Investigation of the influence of uniaxial compression of a sample on the threshold of parametric excitation of magnons

A. V. Andrienko

I. V. Kurchatov Institute of Atomic Energy
(Submitted 7 May 1991)
Zh. Eksp. Teor. Fiz. **100**, 1358–1364 (October 1991)

The influence of uniaxial compression of a sample of the antiferromagnet $CsMnF_3$ on the threshold of parallel pumping of magnons was investigated. The external pressure imposed an effective magnetoelastic anisotropy, which altered the ground state of the antiferromagnet. Consequently, the anisotropy of the threshold field observed earlier [B. Ya. Kotyuzhanskiĭ and L. A. Prozorova, JETP Lett. **24**, 149 (1976)] lost its hexagonal nature: peaks at the threshold were shifted by an angle α, the magnitude and sign of which depended on the magnetic field intensity and on the magnitude and direction of pressure. The results demonstrated that parallel pumping of $CsMnF_3$ created spin waves parallel to the magnetic moment of the sample and the magnon relaxation process was characterized by a 60° anisotropy in the basal plane. The magnetic-field and temperature dependences of the anisotropic part of the relaxation process were accounted for satisfactorily by elastic scattering of magnons on defects.

Easy-plane antiferromagnets are free of anisotropy in the basal plane and, therefore, they exhibit a zero-activation branch of spin waves (magnons) which can be excited parametrically by parallel pumping with a microwave magnetic field.[1,2] In the course of parametric excitation a microwave pump photon of frequency ν_p creates two magnons of frequencies $\nu_k = \nu_p/2$ and with equal but opposite wave vectors **k** and $-$**k**. A parametric instability appears when the microwave field h exceeds the threshold or critical value h_c, which is related linearly to relaxation of the excited quasiparticles: $\Delta\nu = h_c V$, where V is a coefficient representing the coupling of magnons to the pump field.

The simplest theory of parametric excitation[3] imposes no restrictions on the direction of the magnon wave vector. However, experiments on parallel pumping of electron magnons in $CsMnF_3$ (Ref. 4) have revealed a strong (a factor of ≈ 2) 60° anisotropy of the threshold field h_c when the static magnetic field **H** is rotated in the basal plane of this crystal. A later study of the excitation of nuclear spin waves[5] in $CsMnF_3$ revealed not only the 60° anisotropy of the threshold fields, but also a giant (a factor of up to 10^2) anisotropy of the modulation response of the steady state of nuclear magnons above the excitation threshold.

A detailed theoretical analysis of the amplitudes of the interaction of spin waves allowing for the dipole—dipole interaction is given in Ref. 6. It is shown there that the interaction anisotropy is weak, being smaller by $2\pi M/H_E$ (where M is the magnetic moment of a sublattice and H_e is the exchange field), which in the case of $CsMnF_3$ is less than 1%. Therefore, the magnitude of the anisotropy reported in Refs. 4 and 5 and its variation from sample to sample cannot be explained by the proposed theory.[6]

Parallel pumping in a field $H \approx 1.5$ kOe, used in the experiments of Ref. 4, excited electron magnons with $\mathbf{k} \| \mathbf{H}$, so that the anisotropy of the pump threshold could be related to the 60° anisotropy of magnon relaxation. Variations of the anisotropy and, consequently, of the rate of relaxation from sample to sample clearly indicated that the additional contribution to the relaxation process was due to crystal defects.

The present paper reports a further investigation of the anisotropy of the parametric magnon excitation threshold, carried out with the aim of identifying the origin of this anisotropy.

EXPERIMENTAL METHOD AND SAMPLES

Our experiments were carried out using a direct-amplification microwave spectrometer. A sample was placed at an antinode of a microwave magnetic field in a rectangular or cylindrical cavity resonator, which was filled with liquid helium. The input coupling with the resonator was close to critical, but the output coupling was much less than 1; the Q factor in the presence of a load was 10^3–10^4. A sample in a rectangular resonator could be subjected to uniaxial compression. The applied pressure was created using a device shown schematically in Fig. 1. A sample 4 was placed next to the resonator wall 7 and was pressed against the wall by a quartz mushroom-shaped plunger 9. The plunger 9 was pushed by a lever 3 which transmitted the pressure applied by a bellows 6. At atmospheric pressure inside and outside the bellows the sample was pressed lightly against the resonator wall by rotating a screw 5. The resonator with the sample was then placed inside a helium dewar. Since the experiments were carried out at $T \approx 1.2$ K, the ^{4}He saturated vapor pressure in the dewar was ≈ 1 torr. The working gas in the bellows was also ^{4}He, which was supplied along a capillary 8 via a valve located in the cryostat cover. Application of a pressure up to 1 bar inside the bellows made it possible to create pressures up to 100 bar because of the difference between the cross-sectional areas of the sample (6 mm^2) and the bellows (200 mm^2), and because the lever increased the pressure in the ratio 1:3. When the bellows was fully evacuated the sample experienced a slight pressure due to the initial elastic compression of the bellows. We estimated this pressure to be less than 10 bar.

Klystron oscillators operating in the range $\nu_p = 18$–36 GHz with an output power up to 30 mW were used as the microwave sources. Microwaves were generated in the form of millisecond pulses at a repetition frequency of 50 Hz. A microwave pulse which crossed the resonator was detected

0038-5646/91/100752-04$03.00

The parametric excitation process was "hard": the excitation threshold of spin waves h_{c1} exceeded the quenching threshold h_{c2}. Since the anisotropy was observed only at the threshold h_{c1} and the applied pressure had the strongest influence on this threshold, all the results reported below were obtained by measuring the threshold h_{c1}, which we shall in future simply call h_c.

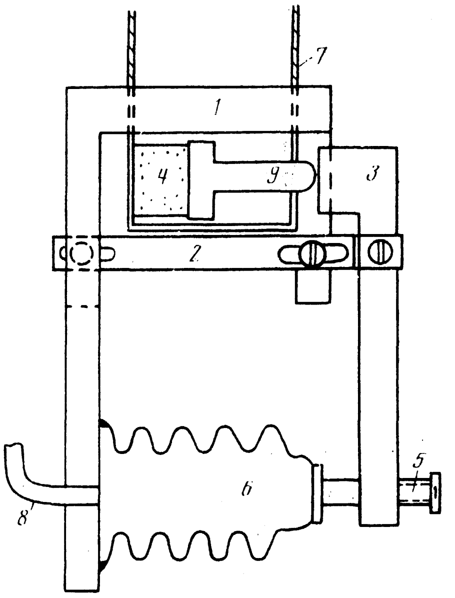

FIG. 1. Schematic diagram of the device used to compress the sample uniaxially in a rectangular cavity resonator.

and applied to an oscilloscope. Excitation of parametric magnons was detected when a pulse exhibited an abrupt change in the profile, representing the appearance of microwave absorption by the sample. The relative value of the threshold field h was calculated to within 2% using the readings of a calibrated precision attenuator placed at the entry to the resonator. The absolute values of h were not determined.

The sample was a single crystal of $CsMnF_3$ in the form of a rectangular parallelepiped with dimensions $3\times2\times2$ mm.[3] The easy magnetization plane coincided with the 2×2 mm^2 face. The external pressure was applied to one of the 3×2 mm^2 faces parallel to the basal plane of the crystal. Since the thickness of the crystal along the compression axis (2 mm) was approximately equal to its linear dimensions in the plane of compression, the edge effects clearly resulted in a considerable inhomogeneity of the strain over a large part of the sample.

The microwave field **h** was also oriented in the easy plane and was always perpendicular to the direction of pressure. The static magnetic field **H** was rotated in the easy plane by simultaneous varying of the angles between **H** and **h**, and between **H** and the pressure axis.

EXPERIMENTAL RESULTS AND DISCUSSION

We investigated first the dependences of the threshold anisotropy on the magnetic field in the absence of pressure on the sample. It was found that sharp 60° peaks at the threshold were observed only in static fields $H>1$ kOe. When this field was reduced, the peaks began to broaden, their amplitude fell, and finally in a field $H\approx0.5$ kOe the anisotropy of the threshold field disappeared. Since the peaks at the threshold were clearly due to the fact that the relaxation rate of magnons with $\mathbf{k}\perp\mathbf{c}_2$ was higher than that of magnons with other directions of propagation,[4] it seemed of interest to determine the behavior of this additional contribution to the relaxation process when the field was varied.

According to the theory of Ref. 3, the coefficient representing the coupling between spin waves and the pump field is

$$V=2\gamma^2 H\nu_p^{-1},$$

where $\gamma=2.8$ GHz/kOe is the magnetomechanical ratio.

Figure 2a shows the field dependence of the magnon relaxation rate calculated from the threshold h_c for two directions of the static magnetic field: at the peak ($\mathbf{H}\perp\mathbf{c}_2$) and 15° from the peak. Both dependences had a maximum of $\Delta\nu$ in a field $H_{\rm mph}=2.03$ kOe, corresponding to crossing of the magnon (m) and phonon (ph) spectra. The boundary field $H_b=2.45$ kOe, identified in Fig. 2a, was the field in which magnons with $\mathbf{k}=0$ were excited.

Figure 2b shows the field dependence of the difference between the relaxation rates for two directions of **H**. The continuous curve is the theoretical dependence $\Delta\nu(H)\propto k$, typical of the elastic scattering of spin waves on defects and fluctuations of the nuclear magnetization.[7] Clearly, this curve describes satisfactorily the experimental results obtained in fields $H>1.2$ kOe, i.e., before the anisotropy of h_c began to disappear.

It was pointed out in Ref. 4 that the difference $h_{c\,\max}-h_{c\,\min}$ between the thresholds was independent of temperature. Since the coefficient V of the coupling to the pump was independent of temperature, the experiments of

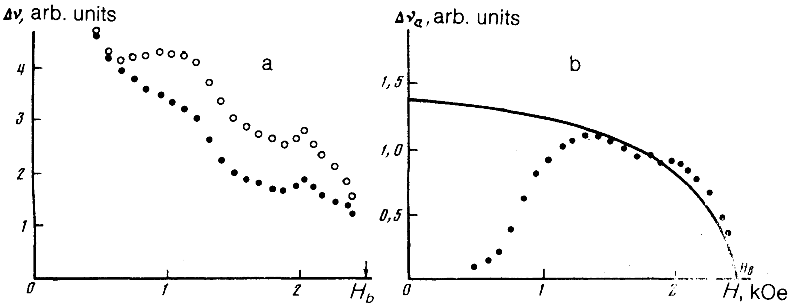

FIG. 2. a) Dependence of the rate of relaxation of spin waves in $CsMnF_3$ on a magnetic field H applied along two directions: ○) $\mathbf{H}\perp\mathbf{c}_2$ (at the peak); ●) angle between **H** and $\mathbf{c}_2$ amounting to 75° (i.e., 15° from the peak). $T=1.38$ K, $\nu_p=18.26$ GHz. b) Field dependence of the magnon relaxation rates for two directions of **H**, plotted on the basis of the data in Fig. 2a. The continuous curves represent the theoretical dependence for the processes of elastic scattering of spin waves $\Delta\nu(H)\propto k$.

Ref. 4 demonstrated that the additional contribution to the magnon relaxation process was also independent of temperature. This result, moreover, was in agreement with the theory of elastic scattering of magnons by defects. Therefore, the temperature and field dependences of the anisotropic contribution to the relaxation of spin waves were described satisfactorily by the theory of elastic scattering on defects.

It was pointed out in Ref. 4 that defects could become aligned along specific crystallographic directions. Obviously, this could not be true of point defects, but applies to extended defects (dislocations) with considerable dimensions along specific crystal axes, which were quite likely the cause of the observed anisotropy of $\Delta\nu_a$: motion of a magnon along a dislocation could prolong the influence of the inhomogeneity so that the probability of the interaction of such magnons would be considerably less than in the case of magnons moving in a perpendicular direction.

The question arises why does this interaction cease to play a significant role in weak fields? In our opinion this is due to the fact that the external field becomes comparable with the effective hexagonal anisotropy field. The magnetic moment of a sample is no longer collinear with the external field and its direction is governed by the minimum of the total energy in the external and internal fields. The direction of propagation of parametric magnons is in its turn probably related not to **H**, as stated in Ref. 4, but to the direction of the magnetic moment **m** of a sample and then only in high fields when **m**||**H** and parametric magnons move along **H**. In the limiting case of weak fields the vectors **m** are parallel to the easy magnetization axes irrespective of the direction of **H**. Consequently, the direction of propagation and relaxation of parametric magnons cease to depend on the direction of the external field, which destroys the threshold anisotropy.

This hypothesis was checked in a series of experiments on $CsMnF_3$ samples subjected to uniaxial pressures. Compression along an axis lying in the basal plane of a crystal should contribute an additional 180° anisotropy in this plane.[8] When the energy of the magnetoelastic anisotropy becomes comparable in magnitude with $\mathbf{m}\cdot\mathbf{H}$ and with the energy of the 60° magnetic anisotropy, the ground state of the antiferromagnet changes significantly, i.e., the direction of **m** is altered. If our hypothesis about the collinearity of **k** and **m** and about the anisotropy of the relaxation rate is correct, then compression should disturb the 60° anisotropy of the pump threshold.

Our experiments showed that the influence of the applied pressure appeared even below the pump threshold. An increase in the pressure altered the cavity resonator frequency. This was clearly due to rotation of the magnetic moment of the sample under the applied pressure. An increase in the external field weakened the influence of the pressure on the resonator frequency.

The influence of the pressure on the pump threshold was of the greatest interest. We plotted in Fig. 3 the dependences of the threshold h_c on the angle of rotation of the field **H** in the basal plane of the investigated crystal for two values of the pressure and magnetic field. The peaks of the 60° anisotropy of the threshold corresponded to $\varphi = 52°$ and $\varphi = -68°$. The parallel pumping condition corresponded to $\varphi = \pm 90°$. The condition **H**||**P**⊥**h** was satisfied when $\varphi = 0°$. When the magnetization **m** was parallel to the field

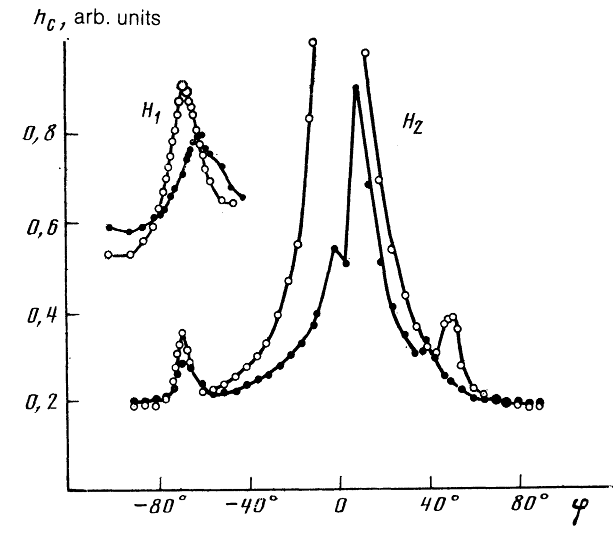

FIG. 3. Parallel pumping threshold of $CsMnF_3$ plotted as a function of the angle of rotation of the external magnetic field **H** in the easy plane, obtained for two values of H ($H_1 = 0.81$ kOe and $H_2 = 1.91$ kOe) and fixed directions of compression in the microwave field **h**: ○) $P = P_{min}$; ●) $P = P_{max}$. **H**||**h** for $\varphi = \pm 90°$, **H**||**P** for $\varphi = 0°$. $T = 1.2$ K, $\nu_p \approx 35.5$ GHz.

H, then for $\varphi = 0°$ we obtained **h**⊥**m** and, according to the theory of Ref. 3, the parallel pumping threshold h_c should approach infinity. Since in our experiments it was impossible to relieve the pressure experienced by the sample completely, we analyzed the data obtained in the range $P_{min} < P < P_{max}$, where $P_{max} \approx 100$ bar and $P_{min} < 0.1 P_{max}$.

It is clear from Fig. 3 that at the highest pressures the pumping was observed even for $\varphi = 0°$. This could be because the effective pressure field $\mathbf{H}_P$ altered the ground state so that **m** was no longer perpendicular to **h**. Moreover, nonuniform compression resulted in a scatter of the values of $\mathbf{H}_P$ in the bulk of the sample, as a result of which the directions of **m** were not the same in different parts of the sample. In-

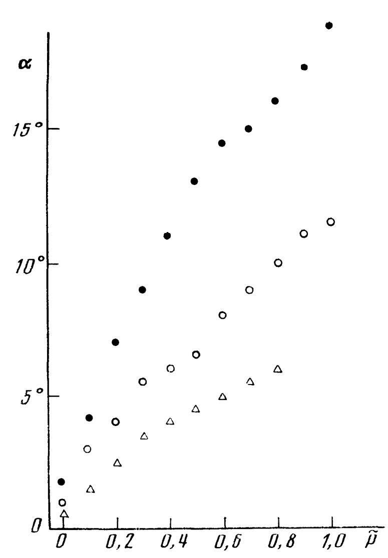

FIG. 4. Dependence of the angle of the shift α of the threshold peaks on the relative pressure $\tilde{P} = (P - P_{min})/(P_{max} - P_{min} =)$ at fixed values of the magnetic field: ●) $H = 1.53$ kOe; ○) $H = 1.91$ kOe; △) $H = 2.3$ kOe. $T = 1.2$ K, $\nu_p \approx 35.5$ GHz.

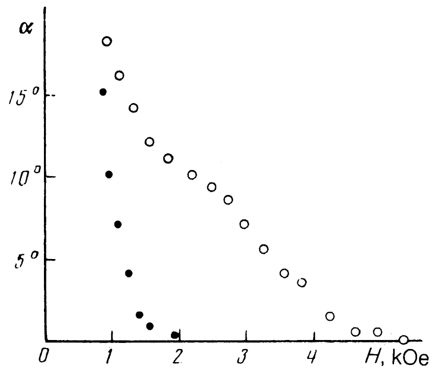

FIG. 5. Dependence of the angle of the shift α of the threshold peaks on the amplitude of the magnetic field at fixed values of the applied pressure: O–) $P = P_{max} \approx 100$ bar; ●) $P = P_{min} < 0.1 P_{max}$. $T = 1.2$ K, $\nu_p \approx 35.5$ GHz.

homogeneity of the compression indicated broadening of the peak at the threshold when the pressure was increased.

It is clear from Fig. 3 that the hexagonal anisotropy of the threshold disappeared under the applied pressure and also that the peak at the threshold shifted toward the compression axis; the shift was greater for the peak closer to this axis ($\varphi = 52°$). The angle α by which the peak shifted under pressure depended on the direction and magnitude of the applied pressure and on the amplitude of the static magnetic field. In weak fields and at the highest pressure the value of α reached 20°.

Figure 4 shows the dependence of the shift of the peak h_c on the pressure applied using three different fields H. Clearly, an increase in the magnetic field weakened the influence of the pressure. The field dependence of the angle α was determined at the maximum and minimum pressures (Fig. 5).

The results obtained confirmed, in our opinion, the hypothesis made above that parametric spin waves propagate along **m** and the rate of their relaxation exhibits a 60° anisotropy. Compression creates an additional 180° anisotropy comparable in magnitude with the energy $\mathbf{m}\cdot\mathbf{H}$. The direction of magnetization is then governed by the minimum of the total energy and it does not coincide with **H**, so that the maxima of the threshold are not observed at $\varphi = 52°$ and $\varphi = -68°$. The peak at h_c can be observed by rotating the static field **H** by an angle α such that the minimum of the magnetic energy corresponds again to the direction $\mathbf{m}\perp\mathbf{c}_2$, when the rate of relaxation of spin waves is maximal.

The sign of the angle α indicates the direction of the effective compression field $\mathbf{H}_P$, which according to our results is perpendicular to the compression axis, $\mathbf{H}_P \| \mathbf{P}$.

This conclusion was supported by one further experiment in which a sample was rotated by 90° and the direction of the applied pressure was almost parallel to one of the $\mathbf{c}_2$ axes (the angle between **P** and $\mathbf{c}_{21}$ was $\approx 8°$). In this case we found no influence of the applied pressure on the resonator frequency or on the threshold peak corresponding to $\mathbf{H}\perp\mathbf{c}_{21}$. In fact, if the effective field had the direction $\mathbf{H}_P \perp \mathbf{P}$, then it was directed at $\approx 82°$ to this axis. Consequently, for $\mathbf{H}\perp\mathbf{c}_{21}$ both **H** and $\mathbf{H}_P$ tended to rotate the magnetic moment in almost the same direction ($\mathbf{m}\perp\mathbf{c}_2$) for which the rate of relaxation of spin waves was maximal. This means, the pressure could not influence the direction of **m** and, consequently, should not alter the resonator frequency or shift the peak at the threshold h_c.

Our results can be explained qualitatively using the following model:

1) parallel pumping of $CsMnF_3$ creates spin waves parallel to the magnetic moment of a sample (we do not know the reason for this);

2) the rate of magnon relaxation has a 60° anisotropy in the basal plane and the functional dependence of the anisotropic part of relaxation on the magnetic field and temperature can be described satisfactorily by postulating elastic scattering of magnons by defects;

3) uniaxial compression of a sample creates a 180° magnetoelastic anisotropy and an effective field perpendicular to the applied pressure which, at a pressure of ≈ 100 bar, is of order 1 Oe.

It should be pointed out that although this model accounts qualitatively for the experimental results, the absence of "hard" parametric excitation and the unexplained role of impurities provide much scope for alternative explanations of the observed effects.

The author is grateful to L. A. Prozorova and V. L. Safonov for valuable discussions.

[1] L. A. Prozorova and A. S. Borovik-Romanov, Pis'ma Zh. Eksp. Teor. Fiz. **10**, 316 (1969) [JETP Lett. **10**, 201 (1969)].
[2] M. H. Seavey, J. Appl. Phys. **40**, 1597 (1969).
[3] V. I. Ozhogin, Zh. Eksp. Teor. Fiz. **58**, 2079 (1970) [Sov. Phys. JETP **31**, 1121 (1970)].
[4] B. Ya. Kotyuzhanskiĭ and L. A. Prozorova, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 171 (1976) [JETP Lett. **24**, 149 (1976)].
[5] A. V. Andrienko, V. L. Safonov, and A. Yu. Yakubovskiĭ, Zh. Eksp. Teor. Fiz. **93**, 907 (1987) [Sov. Phys. JETP **66**, 511 (1987)].
[6] V. S. Lutovinov and V. L. Safonov, Fiz. Tverd. Tela (Leningrad) **22**, 2640 (1980) [Sov. Phys. Solid State **22**, 1541 (1980)].
[7] R. B. Woolsey and R. M. White, Phys. Rev. **188**, 813 (1969).
[8] V. I. Ozhogin and R. M. Farzetdinova, Preprint No. 4451/9 [in Russian], Kurchatov Institute of Atomic Energy, Moscow (1987).

Translated by A. Tybulewicz