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Investigation of magneto-optical effect in transverse magnetic field in He

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Abstract. The non-linear Voigt effect has been studied in He discharge under resonance laser interaction with the $2^3P \to 3^3D$ He transition. The range of non-linear signal existence was determined. The contribution of the lower and upper states to the overall signal was analyzed. The cross-section for depolarizing collisions with ground state He atoms was estimated for the $3^3D_{2,3}$ He state.

PACS. 32.80.Bx Level crossing and optical pumping

1 Introduction

The magneto-optical signals arising from the interaction of a resonant laser radiation with atomic and molecular media in the presence of a magnetic field have been recently the object of intensive studies due to the narrow resonances involved which can find various applications. We have investigated the effect of a magnetic field on light scattered by a medium in the forward direction. The most widely explored case has been that with the laser beam propagating in the direction of the magnetic field — the Faraday effect. The appearance of magneto-optical signals with the magnetic field oriented perpendicularly to the direction of beam propagation (Voigt effect) is much less investigated.

The classical Voigt effect occurs when a weak intensity light source is applied, which does not disturb the medium. The changes of its optical characteristics are due mainly to the influence of the magnetic field. The classical Voigt effect curve has a width of the order of the inhomogeneous Doppler width of the transition studied. When a laser source is used, the resonance laser interaction with the medium alters its dispersion. In the magnetic field dependence near the zero magnetic field there appears an additional resonance called non-linear Voigt effect. Its width is determined by the homogeneous width of the states of the transition. Drake *et al.* [1] and Chen *et al.* [2] published experimental investigation of the non-linear Voigt effect on the Sm and Cs ground states, respectively. Hirano derived a universal formula for the magneto-optical signals applicable to arbitrary orientations of the magnetic field, the pumping radiation and the direction of observation — the signal in the case of Voigt geometry is considered as a particular case [3]. Magneto-optical signals in a transverse magnetic field of excited Ne states were studied in [4] and [5]. The authors of [5] used the laser beam to probe the dichroism in a glow discharge, and took special measures to avoid the non-linear effects stemming from the interaction with the laser field.

The present work continues our investigations on the $2^3P \to 3^3D$ transition in He in the presence of an external magnetic field. In [6], we followed the forward scattering in an axial magnetic field, while in the present work we studied the magneto-optical signal in transverse magnetic field. Our aim was to determine the conditions in which the non-linear Voigt resonance appears and to use these resonances for the determination of the cross-section of depolarizing collisions for the 3^3D He level.

2 Experimental

The experimental set-up shown in Figure 1 is described in detail in [5]. The discharge cell filled with He was connected to a vacuum system allowing variation of the gas pressure, and was placed between two crossed polarizers. A linearly polarized laser beam with frequency in resonance with that of the transition investigated propagated along the tube axis. Helmholtz coils were used to create a magnetic field oriented perpendicularly with respect to the laser beam direction. The magnetic field intensity vector $\mathbf{B}$ formed an angle of 45° with the laser field polarization direction. The magnetic field was varied between −50 and +50 G. The intensity of the light passing through the analyzer (2) and a selective interference filter as a function of the magnetic field applied, $I = I(\mathbf{B})$, was registered by a photomultiplier. To detect only the signal that was due to interaction of the laser beam with the medium, lock-in detection was used with 100% modulation of the laser beam. The signals were stored in a PC which also controlled the magnetic field.

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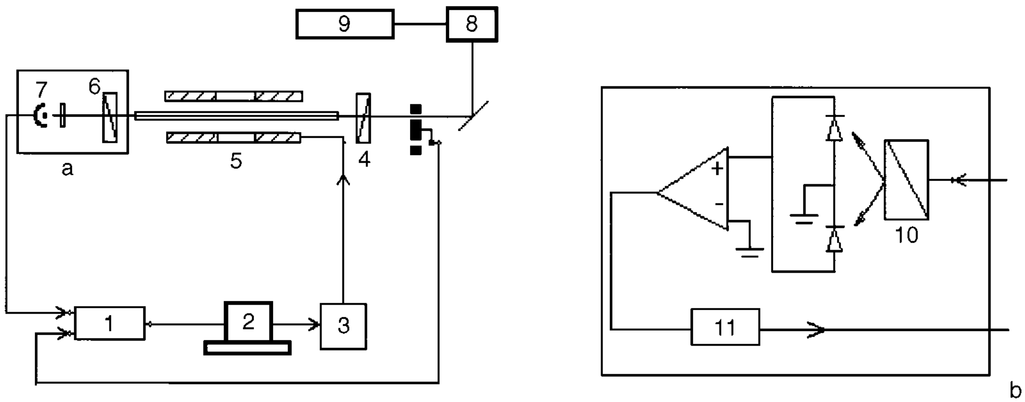

Fig. 1. Experimental set-up. 1: Lock-in; 2: computer; 3: amplifier; 4,6: Glan-Tompson prisms; 5: Helmholz coils; 7: photoamplifier; 8: dye laser; 9: Ar laser; 10: Glan prism; 11: amplifier. a) one channel registration, b) two channels registration: Glan prism divides the FS signal into two parts with perpendicular polarisation detected by two photodiods.

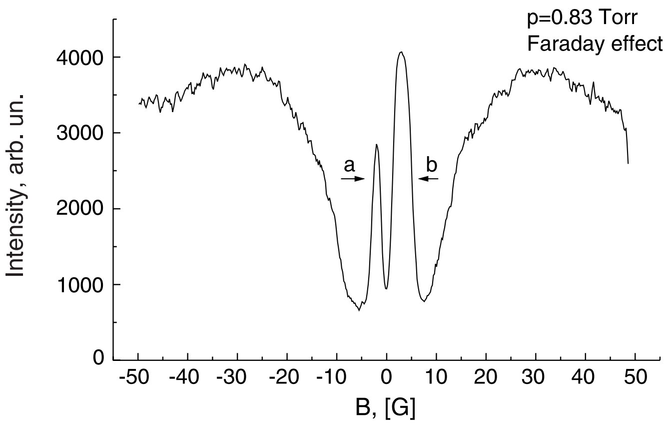

Fig. 2. Comparison between FS signals obtained in Faraday geometry.

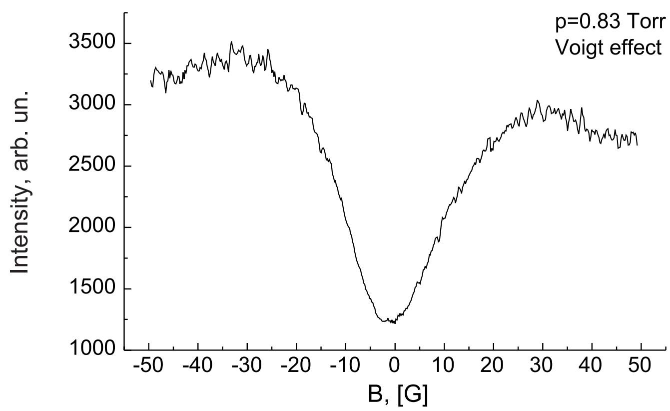

Fig. 3. Comparison between FS signals obtained in Voigt geometry.

The object of our investigations was the non-linear Voigt effect on the $2^3P \rightarrow 3^3D$ He transition, $\lambda = 587$ nm. When the laser is tuned to a resonance with the transition studied, the polarized laser radiation induces anisotropy in the medium. In the case of a linear laser-radiation polarization, the medium becomes uniaxial with properties characteristic for anisotropic media, such as dichroism and birefringence. As a result, the light transmitted through crossed polarizers undergoes changes.

The optical activity of the medium, subjected to resonance laser illumination, depends on the concrete experimental conditions. In our experiment (discharge length 20 cm and laser power 20 mW) a rise in the intensity of the light passing through the analyzer was detected at He pressures below 1.25 Torr. The non-linear Voigt signal was registered only in the range of gas pressure when the medium had already become optically active, *i.e.* below 1.25 Torr.

Under the geometry of our experiment, after a magnetic field was applied, the signal registered could arise both from a difference in the absorption coefficients k for the different polarizations (parallel and perpendicular to the magnetic field — linear dichroism) and from a difference in the indices of refraction (birefringence). The dichroism of the medium causes a tilt of the polarization axis with respect to its initial orientation — the sign of the signal depends on whether it is observed on the left or on the right of the initial polarization direction; in contrast, the signal resulting from birefringence changes the linear polarization into elliptical and is symmetric with respect to the analyzer axis.

To reveal the reason for polarization rotation in our experiment, we registered the signal after detuning the polarizers to 1° to the left and to the right from the orthogonality position.

The dependence thus registered $I = I(\mathbf{B})$ had opposite signs depending on the direction of detuning, which enabled us to conclude that the magneto-optical signal originated mainly from the linear dichroism of the medium.

In Figures 2 and 3 we present the magneto-optical signals obtained in longitudinal (Faraday geometry) and transverse (Voigt geometry) magnetic fields. The asymmetric profiles of the experimental curves in Figures 2 and 3 have different nature. The asymmetry of Figure 3 arises from the influence of the transverse magnetic field on the plasma column. This is irrelevant to the effect

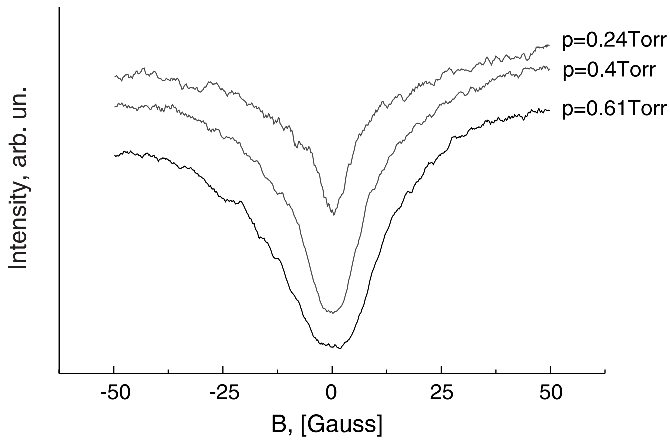

Fig. 4. FS signal obtained by two channels registration for different gas pressures, discharge current $I = 20$ mA, laser power $P = 10$ mW (3.2 mW/mm^2).

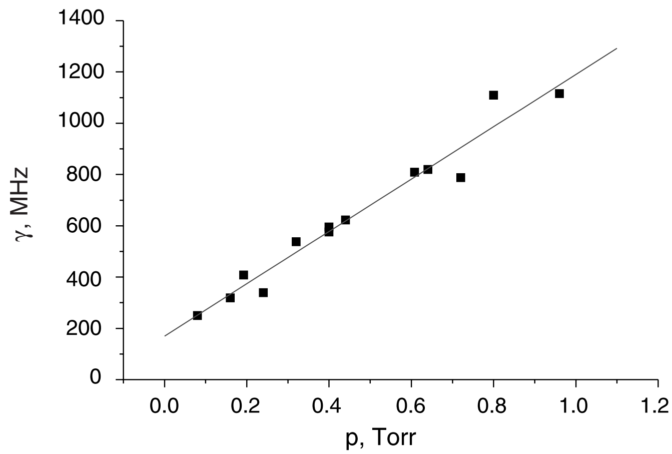

Fig. 5. Gas pressure extrapolation.

investigated and was avoided later by applying two-channel registration. The asymmetry profile of the Faraday signal arises from the difference in absorption coefficients for right and left polarized light. The background of the obtained signals is discussed below.

The non-linear magneto-optical effects are due to the optical pumping processes which connect lower and upper states, thus creating optical coherence and alignment of the atoms via the polarized laser beam which connects Zeeman sublevels (thus creating Zeeman coherences). Having compared the magneto-optical signals detected in a longitudinal (Faraday effect) and transverse (Voigt effect) fields, we found that the non-linear Voigt effect was obtained under the conditions when the structure related to the Zeeman coherence of the medium appeared in the Faraday signal (the region $a \leftrightarrow b$ in Fig. 2).

The width of the resonance γ depends on the decay rate constants of the upper and lower states γ_a, γ_b, the width of the optical transition γ_{ab} and on the values of the angular momenta of the levels participating in the process [7]. A pedestal due to the classical Voigt effect is also present that does not depend on the polarization. This pedestal grows with the pressure due to the coherence narrowing [8] and hinders the precise determination of the width of the resonances. Thus, in order to follow the signal width variation as a function of the pressure, we chose a different registration arrangement. We determined the linear dichroism via measuring the difference of the absorption of light polarized in two orthogonal directions — parallel and perpendicular to the magnetic field direction — using a Glan prism as an analyzer. The optical signal was detected by two photodiodes connected in a current-subtraction mode (Fig. 1b), so that

$$\Delta I(\mathbf{B}) = I_{\parallel}(\mathbf{B}) - I_{\perp}(\mathbf{B}) \sim \Delta k(\mathbf{B}) , \quad (1)$$

where $\Delta k(\mathbf{B})$ is the difference in the absorption coefficients for $I_{\parallel}$ and $I_{\perp}$. This was how we eliminated this part of the population dependence on the magnetic field that is independent of the polarization and is, therefore, identical in the two channels. In addition, this procedure improved the signal-to-noise ratio, since the discharge noises were subtracted.

Using the formalism of irreducible tensors in a coordinate system where the z-axis coincides with the field direction, while the y-axis coincides with the direction of polarized light propagation, one can obtain for Δk:

$$\Delta k(\mathbf{B}) \sim A\rho_0^2 + B\rho_2^2 , \quad (2)$$

where A and B are coefficients; ρ_0^2 describes the longitudinal alignment and ρ_2^2 the transverse alignment. It was experimentally checked that, under our experimental conditions, ρ_0^2 does not depend on the magnetic field, and ΔI depends on $\mathbf{B}$ only through ρ_2^2:

$$I(\mathbf{B}) = \frac{\gamma_a \begin{Bmatrix} 1 & 1 & 2 \\ J_a & J_a & J_b \end{Bmatrix}^2}{(2\gamma_{ab} - \gamma_a)(\gamma_a^2 + 4\omega_a^2)} + \frac{\gamma_b \begin{Bmatrix} 1 & 1 & 2 \\ J_b & J_b & J_a \end{Bmatrix}^2}{(2\gamma_{ab} - \gamma_b)(\gamma_b^2 + 4\omega_b^2)} . \quad (3)$$

Here ω_j is the Larmor frequency in the j-th level; $J_j\,(j = a, b)$ are the angular momenta of the upper and lower levels, respectively. The signal is a sum of two Lorentzians with widths γ_a and γ_b.The contribution of each Lorentzian to the overall signal is determined from the ratio of the angular coefficients C_j^2 for the levels a and b:

$$C_a = \begin{Bmatrix} 1 & 1 & 2 \\ J_a & J_a & J_b \end{Bmatrix} \quad \text{and} \quad C_b = \begin{Bmatrix} 1 & 1 & 2 \\ J_b & J_b & J_a \end{Bmatrix} . \quad (4)$$

The dye laser was tuned to the maximum of the absorption profile of the 587 nm He line. This maximum is determined by $2^3P_2 \rightarrow 3^3D_3$ line, which has the largest intensity. With the dye laser used in the experiment we excited simultaneously $2^3P_2 \rightarrow 3^3D_2$ and $2^3P_2 \rightarrow 3^3D_3$ He transitions, which differ by 75 MHz [9]. These transitions could not be resolved mainly because of the large Doppler width under our discharge conditions (about 3000 MHz). Therefore, the total signal $I(B)$ is the sum of the signals $I_{2\rightarrow 2}(B)$ and $I_{2\rightarrow 3}(B)$. The line intensity ratio of the

$2^3P_2 \to 3^3D_2$ and $2^3P_2 \to 3^3D_3$ He transitions was estimated theoretically to be 5.6. From the experimental curves, published in [10] and obtained at experimental conditions close to ours we estimated it to be near to the theoretical value.

On the other hand, for the $J_a = 2 \to J_b = 2$ transition, $C_a^2/C_b^2 = 1$, and for the $J_a = 3 \to J_b = 2$, $C_a^2/C_b^2 = 21$. The width of the Lorentzian signal, therefore, is determined to a larger extent by the upper level width γ_a.

Thus, we could estimate the cross-section of depolarizing collisions for the 3^3D level of He by measuring the increase of γ with the He pressure:

$$\sigma(2) = \frac{\gamma(2)_{\mathrm{col}}}{P} \frac{1.42 \times 10^{-23} \times \sqrt{T}}{\sqrt{\frac{1}{M_1} + \frac{1}{M_2}}} \mathrm{cm}^2, \tag{5}$$

where T is the temperature in K; M_i the atomic mass of the colliding atoms; $\gamma(2)_{\mathrm{col}}/P$, the pressure broadening in Hz/Torr.

The signal was recorded within the range of He pressure when it existed — from 0.1 to 1.25 Torr. Each experimental point in Figures 4, 5 has been obtained after averaging the signals from 100 sweepings of the magnetic field. From the slope of $\gamma = \gamma(P)$ dependence (Fig. 5), we estimated $\sigma(2)$:

$$\sigma(2) = 1.8(2) \times 10^{-13}\,\mathrm{cm}^2.$$

This cross-section also includes collisions leading to a change in the atoms velocity without destroying the polarization.

3 Conclusion

The non-linear Voigt effect is due to the Zeeman coherence created in the two states of the transition investigated under resonance laser pumping. Because of the transition structure, the contribution of the upper level coherence to the signal creation is predominant. This allows us to estimate the cross-section for depolarizing collisions with He atoms in the ground state of the $3^3D_{2,3}$ level.

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