SOVIET PHYSICS JETP VOLUME 22, NUMBER 1 JANUARY, 1966

OPTICAL ORIENTATION OF ATOMS IN A MAGNETIC FIELD PERPENDICULAR TO A BEAM

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Submitted to JETP editor February 16, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) **49**, 97-106 (July, 1965)

It is demonstrated theoretically and experimentally that an appreciable orientation of atoms can be attained in a magnetic field perpendicular to the orienting light beam. To achieve this a variable magnetic field was imposed on the stationary field. If the directions of these two fields form a small angle, the resulting moment will precess about the stationary field. In this case large time-independent components of the moment directed along the magnetic field and the light arise. The experiment was carried out in cesium vapor. The orienting ray was circularly polarized and consisted of one long-wave component of the resonance doublet.

1. INTRODUCTION

THE well-known phenomenon of optical orientation[1] of atoms consists in the fact that light which is circularly polarized and passes along the magnetic field through a gas produces a stationary magnetic moment of the gas atoms. When the atom absorbs a circular-polarization photon, it takes up the mechanical momentum of the photon. The excited atom loses during the succeeding spontaneous emission (in the general case) a momentum unequal to that which it acquired. This precisely is the cause of the orientation.

If we direct the light ray perpendicular to the magnetic field, then the magnetic moment produced upon absorption of a quantum begins to precess about the magnetic field. Inasmuch as the acts of quantum absorption occur randomly in time, the magnetic moments of the different atoms will have random rotational phases, so that the resultant moment will be equal to zero.

However, as shown by Bell and Bloom,[2] it is possible to obtain the effect of orientation with a magnetic field perpendicular to the beam, if the intensity of the light is modulated at a frequency equal to the precession frequency. The absorption acts occur in this case predominantly during the time of the intensity bursts. The moment produced in the time of one burst executes a complete revolution around the magnetic field and turns out to be directed along the beam precisely at the time of the next burst of intensity, which produces another "shot" of momentum. This produces a resultant rotating moment.

In the present paper we investigate a different method of producing a resultant moment in a magnetic field perpendicular to the beam. This is done by modulating the magnetic field in magnitude at a constant light-beam intensity. Although the rate of production of moments by the light is constant, their angular distribution will no longer be uniform. The moments produced during that half-cycle when the field is smaller than the average value have an angle density higher than average, since they all lie in a sector smaller than a semicircle. (If the field were to be equal to zero during this half cycle, all the moments produced during that time would have subsequently the same angular phase, so that their angle density would be infinitely large.) The moments produced during the next half cycle, when the field is larger than average, have a reduced angle density. The picture is reminiscent of a rotating disc, on which radial arrows, showing the moment, are denser in one semicircle than in the other. If the period of field oscillations is equal to the precession period, then the picture will not become smeared out and a resultant rotating moment will exist. In addition, a constant component of the resultant moment will appear. Its occurrence is connected, in particular, with the fact that the resultant moment does not precess uniformly in the pulsating field; during the half cycle when the field is decreased, the angular velocity of precession is also decreased. This phenomenon has much in common with parametric resonance arising when light is scattered by atoms placed in a pulsating magnetic field.[3]

Under the experimental conditions, the ac component of the magnetic field is produced by a separate coil, and the resultant magnetic moment was registered by determining the change in the absorption of the beam. It was observed that the resonance is strongly broadened, and its amplitude is reduced by the inhomogeneity of the constant magnetic field. It turned out that this resonance signal increases abruptly if the axis of the ac magnetic field coil is inclined at a small angle relative to the direction of the constant magnetic field. This is connected with the appearance of another effect, which we shall now describe.

The main feature of this effect is the occurrence of a constant component of the magnetic moment along the constant magnetic field. Let the constant magnetic field H_0 be directed along the x axis. The light propagates along the z axis. As explained above, owing to the presence of an alternating field component H_x, a resultant magnetic moment **M**, rotating in the YZ plane, is produced. Inasmuch as the precession of the moment **M** is forced, its frequency is equal to the oscillation frequency of the alternating field. At resonance, the frequency is equal to the frequency of free precession, and the phase of the rotation is such that the vector **M** is parallel to the light ray when the x component of the ac component of the field reduces the field H_0 the most. In this case an appreciable influence is exerted by the presence of the component H_y of the alternating field. The solid arrows in Fig. 1a show the vectors **M** and H_y at the instant when H_x is maximal and directed opposite to H_0. We see that the component H_y causes rotation of the vector **M** upward. The dashed arrows show the positions of **M** and H_y one-half cycle later. We see that at that time, too, the component H_y causes the moment **M** to turn upward. Thus, the presence of H_y results in a continuous growth of the constant component of the moment along the x axis.

We now proceed to explain the influence of the component H_z of the alternating field. At resonance, when the frequency of the field oscillations is equal to the frequency of the free precession, the influence of the component H_z is insignificant, since during one-quarter of the period the component H_z causes the moment to turn upward, and during the next quarter of the period it causes it to turn downward. If, on the other hand, we move off resonance by a distance on the order of the line width, then the phase of rotation of the vector **M** in the YZ plane will shift by $\pi/2$ in one direction or the other. Therefore at that instant of time when the field H_0 is weakened the most, the vector **M** will, for example, occupy the position shown in

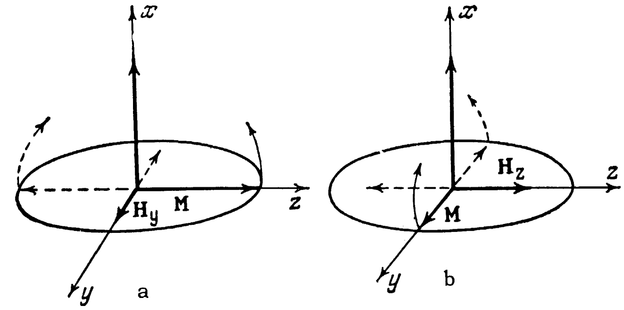

FIG. 1. Illustration of the motion of the magnetic moment.

Fig. 1b by the solid arrow. We see that the field H_z causes in this case the vector **M** to rotate upward. After one-half cycle (dashed arrows) the vector **M** will, as before, turn upward. Thus, the presence of H_z also leads to a continuous growth of the constant component of the moment along the x axis, but the dependence of this effect on the magnetic field H_0 (or on the frequency of the ac component) will be dispersive in its nature.

2. THEORY

To describe the behavior of the magnetic moment of the atoms we use Bloch's equations [4]

$$\dot{m}_z = -\omega_0 m_y - \omega_x' m_y + \omega_y' m_x - \nu(m_z - m_0),$$
$$\dot{m}_y = \omega_0 m_z + \omega_x' m_z - \omega_z' m_x - \nu m_y,$$
$$\dot{m}_x = \omega_z' m_y - \omega_y' m_z - \nu m_x. \quad (1)$$

Here m_x, m_y, and m_z are the projections of the magnetic moment; m_0 —the moment oriented along the light beam, which would be produced were there no magnetic fields; ν —the reciprocal relaxation time, due to the beam itself as well as to the collisions. The quantity $\omega_0 = \gamma H_0$ is the frequency of the spin precession in a constant magnetic field H_0 (γ is the gyromagnetic ratio);

$$\omega_z' = \gamma H_z, \quad \omega_y' = \gamma H_y, \quad \omega_x' = \gamma H_x,$$

where H_x is the x component of the alternating field; thus

$$\omega_x' = \omega_x \sin \Omega t, \quad \omega_y' = \omega_y \sin \Omega t, \quad \omega_z' = \omega_z \sin \Omega t. \quad (2)$$

We have assumed that the constant magnetic field is strictly perpendicular to the light ray, and the alternating magnetic field has all three components. For the solution it is convenient to write Eqs. (1) in circular components

$$m_- = {}^1/_2(m_z - im_y), \qquad m_+ = {}^1/_2(m_z + im_y); \quad (3)$$

$$\omega_-' = {}^1/_2(\omega_z' - i\omega_y'), \qquad \omega_+' = {}^1/_2(\omega_z' + i\omega_y'). \quad (4)$$

They then assume the form

$$\dot{m}_- + (i\omega_0 + \nu)m_- = -i\omega_x' m_- + i\omega_-' m_x + {}^1/_2 \nu m_0, \quad (5)$$

$$\dot{m}_+ - (i\omega_0 - \nu)m_+ = i\omega_x' m_+ - i\omega_+' m_x + {}^1/_2 \nu m_0, \quad (6)$$

$$\dot{m}_x = 2i\omega_+' m_- - 2i\omega_-' m_+ - \nu m_x. \quad (7)$$

If the alternating field were to be strictly parallel to the constant field ($\omega_+' = \omega_-' = 0$), then we would obtain from (7) a stationary solution $m_x = 0$. Then a solution of equation (5) or (6) would describe a moment rotating in the YZ plane. If the alternating field is not directed parallel to the constant field (ω_+' and ω_-' are not equal to zero), then Eq. (7) shows that there exists a nonvanishing stationary solution for m_x. Generally speaking, this solution is a complicated periodic function of the time, containing all the harmonics which are multiples of the frequency Ω of the alternating field. However, under certain conditions the zeroth harmonic (the dc component) will be much larger than all other harmonics. We can see from (7) that these conditions are as follows:

$$\omega_y, \omega_z \ll \Omega.$$

We shall assume below that this inequality is satisfied and, consequently, m_x does not depend on the time. Then Eq. (5) can be solved in the same way as equation (4) of the paper by Khodovoĭ and the authors was solved.[3] As a result we obtain

$$m_-(t) = \sum_{k=-\infty}^{\infty} e^{ik\Omega t} M_k, \quad (8)$$

$$M_k = \frac{i^k}{2} \sum_{n=-\infty}^{\infty} \frac{J_{k+n}(\omega_x/\Omega) J_n(\omega_x/\Omega)}{\nu + i(\omega_0 - n\Omega)} \times \left(\nu m_0 - 2i\omega_- \cdot m_x \frac{\Omega}{\omega_x} n\right). \quad (9)$$

Here ω_x and ω_- are the maximum values of the corresponding components of the alternating field. The quantity $m_+(t)$ is obtained from (8) by complex conjugation.

If we now substitute in (7) the components m_- and m_+ and average this equation with respect to time, we obtain an equation for the determination of m_x. Its solution is quite unwieldy and will not be given here. It is essential that m_x has resonant maxima when the frequency of free precession ω_0 is a multiple of the frequency of the alternating field Ω. Near resonance $\omega_0 \approx n\Omega$ the quantity m_x is of the form

$$m_x^{(n)} = \frac{m_0 \Omega}{\omega_x} n J_n^2\left(\frac{\omega_x}{\Omega}\right) \frac{\nu\omega_y - \omega_z(\omega_0 - n\Omega)}{\nu_n^2 + (\omega_0 - n\Omega)^2}, \quad (10)$$

$$\nu_n^2 = \nu^2 + \frac{\Omega^2}{\omega_x^2} n^2 J_n^2\left(\frac{\omega_x}{\Omega}\right)(\omega_y^2 + \omega_z^2). \quad (11)$$

Using formulas (10) and (9), we obtain a value of M_k near resonance $\omega_0 \approx n\Omega$:

$$M_k^{(n)} = \frac{i^k}{2} \frac{J_{k+n}(\omega_x/\Omega) J_n(\omega_x/\Omega)}{\nu_n^2 + (\omega_0 - n\Omega)^2} \Big[\nu^2 + i\nu(\omega_0 - n\Omega) + \frac{\Omega^2}{\omega_x^2} n^2 J_n^2\left(\frac{\omega_x}{\Omega}\right)(\omega_z - i\omega_y)\omega_z\Big]. \quad (12)$$

It must be noted that the presence of transverse components of the alternating field leads to a broadening of the resonances (saturation effect).

Formulas (8), (10), and (12) give a complete description of the effect under consideration in a uniform field H_0. In fact, the field is not strictly uniform, and therefore formulas (10)—(12) must be averaged over the field distribution. We shall assume, for simplicity, that the distribution is Lorentzian with a characteristic scatter Δ. Then averaging, for example, of the quantity $m_x(\omega_0)$ is carried out in the following fashion:

$$\overline{m}_x = \int_{-\infty}^{\infty} m_x(\omega_0') \frac{1}{\pi} \frac{\Delta}{\Delta^2 + (\omega_0 - \omega_0')^2} d\omega_0'. \quad (13)$$

Proceeding in this manner, we obtain the following expressions:

$$\overline{m}_x^{(n)} = \frac{m_0 \Omega}{\omega_x} n J_n^2\left(\frac{\omega_x}{\Omega}\right) \times \frac{\omega_y(\nu_n + \Delta)\nu/\nu_n - \omega_z(\omega_0 - n\Omega)}{(\Delta + \nu_n)^2 + (\omega_0 - n\Omega)^2}, \quad (14)$$

$$\overline{M}_k^{(n)} = \frac{i^k}{2} \frac{J_{k+n}(\omega_x/\Omega) J_n(\omega_x/\Omega)}{(\Delta + \nu_n)^2 + (\omega_0 - n\Omega)^2} \Big\{\Big[\nu^2 + \frac{\Omega^2}{\omega_x^2} n^2 J_n^2\left(\frac{\omega_x}{\Omega}\right) \times (\omega_z - i\omega_y)\omega_z\Big] \frac{\nu_n + \Delta}{\nu_n} - i\nu(\omega_0 - n\Omega)\Big\}. \quad (15)$$

As can be seen from formula (11), $\nu_n \gg \nu$ provided only the transverse field components ω_y and ω_z are not very small (the value of ν is of the order of 10^2 sec^{-1}, corresponding to a field on the order of 10^{-4} Oe). Therefore the main influence on the effects is exerted by the z component of the alternating field.

3. EXPERIMENT

The purpose of the experiment was to verify the theory in the strongest manifestations of the effect, since the approximate theory describes them most reliably. We investigated in detail the constant and alternating components of the moments m_z and m_x, directed along the beam of the orienting light and along the constant field $\mathbf{H}_0$, respectively, in the vicinity of the first resonance $n = 1$ [see formulas (8), (14), and (15)]. The object of the experiment was cesium, present in the form of saturated vapor at room temperature in a bulb (200 cc) together with argon at a pressure of 10 cm Hg. The bulb with the vapor was placed in the center of two pairs of Helmholtz rings of 35 cm radius, making it possible to produce a constant magnetic field of the required magnitude and direction. The alternating field was produced by an additional pair of rings of 12 cm radius, fed from a 100 I generator, which could be oriented in arbitrary fashion relative to the first system of rings.

The source of resonant radiation was a spherical electrodeless-discharge cesium lamp. The light from the lamp passed through a circular polarizer, an interference filter which transmitted one long-wave line of the resonant doublet, and was directed perpendicular to the magnetic field $\mathbf{H}_0$ onto the cesium-filled bulb. The transmitted light was received with a photomultiplier and used to register the change in the moment m_Z as given by the change in the absorption in the bulb. As shown by Bell and Bloom,[4] the absorption of circularly polarized light depends on the projection of the moment on the direction of light propagation. Moreover, it can be shown[6] that the main part of the absorption is connected with the moment linearly. To register the moment m_X we used an additional, much weaker beam of resonant light from a second lamp, also filtered and circularly polarized. After passage through the bulb, the light of the second source was received by a separate photomultiplier.

The photoreceiver signals were processed in different manners when registering the alternating and constant components of the moments. In the latter case, a modulation registration procedure was used, in which the alternating field was fed in the form of rectangular pulses with an off-duty cycle of 0.5 and with duration of approximately 0.1 sec, that is, with a time longer than the transients in the system. This made it possible to amplify the photosignal with a low-frequency amplifier and then employ synchronous detection. In the synchronous detector, and also in order to shape the ac pulses in the Helmholtz rings, a polarized relay of type RP-4 was used.

The observation of the modulation of the transmitted light at the frequency of the alternating field was greatly hindered by parasitic signals induced in the receiving circuits by the stray alternating magnetic field. To eliminate these signals, the 110 kcs photosignal was converted into an inter-

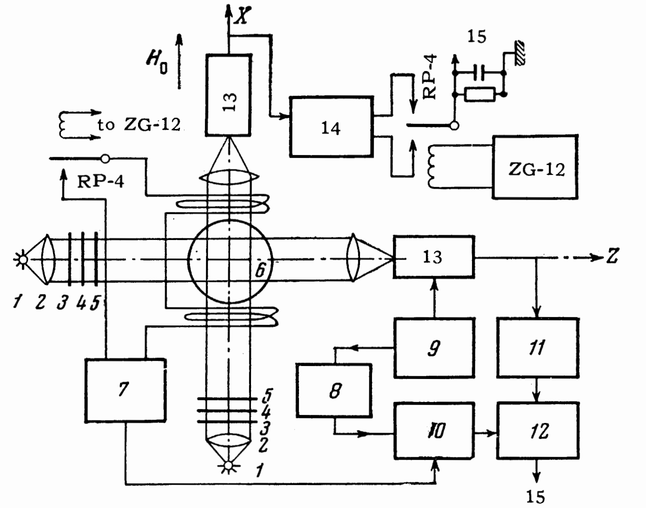

FIG. 2. Block diagram of the experimental setup: 1 – cesium lamp, 2 – lens, 3 – polaroid, 4 – quarter-wave plate, 5 – interference filter, 6 – cell with cesium vapor in argon, 7 – 110 kcs generator, 8 – 50 – 100 kcs converter, 9 – 50 kcs heterodyne, 10 – mixer, 11 – intermediate frequency amplifier of 10 kcs, 12 – synchronous detector, 13 – photomultiplier, 14 – low frequency amplifier, 15 – output.

mediate frequency signal at 10 kcs by applying to one of the dynodes of the photomultiplier a voltage with frequency 50 kcs from a heterodyne. This led to modulation of the sensitivity of the photomultiplier at the double frequency 100 kcs and the appearance of a combination frequency of 10 kcs in its photocurrent (in the presence of the signal).[5] The converted signal was amplified and fed to a diode synchronous detector. The use of such a device together with magnetic screening of the photomultiplier made it possible to eliminate completely the parasitic signals. Figure 2 shows a block diagram of the experimental setup, with the scheme for registering the alternating component of the moment shown for the Z beam and of the constant component for the X beam. All the experiments were made at a fixed alternating-field frequency of 110 kcs. This frequency corresponds to the first resonant value of the dc field intensity H_0, equal to 0.3 G.

4. EXPERIMENTAL RESULTS

1. Alternating component of the moment m_Z. The appearance of modulation of the transmitted light was observed only in the Z beam, as should be the case, since the precession of the moment takes place in the ZOY plane, and the registration was carried out in the directions of the x and z axes. Modulation in the Z beam appeared upon satisfaction of the resonance conditions $\omega_0 = \Omega$, and its depth showed a strong dependence on the angle θ in the ZOX plane, between the alternating

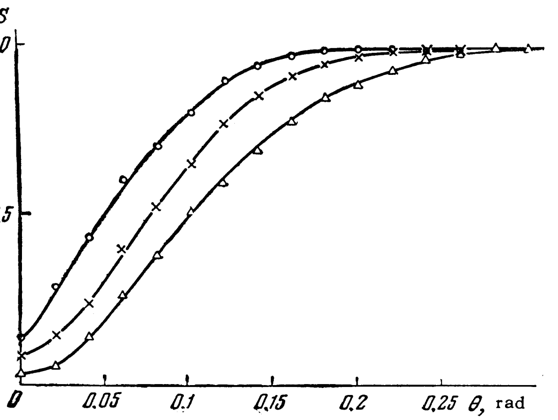

FIG. 3. Dependence of the depth of light modulation on the angle between the constant and alternating fields for three values of the parameter ω_x/Ω (reading upward): 0.2, 0.7, and 1.

and the constant fields. Figure 3 shows the experimental curves plotted for three values of the ac field amplitude.

Modulation in the Z beam was proportional to the alternating component of the z component of the moment m_z. Using formulas (3), (8), and (15) we can obtain the following expression for the first harmonic for m near resonance $\omega_0 = \Omega$ and $\omega_y = 0$:

$$m_{z1} = -\frac{J_1(J_0+J_2)\nu_1(\nu_1+\Delta)}{(\Delta+\nu_1)^2+(\bar{\omega}_0-\Omega)^2} \times \left[\sin\Omega t + \frac{J_0-J_2}{J_0+J_2}\,\frac{\bar{\omega}_0-\Omega}{\nu_1+\Delta}\,\frac{\nu}{\nu_1}\cos\Omega t\right],$$

$$\nu_1^2 = \nu^2 + \frac{\Omega^2}{\omega_x^2}J_1^2\,\omega_z^2 = \nu^2 + \Omega^2 J_1^2\,\mathrm{tg}^2\,\theta. \qquad (16)^*$$

The argument of the Bessel function is the quantity ω_x/Ω. The second term in the square brackets can be neglected, since it contains a factor ν/ν_1, which is small even at small angles.

At small angles the dependence of the effect on the angle is determined (at resonance) by the factor

$$\frac{\nu_1}{\nu_1+\Delta} = \frac{(\nu^2+\Omega^2 J_1^2\theta^2)^{1/2}}{\Delta+(\nu^2+\Omega^2 J_1^2\theta^2)^{1/2}}.$$

The dependence plotted in Fig. 3 is in qualitative agreement with this function. The plateau corresponds to those angles at which the width connected with the saturation exceeds not only the homogeneous but also the inhomogeneous broadening. The depth of the dip in the signal at 0° characterizes the ratio of the homogeneous (ν) and inhomogeneous (Δ) broadenings.

*tg = tan.

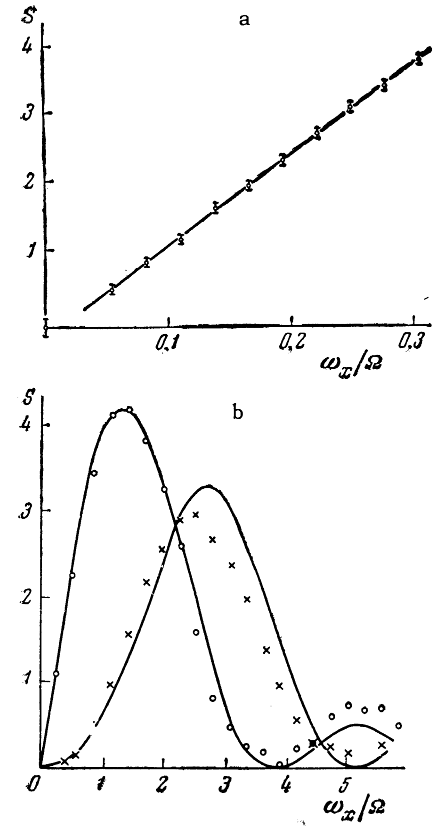

FIG. 4. Dependence of the depth of modulation of light on the amplitude of the alternating field.

The decrease of the signal when the fields are parallel can be readily explained qualitatively. Inasmuch as a characteristic result of parallel arrangement of the fields is independence of the width of the resonance of the amplitude of the alternating field, the only atoms participating in the process are those for which the local magnetic field $\mathbf{H}_0$ is resonant. The fraction of these atoms, in the case of appreciable homogeneity, can be small. The appearance of the components of the alternating field H_x and H_y leads to the broadening of the resonance line—atoms are "drawn" into resonance with different values of the local field, that is, the total number of atoms participating in the resonance increases, and consequently the signal increases.

Figure 4 shows the dependence of the light-modulation signal on the amplitude of the alternating field (at an angle θ corresponding to the plateau on Fig. 2). Figure 4a demonstrates the linearity of the signal [which is the consequence of (16)] at small alternating field intensities. The abscissas represent the parameter ω_x/Ω. Figure 4b shows the change in the magnitude of the signal at large values of the parameter. The continuous curve is the theoretical one [$\sim J_1(J_0+J_2)$], which has been

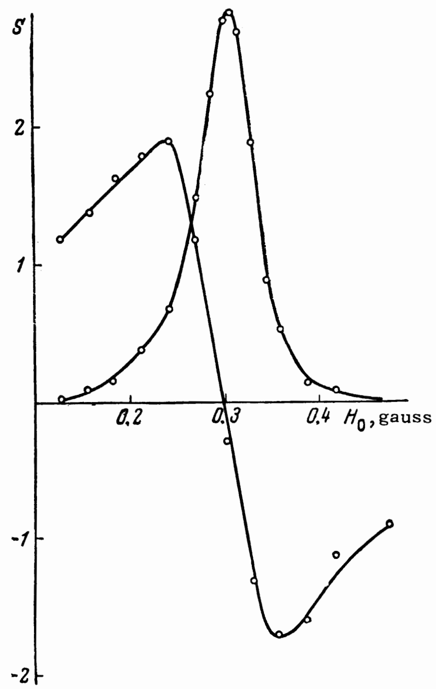

FIG. 5. Dependence of the dc components of the moment on the field H_0.

aligned with the experimental value at the first maximum. The experimental points are marked by circles.

All this pertains to the appearance of modulation of light in the first resonance at $\omega_0 = \Omega$. We observed also higher resonances, the second and third, which appear at large alternating field intensity. The dependence of the modulation depth of light on the amplitude of the alternating field for the second resonance ($\omega_0 = 2\Omega$) is also shown in Fig. 4b (the experimental points are noted with crosses). The scale along the ordinate axis is the same as for the first-resonance curve, so that no additional reconciliation with the theoretical curve $[\sim J_2(J_1 + J_3)]$ was carried out.

2. Constant component of the moment. Figure 5 shows the dependence of the signal corresponding to the average change in intensity of the transmitted light for the X and Z beams, on the value of the constant magnetic field H_0 in the vicinity of the resonance. In accordance with deductions of the theory [see formula (14) with $\omega_y = 0$] the contour of the signal for the X beam has a dispersion character. The width of the resonances depends strongly on the amplitude of the alternating field. The values of both signals are shown in Fig. 5 in relative units and are not reconciled with each other. For the signal connected with the moment m_z, we plotted the dependence on the amplitude of the alternating field. The initial section of this plot has the theoretically predicted quadratic variation.

3. Alternating component of the moment with the alternating field parallel to the constant field ("pure parametric resonance"). In spite of the large inhomogeneity of the field $\mathbf{H}_0$, we attempted to show directly the existence of the light-modulation effect at the strictest parallel arrangement of the fields $\mathbf{H}_0$ and $\mathbf{H}_1$. The most characteristic feature of this effect is the absence of broadening of the resonance with increasing alternating field intensity. A check on this fact was made difficult by two circumstances: the smallness of the signal when the fields were not parallel, and the inexact spatial setting of the fields, again connected with their inhomogeneity. Figure 6 shows three resonant contours, plotted for three values of the ac field amplitude, which differ from the neighboring ones by a factor of 2.

It is seen from Fig. 6 that although the resonances do broaden with increasing amplitude of the alternating field, the broadening is much smaller than is characteristic of paramagnetic resonance in the saturation region. For example, the widths of the resonances are $\omega_x/\Omega = 1.4$ and $\omega_x/\Omega = 0.7$ and differ not by a factor of 4, but altogether by approximately a factor of 1.5. Also typical is the small absolute width of the resonances (see Fig. 4). We note that for $\omega_x/\Omega = 1.4$ the amplitude of the signal at resonance goes through a maximum (see Fig. 4b), so that saturation in amplitude has already been reached.

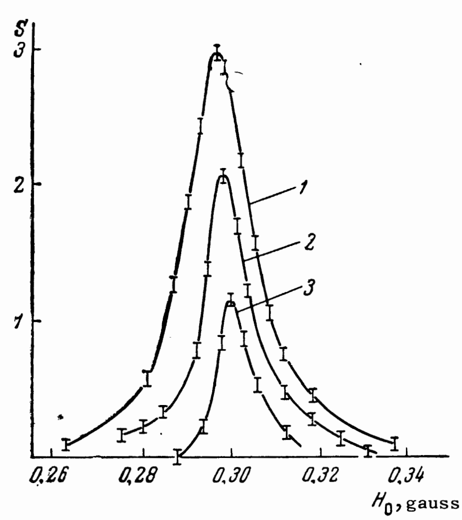

FIG. 6. Broadening of the resonant contour (ac component of the moment) by an alternating field: 1 – $\omega_x/\Omega = 1.4$; 2 – $\omega_x/\Omega = 0.7$; 3 – $\omega_x/\Omega = 0.35$.

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15