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Anomalously low relaxation rate of the second-order magnetic moment component (alignment) in cesium

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The results of studies of linear dichroism signals in cesium due to the dynamics of atomic moment alignment when switching the direction of the transverse magnetic field are presented. An unsteady effect of rotation of the polarization plane of the pump beam is found, indicating the presence of an atomic moment component with an anomalously low relaxation rate. A qualitative explanation of the observed effect is given.

Keywords: optically detectable magnetic resonance, magnetic moment of an atom, optical pumping, alignment, relaxation.

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All currently available diverse quantum optical sensors, which include magnetic field sensors [1–3], rotation sensors [4], etc., are based on various modifications of optical detection of magnetic resonance in the ground state of alkali metals (AMs). All of the above devices use certain methods to slow down the relaxation of the ground state. Specifically, anti-relaxation coatings or a buffer gas added to a cell, which slows down the diffusion of atoms, are used to suppress the destructive effect of collisions of atoms with walls of the cell in which they are contained. In this case, the exchange of spin states between AM atoms becomes the determining mechanism of relaxation. Until now, two effects have been reported to provide partial or even near-complete suppression of spin-exchange relaxation. The best known of these effects is SERF (spin exchange relaxation free), which occurs in zero magnetic field [5]. Less known is the effect wherein almost all AM atoms in a non-zero magnetic field are pumped into a state with partially suppressed spin-exchange relaxation, which Happer called „stretched" [6]. Both these effects arise under conditions of disturbed thermal equilibrium and strong optical pumping (OP). OP in this case is the cause of another relaxation mechanism that induces the so-called light broadening of the resonance proportional to OP intensity. Therefore, the magnetic resonance width normally depends on the OP intensity in a complex way.

The vast majority of quantum optical sensor designs are based on the optical orientation effect. In the hierarchy of magnetic moments, orientation is a first-order moment. It is characterized by an asymmetric distribution of populations of Zeeman sublevels and, as a consequence, by a non-zero average magnetic moment. Orientation arises when AMs are pumped by circularly polarized resonant radiation. The second-order moment (alignment) is characterized by a symmetric distribution of populations of Zeeman sublevels, consequently and a zero zero average magnetic moment. It arises when AMs are pumped by linearly polarized radiation. Although quantum sensors based on alignment are less widespread, they are characterized by such as the lack of dead zones [7], a reduced orientation error [8], and low drift and metrological accuracy over long observation times [9]. A theoretical description of alignment effects in AMs in stationary cases was provided in [10,11]. The concept of a zero-field magnetometer based on the alignment effect has also been developed in [11]. The extreme simplicity of its optical circuit is the key advantage of this device.

In the present paper, we report the results of the study of the second-order moment (alignment) relaxation parameters in the context of switching of the magnetic field direction. In contrast to stationary orientation, stationary alignment may be obtained in systems where the magnetic field (MF) direction does not match the direction of the OP beam. This makes it possible, in particular to investigate the relaxation effects that arise on simple switching of the magnetic field direction. In this case, the effect of linear dichroism is manifested in the difference in coefficients of absorption of resonant light in two limiting cases: when the MF is parallel to the plane of OP polarization and when it is perpendicular to it.

The block diagram of the experimental setup, which has already been described in [12], is shown in Fig. 1, *a*. Although several cells with different buffer gas pressures were investigated, we limit the present analysis to the results obtained for a cell $5 \times 5 \times 5$ mm in size that contained Cs and a buffer gas (~ 35 Torr). On the one hand, this pressure ensured complete mixing of the excited states of Cs; on the other hand, it provided the possibility of separate excitation of any of the four components of the D_1 line. The laser was tuned to the center of absorption line $F = 4 \rightarrow F' = 3$ of the D_1 line of Cs; electric component of the radiation $\mathbf{E}$ was parallel to the x axis. A Glan prism (not shown

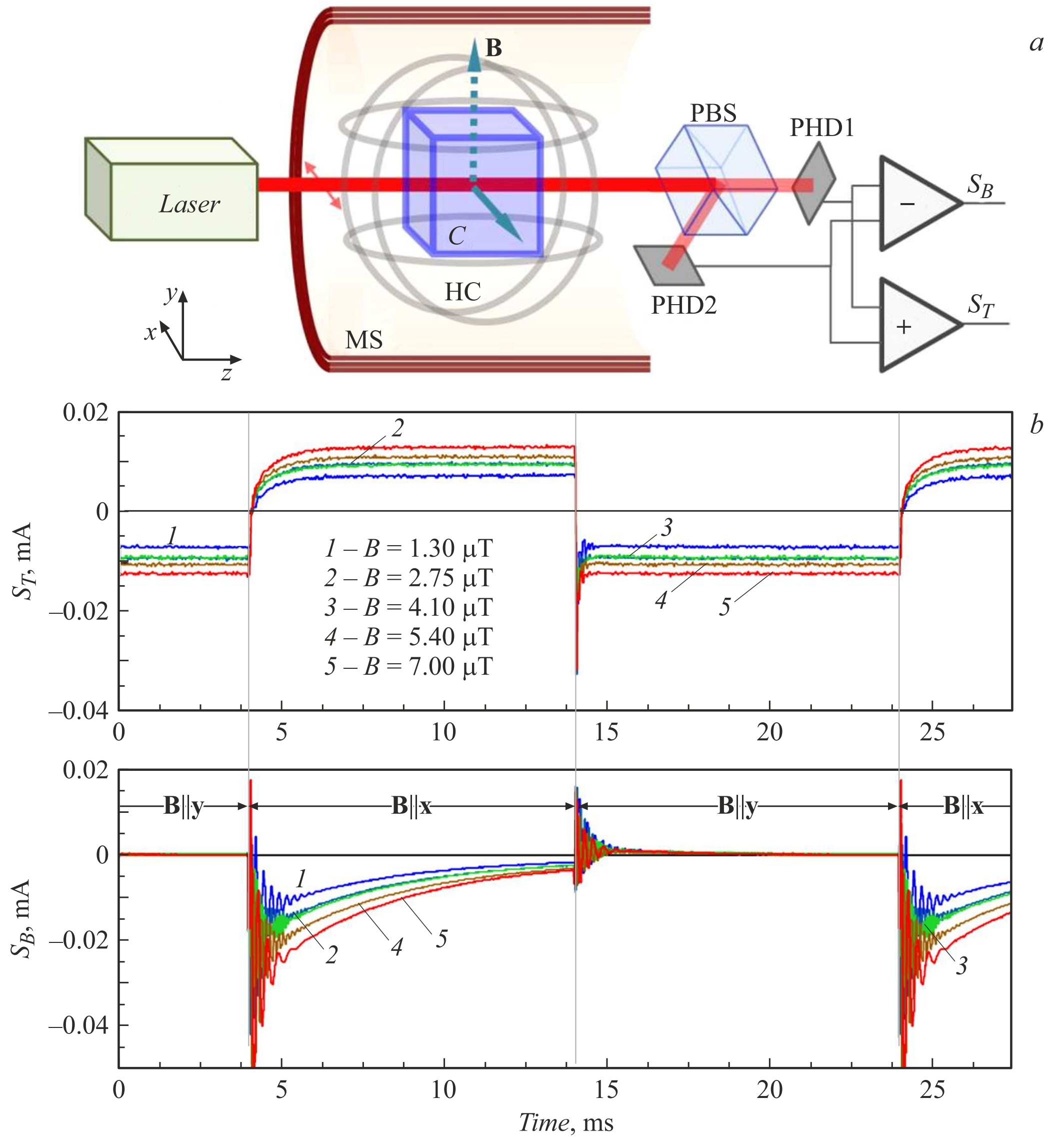

Figure 1. *a* — Block diagram of the setup. MS — magnetic shield; HC — Helmholtz coils system; *C* — cell; PBS — polarizing beam splitter; and PHD1, PHD2 — photodiodes. *b* — Signals recorded (in units of photocurrent) upon MF switching ($T = 82.5^\circ$C, $P_{las} = 3.4$ mW). Visible oscillation frequencies at high MF strengths are distorted by the moire effect.

in the diagram) was used to improve the degree of beam polarization.

Figure 1, *b* shows typical time dependences of the signals of total intensity S_T and differential intensity S_B recorded when switching of magnetic field vector $\mathbf{B}$ between the directions parallel to unit vectors x and y ($\mathbf{B} \parallel \mathbf{x} \leftrightarrow \mathbf{B} \parallel \mathbf{y}$). The S_B signal (Fig. 1, *b*) forms as a result of rotation of the plane of polarization of the pump beam or, in other words, as a result of the emergence of a radiation component polarized along the y axis:

$$I_X = \frac{1}{2}\left(S_T + \sqrt{S_T^2 - S_B^2}\right),$$

$$I_Y = \frac{1}{2}\left(S_T - \sqrt{S_T^2 - S_B^2}\right). \qquad (1)$$

Such a rotation in a stationary state under pumping with linearly polarized light is forbidden from symmetry considerations: the system is mirror-symmetric with respect to all three axes. It was demonstrated in [11] that signals S_T and S_B have a specific physical meaning: they are proportional to the constant longitudinal and oscillating transverse components of alignment, respectively. However, it was revealed in our experiment that a slowly decaying rotation of the plane of polarization, which may reach relatively large magnitudes, emerges in the unsteady case in addition to oscillations. This is the first effect we want to draw attention to in the present paper.

The second effect worthy of study and illustrated in Fig. 1, *b* is the evident asymmetry of relaxation processes with respect to the field direction: with $\mathbf{B} \parallel \mathbf{x} \rightarrow \mathbf{B} \parallel \mathbf{y}$

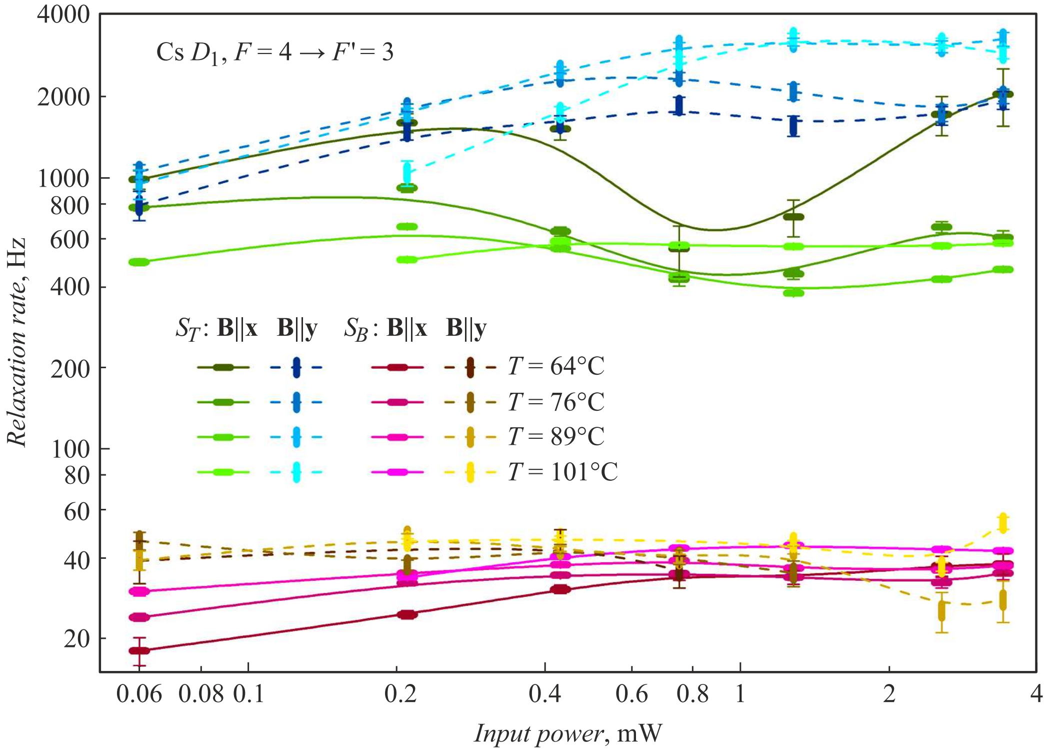

Figure 2. Longitudinal relaxation rates. The calculated magnitude of broadening due to collisions with buffer gas is 6 Hz, while the magnitude of broadening due to collisions with the walls is close to 50 Hz. The calculated spin-exchange broadening varies from 40 to 500 Hz within this temperature range. A color version of the figure is provided in the online version of the paper.

switching, a stationary state is achieved as soon as Larmor oscillations are damped, while the relaxation with $\mathbf{B} \parallel \mathbf{y} \to \mathbf{B} \parallel \mathbf{x}$ switching is exponential with characteristic rates of several hundred hertz.

Figure 2 shows the results of processing a series of records (similar to those presented in Fig. 1, b) obtained at different temperatures. The pump radiation power was varied by approximately two orders of magnitude in each series. The data from Fig. 2 allow us to conclude that there is a third, completely unexpected effect: namely, a component of the moment distribution characterized by an anomalously low (20–50 Hz) relaxation rate that does not reveal any unambiguous dependence on either temperature or pump power and is manifested exclusively in S_B signals. At the same time, the amplitudes of the corresponding signals depend on the same parameters in a quite standard way (similar to the amplitudes of the S_T signals), allowing us to unambiguously attribute them to processes in the atomic ensemble. All the mentioned effects were observed in a varying degree in all the studied cells with pumping of both the $F = 4 \to F' = 3$ line and the $F = 4 \to F' = 4$ line.

A partial explanation for the observed effects may be provided at a qualitative level. Specifically, the first effect (rotation of the polarization plane) can be explained by the to Larmor precession, which disrupts the symmetry of the system when the MF direction is switched, creating an angle between the polarization of pump light and the direction of alignment of the atomic ensemble. Due to the rapid decay of precession, the average value of the effect it produces may differ from zero.

The second effect (asymmetry of relaxation times) may be explained from a geometric standpoint. The alignment at transition $F = 4 \to F' = 3$ occurring at $\mathbf{B} \parallel \mathbf{E}$ is characterized at the limit by the concentration of atoms in states $|m_F| = F$ corresponding to the maximum modulo projections of the moment on the MF. Following rapid $\mathbf{B} \parallel \mathbf{x} \to \mathbf{B} \parallel \mathbf{y}$ field switching, the same distribution of wave function of the moment corresponds to a zero projection of the moment onto the MF. Owing to precession and transverse relaxation, which blurs the distribution in the xz plane, it is transformed as quickly as possible (in a time on the order of transverse relaxation time T_2) into a distribution that essentially corresponds to the concentration of atoms in the $|m_F| = 0$ state. This does not happen in the case of reverse MF switching $\mathbf{B} \parallel \mathbf{y} \to \mathbf{B} \parallel \mathbf{x}$: precession and relaxation transfer the atomic ensemble to a virtually unpolarized state within the same time interval $\sim T_2$, and a longer time, which is specified by longitudinal relaxation time T_1, is needed to return to the maximally „stretched“ state $|m_F| = F$. All of the above also applies to relaxation of the alignment component that contributes to the S_B signal.

The third effect (anomalously low rate of longitudinal relaxation in the S_B signal) is the hardest to explain. It may be assumed that the lower limit of the relaxation rate is set by the rate of relaxation at the cell walls (its value for non-spherical cells may be calculated only approximately, considering the uncertainty of the gas mixture pressure). It may also be concluded that spin-exchange processes, which are characterized by rates up to 500 Hz within this temperature range, do not contribute to the S_B signal relaxation (although, generally speaking, longitudinal relaxation of alignment may be induced by spin-exchange, since both these processes are characterized by conservation of the total angular momentum of the atomic ensemble). We plan to determine the rate of longitudinal relaxation in larger cells experimentally in future studies. The primary objective is to elucidate the physical nature of signal S_B that relaxes at an anomalously slow rate.

In our opinion, further studies into the effects we have discovered are of great interest for understanding the processes of alignment in matter as well as for based on them applications.

Conflict of interest

The authors declare that they have no conflict of interest.

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