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Autler–Townes doublet in the absorption spectra for the transition between excited states of cold cesium atoms*

Liang Qiang-Bing(梁强兵), Yang Bao-Dong(杨保东), Yang Jian-Feng(杨建峰), Zhang Tian-Cai(张天才), and Wang Jun-Min(王军民)†

State Key Laboratory of Quantum Optics and Quantum Optics Devices, and Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China

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Autler–Townes splitting in absorption spectra of the excited states $6\,^2P_{3/2}-8^2S_{1/2}$ of cold cesium atoms confined in a magneto-optical trap has been observed. Experimental data of the Autler–Townes splitting fit well to the dressed-atom theory, by which the fact of the cold atoms dressed by cooling/trapping laser beams is revealed. The results of the theoretical fitting with experiment not only told us the effective Rabi frequency cold atoms experienced, but also could be used for measuring the probability amplitudes of the dressed states.

Keywords: Autler–Townes doublet, dressed state, Rabi frequency, probability amplitude

PACC: 3280P, 4262, 4250

1. Introduction

Atoms could be cooled and trapped relatively easily since the first neutral atom magneto-optical trap (MOT) was implemented by Stevn Chu and his colleagues in 1987.[1] Compared with the hot atomic vapour, cold atoms in MOT[1−3] are free from many broadening effects, such as the Doppler-broadening and transit-time broadening,[4] in which high-resolution and high signal-to-noise ratio (SNR) Doppler-free spectroscopy can reflect the atom–photon interaction more accurately. Cold atoms are quite suitable sample for making scientific researches on atom–photon interaction. So far as we know, high-resolution spectroscopy of cold atoms has been studied widely.[5−7]

There will be strong interaction between light and atoms when Rabi frequency Ω of the incidence light is much bigger than the relevant atom's natural linewidth Γ. In cold atoms, atom–photon interaction could be studied roundly by using the Autler–Townes splitting as shown in high-resolution absorption spectra or fluorescence spectra. In 1993, Fox *et al.*[6] detected the absorption spectra of the $6^2P_{3/2}F'=5-9^2S_{1/2}F''=4$ transition with cold cesium atoms, and measured the fluorescence from the intermediate level $5^2P_{3/2}F'=3$ of the cascade system with cold ^{87}Rb atoms. They analysed the Autler–Townes splitting shown in the absorption spectra.[6] Mitsunaga *et al.*,[7] Grison *et al.*,[8] Tobosa *et al.*,[9] and our group[10] measured the nonlinear absorption spectra of the cold cesium atoms trapped in MOT. Only cesium $6^2S_{1/2}F=4-6^2P_{3/2}F'=5$ cycling hyperfine transition was detected in Refs. [8] and [9], while cesium $6^2S_{1/2}F=4-6^2P_{3/2}F'=3$, 4, and 5 whole three hyperfine transitions were measured in Refs. [7] and [10] and the dispersion-like profiles were also observed. In 2003, Teo *et al.*[11] observed high-resolution Autler–Townes Rydberg spectra of the $5S_{1/2}-6P_{3/2}-44$D cascade of cold ^{85}Rb atoms, in which they studied the nonlinear optical effects of the excited Rydberg states. Chang *et al.*[12] also investigated doubly-dressed states in a ladder-type system with hot cesium atomic vapour. All of the above experiments can be explained well by dressed-atom theory.[13] However, they did not pay more attention to the phenomena how the relative intensity of the Autler–Townes doublet of the atomic excited states change along with the varied detuning of the incident beam.

In this paper, the Autler–Townes splitting in the absorption spectra of the transition between cesium excited states $6^2P_{3/2}F'=5$ and $8^2S_{1/2}F''=4$ is investigated with the cold atoms confined in a MOT. The effective Rabi frequency and the relative intensity

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†Corresponding author. E-mail: wwjjmm@sxu.edu.cn

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of the two components of the Autler–Townes doublet which changes along with the variation of the detuning of cooling/trapping laser beams are measured in the case of fixed power of pumping beams. The experimental results fit well with dressed-atom theory, which help us understand the coupling between cold atoms and cooling/trapping laser beams with different power and frequency detuning. Moreover, the measurement of the probability amplitudes of the dressed states is discussed.

2. Experimental setup

Cesium atoms were cooled and trapped in a MOT.[1–3] The schematic diagram of experimental setup and optical path are shown in Fig. 1. Background pressure of vacuum chamber for MOT was maintained in $\sim 8\times10^{-8}$ Pa ($\sim 6\times10^{-10}$ Torr, 1 Torr=133.322 Pa), and the anti-Helmholtz coils with a typical magnetic gradient of $\sim$ 1 mT/cm ($\sim$ 10 Gs/cm) along the axis. An 852 nm ECDL1 (external-cavity diode laser) was locked to the red detuning $\varDelta_\mathrm{c}$ of the cesium cycling transition $6^2S_{1/2}F = 4 - 6^2P_{3/2}F' = 5$ utilising the modulation-free polarisation spectroscopy (PS) technique,[14,15] and $\varDelta_\mathrm{c}$ could be adjusted continuously from $-4\varGamma$ ($\varGamma/2\pi$ = 5.22 MHz, natural line-width of the cesium D_2 line) to 0 by the acousto-optical modulator (AOM). After spatially filtered by a polarisation-maintaining (PM) fibre and expanded by a telescope, the output laser beam with power of $\sim$ 35 mW (decreasing $\sim$10% due to losses) and $1/e^2$ diameter of $\sim$ 16.5 mm was divided into three beams which were guided by reflecting mirrors to intersect at the central point of the vacuum chamber, and then were retro-reflected. Before incidence on windows of the vacuum chamber, six quarter-wave plates were used to convert the linearly polarised beams into properly circularly polarised beams required for MOT. The repumping beam was provided by a home-made ECDL2@852nm. Its frequency was stabilised to the cesium $6^2S_{1/2}F = 3 - 6^2P_{3/2}F' = 4$ hyperfine transition utilising the saturation absorption spectroscopy (SAS) technique. Output laser beam with power of $\sim$ 3 mW after spatially filtered by another PM fiber was expanded to $1/e^2$ diameter of $\sim$ 16.5 mm and overlapped with one of the three cooling/trapping beams. Approximate spherical cold cloud was confined in MOT after adjusting appropriately the cooling/trapping laser beams as well as the three-dimensional compensated magnetic field. A cold cloud with diameter of $\sim$ 500 μm was prepared in MOT.

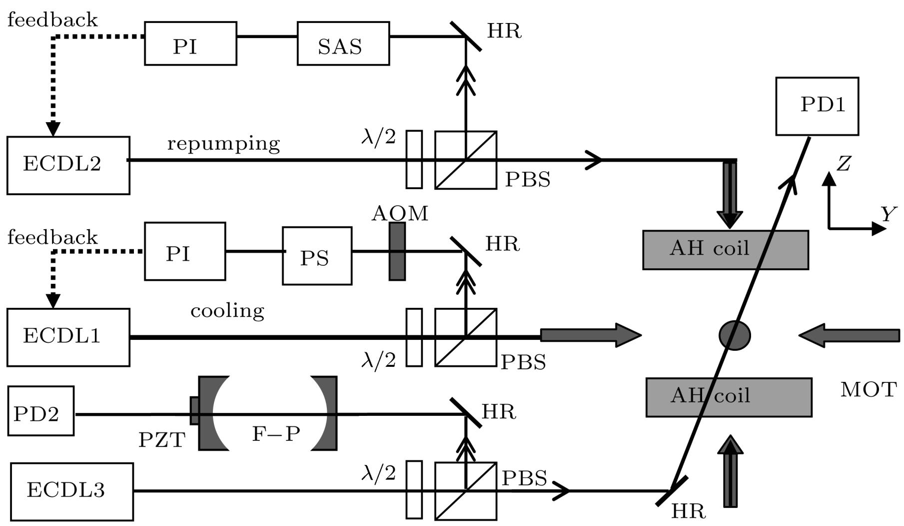

Fig. 1. Schematic diagram of the experimental setup. Solid line is for the optical path, and dashed line for the electrical one. PI, proportional-integral circuit; ECDL, external-cavity diode laser; SAS, device of saturation absorption spectroscopy; PS, device of polarisation spectroscopy; AOM, acousto-optical modulator; $\lambda/2$, half wave-plate; PDs, photo-detectors; HR, 45° reflection mirror; PBS, polarisation beam splitter cube; AH coils, anti-Helmholtz coils.

The probe beam provided by ECDL3 (Toptica DL-100@794.6 nm) working around cesium $6^2P_{3/2}F' = 5 - 8^2S_{1/2}F'' = 4$ transition was also filtered by a PM fibre and expanded to $1/e^2$ diameter of $\sim$ 1 mm in order to overlap the trapped atom cloud. The power of probe beam was set to

$\sim 30\ \mu$W, which was low enough so that it did not perturb the trap dynamics or the absorption line shape. The probe beam passed through the cold cloud and was collected by a convex lens and a photo-detector (Model 2051, New Focus) whose output signal was observed and registered in a digital oscilloscope. Absorption spectrum could be obtained, as shown in Fig. 3 by scanning the probe beam across the transition $6^2P_{3/2}F' = 5 - 8^2S_{1/2}F'' = 4$. One part of the laser out of ECDL3 was delivered into a home-made confocal Fabry–Perot cavity with fineness of ~ 100 and free spectra range (FSR) of 503 MHz, and the transmission signal could be used for adjusting the laser and calibrating frequency of the spectra. In addition, we increased the power of cooling/trapping beams and expanded its diameter for enhancing the optical density (OD) of the cold atoms in MOT. By this way, not only the SNR was further improved, but also enhanced the Rabi frequency $\Omega_{\rm c}$.

3. Experimental results and theoretical analysis

Cesium $6^2S_{1/2}F = 4$ hyperfine state, $6^2P_{3/2}F' = 5$ intermediate state, and $8^2S_{1/2}F'' = 4$ hyperfine state are labeled as $|1\rangle$, $|2\rangle$, and $|c\rangle$, respectively, as shown in Fig. 2. These hyperfine levels could be treated as a ladder-type three-level system. In our experiment, there were strong interactions between the cold atoms and the laser mode due to the mediate intensity of cooling/trapping laser beams.

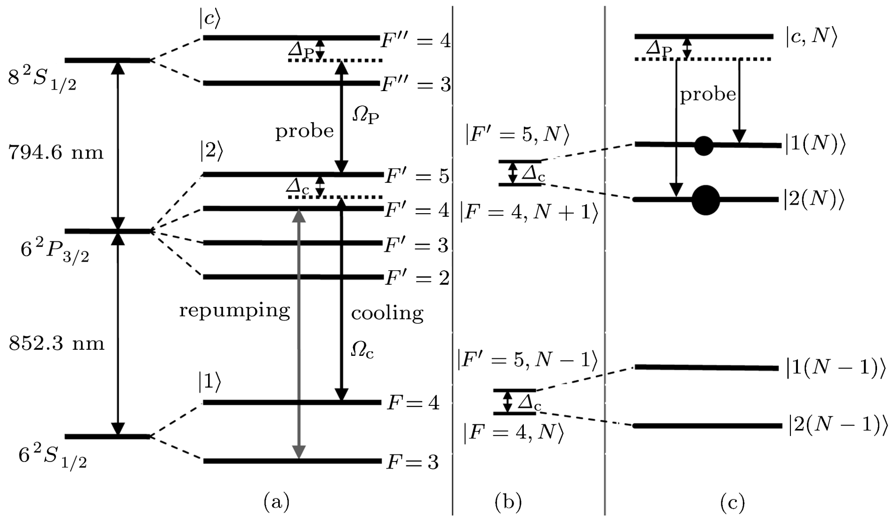

Fig. 2. Diagram of relevant energy levels of cesium atoms: (a) bare states, (b) uncoupled states, and (c) dressed states. The size of the black ball represents the population of corresponding dressed states.

In the dressed-atom approach, considering the coupling between the two uncoupled states $|6^2P_{3/2}F' = 5, N\rangle$ and $|6^2S_{1/2}F = 4, N+1\rangle$ nearby the bare state $|2\rangle$, we obtain two dressed states $|1(N)\rangle$ and $|2(N)\rangle$ which are separated by an interval $\hbar\Omega$. Another two dressed states, $|1(N-1)\rangle$ and $|2(N-1)\rangle$, are also formed near the bare state $|1\rangle$. The dressed states $|1(N)\rangle$ and $|2(N)\rangle$ can be expressed as follows:[13]

$$|1(N)\rangle = \sin\theta|6^2S_{1/2}F = 4, N+1\rangle + \cos\theta|6^2P_{3/2}F' = 5, N\rangle, \tag{1}$$

$$|2(N)\rangle = \cos\theta|6^2S_{1/2}F = 4, N+1\rangle - \sin\theta|6^2P_{3/2}F' = 5, N\rangle, \tag{2}$$

where $2\theta = \arctan(-\Omega_{\rm c}/\Delta_{\rm c})$, $0 \le 2\theta < \pi$.

When $\Omega_{\rm c} > \Gamma$ and the probe beam are scanned across the $6^2P_{3/2}F' = 5 - 8^2S_{1/2}F'' = 4$ transition, the absorption spectra including Autler–Townes doublet with a separated frequency interval of $(\Delta_{\rm c}^2 + \Omega_{\rm c}^2)^{1/2}$ can be detected, from which we can understand the dressed effect between laser field and the atomic state $|2\rangle$. One of the absorption spectra has been measured as shown in Fig. 3, while the total power of cooling beams is 31.5 mW and $\Delta_{\rm c}/2\pi = -10$ MHz is detuned to the transition $|1\rangle \leftrightarrow |2\rangle$.

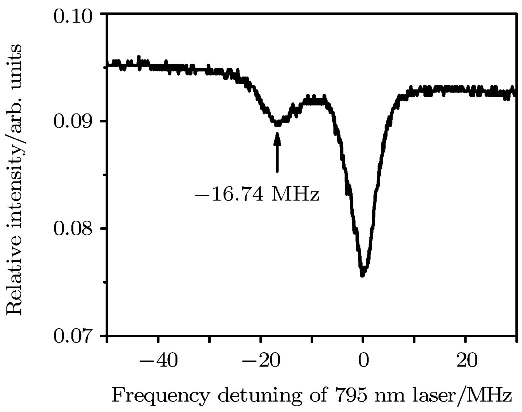

Fig. 3. Autler–Townes doublet in absorption spectra. The total power of cooling/trapping beams of the MOT is 31.5 mW, and the detuning is $\Delta_c/2\pi = -10$ MHz. The other absorption spectra observed at the detuning $\Delta_c/2\pi$ of −4 MHz, −6 MHz, −8 MHz, −12 MHz and −14 MHz are not shown here.

The dressed atom approach tells us that the relative intensity of each component $|i(N)\rangle$ $(i = 1, 2) \leftrightarrow |c, N\rangle$ of the Autler–Townes doublet could be written as follows: if the level $|c, N\rangle$ is unpopulated in the absence of the probe beam, we have

$$I_i = \pi_i^{\rm st} \Gamma_{i\to c} \quad (i = 1, 2), \tag{3}$$

where $\pi_i^{\rm st}$ is the steady-state population of the level $|i(N)\rangle$ (i=1, 2); $\Gamma_{i\to c}$ is the transition rate from $|i(N)\rangle$ $(i = 1, 2)$ to $|c, N\rangle$, and it is proportional to $|\langle i(N)|6^2P_{3/2}F' = 5, N\rangle|^2$. Then, we obtain

$$I_1 = \pi_1^{\rm st} \Gamma_{1\to c} = k_1 \cos^2\theta \sin^4\theta/(\cos^4\theta + \sin^4\theta), \tag{4}$$

$$I_2 = \pi_2^{\rm st} \Gamma_{2.\to c} = k_2 \cos^4\theta \sin^2\theta/(\cos^4\theta + \sin^4\theta), \tag{5}$$

$$I_2/I_1 = k_3 \cot^2\theta, \tag{6}$$

where $\Delta_c < 0$, $0 < \theta < \pi/4$, k_1, k_2, and k_3 are the proportional coefficients.[13]

The other absorption spectra, in which we found that the Autler–Townes splitting decreased with reduced detuning were observed at the different detuning but the fixed intensity of the cooling/trapping laser beams. Effective Rabi frequency Ω_c of 12.90 ± 0.46 MHz experienced by cold atoms was deduced by fitting the experimental data to the dressed-atom theory, as shown in Fig. 4. When we took ∼ 10% loss of cooling/trapping beams' total intensity into account, it was in agreement with the effective Rabi frequency $\Omega_c \approx 13.39$ MHz, which was estimated by the equation $I/I_s = 2\ \Omega_c^2/\Gamma^2$ ($I_s = 1.12$ mW/cm^2 is the saturation intensity of the $\sigma^{\pm}$-polarised light around the cesium D_2 line; I is the intensity of cooling/trapping beams; $\Gamma/2\pi = 5.22$ MHz).

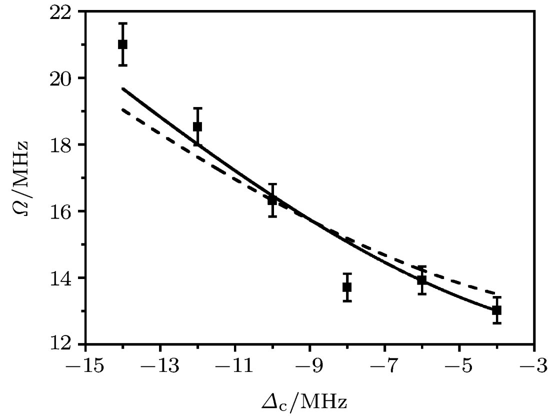

Fig. 4. The Autler–Townes splitting versus the detuning Δ_c. The dashed line is the fitting in theory without consideration of the frequency shift error caused by AOM, while the solid line is the fitting with ∼ 10% modification of the detuning Δ_c. The solid squares with the error bar represent the experimental data with consideration of ∼ 3% modification of the FSR of the home-made confocal Fabry–Perot cavity.

Simultaneously, the relative intensity of the Autler–Townes doublet changes with the varied detuning of cooling/trapping beams in the case of the fixed power, so that the ratio of the relative intensity decreases and tends to be equal when $\Delta_c = 0$ MHz, that is $k_3 = 1.0$, which is in good agreement with the prediction by Eqs.(4)–(6). By the way, the effective Rabi frequency Ω_c of the cooling/trapping beams is obtained, once again and equal to 12.25 ± 0.43 MHz, nearly in accordance with the other two results in previous treatments.

Finally, we deduce the proportion coefficient of Eq. (6) $k_3 = 1.0$ from the fitting of Fig. 5. According to Eqs. (4)–(6), we find that k_1 is equal to k_2 and the relative intensity of the smaller peak of the Autler–Townes doublet is proportional to $\sin^2\theta$, while the larger one proportional to $\cos^2\theta$. Based on Eqs. (1) and (2), we can conclude that the relative intensity of the Autler–Townes doublet represents the probability with which atoms are populated in the two uncoupled states.

It is needed to point out that only four of the Zeeman sublevels ($6S_{1/2}F = 4$, $m_{\rm F} = \pm 4$ and $6P_{3/2}F' = 5$, $m_{\rm F'} = \pm 5$) should be considered for simplicity in a cesium MOT, although there is a gradient in magnetic field around the centre of a MOT.[16,17] However, we have ignored these Zeeman sublevels for convenience although a few little errors caused by the Zeeman shift would be introduced, ~ 0.7 MHz for the maximum splitting of the sublevels $6S_{1/2}F = 4$, $m_F = \pm 4$ and ~ 2.1 MHz for $6P_{3/2}F' = 5$, $m_{F'} = \pm 5$, respectively for a cold atomic cloud with the diameter of ~ 500 μm. Maybe that is the very reason why there are errors that force us to modify the relevant parameters when the theoretical formula is used to fit the experimental data, for example, as shown in Fig. 4 especially.

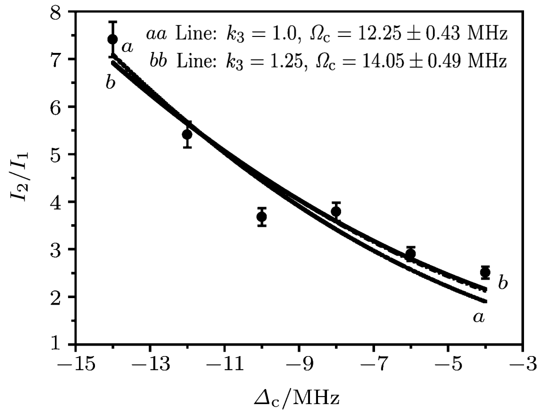

Fig. 5. Ratio of the relative intensity I_2/I_1 of Autler–Townes doublet versus the frequency detuning Δ_c of cooling/trapping laser beams. Line aa is the fitting in theory assumed the coefficient of Eq. (6) $k_3 = 1.0$, while $k_3 = 1.25$ for line bb as a typical fitting under the condition of $k_3 \neq 1.0$. There are four lines for 0, 10%, 50%, and −20% modification of the detuning Δ_c, respectively, which are almost coincided with each other both in line aa and line bb. The solid circles with the error bar represent the experimental data in consideration of $\sim 5\%$ modification of the frequency errors caused by the nonlinear scanning for the Fabry–Perot cavity.

In addition, cooling/trapping beams for MOT play the role of the pumping beam of the pump–probe process in our experiment. Although the power of the cooling/trapping beams is fixed, the parameters of the cold atoms in MOT, such as OD, effective temperature, atom number N, and the size of cold cloud, will change because of the different trapping conditions that caused by the varied detuning Δ_c. Mitsunaga *et al.*[7] solved this problem by introducing a second mediate laser beam to dress cold atoms, and divided the time for cooling/trapping period and pump–probe period independently. For convenience, taking advantage of the cooling/trapping laser, we plan to use time division multiplexing technique, in which after the cooling/trapping stage cooling/trapping laser beams are adjusted immediately and used as the pumping beams for pump–probe stage. By this way, absorption spectra obtained in different detuning will be detected in a nearly identical cold atom sample.

4. Conclusions

In conclusion, we have paid more attention to the change of the Rabi frequency and the relative intensity of the Autler–Townes doublet, which are shown obviously in absorption spectra of the excited states with cold cesium atoms confined in a MOT. We fit the experimental data to the dressed-atom theory, and the effective Rabi frequency of the cooling/trapping beams is deduced.

The results not only provide a direct method to measure the effective Rabi frequency experienced by cold atoms, but also confirmed once again that the dressed-atom theory could be used for understanding the strong coupling between the light field and atoms.

Similarly, we have also deduced the proportion coefficient of Eq. (6) $k_3 = 1.0$ from the fitting, based on which the probability amplitudes of dressed states population could be measured. It follows that the relative intensities of the Autler–Townes doublet tend to be equal with the decrease of cooling beam's detuning, from asymmetry to symmetry; this reflects that the population in two the uncoupled states changes as a result of the varied coupling effect between them.

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