Cooling of the spin system of semiconductor lattice nuclei in the field of electrons oriented by light

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Cooling of the spin system of semiconductor lattice nuclei in the field of electrons oriented by circularly polarized light is considered. As a result of cooling application of an external magnetic field induces a considerable nuclear polarization and an additional nuclear field \( H_N \) acts on the electron spins. An equation is derived for the behavior of the z-component of the mean electron spin \( \langle S_z \rangle \) in a transverse field \( H_L \) when cooling depends only on the oriented electron field. Characteristic features of the dependence of \( \langle S_z \rangle \) on \( H_L \) are a narrow line near \( H_L = 0 \) and an additional peak in strong fields. Instability and hysteresis may arise in the case of a positive electron g-factor \( g_e > 0 \). Experimental results for a p-AlxGa1-xAs crystal \( (g_e > 0) \) with an acceptor (Zn) concentration \( \approx 10^{16} \) cm\(^{-3} \) confirm the model under consideration. The effect of variable magnetic fields which alter the nuclear spin system temperature and hence the values of \( H_N \) and \( \langle S_z \rangle \) is demonstrated. A reduction of the nuclear spin temperature down to values lying in the range of negative temperatures, since the energy \( (S) \) of the nuclear spin system is bounded from above. With dynamic cooling in strong field \( H_{\text{max}} \) at 100% polarization of the nuclei \( \langle S_z \rangle = H_{\text{max}}/2.7h \). Experimental results for a p-AlxGa1-xAs crystal show that the change of the energy of the ZP is accompanied by a change of the energy of the nuclear spin system. The change of the energy of the nuclear spin system due to dynamic cooling in strong field \( H_{\text{max}} \) at 100% polarization of the nuclei \( \langle S_z \rangle = H_{\text{max}}/2.7h \). The change of the energy of the nuclear spin system due to dynamic cooling in strong field \( H_{\text{max}} \) at 100% polarization of the nuclei \( \langle S_z \rangle = H_{\text{max}}/2.7h \).

1. INTRODUCTION

The absorption of circularly polarized light under conditions of optical orientations of the electrons is accompanied by dynamic polarization of the nuclei. \(^{(1–3)}\) In the presence of an external magnetic field \( H > H_L \), where \( H_L \) is the local field of the nuclei, the dynamic polarization is well described within the framework of the Overhauser effect. The average spin \( \langle I_z \rangle \) of the nuclei along the propagation direction of the exciting light is determined by the deviation of the average spin \( \langle S_z \rangle \) of the photoexcited electrons from the thermodynamic-equilibrium value \( \langle S_z \rangle \). It was observed recently that optical orientation is accompanied by an appreciable nuclear polarization also in the case \( H < H_L \). \(^{(4–6)}\) In this range of fields, the Zeeman energy of a nucleus is commensurate with the energy of its spin-spin interaction with the neighboring nuclei. The change in the energy of the nuclear Zeeman pool (ZP) due to the hyperfine interaction with the electrons oriented by the light is accompanied by a change of the energy of the nuclear spin-pool (SP). The change of the energy of the ZP is proportional to \( \langle S_z \rangle H \). Depending on the sign of this product, the energy of the SP increases or decreases as a result of its "thermal" contact with the ZP. With increasing energy of the SP, one can speak of cooling in the region of negative temperatures, since the energy spectrum of the SP is bounded from above. With decreasing energy of the SP, cooling takes place in the region of positive temperatures. Thus, under conditions of optical orientation in weak fields \( H \ll H_L \), it is possible to cool the spin system of the nuclei, in analogy with dynamic cooling in strong field \( H \gg H_L \) following radio-frequency saturation of the transitions near the resonance frequency. \(^{(7)}\)

The theory of the cooling of the spin system of lattice nuclei of a semiconductor in the case of optical orientation was developed by D'yakonov and Perel'. \(^{(8)}\) An interesting possibility of dynamic polarization of nuclei under conditions of optical orientation is cooling at a zero external magnetic field, when the change of the Zeeman energy of the nuclei can be obtained as a result of the field of optically-oriented electrons. Allowance for this field leads to a number of interesting features that manifest themselves in experiments on optical orientation in weak fields.

2. CHANGE OF ELECTRON-SPIN ORIENTATION IN A TRANSVERSE MAGNETIC FIELD (HANLE EFFECT) UPON COOLING OF THE SPIN SYSTEM OF THE LATTICE NUCLEI

The lowering of the spin temperature \( \Theta \) of nuclei leads to an increase of the nuclear polarization along the external field \( H \). If the polarization is much less than the limiting value and if the lattice consists of nuclei of one sort, then

\[
\langle I \rangle = (I + 1) \mu_I H/2
\]

where \( I \) is the spin of the nucleus, \( \mu_I \) is its magnetic moment and \( \langle I \rangle \) is the average value of the projection of the nuclear spin on the direction of the magnetic field, while \( \Theta \) is expressed in energy units. The increase of the nuclear polarization is accompanied by an increase of the effective magnetic field \( H_N = h_N I \) acting on the electron spins. The value of \( h_N \) determines the maximum field \( H_{\text{max}} \) at 100% polarization of the nuclei \( \langle S_z \rangle = H_{\text{max}}/2.7h \).

If the light orients the electron spins along \( z \), then the average value \( \langle S_z \rangle \) of the projection of the electron spins along \( z \) will change as a result of the action of the combined field \( H_z = H + H_N \). In this case the field \( H_N \) can manifest itself by a change in the relaxation time \( \tau_g \) (see\(^{(9)}\)) in the presence of a component \( H_N \) along \( z \), or else in a change in the transverse component of the magnetic field on account of \( H_N \) under conditions of the Hanle effect in an oblique field. \(^{(10)}\) In a pure transverse

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The field of the oriented electrons at the nuclei. At
by the second term of (5), is oriented along the
fluence only the precession of $\sigma$ about the
as $[8xH] - [8 \times H]$ (see (5»). At
Taking the vector product of (5) and (8), we obtain

$$\frac{\tau}{\Theta} = \frac{4f(S)H}{\mu_B(H^2 + 3H_x^2)}.$$  

(2)

(The vanishing of $1/\Theta$ denotes that the temperature of the nuclear spin system does not differ from the lattice temperature, taken to be $\infty$. Nonetheless, strong manifestations of $H_x$ are observed in experiments in a purely transverse geometry (see [4, 12]). To explain the observed effect it is necessary to assume that the light produces a longitudinal magnetic-field component.

D'yakonov and Perel' pointed out the role of the effective field $H_e$ of the electrons oriented by the light. The influence of this field in oblique geometry is considered in a paper by Paget. [10] Assume that $H_e = h_e(S_e) (h_e/2$ is the field of the fully oriented electrons) is appreciable and let us calculate the function $S_e(H)$ under conditions when the spin system of the lattice nucleus is cooled in the field $H_x$. The experimental results presented below confirmed the presence of cooling and justified the choice of the considered model.

The change of the average electron spin with time is described by the Bloch equation

$$\dot{S} = \frac{S_e - S}{\tau} + \gamma_e \langle S \rangle H_x H_t,$$  

(3)

where $\gamma_e$ is the gyromagnetic ratio for the electrons, $\tau$ is the lifetime of the photoexcited electrons, and $S_e$ is the maximum attainable average spin ($S_e = 0.25$ in crystals of the GaAs type). Under stationary conditions we have

$$\frac{\tau}{\Theta} = \frac{S_e - S}{\tau} + S \langle S \rangle H_x H_t,$$  

(4)

where $T$ is the total lifetime of the spin orientation and is determined by the equation $T^{-1} = \tau^{-1} + \tau_S^{-1}$.

Using (1) and (2), we express $H_t$ in the form

$$H_t = H + \frac{4f(I + 1)h_e}{3} (H + h_e(S) \langle S \rangle (H + h_e(S))) (H + h_e(S))^2 + 3H_x^2.$$  

(5)

$H$ in (2) has been replaced here by $H + h_e(S)$ to allow for the field of the oriented electrons at the nuclei. At $H = 0$ we have $S = (S_e) = T \Theta / \tau$. The additional field, defined by the second term of (5), is oriented along the resultant of the fields $H$ and $h_e(S)$, and the inclination of the field $H_t$ varies in a complicated manner in space when the value of $H_x$ varies. This notwithstanding, the precession of the vector $\langle S \rangle$ is determined only by the field component $H_x$ directed along the external field, as much as $[S \times H_x] - [S \times H]$ (see (5)). At $H = H_x$ the field $H_x$ influences only the precession of $\langle S \rangle$ about the $x$ axis.

Taking the vector product of (5) and (6), we obtain

$$[S \times H_x] = [(S) \times H] \left(1 + \frac{\langle S \rangle H_x}{H^2 + h_e(S)^2 + 3H_x^2} \right).$$  

(6)

Here $K_y = 4f/(I + 1)h_e/3$.

At $H = H_x$, the cooling of the spin system of the nuclei in the field of the electrons oriented by the light leads to the appearance of an additional transverse field, equal to

$$H_x (S) h_e h_e'/((H^2 + h_e(S)^2 + 3H_x^2) 1).$$

This field is either added to the external field $H_t$ or subtracted from it, depending on the sign of the product $h_e h_e'$.

The hyperfine interaction energy $\varepsilon_{1, S}$ can be expressed both in terms of the field $H_e$ and in terms of the field $H_x$, with

$$\varepsilon_{1, S} = \text{sign} [g_e \mu_B (S) H_e] = \text{sign} [-\gamma_e h_e (H)] = \text{sign} [g_e \mu_B (S) H_e].$$  

(7)

Here $g_e^* = g_e$ and $\mu_B$ is the Bohr magneton, $\gamma_e$ is the gyromagnetic ratio for the nuclei, and $\hbar$ is Planck’s constant. Substituting the values of $H_e = h_e(S)$ and $H_x = h_e(S)$ we see that at $\gamma_e > 0$ we have $h_e h_e' < 0$ if $g_e^* > 0$. If the $g$-factor is negative, then $h_e h_e' > 0$.

In the case of a positive $g$-factor, cooling takes place in the region of negative temperatures, and the additional field connected with the polarization of the nuclei is directed opposite to the external field. At $g_e^* < 0$ these fields are in the same direction.

Let us find an equation connecting $S_e$ and $H_x$. Taking the scalar product of (4) and $\langle S \rangle$ and using (6), we find that

$$S_e (S_e) - \langle S \rangle = T \tau \langle S \rangle,$$

$$S_e (S_e) + \langle S \rangle H_x H_t = H_t (1 + \langle S \rangle^2 + 3H_x^2 + 3H_e^2).$$

Introducing the dimensionless parameters $a = 3T^2 \gamma_e^2 H_x^2$ and $b = \langle S \rangle^2 h_e h_e'/3H_x^2$, we obtain an equation that relates the dimensionless variables $\chi = \langle S \rangle / \langle S \rangle_0$ and $b = H_x^2 / 3H_x^2$:

$$(1 - \chi) (1 + b)^2 = a b (1 + b + \frac{a}{b})^2.$$  

(8)

This equation describes the behavior of the $z$ component in a transverse field $H_t$ under conditions of optical cooling of the spin system of the nuclei in the fields of electrons oriented by light. It is easily seen that in the absence of an electron field ($\beta = 0$) Eq. (8) goes over into the equation $\chi = 1/(1 + ab)$, which corresponds to the usual Lorentz curve that describes the Hanle effect, $\langle S \rangle = S_0 \tau / \tau (1 + \gamma_e^2 T^2 H^2)$, with half-width $H_t/\tau$ equal to $1/\gamma_e T$.

We see thus that the effect of cooling of the spin system of the nuclei in the field of the electrons is taken into account in (8) by the single parameter $\beta$. An important role is played by the spin of $\beta$. Figure 1a shows plots of $\chi(b + 1/2)$ for positive $\beta$ at $a = 0.01$. A characteristic feature of these plots is the presence of a narrow line in the region of weak fields ($H \leq \hbar$) and of an additional maximum in the region of strong fields. The depth of the minimum of $\chi$ increases with increasing $\beta$, and its position depends little on $\beta$. At the same time, the additional maximum shifts towards stronger fields with increasing $\beta$. The entire $\chi(b + 1/2)$ curve lies under

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The solid lines correspond to $\alpha = 0.1$ and the dashed lines to $\beta = -40$, $\alpha = 0.25$ and $\alpha = 0.05$. The instability regions can arise in fields for which $|\beta| > 3$. Figure 1b shows plots of $\langle S_z \rangle / \langle S_z \rangle_0$ against the transverse magnetic field $H_M$ (the Hanle effect) in the dimensionless coordinates $\chi = \langle S_z \rangle / \langle S_z \rangle_0$ and $H_M^{1/2} = H_M^{1/2} / H_L$. The influence of the cooling of the lattice-nuclei spin system in the field of electrons oriented by light is characterized by the parameter $\beta$. At $\beta = 0$ there is no nuclear field at the electrons and the half-width of the $\chi(b^{1/2})$ curve is determined by the parameter $\alpha$. a) $\beta > 0$, $\alpha = 0.01$. b) $\beta < 0$. The solid lines correspond to $\alpha = 0.1$ and the dashed lines to $\beta = -40$, $\alpha = 0.25$ and 0.05.

In the experiment, the value of the field $h_N$ can be determined if the field $H$ is inclined to the $x$ axis at a small angle $\varphi \ll 1$. Equation (8) then goes over into

\[
(1 - \chi)(1 + b) = a_0 H_M^{1/2} \left( \chi + b \right) - a_0 \beta x + \delta b \phi q.
\]

(9)

which differs from (8) in the additional term $b^{1/2}$, where $\delta = h_N^2(S_z)_0 \sqrt{|3H_L|}$. Different signs correspond to opposite directions of the external field $H$ and are a reflection of the appearance of asymmetry in the dependence of $\langle S_z \rangle$ on $H$. The relative shift $|H_M^1 - |H_M^1|$, the positions of the additional maxima and the dependence of $\langle S_z \rangle$ on $H$ for opposite directions of $H$ determines the value of the field $h_N$:

\[
|H_M^1| - |H_M^1| \approx \delta h_N^2(S_z)_0 / |\langle S_z \rangle_0| \varphi.
\]

(10)

At $h_N$ of the order of $10^4 - 10^5$ Oe, an appreciable asymmetry should appear already at very small angles $\varphi$.

The narrow line near $H = 0$ under the condition $b \ll 1$ is described by the equation

\[
b = -(1 - \chi) / |\chi| (1 - |\beta|)^3.
\]

(11)

In the case of large $\beta$, when $|\beta| \gg 1$, this line can be conveniently used to determine the values of the local fields, by measuring $H_M$ and $H_1/2$

\[
3H_L = (H_M^1 / H_0) \left( \partial H / \partial \eta \right)_\varphi, \quad \eta = (1 - \chi / \chi').
\]

(12)

This formula is valid if $\partial H / \partial \eta \approx \text{const}$ for an appreciable fraction of the lines, starting with $H = 0$.

We present below experimental results that confirm the reality of the considered process of cooling of the spin system of lattice nuclei in the field of electrons oriented by light. A preliminary report of these results was published earlier.\(^{[5]}\)

3. EXPERIMENT

The simplest way to investigate the dependence of $\langle S_z \rangle$ on $H$ is to measure the degree of the circular polarization $\rho$ of the recombination radiation with participation of optically oriented electrons. For GaAs crystals and for solid solutions on its basis, the numerical value of $\rho$ is equal to that of $\langle S_z \rangle$ if the investigated radiation is in the direction of the $x$ axis. Figure 2 shows a simplified diagram of the experiment. A linearly polarized He–Ne laser beam passes through a quarter-wave plate $\chi / 4$ and produces optical orientation in the sample. The crystal is oriented in such a way that the incident and reflected rays are superimposed. The luminescence is registered in a "reflection" geometry in a direction making a small angle with the $x$ axis. The value of $\rho$ is measured with a circular-polarization analyzer (PA), which comprises a quartz phase modulator and a linear polarizer. The necessary spectral range is chosen with the aid of a spectral instrument (SI). The radiation is registered with a cooled photomultiplier operating in the photon-counting regime. The quartz modulator is analogous to that described by Jasperson and Schnatterly.\(^{[11]}\) The piezoelectric quartz,
exciting the longitudinal oscillations in a bar of fused quartz is connected in the negative-feedback circuit of the oscillator QO. The oscillator operates at a frequency 30.265 kHz. Adjacent half-cycles of the fused-quartz bar correspond to predominant transmission of photons having opposite signs of the circular polarization (\( \sigma^+ \) and \( \sigma^- \)) through the polarization analyzer system. If the number of these photons is \( N^+ \) and \( N^- \), respectively, then \( \rho = (\sigma/2, 30)(N^+ - N^-)/(N^+ + N^-) \). The coefficient \( \sigma = 2.36 \) is determined by the form of the transmission function of the PA. The switching system (SS) ensures sequential switching, in synchronism with the quartz operation, of the counting channels of a two-channel scaler unit (SU) to the photomultiplier output. The digital printout unit (DPU) records the ratios \( N'/N'' \). A more detailed description of the system for measuring \( \rho \) in the photon-count regime was published earlier. [12]

The earth’s magnetic field is cancelled out by three pairs of Helmholtz coils (M1, M2, M3). The axis of the coil pair M1 is aligned with the \( x \) axis or is turned through an angle \( \varphi \) around the \( y \) axis. The coils M2 are used to investigate the effect of an alternating magnetic field of low frequency on the spin system of the nuclei. Most measurements were performed at \( 77 \)°K.

The investigations were performed on \( p\)-Al\(_{1-x}\)Ga\(_x\)As crystals with constant composition gradient (+ 0.01 \( \mu \)) with \( x = 0.26 \) on the surface. The crystals were not compensated and the Zn acceptor concentration was \( \sim 10^{18} \) cm\(^{-3} \).

Figure 3 shows plots of \( \chi = p'/p \) against \( H \) for the angles \( \varphi = 0^\circ \) (curve 1), 5\(^\circ\) (2), 15\(^\circ\) (3) and 25\(^\circ\) (4) (\( \rho \) is the value of \( \rho \) at \( H = 0 \) Oe). As seen from the figure, even at small values of \( \varphi \) the \( \rho(H) \) curve becomes strongly asymmetrical. A narrow line is observed near \( H = 0 \), as well as additional maxima followed by steep drops. However, the heights of the additional maxima do not reach \( \chi = 1 \), probably because of the inhomoogeneity of the field \( H \) (see below). The presented curves correspond to the case \( \beta < 0 \), which should be expected for a crystal with a positive \( g \)-factor. In accordance with the model developed above, elimination of the effective field of the nuclei at the electrons should be accompanied by an increase of \( \rho \) in the region of weak fields and by a decrease of \( \rho \) in the region of the additional maximum and directly beyond it. This is observed in experiment. The saturating low-frequency field acting along the \( y \) axis, produces in \( \rho \) changes of opposite signs for different sections of the \( \rho(H) \) curve. The fact that \( \rho \) decreases in the fall-out region past the additional maximum demonstrates that the field \( H_x \) decreases the depolarizing action of the external field, i.e., that these fields are oppositely directed.

Figure 4 shows the frequency dependence of the variation of following application of \( H_x \) for two values of the field \( H_z \).

The next fact that confirms the cooling of the nuclear spin system is the possibility of changing \( \rho \) in the case of synchronous modulation of the circular polarization of the exciting beam and a field \( H_x \) parallel to this beam. Turning to (2), we note that if the time-averaged value of \( (S \cdot H) \) is not equal to zero, then \( \Theta \) decreases. Depending on the phase difference between the oscillations of \( S \) and \( H_z \), the cooling takes place in the region of positive or negative temperatures. The polarization of the nuclei cooled in the oscillating magnetic field is determined by the thermodynamic-equilibrium value in the constant electric field \( H \) (see (1)). A more detailed analysis of the cooling in an oscillating magnetic field is given elsewhere. [13] The lifetime of the photoexcited electrons is <10\(^7\) sec and if the polarization of the excited light is modulated at a frequency \( \sim 30 \) kHz the value of \( \chi = p'/p \) changes in phase with the variation of this po-

![FIG. 2. Simplified diagram of experiment. M1, M2—operating coils, M3, M4—Helmholtz coils to cancel the earth's magnetic field, L1, L2—focusing lenses, PA—polarization analyzer, \( \lambda/4 \)—quarter-wave plate, He-Ne—helium-neon laser, SI—spectral instrument, PM—photomultiplier, QO—quartz-modulator oscillator, SS— switching system, SU—scaler unit, DPU—printout unit.](image1)

![FIG. 3. Haale effect in transverse (curve 1) and inclined magnetic field (2—\( \varphi = 5^\circ \), 3—\( \varphi = 15^\circ \), 4—\( \varphi = 25^\circ \)), at a fixed sign of the circular polarization of the exciting light \( \sigma \).](image2)

![FIG. 4. Frequency dependences of the variation of the luminescence polarization following application of an alternating magnetic field \( H_x \), at \( H_z = 12.5 \) Oe and 40 Oe. Excitation \( \sigma_x \). The arrows show the direction of the variation of \( \rho \).](image3)
lunarization. To perform the experiment, the positions of the quartz modulator and of the λ/4 plate were interchanged (see Fig. 2), and the reference voltage from the quartz oscillator was applied through a phase shifter and an amplifier to the coils M₂. Figure 5 shows the variation of ρ with changing phase difference φ between the oscillations of (S₁) and Hₜ, corresponding to variation of Θ (see (2) and (11)).

A nuclear spin system can be cooled not only in an oscillating magnetic field but also in the oscillating field of optically-oriented electrons. This effect decreases with increasing modulation frequency of the exciting-light polarization, but at a frequency ~ 30 kHz it is still distinctly observed. Figure 6 shows a plot of ρ(H) (curve 1) in the case of a sharply-focused laser beam with modulated polarization. The additional maximum is distinctly observable. It is obvious that this curve corresponds to smaller values of β than in the case of the curves shown in Fig. 3. With decreasing intensity of the exciting light, when the effective field of the electron decreases, the ρ(H) curve becomes smoother. Smoothing is observed also when a low-frequency alternating field (not in synchronism with the polarization modulation) is turned on. This field heats the spin system of the nuclei. Curve 2 corresponds to turning on an additional magnetic field Hₜ with amplitude 1 Oe and frequency 5 kHz. The frequency dependence of the heating effect is shown in the upper part of curve 6 for a field Hₜ = 37 Oe. The results shown in Figs. 5 and 6 offer evidence of cooling of the spin system of the lattice nuclei in the oscillating field at relatively high modulation frequency, when the period of the variation of (S) is comparable with the time T₂ of the transverse nuclear relaxation (10⁻⁴–10⁻⁵ sec).

To exclude the influence of the nuclei and to realize the case β=0 in the case of excitation by light of fixed circular polarization, it is possible to apply along y an alternating field Hₜ that saturates the nuclear transitions. It is impossible to eliminate the influence of the nuclei completely. As a result, ρ is overestimated in the region of the additional maximum and underestimated in the region of the minimum. We can thus obtain the upper and lower bounds of the half-width H₁/₂ of the pure "electronic" (β = 0) luminescence-depolarization curve in a transverse magnetic field.

Curve 3 of Fig. 7 was obtained by averaging the measured values of ρ(Hₜ) for the points marked by the arrows under conditions of saturation of the nuclear transitions. Curve 1 corresponds to Hₜ = 0. The same figure shows a plot of ρ(Hₜ) at ~ 100 OK (curve 2). It is seen that raising the temperature also smooths out the ρ(Hₜ) curve, i.e., eliminates the influence of the nuclei.

4. DISCUSSION OF RESULTS

All the obtained experimental dependences confirm the considered model. The characteristic form of the depolarization curves in a transverse field, including the narrow line near H = 0, the additional maximum and the fall-off that follows it, the strong asymmetry in the case of small rotation of the field H, the opposite signs of ρ when an alternating field Hₜ is turned on at different Hₜ—all these follow from the model with cooling of the nuclear spin system in the field of optically-oriented electrons with positive g-factor. In the experiment, the ratio ρ₀/ρₚ = x = 1 is not reached in the additional maximum (see Fig. 1b). This is probably due
to the spatial inhomogeneity of the spin density in the excitation volume inasmuch as, first, the intensity in the laser beam is not uniformly distributed, and second, the diffusion of the oriented electrons leads to the appearance of a gradient of $S_\parallel$ directed normal to the surface of the crystal. This results in a spatial inhomogeneity of the parameter $\beta$ and the experimentally observed relations correspond to averaging of $\beta$ over the luminescent body. In the calculation presented above we considered a lattice consisting of nuclei of one sort. In the experiments, we investigated a crystal containing four isotopes. Exact expressions for $\langle \beta \rangle$, $r$, and $\Theta$ for this case are given in the paper of D'yakonov and Perel'.

Figure 8 shows a section of the narrow line near $H_z = 0$, plotted in the coordinates $H_x$ and $\langle S_\parallel \rangle$, determined from the data of Figs. 7 and 8. The fact that the plot is almost linear confirms the possibility of describing the narrow line by Eq. (11). Substituting in (12) the values of $h_N$, we have $h_N \approx (4.9 \pm 0.9) \times 10^{-2}$ and $\beta = 15 \pm 2$. By varying the degree of polarization of the exciting beam, its intensity, etc., we can vary the effective field of the electrons at the nuclei and consequently change $\beta$. Experiment reveals a shift of the additional maxima with changing intensity. A correlation between $H_M$ and $\langle S_\parallel \rangle$ is also observed.

Figure 9 shows plots of $\rho(H)$ at $\varphi = 2^\circ$ for two values of $\langle S_\parallel \rangle$, demonstrating this correlation. The quantity $h_N$, determined from the asymmetry of the additional maxima (see (12)), amounted to $(1.5 \pm 0.3) \times 10^4$ Oe.

So far we have disregarded the influence of the additional relaxation channels of the nuclear spins, which leads to the appearance of a leakage factor and to a lowering of the maximum attainable value of $1/\Theta$. The leakage can be taken into account by introducing the parameter $\delta$ and a factor $k < 1$. This is equivalent to replacing $h_N$ by $kh_N$. The experimentally determined value of $h_N$ agrees with $kh_N$. In this case $kh_N \approx 3 \times 10^4$ Oe. A comparison with the calculated maximum nuclear field in the GaAs crystal shows that $k$ is of the order of 0.1. The field $h_N$ of the optically-oriented electrons can be determined from the relation $h_N = \Delta H^2 \beta / k h_N$. Using the obtained values of $h_N$, $\beta$, and $kh_N$, we obtain $h_N = (5.4 \pm 1.7) \times 10^4$. The additional field of the nuclei $h_M = h_N(1/2)$ is directed opposite to the external field $H_x$. At $H_x < H_M$ we have $|H_M| > |H_x|$ and at $H_x > H_M$ we have $|H_M| < |H_x|$. The spin temperature of the nuclei can be determined from the experimentally observed values of the field $H_x$

$$\Theta = \Theta_M/\Theta_S, \quad \Theta_S = h_N(1+1/2)\mu_b/3.$$
volume. This result may be due to the spatial inhomogeneity of the spin density, due both to the distribution of the intensity of the exciting light in the semiconductor volume and to the possible localization of the oriented electrons.

We note the strong temperature dependence of the observed effect when the temperature $T_0$ is raised from 77 K to 100 K. In this range, the electron spin-relaxation time is $\tau_0 = T_0^2$, where $n = 2 - 3$. If $T_0/\tau_0$ is small, so that $\langle S^z \rangle = 0.25 T/\tau = 0.25 T^2/\tau_0$, then $\beta = -\langle S^z \rangle^2/2T_0^2 - T_0^2$. The experimentally observed (Fig. 7) vanishing of the structure of the $\rho(H)$ curve when $T_0$ changes from 77 K to 100 K can be attributed to the abrupt decrease of $\beta$. At $T_0 = 4.2$ K, the plots of $\rho(H)$ do not differ qualitatively from those observed at 77 K.

We have not considered here transient processes or a number of dynamic effects (excitation by intermittent light, application of a pulsed magnetic field, etc.) which indicate that the stationary values of the polarization take a long time to reach the steady state. A quantitative interpretation of these results calls for an additional analysis. In particular, it is necessary to explain the difference between the half-widths of the $\rho(H)$ curves when the semiconductor is excited with light with constant and alternating-sign circular polarization.

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Magnetization precession in superfluid phases of He$^3$

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Solutions of the Leggett equations are obtained which describe the motion of magnetization in both superfluid phases of He$^3$ located in a strong dc magnetic field. Rotation of magnetization by an ac magnetic field is described. The results are compared with available experimental data.

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1. INTRODUCTION

Progress in the understanding of the nature of the superfluid phases of He$^3$ is due to a considerable degree to the study of the properties of these phases by the NMR method. The corresponding experiments lend themselves to a quantitative interpretation with the aid of the system of equations for spin dynamics in triplet pairing, obtained by Leggett$^{(1)}$:

$$S = \gamma [S \times H] + R_o (d),$$

where $H$ is the external magnetic field, $S$ is the total spin of the considered amount of helium, $\gamma$ is its magnetic susceptibility, $\chi$ is its gyromagnetic ratio for the He$^3$ nuclei, and $d$ is a vector in spin space and characterizes the spin structure of the wave function of the condensate. Its exact determination (see$^{(2)}$, p. 367), will not be needed here. When the pairing is in the $p$ state, as is the case in He$^3$, $d$ depends linearly on the

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