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Atomic transitions of Rb, D_2 line in strong magnetic fields: Hyperfine Paschen–Back regime

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ABSTRACT

An efficient $\lambda/2$-method (λ is the resonant wavelength of laser radiation) based on nanometric-thickness cell filled with rubidium is implemented to study the splitting of hyperfine transitions of ^{85}Rb and ^{87}Rb D_2 lines in an external magnetic field in the range of B=3–7 kG. It is experimentally demonstrated that at $B>3$ kG from 38 (22) Zeeman transitions allowed at low B-field in ^{85}Rb (^{87}Rb) spectra in the case of σ^+ polarized laser radiation there remain only 12 (8) which is caused by decoupling of the total electronic momentum $\boldsymbol{J}$ and the nuclear spin momentum $\boldsymbol{I}$ (hyperfine Paschen–Back regime). Note that at $B>4.5$ kG these 20 atomic transitions are regrouped into two completely separate groups of 10 atomic transitions each. Their frequency positions and fixed (within each group) frequency slopes, as well as the probability characteristics, are determined. A unique behavior of two atomic transitions is stressed: one transition belongs to ^{85}Rb, the other to ^{87}Rb and for low magnetic fields they could be presented as transitions $F_g=3, m_F=+3 \rightarrow F_e=4, m_F=+4$ and $F_g=2, m_F=+2 \rightarrow F_e=3, m_F=+3$, correspondingly. The experimental results of the atomic transition frequency shifts and the modification of their probabilities agree well with the theory. A comparison of the behavior of the D_1 and D_2 atomic transitions is presented. Possible applications are described.

1. Introduction

It is well known that in an external magnetic field B the energy levels of atoms undergo splitting into a large number of Zeeman sublevels which are strongly frequency shifted, and simultaneously, there are changes in the atomic transition probabilities [1,2]. Since cesium and rubidium are widely used for investigation of optical and magneto-optical processes in atomic vapors as well as for cooling of atoms, for the Bose–Einstein condensation, and in a number of other problems [3,4], therefore, a detailed knowledge of the behavior of atomic levels in external magnetic fields is of a high interest. The implementation of recently developed technique based on narrow-band laser diodes, strong permanent magnets and nanometric-thickness cell (NTC) makes the study of the behavior of atomic transitions in an external strong magnetic field simple and robust, and allows one to study the behavior of any individual atomic transitions of ^{85}Rb and ^{87}Rb atoms for D_1 line [5,6].

Recently, a number of new applications based on thin atomic vapor cells placed in a strong magnetic field have been demonstrated: (i) development of a frequency reference based on permanent magnets and micro- and nano-cells widely tunable over the range of several gigahertz by simple displacement of the magnet; (ii) optical magnetometers with micro- and/or nanometric spatial resolution [5,6]; (iii) a light, compact optical isolator using an atomic Rb vapor in the hyperfine Paschen–Back regime is presented in [7,8]; (iv) it is demonstrated that the use of Faraday rotation signal provides a simple way to measure the atomic refractive index [9]; (v) widely tunable narrow optical resonances which are convenient for a frequency locking of diode-laser radiation [10].

Strong permanent magnets produce non-homogeneous magnetic fields. In spite of the strong inhomogeneity of the B-field (in our case it can reach 15 mT/mm), the variation of B inside the atomic vapor column is by several orders less than the applied B value because of a small thickness of the cells. In case of micrometer thin cells with the thickness L in the range of 10–50 μm the spectral resolution is limited by the absorption Doppler line-width of an individual atomic transition (hundreds of megahertz). If the frequency distances between Zeeman sublevels are small a big number of atomic transitions are strongly overlapped and it makes absorption spectra very complicated. Fortunately, as demonstrated for Cs D_2 line, at strong ($B>4$ kG) magnetic fields 16 atomic transitions in the absorption spectrum (there are 54 atomic transitions in moderate magnetic fields for circular polarization

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of the excitation field) are frequency separated from each other by a value slightly larger than the absorption Doppler line-width of an individual atomic transition [11]. That is why in this case even the use of micrometer thin cells allows one to separate practically all 16 atomic transitions (the so-called hyperfine Paschen–Back regime (HPB)).

Note that even for such large values as $B > 4$ kG, the atomic transitions of ^{87}Rb and ^{85}Rb D_2 lines are strongly overlapped, so pure isotope ^{87}Rb and 1 mm-atomic vapor cell have been used to separate eight Zeeman transitions [7–9]. However with this technique even in the case of using pure isotope ^{85}Rb, the atomic lines will be strongly overlapped.

Although, the HPB regime was discovered many decades earlier (see Refs. [2,12,13]), however the implementation of recently developed setup based on narrowband laser diodes, strong permanent magnets and NTC makes these studies simple and robust, and allows one to study the behavior of any individual atomic transition of ^{85}Rb and ^{87}Rb atoms; the simplicity of the system also makes it possible to use it for a number of applications.

In this paper we present (for the first time to our best knowledge) the results of experimental and theoretical studies of the Rb D_2 line transitions (both ^{87}Rb and ^{85}Rb are presented) in a wide range of magnetic fields, namely for 3 kG $< B <$ 7 kG. It is experimentally demonstrated that in the case of $B > 4.5$ kG and σ^+ polarized laser radiation, there remain only 20 Zeeman transitions. In the absorption spectrum these transitions are regrouped into two separate groups each of 10 atomic transitions (HPB regime), while there are 60 allowed Zeeman transitions at low B-field.

2. Experimental details

2.1. Nanometric-thin cell construction

The design of a NTC is similar to that of extremely thin cell described earlier [14]. The modification implemented in the present work is as follows. The rectangular 20 mm $\times$ 30 mm, 2.5 mm-thick window wafers polished to < 1 nm surface roughness are fabricated from commercial sapphire (Al_2O_3), which is chemically resistant to hot vapors (up to 1000 °C) of alkali metals. The wafers are cut across the c-axis to minimize the birefringence. In order to exploit variable vapor column thickness, the cell is vertically wedged by placing a 1.5 μm−thick platinum spacer strip between the windows at the bottom side prior to gluing. The NTC is filled with a natural rubidium (72.2% ^{85}Rb and 27.8% ^{87}Rb). A thermocouple is attached to the sapphire side arm at the boundary of metallic Rb to measure the temperature, which determines the vapor pressure. The side arm temperature in the present experiment was 120 °C, while the windows temperature was kept some 20 °C higher to prevent condensation. This temperature regime corresponds to the Rb atomic number density $N = 2 \times 10^{13}$ cm^{-3}. The NTC operated with a special oven with two optical outlets. The oven (with the NTC fixed inside) was rigidly attached to a translation stage for smooth vertical movement to adjust the needed vapor column thickness without variation of thermal conditions. Note that all experimental results have been obtained with Rb vapor column thickness $L = \lambda/2 = 390$ nm. For more details see [15].

2.2. Experimental setup

Fig. 1 presents the experimental scheme for the detection of the absorption spectrum of the nano-cell filled with Rb. It is important to note that the implemented $\lambda/2$-method exploits strong narrowing of absorption spectrum at $L = \lambda/2$ as compared with the case of an ordinary cm-size cell [11,14]. Particularly, the absorption line-

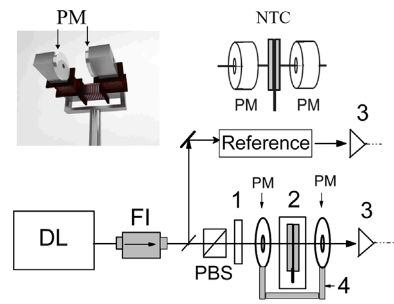

Fig. 1. Sketch of the experimental setup. DL – tunable diode laser, FI – Faraday isolator, 1 – $\lambda/4$ plate, PBS – Polarizing Beam Splitter, 2 – NTC in the oven, Reference – (FR)-auxiliary Rb NTC providing B=0 reference spectrum, PM – permanent magnets, 3 – photo-detectors, 4 – metallic magnetic core.

width for Rb D_2 line ($L = \lambda/2 = 390$ nm) reduces to about 200 MHz (FWHM), as opposed to that in an ordinary cell (about of 500 MHz). In the experiment we used the radiation of a continuous wave narrowband diode laser with the wavelength of 780 nm and the width of 10 MHz. In the current experiment we had the choice to use a diode laser with the line-width of ≈ 1 MHz, however the mode hope free region is only of 5 GHz, which is too small to register all 20 atomic transitions. Meanwhile with the laser used in the experiment the mode hope free tuning range is 40 GHz. The linearity of the scanned frequency was tested by simultaneously recorded transmission spectra of a Fabry–Pérot etalon (not shown). The nonlinearity has been evaluated to be about 1% throughout the spectral range.

The strong magnetic field was produced by two ∅50 mm permanent magnets (PM) with 3 mm holes (to allow the radiation to pass) placed on the opposite sides of the NTC oven and separated by a distance that was varied between 40 and 25 mm (see the upper inset in Fig. 1). The magnetic field was measured by a calibrated Hall gauge. To control the magnetic field value, one of the magnets was mounted on a micrometric translation stage for longitudinal displacement. In the case where the minimum separation distance is of 25 mm, the magnetic field B produced inside the NTC reaches 3600 G. To enhance the magnetic field up to 6 kG, the two PMs were fixed to a metallic magnetic core with a cross section of 40 mm $\times$ 50 mm. Additional form-wound Cu coils allow for the application of extra B-fields (up to ± 1 kG) (see the inset of Fig. 1).

The beam with σ^+ circular polarization was formed by a $\lambda/4$ plate. The beam was focused by a lens (F=20 cm) on the NTC to create a spot size ($1/e^2$ diameter) in the cell of d=0.6 mm and then collimated by a second lens (not shown in Fig. 1). To form the frequency reference (from which the frequency shifts were measured), a part of the laser beam was directed to a unit composed of an additional NTC with $L = \lambda/2$. The absorption spectrum of the latter at the atomic transition $F_g = 1 \rightarrow F_e = 1,2$ served as a reference (another weak transition $F_g = 1 \rightarrow F_e = 0$ is not well seen) [10].

3. Experimental results and discussions

3.1. Magnetic field $B < 3$ kG

In case of relatively low magnetic fields (~ 1 kG) there are 60 allowed Zeeman transitions when circular laser radiation excitation is used, with 22 atomic transitions belonging to ^{87}Rb, and 38 transitions belonging to ^{85}Rb D_2 line. These numerous atomic transitions are strongly overlapped and can be partially resolved in case of using ^{87}Rb or ^{85}Rb isotope. When using natural Rb, the implementation of $\lambda/2$-method allows one to resolve practically any individual atomic transition only for $B \geq 3$ kG.