ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

L.M. Barkov, D.A. Melik-Pashayev
and M.S. Zolotorev

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L.M.Barkov, D.A.Melik-Pashayev and M.S.Zolotorev
Institute of Nuclear Physics, Novosibirsk 630090, USSR

Experiments on nonlinear magnetic optical (Faraday) rotation on resonance transitions of atomic samarium are described. Measurements were carried out on transitions with different angular momenta of upper and lower states: 1->0, 0->1 and 1->1. Qualitative explanations of observed phenomena are given.

1. Introduction

Studies of the nonlinear Faraday effect (rotation of the plane of polarization in a longitudinal magnetic field) on resonance atomic transitions have been reported in a number of theoretical and experimental papers [1-8]. The nonlinear effect manifests itself at moderate laser intensities in the absence of atomic collisions. It leads to narrow peaks in the magnetic field dependence of Faraday rotation in the region of small fields. The rotation angles on these peaks may exceed the linear contribution by many orders of magnitude. In addition, the nonlinear rotation exhibits a vastly different dependence on laser detuning. In the present work nonlinear Faraday rotation was observed on a number of samarium transitions in a variety of experimental conditions.

The main mechanisms responsible for nonlinear Faraday rotation are related to the laser light-induced coherences between the Zeeman components of atomic states and also to the Bennett structures within the atomic velocity distributions.

The simplest systems where coherence effects can be observed are the so-called V- and Λ-systems. Coherence of Zeeman sublevels with $M=\pm 1$ arises here due to stimulated absorption and emission. The origin of optical rotation can be understood from a simple classical picture. Linearly polarized radiation induces in the medium an oscillating dipole moment. In the presence of a longitudinal magnetic field this moment precesses around the field direction causing rotation of the polarization plane of the radiation. This effect is similar to the Hanle effect (see e.g. [9]). The magnitude of optical rotation is maximum when, during

the coherence relaxation time, the oscillating dipole moment rotates by an angle of the order of a radian. Thus, peaks arise in the magnetic field dependence of optical rotation with a width determined by the Zeeman coherence relaxation rate. For Λ-systems with metastable lower states this rate can be much smaller than the natural width of the transition.

Consider the influence of Bennett structures on Faraday rotation. In the presence of a magnetic field, left and right circularly polarized photons interact in general with different velocity groups of atoms. The arising Bennett structures (an example of such structure - the velocity distribution for the J=0 level in a Y-system is sketched in fig.1) are shifted in opposite directions with respect to the velocity groups resonant to the right and left circular polarizations. This causes a difference in refractive indices for the two circular components and leads to the Faraday rotation. The corresponding peaks in the magnetic field dependence of the rotation have a width determined by the Bennett structure, i.e. by an aggregate of the natural width of the transition, the laser bandwidth and the transit width.

Often studies of nonlinear Faraday rotation have addressed only one of the mechanisms mentioned above - either the coherence effects or the influence of Bennett structures. In the present work conditions were realized under which peaks of comparable size and different width arose in the magnetic field dependence of the rotation due to both the effects.

2.Experimental

The measurements were carried out on atomic samarium transitions with the following upper and lower state angular momenta: 1->0, 0->1, 1->1. The transitions [10] studied in this work are shown in fig.2.

Samarium vapor was produced by heating a metal sample up to about 900 K in a cell consisting of a beryllium oxide tube with inner diameter 7 mm and length 50 cm inserted inside a metal jacket. Beryllium oxide is used because of its resistance to samarium at high temperatures. An ohmic heater was wound around the central part of the cell. The ends of the cell with optical windows attached to them were kept at room temperature. The cell

was evacuated and it was possible to fill it with a buffer gas. Over the jacket there was a coil which produced a longitudinal magnetic field. In order to reduce stray magnetic fields the entire apparatus was covered with a double permalloy screen. To eliminate the magnetic field of the heater it was turned off during a measurement. Note that using beryllium oxide as a cell material gives another advantage: as samarium is contained in an insulating tube, a potential source of stray magnetic fields related to thermoelectricity is eliminated here. A cw single frequency tunable dye-laser (Spectra Physics Model 580) was used as a light source. In the cell the laser beam diameter was about 1 mm. The cell was situated between a polarizer and an analyzer with the axes rotated by 45° with respect to each other. The analyzer divided the beam into two orthoganally polarized components which were detected by photodiodes. The difference of two photodiode signals was the measure of the polarization plane rotation angle.

The Faraday rotation measurements were carried out in two modes. In the first mode the laser frequency was scanned at a constant magnetic field, in the second - the laser frequency was fixed and the magnetic field was scanned. In both modes, control of the parameters and data acquisition was done by a microcomputer through a CAMAC system, 250 points were taken with a total measurement time of 10-20 sec.

3.Results and discussion

To illustrate the difference of the linear and nonlinear Faraday effects let us start with a typical recording of the Faraday rotation in experimental conditions under which nonlinear effects can be neglected. The dependence of optical rotation on the laser frequency for the 651 nm transition (see fig.2), recorded with magnetic field 8 Oe, laser power 0.1 mW and buffer gas helium pressure 15 Torr is shown in fig.3a. The samarium vapor optical length did not exceed an absorption length. In the present work a samarium sample of natural isotope mixture was used. Peaks corresponding to even isotopes are clearly seen in fig.3a. They have the typical sign-changing shape corresponding to the Faraday rotation lineshape for a single line. Positions of odd isotopes (149,147) are not shown on the figure because

their lines consist of several hyperfine components and the Faraday rotation on them has a more complicated structure.

Fig. 3b shows the dependence of optical activity on the frequency for the same transition but in the absence of buffer gas and with magnetic field 0.04 Oe. Under these conditions the Faraday rotation significantly differs from the case shown in fig.3a. Firstly, the rotation at the peak cetetrs has changed sign. Secondly, the sign of rotation is the same for all frequences. Thirdly, although the magnetic field was decreased by a factor of 200, the peak rotation has increased 5-fold. Another important difference is the absence of optical rotation on the odd isotopes. Fig.3c shows a Faraday rotation recording with the same conditions but at magnetic field 0.4 Oe. At this field the Faraday rotation has again changed its sign and the optical activity on the odd isotopes starts to manifest itself as evidenced by the perturbations in rotation angle in the odd isotope region.

Related phenomena were also observed on the 639 hm and 654 nm transitions (the 639 nm line was previously studied in [7]). For the transitions under discussion, the dependences of Faraday rotation on magnetic field with fixed laser frequences are shown in fig.4 together with corresponding diagrams of Zeeman sublevels. As the isotope splitting for neighboring isotopes exceeds the Doppler width (≈1 GHz), it is possible to tune the laser frequency so that the radiation would primarily interact with one of the isotopes. In the present work measurments of the magnetic field dependence of optical rotation were made for the ^{152}Sm isotope. Note that in the case of odd isotopes one has to deal with a complex system of energy levels (nuclear spin I=7/2) and the analysis of nonlinear effects for this situation lies beyond the scope of this paper.

The 639 nm transition (0->1; fig.4a) is an example of a V-system. Relaxation of coherence of Zeeman sublevels of the upper J=1 level is determined by the same processes that cause population relaxation: radiative decay of the upper state and transit of atoms through the laser beam. Thus if the effective laser bandwidth i.e. the frequency instability during the transit time can be neglected, maxima in the magnetic field dependence of optical rotation due to coherence and Bennett structures should occur at the same magnetic field, corresponding to

$g\mu H \sim \Gamma$, where Γ is the sum of the transit width (~100 kHz) and the natural width of the transition. In fact, in fig.4a there is only one peak (The dependences are antisymmetric in magnetic field. Here and below only half of the curve with $H \geq 0$ is discussed). For the upper level of the 639 nm transition g=-0.13 [10]. This can be used to estimate a value for Γ of ~200 kHz.

For the 654 nm transition (1->0; fig.4b) there is also one peak in the magnetic field dependence of optical rotation. Here we deal with a Λ-system and one could have expected the peaks due to coherence and Bennett structures to be distinguishable, because their effective widths are of different origin. The width for the coherence effect is now determined solely by the transit time, while for the Bennett structure effect as in the case of a V-system it is determined by an aggregate of the transit and the natural width. The upper state lifetime for the 654 nm transition is unknown. Apparently the peaks in magnetic field dependence of the Faraday rotation proved to be indistinguishable because the natural width of the transition is of the order of magnitude or smaller than the transit width. Change of sign of the effect relative to the 639 nm transition and the scale of magnetic field at which peak rotation is achieved is due to the g-value of the J=1 state: in this case g=1.5. One can also see in fig.4b a small contribution of the linear Faraday effect.

For the 651 nm transition (1->1; fig.4c) there are peaks corresponding to two values of magnetic field. A 1->1 transition can be considered as an aggregation of a Λ- and a V-system, coupled only through spontanious transitions. This manifests itself in the magnetic field dependence of Faraday rotation: the curve in fig.4c is actually the sum of curves in figs.4a,b.

For the nonlinear Faraday effect it would have been natural to expect a linear dependence of the optical rotation angle on laser power. However, the measured optical rotation for the transitions under discussion was practically independent of laser power in the range 0.05 - 0.2 mW. The increase of laser power caused only a minor broadening of peaks in the magnetic field dependence of rotation. This behavior can be accounted for by saturation of nonlinear effects at the given power levels. Actually, for both nonlinear Faraday rotation mechanisms the saturation parameter in the given case can be estimated as $\varkappa \sim d^2E^2/(\Gamma \cdot \Gamma_{rel})$. Here d is the transition dipole moment, E -

electric field amplitude of the light wave, Γrel - relaxation rate. In our case Γrel is determined by the transit time. With the laser beam diameter 1 mm this parameter turns to unity at the power level of about 10 μW.

Since the saturation of absorption is also determined by the same parameter, saturation can be checked by measuring the power transmitted through the vapor cell as a function of the input power. Shown in fig.5 is a graph, illustrating this measurement for the 654 nm transition at zero magnetic fied. The dependences proved to be significantly nonlinear and could be satisfactorily approximated with a function $I=I_0\exp(-l/l_0(1+\varkappa))$. For the curve shown in fig.5, $l/l_0=2$, $\varkappa=I_0/10$ μW. This illustrates that the onset of saturation in fact occurs at ~10 μW. Power broadening of peaks in the magnetic field dependence of Faraday rotation is seen in fig.6 which shows recordings of this dependence for the 654 nm transition with laser power 10 and 100 μW.

Nonlinear Faraday rotation was also studied for the 571 nm transition (1->0). For this transition the upper state lifetime is known and the corresponding radiative width is ≈500 kHz [11]. On the magnetic field dependence of optical rotation (fig.7) there are peaks of opposite signs, corresponding to two effective widths: $g\mu H\approx 60$ kHz and 1000 kHz (g=1.5). In this case the narrower peak can be ascribed to the coherence effect (transit width), while the broader one - to the Bennett structures.

Note that nonlinear Faraday rotation on the 571 nm transition was studied earlier [4], but only one peak in the magnetic field dependence of nonlinear signal was observed in that work. Apparently, this is due to the different experimental conditions realized in [4]: significantly higher light intensities, presence of a buffer gas, etc.

On fig.7 the rise of Faraday rotation at high magnetic field is due to the linear effect. At low fields the nonlinear Faraday rotation exceeds the linear contribution by four orders of magnitude. By using a broader laser beam it is possible to increase the transit time and thus to obtain smaller effective width for the coherence effect and consequently - a larger enhancement of Faraday rotation in the low field region. Note that this enhancement can be applied to measurements of small magnetic fields. Analogous effects also can be used in experiments on the search for optical activity of atoms and molecules in longi-

tudinal electric fields [12,13], caused by violation of parity and T-invariance.

The nonlinear effects are very sensitive to atomic collisions. After adding ~0.1 Torr of a buffer gas (Ar, He) the nonlinear Faraday rotation amplitude decreased by an order of magnitude and at ~1 Torr nonlinear effects could not be observed at all with light power ~0.1 mW. Shown in fig.8 is the magnetic field dependence of Faraday rotation for the 571 nm transition without buffer gas (a) and with 0.05 Torr of argon (b). It can be seen from the figure that addition of buffer gas, apart from decreasing the signal amplitude, also changes its form. Detailed analysis of nonlinear Faraday effect in the presence of buffer gas lies beyond the scope of this paper.

4.Conclusion

Nonlinear Faraday rotation in atomic samarium was experimentaly studied in this work. Measurements were carried out on several transitions with different angular momenta of upper and lower states, at a variety of laser powers and buffer gas pressures. The observed phenomena can be accounted for by two mechanisms: the establishment of Zeeman coherences and formation of Bennett structures on the velocity distributions of individual atomic states.

A remarkable feature of nonlinear optical activity is a significant enhancement of rotation with respect to the linear case in the low field region. This enhancement can apparently be used in a variety of applications, including the search for (P+T)-odd interactions.

Acknowledgements

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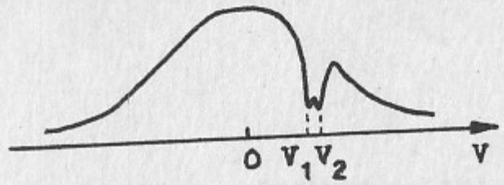

Fig.1. Distribution of atomic velocity projections on the light propagation direction for the J=0 state in a V-system with longitudinal magnetic field H. Values $v_{1,2}$ are determined by the relation $\nu(1-v_{1,2}/c)=\nu_0\pm g\mu H$, where ν is the light frequency, ν_0 - central frequency of the transition. $v_{1,2}$ are the velocity projections of atoms that are in resonance with right and left quanta respectively.

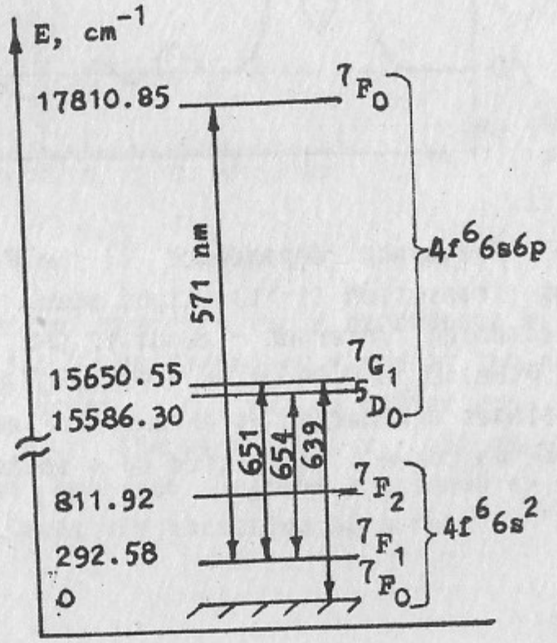

Fig.2. Diagram of samarium transitions studied in this work.

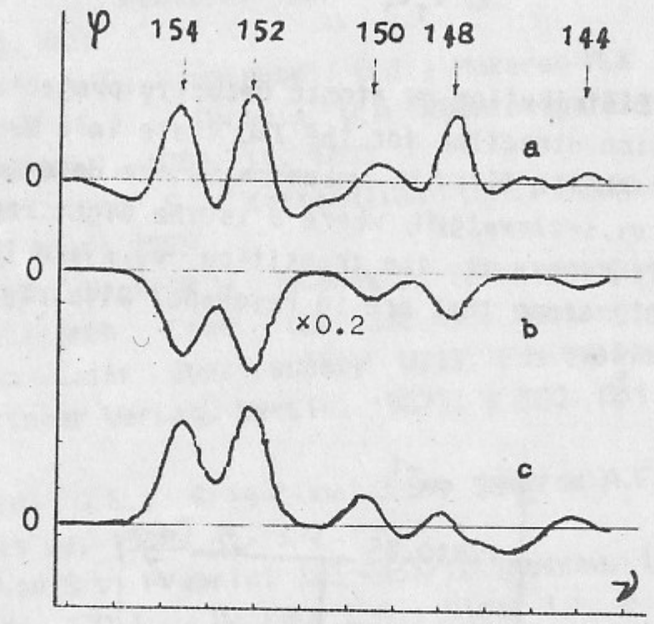

Fig.3. Frequency dependence of the Faraday rotation for the 651 nm transition (1->1). Light power - 0.1 mW. The total frequency scanning interval - about 12 GHz. a - P(He)=15 Torr, H=8 Oe; b - P(He)=0, H=0.04 Oe; c - P(He)=0, H=0.4 Oe. Positions of even isotopes are marked by arrows. For easiness of comparison the scale on curve b is reduced by a factor of 5.

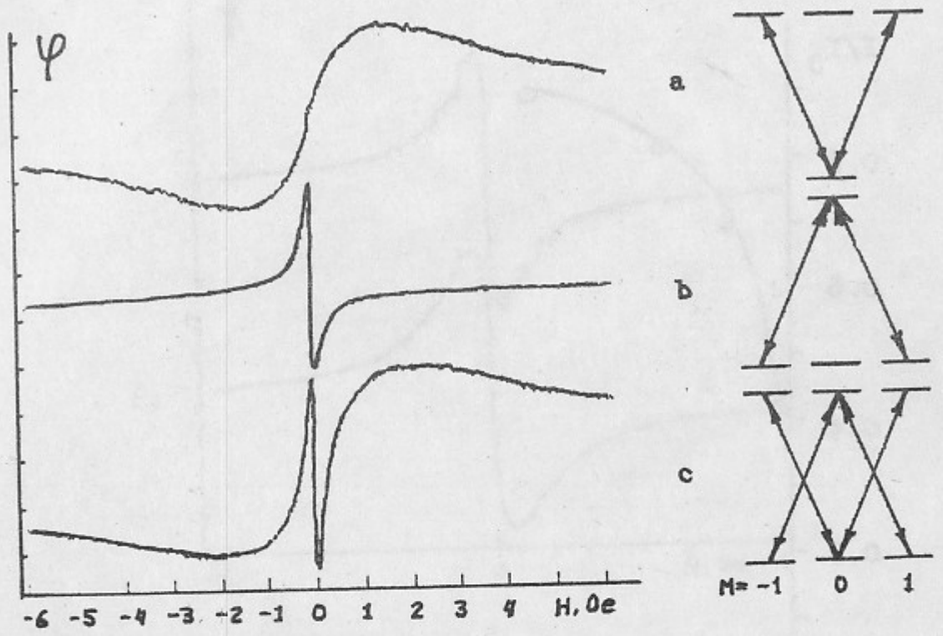

Fig.4. The form of magnetic field dependence of the Faraday rotation with the laser frequency fixed at the peak of the 152 isotope. Laser power - 0.1 mW, no buffer gas. a - 639 nm transition (0->1); b - 654 nm (1->0); c - 651 nm (1->1). The corresponding Zeeman sublevel diagrams are shown on the right. Laser-induced transitions are indicated by arrows.

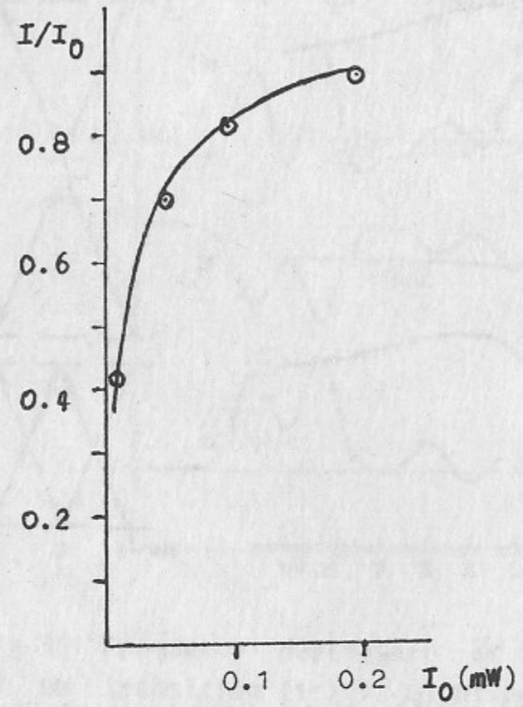

Fig.5. Ratio of the light power I at the output of samarium cell and the input power I_0 for the 654 nm transition, no buffer gas. Circles - experimental values, solid line is the function $I/I_0=\exp(-l/l_0(1+\varkappa))$ with $l/l_0=2$, $\varkappa=I_0/10$ μW.

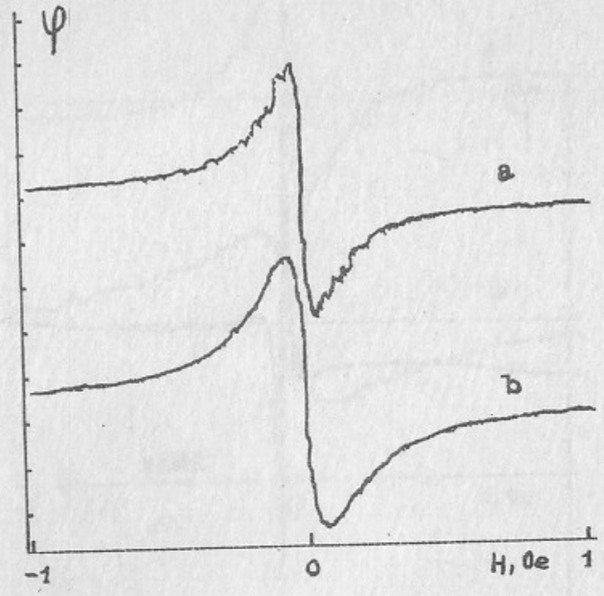

Fig.6. The form of magnetic field dependence of the Faraday rotation for the 654 nm transition in a detailed scale. No buffer gas. a - light power - 10 μW, b - 100 μW. For easiness of comparison the curves are presented with the same vertical size. Curve b is considerably broadened with respect to curve a.

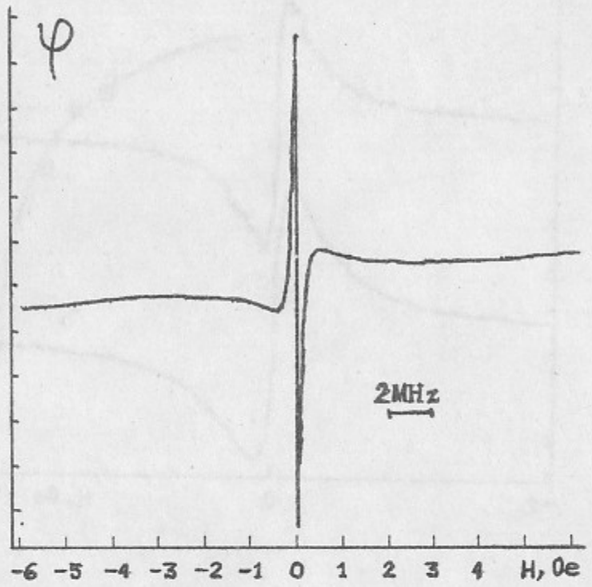

Fig.7. Magnetic field dependence of Faraday rotation for the 571 nm transition (1->0). Laser power - 5 μW, no buffer gas. Sample shows the scale of gμH values.

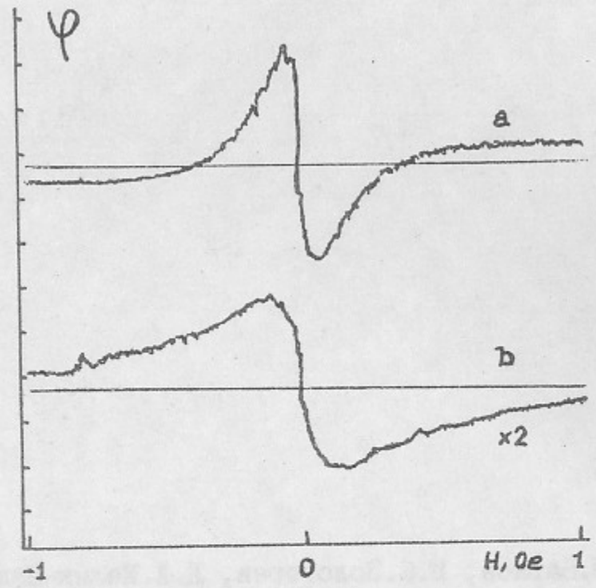

Fig.8. Magnetic field dependence of Faraday rotation for the 571 nm transition. Laser power - 60 μW. a - no buffer gas; b - buffer gas argon, P(Ar)≈0.05 Torr.

Л.М.Барков, М.С.Золоторев, Д.А.Мелик-Пашаев

НЕЛИНЕЙНОЕ ФАРАДЕЕВСКОЕ ВРАЩЕНИЕ В ПАРАХ САМАРИЯ

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