling field to the cycling transition, and $\Omega = \sqrt{\Omega_\mathrm{C}{}^2 + \Delta^2}$, where Ω_C is Rabi frequency of the coupling field. The steady-state populations is qualitatively indicated by the black balls. The dashed arrows indicate resonance positions of the probe. Because the coupling field is far off-resonance, $F' = 3$ and $F' = 4$ states are only weakly perturbed.

From this simple model, we also expect that the large absorption peaks corresponding to $F = 4 - F'$=3, 4 and 5 hyperfine transitions in Fig.3(a) will have a blue detuning. These points are also confirmed in our experiment by frequency calibration by using SAS. If we make calculations by using this dressed-atom model, we can find that frequency span between the Autler-Townes doublets (indicated by solid circles in Fig.3(a)) is somewhat larger than the calculated value. But this is not mainly due to the error of estimated Rabi frequency of coupling field. This is also confirmed by recent similar experiment in ^{87}Rb MOT.[25] It is associated with photon re-scattering process in cold atomic cloud, which may increase the effective Rabi frequency of the coupling field.[25]

In summary, the absorption spectra of cold caesium atoms confined in a MOT around the D_2 line at 852nm are measured, and absorption reduction dips due to the EIT effect in the V-type three-level system are observed. Some mechanisms, which are negative to EIT in the V-type configuration, are discussed briefly. A simple dressed atom model is quoted to interpret the absorption spectra of cold caesium atoms in the MOT. To obtain more information and a clearer physical picture, systemic experimental measurements and relevant theoretical calculations should be made. But we can gain some information about light–atom interaction in the MOT from the probe absorption spectrum and from the above qualitative analysis at this stage.

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