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Coherent spectroscopy of the ^{87}Rb $F_g = 1 \rightarrow F_e = 0$ closed transition*

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This paper has observed linewidth narrowing of dark states in rubidium cell by using the Hanle configuration. The reduction of the coherent resonance width under the transition of ^{87}Rb $F_g = 1 \rightarrow F_e = 0$ is observed and the qualitative explanation about its mechanism is presented. Multiple subnatural width dips are obtained with a linearly polarized laser beam for the transitions of ^{87}Rb $F_g = 1 \rightarrow F_e = 0$, 1, 2. The feature of negative and positive slope, namely dispersionlike feature, is observed in the transmitted light.

Keywords: coherent population trapping, Hanle effect, subnatural width, dispersionlike feature
PACC: 3270J, 3280B, 3350D

Interests in coherent population trapping (CPT)[1] in the coupling of two ground states to a common excited state by means of two coherent lasers is growing because of increasing applications of lasing without inversion,[2] laser cooling,[3] ultraslow group-velocity propagation of light[4] and many others. Picque first observed the coherent effect in a sodium atomic beam under Hanle configuration.[5] Loss population under different transitions was reported by Renzoni *et al.*[6] The CPT phenomena of degenerate two-level systems for the analysis of coherent effects among multiple sublevels of hyperfine (hf) transition in rubidium cell have been investigated.[7] Detailed results for coherent fluorescence spectra at the D_1 and D_2 lines of Rb with linearly and circularly polarization are presented by Alzetta *et al.*[8]

It should be pointed out that coherent effects occurring in hf transitions both in vacuum and buffer Cs gas cells have been studied experimentally and theoretically.[9] The observed narrow resonances (full width at half maximum (FWHM): few tens of kHz) and their sensitivity to weak magnetic fields were applied for precise magnetometers.[10]

In this paper we analyse the population-loss-induced effect on a closed ^{87}Rb $F_g = 1 \rightarrow F_e = 0$ transition. The spectroscopy of multiple subnatural width dips on Doppler profile and population distribution at lower laser intensity is given. We also investigate the dispersionlike transmission spectra through the absorbing medium.

The experimental setup is shown in Fig.1. The fluorescence perpendicular to the laser beam propagation direction is collected by a large area Si photodiode (PD1 Hamamatsu S2386-44 K). The laser beam emitted from an extended cavity diode laser (ECDL) system has elliptical shape with dimension 5 mm × 2.5 mm for which the order of linewidth is 1 MHz. The incident laser beam is linearly polarized along the y-axis.

In order to decrease the inhomogeneous laboratory magnetic field, a Rb cell which is 3 cm long is situated inside a magnetic shield made of a three-layer μ-metal cylinder at 300 K. The magnetic field parallel to the direction of the laser beam, driven by the signal generator (Agilent 33250 A), is produced by a solenoid. The scan rate of the magnetic field is limited at several tens of Hz. For investigation of the transmitted light, two $\lambda/4$ plates and a polarized beam splitter were added. The transmission light is divided into two parts which are recorded by two cube photodiodes (PD2 and PD3). All the signals are recorded by a digital oscilloscope (Tek TDS 1002) which are

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averaged up to 16 times.

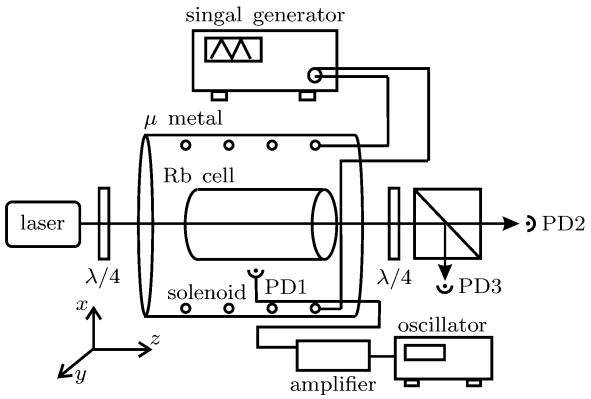


Fig.1. Experimental setup for coherent population trapping under Hanle configuration, see texts for description.

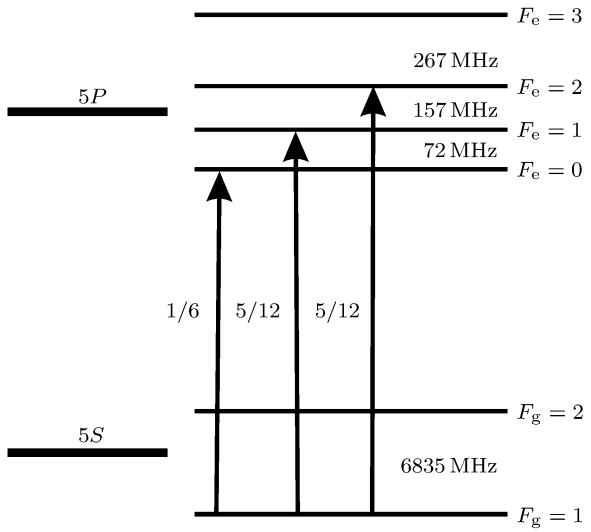


Fig.2. Energy levels and hyperfine transitions of ^{87}Rb D_2 line including transition strength factor.

The hyperfine splitting of ^{87}Rb D_2 line is shown in Fig.2. The coherent resonance spectra with linearly polarized light of the transition ^{87}Rb $F_g = 1 \rightarrow F_e = 0$ at $0.2\,\mathrm{mWcm^{-2}}$ and $250\,\mathrm{mWcm^{-2}}$ are shown respectively in Fig.3(a), (b). The narrowest coherent resonance which is shown in Fig.3(a) has a FWHM of $1.66 \times 10^{-4}\,\mathrm{mT}$. Because the Zeeman splitting of the two ground hf levels in the presence of magnetic field is about $7\,\mathrm{MHz \cdot mT^{-1}}$,[11] the FWHM of the dark resonance is 116 kHz, which is significantly narrower than the natural width of rubidium (around 6 MHz). The FWHM in Fig.3(b) is about $4.64 \times 10^{-4}\,\mathrm{mT}$ and almost 4 times larger than the previous one.

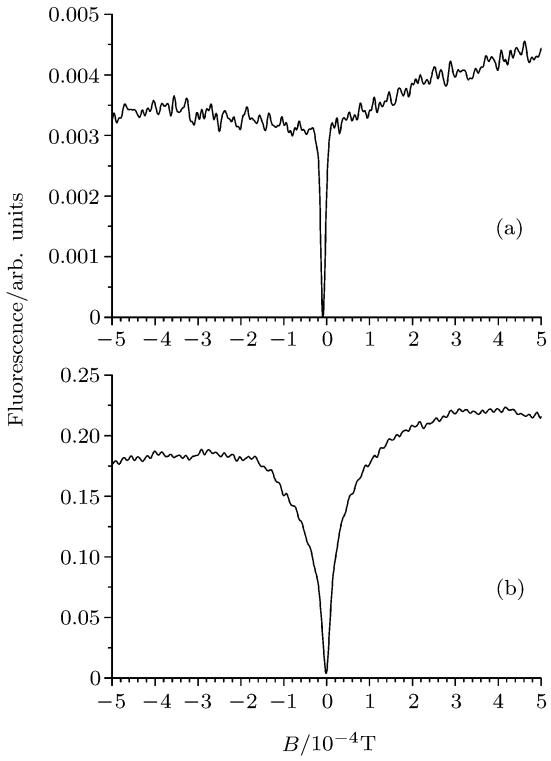


Fig.3. Subnatural width dip with the transition ^{87}Rb $F_g = 1 \rightarrow F_e = 0$ for laser intensity (a) 0.2 $\mathrm{mWcm^{-2}}$, (b) $250\,\mathrm{mWcm^{-2}}$.

In Fig.4(a), the FWHM of the coherent resonance is plotted as the increase of the beam intensity. When laser power is lower than 33 $\mathrm{mWcm^{-2}}$, the width of the subnatural width signal grows quickly and reaches its maximum value 750 kHz. The question is why the FWHM of coherent spectroscopy decreases when beam intensity is larger than 33 $\mathrm{mWcm^{-2}}$. The answer to this can be found by the saturation absorption coefficient and Doppler hyperfine level overlapping. We suppose a two-level system for which the lower and upper level are denoted by i, k. The relation between the population difference with radiation and without radiation can be described as below:

$$\Delta N(v) = \frac{\Delta N_0}{1 + 2\gamma_s/(\gamma_i + \gamma_k)} = \frac{\Delta N_0}{1 + S(v)}, \qquad S(v) = \frac{2\gamma_s}{\gamma_i + \gamma_k} = \frac{\sigma_{ik} I(v)}{\bar{\gamma}}, \tag{1}$$

where ΔN, ΔN_0 is the population difference with and without light field. The decay rates of $i \rightarrow k$ and $k \rightarrow i$ are denoted by γ_i, γ_k for which the average decay rate is $\bar{\gamma} = (\gamma_i + \gamma_k)/2$. The stimulated rate of state i is γ_s, and σ_{ik}, $I(v)$ are the section of stimulated field and intensity of the radiation field respectively. As the intensity of incident light increases, the population of upper state k increases simultaneously. Under

the assumption that all atoms are trapped in the dark state,[12] the width of subnatural dip can be expressed as:

$$\Gamma_{\rm cpt} = \Omega^2/W_{\rm D}. \tag{2}$$

The experimental results fit very well when the laser intensity is 33 mWcm^{-2} (where Ω is the Rabi frequency of the driving light and $W_{\rm D}$ is Doppler linewidth). However, the Doppler width of rubidium at room temperature is about 500 MHz which is larger than the upper hf level spacing of ^{87}Rb D_2 line as shown in Fig.2. Thereby, the laser interacts with the atoms in three different velocity groups which make contribution to the coherent resonance independently. The components $V_i(2\pi(v - v_{i0})/k)$ of the velocities along the direction of laser beam is determined by the detuning of the laser frequency v corresponding to the transition of ^{87}Rb $F_{\rm g} = 1 \rightarrow F_{\rm e} = 0$ where k is the wavevector.[13] According to the result of Alzetta *et al*,[8] we obtained $\alpha(F_{\rm e} = 1) = 0.2, \alpha(F_{\rm e} = 2) = 1$. The whole system is no longer close and population of ^{87}Rb $F_{\rm e} = 0$ will be lost to other hf levels.

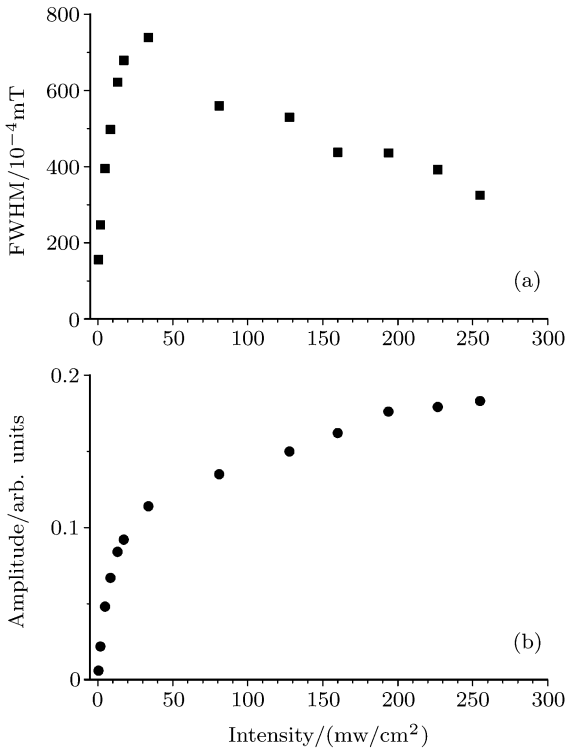


Fig.4. (a) The FWHM of coherent resonances dependence on the incident laser intensity. (b) Dependence of the amplitudes of the subnatural width dips on the incident power density.

Depopulation on the close hf level and participation of open hf transitions result in the reduction of the width of the coherent resonance. Javan *et al* have also predicted that the linewidth of open system is smaller than that of close system.[14] The relation between the amplitude of the subnatural width dips and the incident power density is shown in Fig.4(b).

The fluorescence signal of transition ^{87}Rb $F_{\rm g} = 1 \rightarrow F_{\rm e} = 0, 1, 2$ excited by linearly polarized light is illustrated in Fig.5. It shows that multiple dark narrow dips superimposed on the Doppler profile. At room temperature, the RMS (root mean square) velocity of rubidium is about 300 ms^{-1} which corresponds to 400 MHz Doppler frequency shift. There will be few atoms which can be acted besides hf level of ^{87}Rb $F_{\rm e} = 0$ at low intensity. Thereby, the coherent resonances vanished when the laser frequency detuning from ^{87}Rb $F_{\rm e} = 0$ is larger than 400 MHz.

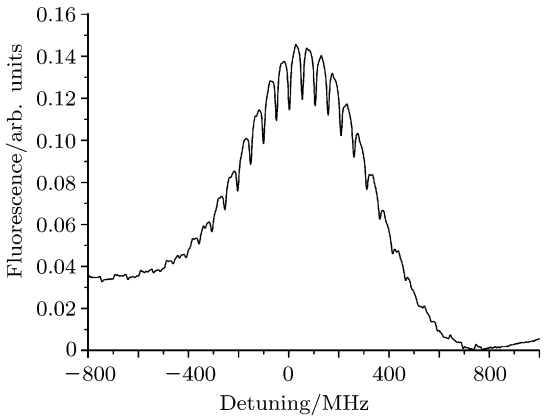


Fig.5. Dark resonances on the ^{87}Rb $F_{\rm g} = 1$ Doppler profile depending on the detuning from the ^{87}Rb $F_{\rm g} = 1 \rightarrow F_{\rm e} = 0$ transition, the laser power is 14.5 mWcm^{-2}.

In Fig.6, the signals of the transmitted light were measured when the fast axis of quarter-wave plate is along the y direction. The signals of PD3 are reduced 100 times as before. Anomalous dispersionlike feature is observed with power intensity of 0.20 mWcm^{-2} (a) and 80 mWcm^{-2} (b) respectively. It's interested that the spatial span of the dispersionlike curve with negative slope is in the same magnitude of the FWHM of the dip which is only hundreds of milligauss. The component of circular polarization in transmitted light is shown in Fig.7(a) with linearly polarized light. Rotating the fast axis of quarter-wave plate at angle of 45 degrees along the y direction, we find that the shape of σ^+ polarization from PD2 (denoted as 2) is more like a dip whose width was 30% larger than the fluorescence signal. The positive dispersionlike feature is obtained in the profile of σ^- polarization from PD3 (denoted as 3). In Fig.7(b), EIA (electromagnetically induced absorption) is obtained by circularly polarized beam.

As we turn the fast axis of quarter-wave plate at angle of −45 degree along the y direction, the signal of PD2 is changed to peak while the signal of PD3 remains to have positive dispersionlike feature.

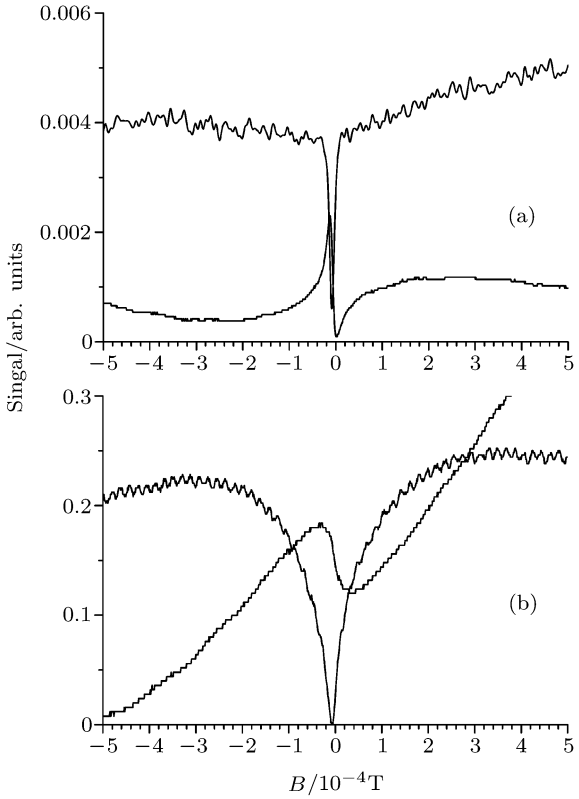


Fig.6. Negative dispersionlike curve in the transmitted light from PD3 in comparison with subnatural width fluorescence, the laser intensity is (a) 0.2 mWcm^{-2}, (b) 80 mWcm^{-2}.

In summary, the subnatural width coherent resonances have been observed under the transition ^{87}Rb $F_g = 1 \rightarrow F_e = 0, 1, 2$. The minimum FWHM was obtained with laser intensity of 0.2 mWcm^{-2}. In the case of strong incident laser power, due to Doppler effect and depopulation from upper hf level ^{87}Rb $F_e = 0$, the FWHM of fluorescence decreased with the increase of laser power. Positive and negative slope dispersionlike curves are observed. It may be helpful to realize the superluminal[15] and slow light propagation[16] within Zeeman sublevels.

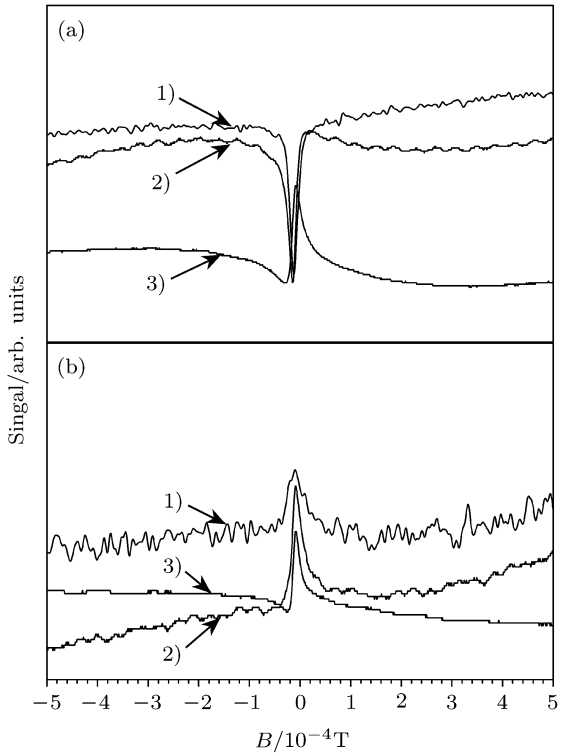


Fig.7. Fluorescence signal from the photodiode (PD1) and absorption spectroscopy from photodiodes (PD2, PD3) denoted by 1, 2, 3 respectively: (a) the incident light polarization is linear, (b) the incident light polarization is circular.

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