Here, v_0 is the velocity of electrons photoexcited to the conduction band; τ is the lifetime and τ_{ph} is the time between collisions with phonons; μ is the mobility; $P_0 = ea^{-2}$; a is the size of a unit cell.

The other terms in the expansion (3) can be estimated as follows[4]

$$\delta F^{(4)} \sim \frac{P^2}{P_0^2} \delta F^{(2)}.$$

We shall now estimate the shift of the Curie point. Substituting in Eq. (4) the value of $C = 10^{-5}$ °K (which is a typical value of the Curie–Weiss constant), we obtain

$$\delta T_c \gtrsim 2\ ^\circ\mathrm{K}.$$

The sign of the shift is governed by the direction of $\mathbf{j}_{pg}$. In most experiments we have $\mathbf{j}_{pg} \uparrow\downarrow \mathbf{P}$, i.e., it agrees with the direction of the current associated with the photoexcitation of electrons.[3,4] Under these conditions illumination of a crystal lowers the ferroelectric transition temperature.

The estimates obtained indicate that the contribution of the photogalvanic effect to the free energy may be considerable, together with the corrections $\delta\bar{F}$ due to the filling of trapping levels by photoelectrons.[8] In this connection we must mention that the photogalvanic effect is in no way related to the presence of impurity levels; it exists and can have a large value even in pure crystals.[6]

The author is grateful to V. I. Belinicher for valuable discussions.

[1] This is supported directly by the experimental evidence.[6]

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Translated by A. Tybulewicz

Characteristics of the antiferromagnetic resonance spectrum of RbMnCl$_3$

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An investigation was made of the low-frequency branch of antiferromagnetic resonance (AFMR) in RbMnCl$_3$ single crystals ($T_N = 94.6$ °K) with hexagonal structure at room temperature. The measurements were carried out in the frequency range $\nu = 16$–75 GHz applying magnetic fields up to 45 kOe at temperatures of $T = 1.2$–4.2 °K. Three resonance absorption lines, $\Delta H = 100$–300 Oe wide, were observed; the dependences of the positions of these lines on the angle between the static magnetic field H and the binary axis, on the one hand, and the basal plane, on the other (angles φ and θ), were found to be described by an empirical formula (6), given below. The value $H = 6.6 \pm 0.2$ kOe was in agreement with the spin-flopping field obtained from the static measurements [A.N. Bazhan, N.V. Fedoseeva, and S. V. Petrov. Abstracts of Papers presented at the Nineteenth All-Union Conf. on Physics of Low Temperatures, September, 1976, Institute of Solid State and Semiconductors, Academy of Sciences of the Belorussian SSR, Minsk, p. 599]; $H_\Delta = [(14 \pm 1)/T]^{1/2}$ kOe was the gap due to the hyperfine interaction. The AFMR spectrum of a hexagonal antiferromagnet was calculated. This spectrum did not agree with the experimental dependence $\nu(H)$ for RbMnCl$_3$.

PACS numbers: 76.50.+g

X-ray structure investigations[1,2] of rubidium trichloromanganate, carried out at room temperature, have shown that RbMnCl$_3$ has the barium titanate structure (space group D_{6h}^4) with the lattice parameters $a = 7.11 \pm 0.01$ Å and $c = 17.65 \pm 0.01$ Å. The Mn^{2+} ions occupy inequivalent positions: one-third of them are located in the octahedra of chlorine ions, connected by vertices to other octahedra, and the other two-thirds are at octahedra joined by faces. Neutron-diffraction investigations, carried out by Melamud *et al.*[2] in a wide temperature range from 4.2 to 300 °K, demonstrate that the magnetic and chemical unit cells are identical and that the magnetic structure is a set of ferromagnetic layers of Mn atoms, which are antiferromagnetically coupled. The Néel temperature of RbMnCl$_3$ is 94.6 °K.[3] According to Turov,[4] antiferromagnets with the $6_z^- 2_d^+$ structure cannot exhibit weak ferromagnetism of the kind associated with second-order invar-

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iants in the magnetic Hamiltonian and with the g-factor anisotropy. However, terms of the higher (fourth) order may give rise to a spontaneous magnetic moment. This moment should be directed along the hexagonal axis c_6. Weak ferromagnetism in $RbMnCl_3$ crystals was discovered by Fedoseeva and Beznosikov.[3] A more detailed investigation of the static magnetic properties of rubidium trichloromanganate was carried out by Bazhan *et al.*[5] They found that the application of an external field H in the easy plane parallel to the binary axis gave a magnetization curve $M(H)$ with a discontinuity in a field $H_{st}=6.3\pm0.2$ kOe, due to reorientation of the antiferromagnetic vector $\mathbf{l}$ (from the $\mathbf{l}\parallel\mathbf{H}$ position to $\mathbf{l}\perp\mathbf{H}$), known as spin flopping. This effect was repeated with a period of 60° when the field was rotated in the basal plane of the crystal. This reorientation of $\mathbf{l}$ was accompanied by the appearance of a spontaneous magnetic moment along the hexagonal axis, which was absent from the ground state in zero field or in weak fields in the range $H<H_{st}$. The magnetization along the c_6 axis at $T=4.2$ °K was $\sigma_z=4\pm1$ cgs emu/mole. Thus, rubidium trichloromanganate is so far the only hexagonal substance for which spontaneous magnetization perpendicular to the easy plane, predicted by Turov, has been observed experimentally. This makes $RbMnCl_3$ extremely interesting for further studies of this kind.

Our task was to study antiferromagnetic resonance (AFMR) in $RbMnCl_3$.

Electron resonance in $RbMnCl_3$ was investigated earlier.[6,7] The measurements were carried out at a frequency $\nu_p=69.8$ GHz for an arbitrary direction of an external field H at temperatures quite close to T_N, so that

$$(\nu/\gamma)^2>2H_AH_E.$$

Here, H_E is the exchange field, H_A is the anisotropy field, and $\gamma=2.8$ GHz/kOe is the gyromagnetic ratio. When this condition is satisfied, it is possible to study the behavior of the high-frequency AFMR branch near the ordering point. Cooling increases the gap $2H_AH_E$ in the spectrum of the high-frequency branch and reduces the resonance field for $\nu=$const. According to the experimental data,[7] H_{res} falls to zero at a temperature separated by ≈5 °K from T_N; clearly, at this temperature, we have $2H_AH_E\approx(\nu/\gamma)^2$. It is also pointed out there [7] that the temperature dependence of $H_{res}(T)$ exhibits an interesting hysteresis: at a given temperature, the values of H_{res}, obtained by increasing and decreasing the field, differ by a few kilooersted.

SAMPLES AND MEASUREMENT METHOD

Single crystals of $RbMnCl_3$ were grown by B. V. Beznosikov at the L. V. Kirenskiĭ Institute of Terrestrial Physics, Siberian Branch of the USSR Academy of Sciences, and by S. V. Petrov at the Institute of Physics Problems, Academy of Sciences of the USSR, Moscow; the Bridgman method was used in a vertical tubular furnace. The crystals were orange in color and cut into cubes of side 2–3 mm. The orientation of these cubes was found by x-ray diffraction. The samples were hygroscopic and, therefore, were stored in transformer oil and coated with a cellulose nitrate varnish during the measurements.

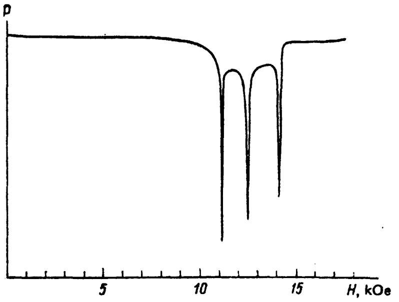

FIG. 1. Automatic record of the amplitude P of a signal transmitted by a measuring cell.

The AFMR measurements were carried out using a microwave spectrometer similar to that described earlier.[8] A sample placed in a measuring cell could be rotated and subjected to uniaxial pressure up to ≈150 kg/cm². The measurements were carried out in the frequency range $\nu_p=16-75$ GHz in fields up to 45 kOe in the temperature range $T=1.2-4.2$ °K.

EXPERIMENTAL RESULTS

Our $RbMnCl_3$ single crystals exhibited resonance absorption corresponding to the high-frequency branch of the AFMR spectrum. We studied in detail the dependences of this branch of the spectrum on the direction of a static magnetic field H relative to the crystallographic axes of the crystal and on temperature. The main results were as follows.

1. When H was directed so that $c_6\parallel z$, three AFMR lines were observed in the frequency range $\nu_p>20$ GHz. Figure 1 shows a typical record of a resonance line obtained for $\nu=$const. The line width varied from crystal to crystal in the range 100-300 Oe.

2. Rotation of the static field H in the easy plane revealed strong anisotropy of the positions of the AFMR lines. The dependence of the square of the resonance field H^2 on the angle of rotation φ is shown in Fig. 2. The cases of H parallel to the binary axis c_2 corresponded to $\varphi=0^0$ or 60°.

The experimental results fitted well a sinusoid of period 180° and amplitude 43.5 kOe². The axis of the H_S^2 sinusoid was close to $H_{ESR}^2=(\nu/\gamma)^2$. Each AFMR

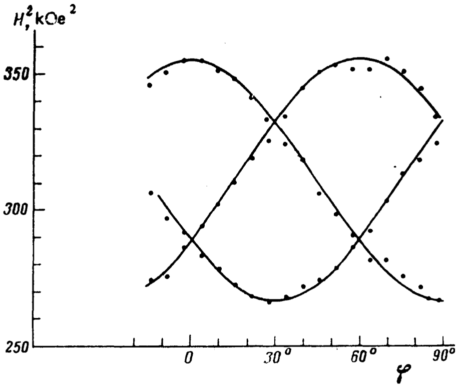

FIG. 2. Dependence of the resonance field on the angle of rotation in the easy plane. The H || c_2 case corresponds to $\varphi=0$ and $\varphi=60°$; frequency $\nu=49.5$ GHz.

line had its own sinusoid. The sinusoids associated with different absorption lines were shifted relative to one another by 60°.

3. When H was inclined at an angle θ to the easy plane, the resonance lines obtained for $\nu=\text{const}$ were shifted toward higher fields so that the projection of H_{res} onto the easy plane remained constant.

4. Measurements were made of the spectrum $\nu(H)$ for several directions of H. The dependence $\nu^2(H)$, obtained for $\varphi=13°$ and $\theta=0$, is shown in Fig. 3.

All the above results were obtained at 4.2°K.

5. Cooling shifted the resonance curves toward lower fields in such a way that $H_\Delta^2=H_{\text{ESR}}^2-H_S^2$ varied in accordance with the law $H_\Delta^2=K/T$ (Fig. 4).

6. A study was made of the influence of uniaxial compression on the absorption spectrum. A crystal was compressed along one of the binary axes by stresses up to 150 kg/cm².

When a sample was cooled from room temperature to 4.2°K under pressure, the intensity of one of the lines I_1 became 6 – 8 times less than the intensities I of the other two lines: $\sigma=I/I_1=6-8$ (Fig. 5).

The dependence $H_{\text{res}}(\varphi)$ for this low-intensity line had a 180° anisotropy. When the pressure was removed from the sample, the value of σ was practically unaffected.

A study was also made of the influence of the pressure applied to a sample at a temperature below the point of transition to the ordered state. At $T=4.2°$K, the resonance lines had the same intensity ($\sigma=1$) in the absence of pressure. An increase in pressure did not affect the absorption right up to 70 kg/cm² but, at higher pressures, one resonance peak began to decrease rapidly and the other two began to increase in intensity. At the highest pressure employed, the ratio of the intensities was $\sigma\approx 3-4$. After removal of the pressure, the line intensities I were partly restored to the initial value but we still found that $\sigma\approx 2-3$. Compression only affected the intensity of the absorption lines and not the resonance fields.

7. It was not possible to excite oscillations of the high-frequency AFMR branch at frequencies up to $\nu=75$ GHz.

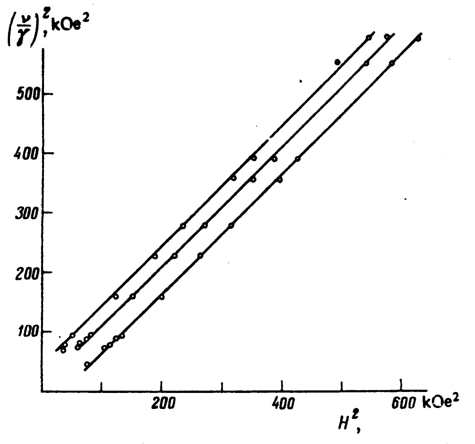

FIG. 3. Antiferromagnetic resonance spectrum plotted in the coordinates $\nu^2(H^2)$ for $\varphi=13°$ and $\theta=0$.

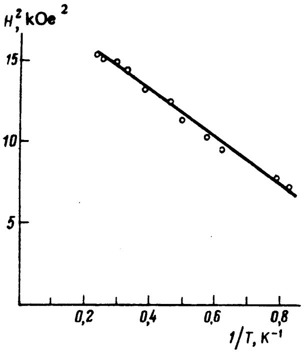

FIG. 4. Temperature dependence of the resonance field, plotted as $H^2(1/T)$ ($\nu=21.82$ GHz, $H\perp c_2$).

8. At room temperature, there was only one absorption line corresponding to the ESR of the Mn²⁺ ions.

9. The hysteresis described by Shane *et al.*[7] was not observed.

CALCULATION OF THE AFMR SPECTRUM OF A HEXAGONAL EASY-PLANE ANTIFERROMAGNET

According to Turov,[5] the Hamiltonian of an antiferromagnet with the $6_z^-2_x^+$ structure should have the following form, apart from the sixth-order magnetic anisotropy terms (a model of two magnetic sublattices is assumed)¹⁾:

$$\mathcal{H}=\frac{A}{2}\mathbf{m}^2+\frac{a}{2}m_z^2+\frac{b}{2}l_z^2+\frac{t}{2i}[(l_x+il_y)^3-(l_x-il_y)^3]m_z$$
$$+rl_z[m_y(l_x^2-l_y^2)+2m_xl_xl_y]+\frac{e}{2}[(l_x+il_y)^6+(l_x-il_y)^6]-\mathbf{mH}_0. \qquad (1)$$

The variables in the Hamiltonian (1) are H_0, l, and m, which can be expressed in terms of the magnetic moments $\mathbf{M}_1$ and $\mathbf{M}_2$ of the first and second sublattices:

$$\mathbf{l}=\frac{\mathbf{M}_1-\mathbf{M}_2}{M_0},\quad \mathbf{m}=\frac{\mathbf{M}_1+\mathbf{M}_2}{M_0},\quad \mathbf{H}_0=M_0\mathbf{H},$$

where M_0 is the maximum possible value of the magnetization of the system $M_1^2=M_2^2=(M_0/2)^2$. In the Hamiltonian (1), A denotes the exchange constant, b and a represent the relativistic interactions governing the position of the antiferromagnetic vector l relative to the hexagonal axis, and the magnetic susceptibility anisotropy. The invariant

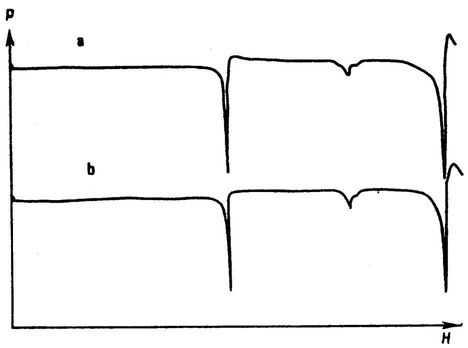

FIG. 5. Records of AGMR lines for a sample cooled from room temperature to 4.2°K under pressure: a) lines recorded under pressure; b) lines recorded after removal of pressure.

$$\frac{t}{2i}[(l_x+il_y)^3-(l_x-il_y)^3]m_z$$

is responsible for weak ferromagnetism along the hexagonal axis of the crystal, whereas the invariant with r causes the vector l to emerge from the basal plane of the crystal; e represents the anisotropy of the magnetic properties in the easy plane.

In calculating the AFMR spectrum of a hexagonal easy-plane antiferromagnet, we shall use the Landau-Lifshitz equations[9] and the Hamiltonian (1). In high fields,

$$H_{0\perp}{}^2 \gg H_\varphi{}^2 M_0{}^2 \approx 9|t^2+4eA|, \tag{2}$$

the spectrum is described by the following expressions.

1) *Magnetic field* H *parallel to the binary axis* ($\mathbf{H} \parallel c_2 \parallel x$). In this case, all the vectors l are perpendicular to the x axis and we have a weakly ferromagnetic state with the Dzyaloshinskiĭ field directed along the z axis, where $m_z = t/(A+a)$. In the $e \ll b, e \ll a$ case, the following approximate expressions are obtained for the AFMR spectrum:

$$\begin{aligned}(\nu_1/\gamma)^2 &= H^2+[9t^2+36e(A+a)]/M_0{}^2,\\ (\nu_2/\gamma)^2 &= [Ab+4t^2+6Ae+6be]/M_0{}^2.\end{aligned} \tag{3}$$

2) *Magnetic field* H *perpendicular to the binary axis* x. In this case, we have $\mathbf{l} \parallel x$, $m_z = 0$, and the resonance frequencies are

$$\begin{aligned}(\nu_1/\gamma)^2 &= H^2-[9t^2+36e(A+a)]/M_0{}^2,\\ (\nu_2/\gamma)^2 &= [Ab-6Ae-6be]/M_0{}^2.\end{aligned} \tag{4}$$

If $t^2+4e(A+a)<0$, then ${}^{(6)}H_\varphi^2 = -9[t^2+4e(A+a)]/M_0^2$, and Eqs. (3) and (4) for the high-frequency branch of AFMR become

$$\begin{aligned}(\nu_1/\gamma)^2 &= H^2-{}^{(6)}H_\varphi{}^2, \quad \mathbf{H}\parallel c_2,\\ (\nu_1/\gamma)^2 &= H^2+{}^{(6)}H_\varphi{}^2. \quad \mathbf{H}\perp c_2.\end{aligned} \tag{5}$$

In the $t+4e(A+a)>0$ case, the signs in front of ${}^{(6)}H_\varphi^2$ are reversed. A calculation of the spectrum for an arbitrary direction of H in the easy plane is highly complicated and, therefore, will not be given here; however, it is clear from general considerations that a hexagonal anisotropy of the resonance properties should occur in the basal plane and it should be analogous to the case of the $3_z^+2_y^-$(MnCO$_3$) structure considered by Turov.[4] Thus, at a constant frequency, the value of H_{res}^2 should depend on the angle φ as follows: it should oscillate around H_{ESR}^2 with an amplitude ${}^{(6)}H_\varphi^2$ and the period of these oscillations should be 60°.

If the magnetic ions are in two crystallographically inequivalent positions, the properties of such a system have to be described using a model of four or even six magnetic sublattices. This gives rise to a new AFMR branches[10] whose frequencies are governed by the exchange field:

$$\nu_E \approx \gamma H_E.$$

The dependence $\nu_{1,2}(H)$ is given by the same formulas as in the two-sublattice model and, therefore, in describing the optical and acoustic branches of the spectrum, it is sufficient to consider a model of two magnetic sublattices.

DISCUSSION OF RESULTS

1. *Magnetic structure of* RbMnCl$_3$. Experimental investigations of the AFMR spectra have shown that the reorientation of the angular momentum l (spin flopping) occurs in $H \parallel c_2$ and, consequently, in the absence of an external field, the anisotropy field in the easy plane orients l along the binary axes. In fields higher than the spin flopping value, all the angular momenta l are perpendicular to $H\perp$ and, in accordance with the theoretical model, for every angle φ there should be one low-frequency AFMR line which has a 60° anisotropy in the easy plane. On the whole, the experimental dependence H_{res}^2 (Fig. 2) has a period of 60°, which indicates that the crystal has hexagonal symmetry but the presence of three resonance lines and the 180° anisotropy of each line are not in agreement with the above theoretical model.

Summarizing the results of measurements of the dependence $H_{\text{res}}(\varphi, \theta, \nu, T)$, we can describe the low-frequency AFMR spectrum of RbMnCl$_3$ in $H \gg H_\varphi$ by the empirical formula:

$$(\nu_i/\gamma)^2 = H_{\text{res}}^2 \cos^2\theta - H_\varphi{}^2 \cos 2\varphi_i + H_\Delta{}^2. \tag{6}$$

Here, φ_i is the angle between the i-th binary axis and the projection of H on the easy plane, γH_Δ is the temperature-dependent gap in the AFMR spectrum, γH_φ is the maximum of the anisotropic gap, and $i = 1, 2, 3$.

The value $H_\varphi = 6.6 \pm 0.2$ kOe deduced from the resonance measurements is in agreement with the spin-flopping field $H_{sf} = 6.3$ kOe, deduced from static measurements of the magnetization.[5]

If we apply Eq. (6) to any specific value of i, we can easily see that it describes a biaxial antiferromagnet whose difficult-magnetization axis coincides with the z axis and which also exhibits anisotropy in the easy plane with the easy-magnetization axis coinciding with the x axis. The existence of three AFMR lines and their complete identity (apart from the angular shift) is evidence of three such biaxial antiferromagnets with a common difficult axis and with the easy magnetization axes turned through 120°. We shall show that RbMnCl$_3$ cannot be regarded as a hexagonal antiferromagnet even on the basis of the results of magnetostatic measurements.[5,12]

Bar'yakhtar and Sobolev[11] calculated the ground states of a hexagonal antiferromagnet with an easy-plane anisotropy in an external magnetic field parallel to the basal plane. It follows from these calculations that the spin flopping of the sublattices in a hexagonal antiferromagnet and, consequently, the magnetization discontinuities should occur not only when $\mathbf{H} \parallel \mathbf{l}$ (i.e., in our case, when $\mathbf{H} \parallel c_2$) but for any direction of H in the easy plane of a crystal. For example, when the field is directed at an angle of 30° to the binary axis ($\varphi = 30°$), the rotation of l cannot occur *smoothly up to* the $\mathbf{l} \perp H$ state because, for $\eta > 30°$ (η is the angle between l and the c_2 axis), the anisotropy fields in a plane will tend to turn l in the same direction as H and, consequently, there will be no stable states with these values of η.

Bar'yakhtar and Sobolev demonstrated that an increase in the field from $H=0$ to $H_1=|12Ae|^{1/2}$ caused smooth rotation of the antiferromagnetic vector in the basal plane from $\eta=0$ to $\eta=15°$. In a field $H=H_1$, when $\eta=15°$, the magnetic moment suddenly switches to the $\mathbf{l} \perp \mathbf{H}$ state.

The field H_1 is related to the spin-flopping field in the $\mathbf{H} \parallel c_2$ case by $H_1^2=H_{sf}^2/3$.

The sudden changes in the magnetic moment mentioned above should be observed in static magnetization measurements but the experiments carried out on $RbMnCl_3$ revealed only one magnetization discontinuity[12] in a field $H_{sf}=6.3$ kOe ($\mathbf{H} \parallel \mathbf{l}$). Thus, the reported results[5, 12] cannot be explained on the basis of the theory of hexagonal antiferromagnets and the 60° periodicity of the results of the static measurements (similar to the 60° symmetry of the resonance measurements) does not prove that the substance in question is hexagonal. On the other hand, the absence of other discontinuities of the magnetic moment is not in conflict with the model of three types of biaxial antiferromagnets. In crystals of this symmetry, the vector $\mathbf{l}$ should spin flop in a field $\mathbf{H} \parallel \mathbf{l}$, whereas in a field $\mathbf{H}$ oriented at an arbitrary angle with respect to $\mathbf{l}$, there should be a continuous rotation of the sublattice magnetic moments, which has indeed been observed.[5, 12] Thus, the main experimental results of the magnetostatic and resonance measurements can be explained by postulating the existence of three types of domain in $RbMnCl_3$ and each type is a biaxial antiferromagnet.

The transition of a hexagonal crystal to the ordered antiferromagnetic state at the Néel point may be accompanied by the splitting of this crystal into domains. The antiferromagnetic axes of these domains should coincide with certain preferred directions in the basal plane. The crystal lattice in each domain may be distorted by magnetostriction and this may give rise to the 180° anisotropy in the easy plane of each domain.

However, in fields $H>H_\varphi$, all the vectors $\mathbf{l}$ are oriented at right-angles to $\mathbf{H}$. Consequently, the antiferromagnetic domains then cease to exist and the AFMR spectrum should be described by the expressions in Eq. (5).

The results of measurements of the AFMR spectrum can be explained assuming that $RbMnCl_3$ undergoes a crystallographic transition, as a result of which the crystal splits into three types of orthorhombic crystallite. Each such crystallite has a 180° anisotropy in the basal plane, which is related to its crystal structure and is independent of the direction of the vector $\mathbf{l}$, which may be rotated in the easy plane by an external field $\mathbf{H}$. Clearly, the temperature of such a structure transition may not coincide with T_N.

The experimental evidence shows that the intensities of the absorption lines of all three types of crystallite are approximately the same and, consequently, an approximately the same number of crystallites is formed at the transition point.

Clearly, if a sample is subjected to some external force at the transition point, one can create a single crystal (which is not split into crystallographic domains) below the structure transition point. We investigated the influence of the external field and uniaxial compression on the AFMR spectrum. Cooling in an external field of $H\approx 10$ kOe from room to helium temperature ensured that the intensities of the AFMR lines at helium temperature were approximately equal.

The application of external pressure along the c_2 axis made it possible to alter the line intensities. These experimental results on the influence of uniaxial compression on the line intensities can be interpreted as follows.

At the structure transition point, the various parts of a crystal become elongated along different binary axes and this produced three types of crystallite. However, if, at the transition point, a sample is compressed along one of the binary axes of a crystallite, the formation of this type of structure domain is difficult, fewer domains appear, and, consequently, the intensities of the AFMR lines corresponding to these domains are lower.

If the same pressure is applied below the transition point, some of the crystallites oriented along the compression axis are modified to other types of domain but this effect is clearly less important than that just described. Since the measurement results are independent of the magnetic field applied at the transition point and the compression has a considerable effect, it follows that the domains in $RbMnCl_3$ are not magnetic in nature. However, an objection can be raised against the conclusion that the magnetic anisotropy in the basal plane is due to a change in the lattice parameters resulting from the crystallographic transition. The neutron diffraction experiments[2] show that the diffraction pattern lines broaden at low temperatures and this is attributed to weak distortions of the crystal lattice. The changes in the lattice parameters estimated in this investigation do not exceed 0.01%.

Distortions of the same order of magnitude can be created in a crystal by a pressure of 100 kg/cm² and it would seem that this should also alter the anisotropy field. However, the position of the AFMR line is not affected. Thus, we cannot say that the observed AFMR anisotropy in the easy plane of $RbMnCl_3$ is associated with the distortion of the crystal lattice.

It follows that the origin of this anisotropy is still not clear.

2. Hyperfine interaction. de Gennes *et al.*[13] show that allowance for the hperfine interaction gives the following expression for the AFMR frequency:

$$\nu_p^2=\nu_p^{0\,2}+\nu_{hf}^2, \tag{7}$$

where ν_p^0 is the AFMR frequency in the absence of the hyperfine interaction, ν_{hf} is the effective frequency proportional to the hyperfine interaction:

$$\nu_{hf}^2=\gamma^2\cdot 2H_{hf}H_E, \tag{8}$$

and $H_{hf}\propto 1/T$.

It is clear from Eq. (7) that the hyperfine interaction can significantly alter the AFMR spectrum if ν_p^0 is com-

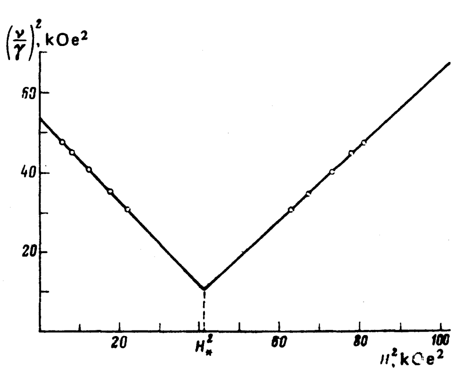

FIG. 6. Dependence of the resonance frequency on the magnetic field before and after spin flopping in the H || c_2 case at $T = 1.25$°K.

parable with ν^0_{hf}. At helium temperature, the hyperfine interaction has a considerable influence on AFMR in the centimeter range. The resonance fields corresponding to this frequency range in the case of $RbMnCl_3$ are close to the spin-flopping field H_φ.

We can determine ν_{hf} if we know the dependence (H). The exact form of the spectrum is known only for $\mathbf{l} \perp \mathbf{H}$. In fields $H \approx H_\varphi$, this happens in the two cases listed below:

$$\mathbf{H} \| c_2, \quad H > H_\varphi. \tag{I}$$

$$\mathbf{H} \perp c_2. \tag{II}$$

In the first case, the vector l is in the reoriented state and, in the second, it is perpendicular to the field.

The experimental results show good agreement between the values of $H_\Delta^2 = \nu^2_{\text{hf}}/\gamma^2$ for the states I and II. The precision of the measurements of H_Δ^2 decreases on increase in the field. Therefore, the contribution of the hyperfine interaction to the AFMR spectrum can be determined most accurately from the AFMR measurements in the orientation $\mathbf{H} \perp c^2$ in fields $H < H_\varphi$ (Fig. 4). We then have

$$H_\Delta^2 = (14 \pm 1)/T \ [\text{kOe}^2].$$

The hyperfine interaction also occurs in fields $\mathbf{H} \| c_2$ at sufficiently low frequencies when AFMR can be observed before and after spin flopping. The dependence $\nu(H)$, plotted using the coordinates ν^2 and H^2, then gives straight lines (Fig. 6). The coordinates of the points of intersection for $H_*^2 (\nu/\gamma)_*^2$ can be used to find $H_\varphi = \sqrt{H_*^2} = 6,4$ kOe and $H_\Delta^2 = (\nu/\gamma)_*^2 = 13.7/T$ kOe². These values are in good agreement with the corresponding fields given above.

Using the value of H_Δ^2 obtained from AFMR and the exchange field $H_E = 860 \pm 40$ kOe, measured by the magnetostatic method,[12] we can apply Eq. (8) to find the effective hyperfine interaction field

$$H_{\text{hf}} = (8.1 \pm 1)/T \ [\text{Oe}].$$

This value is close to the hyperfine field of the Mn^{2+} ions obtained for other crystals: in the case of $CsMnF_6$, we have $H_{hf} = 9.15/T$[Oe],[14]; for $MnCO_3$, we find that $H_{hf} = 9.1/T$[Oe] (Ref. 15), and, for $KMnF_3$, this field is $H_{hf} = 9.7/T$[Oe].[16]

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[1)] Turov[4] gives in his book an expression which differs from Eq. (1). In the Turov Hamiltonian, the constant in front of the sixth-order term is e and not $e/2$ and the expression for the spin flopping field differs from Eq. (2) by the factor 9, which is evidently due to misprints.

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