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Autler–Townes doublet in novel sub-Doppler spectra with caesium vapour cell*

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With a coupling laser locked to caesium $6S_{1/2}$ F_g=4–$6P_{3/2}$ F_e=5 cycling transition and a co-propagating probe laser scanned across $6S_{1/2}$ F_g=4–$6P_{3/2}$ F_e=3, 4 and 5 transitions, a novel scheme for sub-Doppler spectra in Doppler-broadened V-type three-level system is demonstrated by detecting the transmission of the coupling laser through a caesium vapour cell. The Autler–Townes doublet in the sub-Doppler spectra of the coupling laser is clearly observed. The effects of coupling laser intensity on the splitting and linewidth of the Autler–Townes doublet are experimentally investigated and the results agree well with theoretical predictions. Taking the multiple hyperfine levels of caesium atom into account, a brief analysis is presented.

Keywords: sub-Doppler spectra, Autler–Townes doublet, caesium atoms
PACC: 4262, 3200, 3280

1. Introduction

The light–atom interaction is one of the most important subjects in quantum optics and laser spectroscopy. Originally, Autler and Townes developed a theory and proved experimentally the AC Stark splitting of energy levels driven by a microwave field, named the Autler–Townes doublet.[1] The results were introduced into optics[2] and elicited a series of experimental research works which aimed to the features of two-level atomic system driven by a resonant field. Then a breakthrough for understanding of the spectra and the light–atom interaction was achieved using dressed atoms model.[3] From then on the Autler–Townes doublet has occupied an important position in laser spectroscopy. To explore the implication of Autler–Townes doublet, generally one directs a weak scanning probe laser into a thermal atomic vapour cell, which is illuminated by an intense coupling laser, to observe a probe transmission spectrum. However, it is inevitable that the spectra always contain a Doppler background due to the motion of thermal atoms in the vapour cell, and the Doppler broadening limits the resolution of the spectra greatly.

Indeed, the absorption spectra of cold atoms may perfectly meet the requirement of Doppler-free spectroscopy,[4,5] but it cannot be applied widely and easily because of the complex laser cooling and trapping system. So the sub-Doppler spectra in thermal atomic system are still the object many physicists pursue in this field. Several sub-Doppler technical approaches[6−11] have emerged as the practice requires, for example, saturation absorption spectroscopy (SAS), polarization spectroscopy, two-photon spectroscopy, and selective reflection spectroscopy.

Considering a Λ-type or a ladder-type three-level system, Refs.[8] and [12] predict the sub-Doppler Autler–Townes doublet, even sub-nature Autler–Townes doublet in a Doppler-broadened system based on the density-matrix motion equations. The V-type system also has the same behaviour.[10,13] Subsequently, all these predictions are experimentally observed.[8−10] These results have made a large step

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to precise spectroscopy and were used to measure the interval of hyperfine levels of atoms.[11]

In this paper, with an intense coupling laser locked to caesium $6S_{1/2}$ F_g=4–$6P_{3/2}$ F_e=5 cycling transition and a copropagating weak laser scanned across $6S_{1/2}$ F_g=4–$6P_{3/2}$ F_e=3, 4 and 5 transitions, we demonstrate novel sub-Doppler spectra in a Doppler-broadened V-type three-level system by detecting the transmission of the coupling laser through a caesium vapour cell. The splitting and the linewidth of the Autler–Townes doublet in the sub-Doppler spectra are systematically measured and compared with the theoretical predictions.

2. Experimental arrangement

Figure 1 shows the relevant caesium hyperfine levels and transitions in our experiment. An 852nm grating external-cavity diode laser (ECDL, Toptica DL100) was locked to F_g=4–F_e=5 transition as the coupling laser, while an 852nm distributed-Bragg-reflector (DBR) diode laser (SDL-5712-H1) scanned across F_g=4–F_e=3, 4, 5 transitions as the probe laser. The linewidth of model DL100 ECDL is about 1 MHz, and DBR laser's linewidth is typically 3 MHz at a time scale of 1 second.

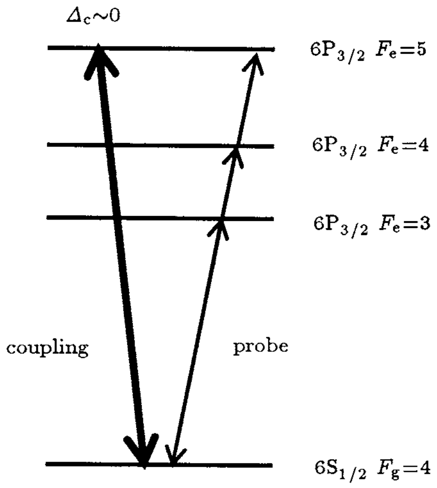

Fig.1. The relevant hyperfine levels of caesium atoms. The coupling laser is locked to $6S_{1/2}$ F_g=4–$6P_{3/2}$ F_e=5 cycling transition (detuning to the cycling transition $\Delta_c \sim 0$), while the probe laser is scanned across the whole $6S_{1/2}$ F_g=4– $6P_{3/2}$ F_e=3, 4, 5 three transitions.

The sketch of our experimental setup is depicted in Fig.2. The coupling and probe lasers were shaped by anamorphic prism pairs to a nearly circular spot with diameter 2.1mm and 1.5mm, respectively. The SAS technique is used to lock the coupling ECDL

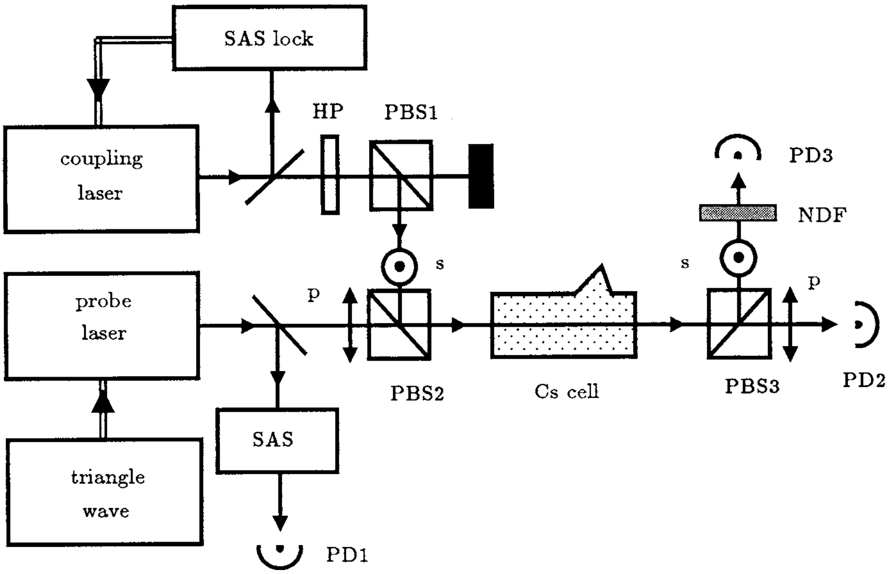

Fig.2. Schematic diagram of the experimental arrangement. The saturation-absorption-spectroscopy locking technique (SAS lock) is utilized to actively stabilize the coupling laser to F_g=4–F_e=5 cycling transition. An adjustable attenuator consisting of a half-wave plate (HP) and a polarized beams splitting cube 1 (PBS1) is for controlling the coupling intensity. The SAS device provides a reference frequency standard as the function generator to scan the probe laser's frequency across F_g=4–F_e=3, 4 and 5 transitions. PBS2 is used to combine the s-polarized coupling beam and the p-polarized probe beam before entering the caesium cell, and PBS3 to separate them after the cell. PDs: photodiodes; NDF: neutral density filter.

laser and provides a frequency standard for calibrating the probe frequency detuning. In the region of 40mm-long caesium vapour cell, the probe beam's power is kept at about 35 μW, while the coupling beam's power can be modified from 0 to 30mW through a half-wave plate (HP) and a polarized-beam splitting cube (PBS1). PBS2 and PBS3 with typical extinction ratio of 50dB are used to combine and separate the coupling and probe lasers. So the coupling and probe beams copropagate in the caesium cell with orthogonal linear polarizations (s-polarization for the coupling beam and p-polarization for the probe beam, indicated as "s" and "p" in Fig.2). Transmission beams of probe and coupling lasers are received by photodiodes PD2 and PD3 respectively, and recorded with a digital oscilloscope (not shown in Fig.2) which is trigged by the synchronistic signal from the triangle wave generator for probe laser scanning.

3. Experimental results and discussion

Generally, one detects the transmission of the probe laser to study the interaction of atom and coupling beam. However, the Doppler background is the most annoying issue. In this paper, we prefer to detect the coupling transmission as well as the probe absorption signal. Since the frequency interval of F_e=5 and F_e=4 is 251MHz (much larger than the coupling laser linewidth ~1MHz), and the coupling laser is frequency-locked to F_g=4–F_e=5 cycling transition, the absorption of the coupling laser attributes mainly to the zero velocity atoms in the direction parallel to that of laser propagation.[10] As soon as the coupling laser is guided into the vapour cell with a certain intensity, it will immediately reach a population balance between ground state and excited state and experience a stable transmission signal. The transmission signal only varies with the coupling intensity. Only if the probe laser drives these atoms to another hyperfine level such as F_e=3 or F_e=4, the population balance will be disturbed, and the absorption intensity of the coupling laser in the atomic system will be different. So the Autler–Townes doublet is also observed in the transmission spectra of coupling laser while scanning the probe laser frequency.

In trace *a* of Fig.3 the saturation absorption spectrum is given for frequency calibration of the probe frequency detuning. The probe's transmission spectrum is shown as trace *b* of Fig.3. From left to right, it shows electromagnetically induced transparency (EIT) peaks of V-type three-level system located at the frequency position of F_g=4–F_e=3, F_g=4–F_e=4 and electromagnetically induced absorption (EIA) absorption-enhanced peak of nearly degenerate two-level system located inside an absorption-saturated dip at F_g=4–F_e=5. The relevant analysis and detailed experimental results are presented in Refs.[14] and [15].

When the probe laser frequency is smoothly scanned across F_g=4–F_e=3, 4 and 5 transitions the sub-Doppler spectra in the coupling laser's transmission are recorded and shown as traces *c* and *d* in Fig.3 with different coupling intensity. Obviously trace *c* displays sub-Doppler character without any Doppler background. With a moderate coupling intensity the Autler–Townes doublet is clearly observed in the sub-Doppler spectra (trace *d* of Fig.3).

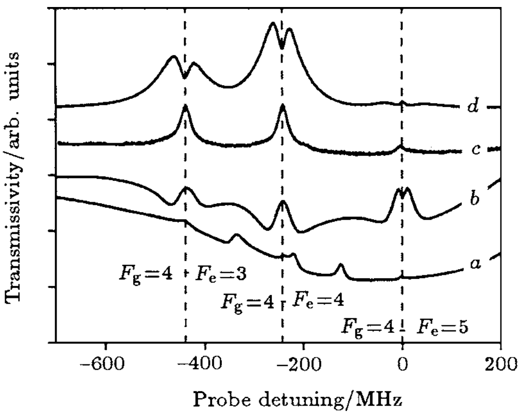

Fig.3. Transmissive spectra of the probe and coupling beams. Trace *a* is the typical Doppler-broadened saturation absorption spectrum, which is for frequency calibration. F_g=4–F_e=5 cycling transition is reasonably selected as zero point of probe detuning. Trace *b* from PD2 is for probe beam. Trace *c* from PD3 is the transmissive signal of weak coupling beam. From left to right the three Doppler-free peaks correspond to F_g=4–F_e=3, 4, 5 transitions respectively. Trace *d* also from PD3 is the transmissive signal of the intense coupling beam. Autler–Townes doublet can be clearly seen around F_g=4–F_e=3 and F_g=4–F_e=4 transitions because the intense coupling beam splits F_g=4 state into two dressed states.

In order to explain the physical processes behind the doublet, many theoretical analyses have been presented. Here we only recall the V-type three-level system with an intuitive dressed-atoms picture.[13] When an intense coupling field is applied to a stationary two-level atomic system, the AC Stark shift induced by the coupling field deeply modifies the atomic energy-level structure and leads to a new resonance. This modification or interaction between the two-level system and the intense coupling field could be understood as the dressed atoms.[3] The absorption spectra of these dressed atoms were separated into two peaks located at the position of two dressed states, named the Autler–Townes doublet. Their locations are given by[13]:

$$\varDelta_{1,2} = \frac{\varDelta_c}{2} \pm \frac{1}{2}\sqrt{\varDelta_c^2 + 4\varOmega_c^2}. \quad (1)$$

And the linewidths of the two Autler–Townes peaks are expected as

$$(\varDelta\nu)_{1,2} = \frac{\varGamma}{2}\left(1 \mp \frac{\varDelta_c}{\sqrt{\varDelta_c^2 + 4\varOmega_c^2}}\right), \quad (2)$$

where $\varOmega_c$ is the Rabi frequency of the coupling laser, $\varDelta_c$ is the detuning of the coupling laser and $\varGamma$ is the natural linewidth of hyperfine level ($\varGamma = 2\pi \times 5.2$MHz for caesium $6P_{3/2}$ state). If $\varDelta_c \approx 0$, the location ($\varDelta_{1,2}$) of the two peaks have $\pm\varOmega_c$ symmetrically shifted away from the atomic hyperfine transition and their linewidth $(\varDelta\nu)_{1,2}$ will keep at $\varGamma/2$. In this situation, the splitting between the two Autler–Townes peaks uniquely depends on the coupling intensity. In our experiment, the transmission signal of the locked coupling laser obtained with PD3 reveals mainly the zero-velocity atoms' behaviour (no Doppler shift for these atoms). It is clear from the above expression that, if $\varDelta_c \approx 0$, the two peaks of the doublet are symmetric and have identical linewidth. However, the actual situation is not so simple. We could not consider only the zero velocity atoms practically. The non-zero velocity atoms also have a certain probability to absorb the coupling and probe beams, and the locked coupling laser does not run exactly at the resonate frequency and exist a certain detuning. As a result, the doublet is somewhat asymmetric though the coupling laser is locked (trace d of Fig.3).

Figure 4 is the Autler–Townes splitting for F_g=4–F_e=3 transition as a function of optical power of the coupling beam with $\varDelta_c \approx 0$. The theoretical result from Eq.(2) is also given as the curve. The experimental data are in good agreement with the theoretical result.

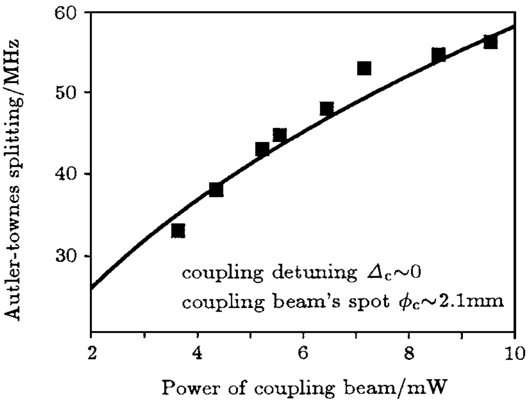

Fig.4. The frequency splitting of the Autler–Townes doublet in coupling beam's transmission for F_g=4–F_e=3 transition versus power of coupling beam. The solid squares are experimental data. Probe beam is kept at 35μW. Diameters of beam spots are approximately 1.5mm for probe beam and ~ 2.1mm for coupling beam in the caesium cell region. The solid curve is the theoretical result.

According to Eq.(2) the linewidth of the Autler–Townes doublet is $\varGamma/2$ and independent of the coupling intensity. The linewidths of the Autler–Townes peaks for F_g=4–F_e=3 transition are measured at different coupling powers (see the solid circles in Fig.5) and it is shown that these linewidths are much larger than $\varGamma$. It can be seen that the stronger the coupling, the larger the linewidth. Actually, if taking the optical power broadening into account, the linewidth will depend upon $\varGamma/2\sqrt{1+s}$ (see the solid curve in Fig.5), here $s = I_c/I_s$ is the saturation parameter, I_c is the intensity of the coupling beam and $I_s = 1.12\text{mW/cm}^2$ is the saturation intensity for caesium atoms. A remarkable difference between experimental measurements and theoretical prediction is probably due to other reasons, such as misalignment of the coupling and probe beams in the caesium cell, geomagnetic field, other stray magnetic fields, and collisions broadening. All these factors will further broaden the Autler–Townes doublet.

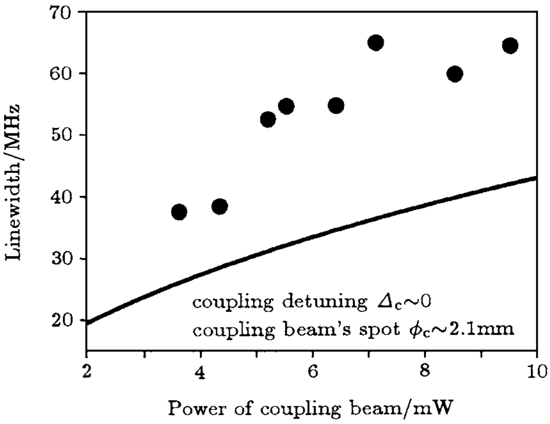

Fig.5. Linewidths of the Autler–Townes doublet in coupling beam transmission for F_g=4–F_e=3 transition versus power of coupling beam. The solid circles are measured linewidths based on Lorentzian profile. The solid curve gives theoretical prediction when only taking power-broadening effect into account.

4. Conclusions

Normally the absorption of probe laser was used to investigate the sub-Doppler spectra. Here the sub-Doppler spectra of V-type three-level caesium system are demonstrated via transmission of the locked coupling laser, and the Autler–Townes doublet is clearly observed. In this case the ground state may be depicted with dressed state model. The frequency splitting and sub-Doppler linewidth depending upon the coupling intensity are experimentally investigated. The results are compared with the theoretical predictions.

With simple experimental equipment, the sub-Doppler coupling transmission spectra will have promising application in precision spectroscopy. Now the novel approach has been developing as an accurately measurement tool.[11] With a given coupling intensity, trace c and trace d in Fig.3 present distinct peaks that depends on the probe frequency. This feature may be used as a standard to lock the probe laser and transfer stability from the coupling laser to the probe laser.

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