Double parametric resonance of nuclear magnons in easy-plane antiferromagnets

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(Submitted 24 April 1981)
Zh. Eksp. Teor. Fiz. **81**, 1456–1461 (October 1981)

Double parametric resonance in the system of nuclear magnons has been detected and investigated experimentally in the easy-plane antiferromagnets $MnCO_3$ and $CsMnF_3$. The effect consists in parametric excitation by a radiofrequency magnetic field ($\Omega/2\pi\sim 100$ kHz) of collective oscillations, at frequency $\Omega/2$, in the system of parametric nuclear magnons ($\omega_k/2\pi\approx 500$ MHz), if the amplitude of the radiofrequency field exceeds a threshold value $H_m^{\rm th}\sim 0.1$ Oe. From the experimental variation of the frequency of the excited collective oscillations with the microwave power, values of the relaxation frequency of the nuclear magnons are obtained.

PACS numbers: 76.70. — r, 75.50.Ee

INTRODUCTION

Antiferromagnets with magnetic anisotropy of the "easy plane" type and with strong hyperfine interaction ($MnCO_3$, $CsMnF_3$) have been used very successfully for study of nuclear magnons, excited parametrically by the method of parallel microwave pumping. Such experiments have made it possible to demonstrate the very fact that nuclear magnons exist and to investigate in detail the relaxation parameter of these excitations, as it depends on their frequency and wave vector.[1,2]

Because of the interaction of parametric magnons (both electronic and nuclear) with each other and with the external pumping field, the spectrum of an excited magnetic crystal contains an additional, low-frequency branch of so-called collective oscillations.[3] These excitations are small oscillations of the number and phase of the parametric magnons against the background of the stationary state beyond the threshold. Uniform collective oscillations have been observed experimentally in the system of parametric electronic magnons of ferrimagnetic yttrium-iron garnet (YIG)[4] and of antiferromagnetic $MnCO_3$.[5] In the first case resonance excitation of the collective oscillations was used, and in the second case nuclear excitation. These experiments also make it possible to measure the relaxation frequencies of the electronic magnons by an independent method.

Zautkin *et al.*[6] predicted, and detected experimentally in YIG, a new phenomenon: double parametric resonance of magnons. The authors observed how, in a system of parametric electronic magnons ($\omega_k/2\pi\approx 5$ GHz), with the help of a radiofrequency (rf) magnetic field ($\Omega/2\pi\sim 1$ MHz), collective oscillations at frequency $\Omega/2$ are excited parametrically if the amplitude of the rf field exceeds a certain threshold value. In contrast to the preceding methods, double parametric resonance in principle makes it possible to study the whole spectrum of collective oscillations, with no limitation to spatially uniform excitations.[7]

Earlier, we investigated double parametric resonance in the system of electronic magnons of antiferromagnetic $MnCO_3$ and $CsMnF_3$,[8] and we observed a peculiarity consisting in the fact that at a sufficient amplitude of collective oscillations (not necesarily uniform) at frequency $\Omega/2$, they in turn excited, parametrically, new collective oscillations with frequency $\Omega/4$ (by analogy with the original phenomenon, this effect may be called triple parametric resonance).

In the present paper, we have succeeded in observing for the first time double parametric resonance of nuclear magnons in $MnSO_3$ and $CsMnF_3$, in verifying experimentally the actual presence of collective oscillations in the nuclear system of an antiferromagnet, and in measuring the relaxation frequency of nuclear magnons.

METHOD

The experiments were performed at temperatures 1.7 and 4.2 K, at microwave pumping frequency $\omega_p/2\pi$ = 1 GHz. The specimens of $MnCO_3$ and $CsMnF_3$ had dimensions $3\times 2\times 0.5$ and $4\times 3\times 2$ mm^3, respectively. Three mutually parallel fields were applied to the specimen in the easy plane of the crystal: $\mathbf{H}_0$, a constant magnetic field; $\mathbf{h}\cos\omega_p t$, the microwave pumping field; and $\mathbf{H}_m\cos\Omega t$, the rf pumping field. The signal from the source of microwave power was fed through a calibrated attenuator to a spiral resonantor, connection with which was made by pins connected to the ends of the spiral. We used a half-wave spiral resonator without a housing, made from copper wire of diameter 0.5 mm. The loaded quality factor of the resonator at liquid-helium temperatures was $Q\sim 500$. The rf field, with amplitude $H_m\leqslant 0.5$ Oe and frequency $F=\Omega/2\pi\leqslant 220$ kHz, was produced by a coil placed around the spiral. The error of measurement of H_m was ~5%. The microwave and rf pumpings were fed to the specimen in the form of continuous signals. The alternating component of the signal of a microwave detector at the output of the resonator was amplified and then recorded on the screen of a spectral analyzer.

Even in the investigation of parametric excitation of electronic magnons, under conditions of modulation of the magnetic field,[8] it was observed that directly beyond the threshold, the modulation frequency Ω was present in the spectrum of the microwave detector signal. A similar picture is observed also in investigation of nuclear magnons. Even at very small values of the amplitude of modulation ($H_m \leqslant 0.01$ Oe), when the effect of modulation on the threshold is negligibly small ($h_c/h_{c0} \leqslant 1.01$), the amplitude of the spectral component Ω is quite sufficient for observation. We used this fact for recording the threshold of parallel pumping, since the other methods of measuring the threshold of parametric excitation of nuclear magnons[2,9] are in our case extremely inconvenient. The identity of the threshold measurements on the basis of microwave absorption and on the basis of the spectral component with frequency Ω was confirmed experimentally.

RESULTS AND DISCUSSION OF THEM

With increase of the amplitude H_m of rf pumping beyond the threshold of parametric excitation of nuclear magnons, the intensity of the spectral component Ω increases, and then, at a certain critical value $H_m^{\rm th}$, there appears in the spectrum a component $\Omega/2$ corresponding to the onset of double parametric resonance. On further increase of H_m, the component $\Omega/2$ disappears in threshold fashion, and then so does Ω; this indicates suppression of parametric excitation of magnons by the modulation.

Figure 1 shows the regions of instability of collective oscillations for $MnCO_3$, in coordinates H_m and h/h_c, at fixed modulation frequencies. With increase of frequency, the region of instability shifts primarily horizontally, toward larger microwave fields. The experimentally observed suppression of double parametric resonance at large H_m cannot be explained within the framework of the theory developed by Zautkin *et al.*,[6] which was based on an approximation quadratic in H_m. The authors of the cited paper express the opinion that this is due to a dependence of the characteristic frequency of the collective oscillations on H_m^2, which leads to violation of the condition for parametric resonance. We note that we did not detect the region of weak oscillations that was recorded in YIG in investigation of double parametric resonance.[6]

Figure 2 shows the $H_m^{\rm th}(F)$ relation at fixed values of the supercriticality h/h_c, plotted from the results of Fig. 1. The dashed lines in this figure represent the theoretical variations of the threshold of instability of collective oscillations with the frequency of the rf field,[6] plotted for relaxation frequency $\Delta\nu = 7$ kHz (see Table I). The theory takes into account excitation at the first stage of uniform collective oscillations only; their frequency is determined by the formula

$$\Omega_0^2=4\gamma^2\frac{2T+S}{S}\left[\left(\frac{h}{h_c}\right)^2-1\right], \qquad (1)$$

where $\gamma = \pi\Delta\nu$ is the relaxation frequency of spin waves, and where T and S are the coefficients of four-wave magnon interaction.

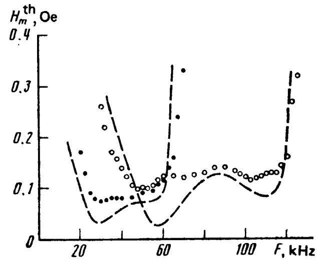

FIG. 2. Experimental and theoretical (dashed lines) variations of the threshold of parametric resonance of collective oscillations with the frequency of the rf field. $MnCO_3$ specimen; $T = 1.7$ K; $H_0 = 0.8$ kOe; $h/h_c = 2.51$ (●) and 4.73 (○).

Double parametric resonance occurs as a result of the action of two mechanisms: parametric resonance of collective oscillations in the rf field with frequency $\Omega = 2\Omega_0$ (decay of a photon of the uniform rf field into two uniform collective modes), and instability of a collective mode excited by an rf field with frequency $\Omega \sim \Omega_0$ with respect to decay into two modes (not necessarily uniform) with frequency $\Omega/2$. The two minima on the theoretical curves are caused by precisely these two mechanisms. In the case of $MnCO_3$, the experimental and theoretical $H_m^{\rm th}(F)$ relations agree quite well. The second minimum, at frequency $\Omega = 2\Omega_0$, shows up, in accordance with the theory, only for a sufficiently large quality factor of the collective oscillations, when $\Omega_0 \gg \gamma$. But the experimental points lie systematically above the theoretical curves. The same picture is observed also in investigation of double parametric resonance in a YIG specimen[6] and is apparently due to an incompleteness of the theory. Similar $H_m^{\rm th}(F)$ relations plotted for $CsMnF_3$ differ from those shown in that the increase of the threshold on the high-frequency side begins not at frequency $\Omega \sim 2\Omega_0$ but at considerably larger frequencies. One may suppose that this is due to excitation of nonuniform collective modes.

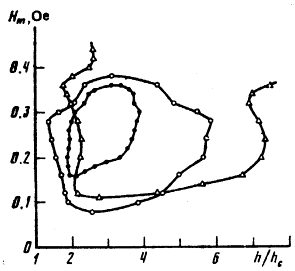

FIG. 1. Regions of parametric instability of collective oscillations at modulation frequencies $F = 20$ (●), 40 (○), and 60 (△) kHz. $MnCo_3$ specimen; $T = 1.7$ K; $H_0 = 0.8$ kOe.

TABLE I. Values of relaxation frequency obtained from experiments on double parametric resonance ($\Delta\nu$) and from measurements of the threshold of parallel pumping ($\Delta\nu^*$, $\Delta\nu^{**}$).

Specimen	T, K	H_0, kOe	k, 10^5 cm	$\Delta\nu$, kHz	$\Delta\nu^*$, kHz	$\Delta\nu^{**}$, kHz
$CsMnF_3$	1.7	2.0	1.1	4±0.6	5.5±1.7	–
	1.7	1.0	2.2	8.5±1.3	7±2.1	–
	4.2	1.0	1.1	15±2.3	23±6.9	–
$MnCO_3$	1.7	0.8	1.7	7±1.1	9.5±2.9	10.5±3.2
	1.7	0.2	3.4	12.5±1.9	20±6	22±6.6
	4.2	0.24	1.7	75±11.3	85±25	70±21

*Our results;
**Results of Ref. 10.

Along with the uniform collective oscillations, there exists in the system of parametric magnons a broad spectrum of spatially nonuniform collective oscillations. The spectrum $\Omega(\varkappa)$ of these waves in the simplest case, when $\varkappa \parallel \mathbf{M}$, and without allowance for damping, has the form[3]

$$\Omega^2(\varkappa)=\left[2(T+S)N+\frac{\partial^2\omega_k}{\partial k_z^2}\frac{\varkappa^2}{2}\right]^2-(2TN)^2. \qquad (2)$$

Here $\varkappa$ is the wave vector of the collective oscillations, ω_k is the spin-wave spectrum, and N is their stationary number.

The experimental method in principle permits excitation not only of uniform but also of nonuniform collective oscillations, according to the condition

$$\Omega_p=\Omega_\varkappa+\Omega_{-\varkappa}.$$

The difference in the experimental relations for $MnCO_3$ and for $CsMnF_3$ is apparently due to the difference in their magnon spectra. Under identical experimental conditions, the value of the second derivative $\partial^2\omega_k/\partial k_z^2$ of the spin-wave spectrum is three times smaller for $MnCO_3$ than for $CsMnF_3$. This leads to the result that the dependence of Ω on $\varkappa$ for $MnCO_3$ is slight, and that over a wide range of wave vectors, $\Omega(\varkappa)$ is practically the same as Ω_0. But in the case of $CsMnF_3$, excitation of nonuniform collective oscillations leads to a broadening of the range of frequencies within which instability of the collective oscillations occurs. Estimates based on formulas (1) and (2) showed that in our experiments, nonuniform collective oscillations with $\varkappa$ up to $\sim 5\cdot 10^3$ cm^{-1} may be excited.

Figure 3 represents the experimental variations of $F_0=\Omega_0/2\pi$ with $(h^2/h_c^2-1)^{1/2}$ for $MnCO_3$ and $CsMnF_3$ for several values of H_0 and T. The results are described sufficiently well by a linear relation.

According to theory,[11] in antiferromagnets of the easy-plane type the coefficients T and S of the Hamiltonian of magnon interaction are equal (with neglect of the dipole-interaction energy). It is then easy to calculate, from the slopes of the lines in Fig. 3, values of the relaxation frequency $\Delta\nu$ of nuclear magnons [see formula (1)]. These results are given in Table I. There also, for comparison, are given the values of $\Delta\nu$ obtained by us and by Gorovkov and Tulin[10] from the threshold of parallel pumping of nuclear magnons. The absolute error of measurement of $\Delta\nu$ from the threshold is ~30%. We estimate the error of measurement of $\Delta\nu$ from excitation of collective oscillations at ~15%. As is seen from Table I, the discrepancy between the values of $\Delta\nu$ obtained by the different methods lies within the limit of error.

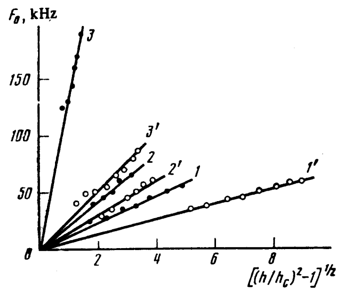

FIG. 3. Experimental variations of the frequency of collective oscillations with supercriticality. •, $MnCO_3$; ○, $CsMnF_3$. The numbers on the straight lines correspond to: 1) $T=1.7$ K, $H_0=0.8$ kOe; 2) 1.7 K, 0.2 kOe; 3) 4.2 K, 0.24 kOe; 1′) 1.7 K, 1.98 kOe; 2′) 1.7 K, 0.96 kOe; 3′) 4.2 K, 1 kOe.

Thus in the present paper, double parametric resonance of nuclear magnons has been observed for the first time, substantiating the presence of collective oscillations in the nuclear system of an antiferromagnet; and the relaxation frequency of nuclear magnons has been measured by an independent method.

We express our deep gratitude to V. I. Ozhogin and V. S. Lutovinov for their interest in this work and for useful discussions.

[1] V. I. Ozhogin and A. Yu. Yakubovskiĭ, Zh. Eksp. Teor. Fiz. **67**, 287 (1974) [Sov. Phys. JETP **40**, 144 (1974)].

[2] V. A. Tulin, Fiz. Nizk. Temp. **5**, 965 (1979) [Sov. J. Low Temp. Phys. **5**, 455 (1979)].

[3] V. E. Zakharov, V. S. L'vov, and S. S. Starobinets, Usp. Fiz. Nauk **114**, 609 (1974) [Sov. Phys. Usp. **17**, 896 (1975)].

[4] V. V. Zautkin, V. S. L'vov, and S. S. Starobinets, Zh. Eksp. Teor. Fiz. **63**, 182 (1972) [Sov. Phys. JETP **36**, 96 (1973)].

[5] L. A. Prozorova and A. I. Smirnov, Zh. Eksp. Teor. Fiz. **67**, 1952 (1974) [Sov. Phys. JETP **40**, 970 (1974)].

[6] V. V. Zautkin, V. S. L'vov, B. I. Orel, and S. S. Starobinets, Zh. Eksp. Teor. Fiz. **72**, 272 (1977) [Sov. Phys. JETP **45**, 143 (1977)].

[7] V. V. Zautkin and B. I. Orel, Zh. Eksp. Teor. Fiz. **79**, 281 (1980) [Sov. Phys. JETP **52**, 142 (1980)].

[8] V. I. Ozhogin, A. Yu. Yakubovskii, A. V. Abryutin, and S. M. Suleymanov, J. Magn. Magn. Mater. **15-18**, 757 (1980).

[9] A. Yu. Yakubovskiĭ, Zh. Eksp. Teor. Fiz. **67**, 1539 (1974) [Sov. Phys. JETP **40**, 766 (1974)].

[10] S. A. Govorkov and V. A. Tulin, Zh. Eksp. Teor. Fiz. **73**, 1053 (1977) [Sov. Phys. JETP **46**, 558 (1977)].

[11] V. S. L'vov and M. I. Shirokov, Zh. Eksp. Teor. Fiz. **67**, 1932 (1974) [Sov. Phys. JETP **40**, 960 (1974)].

Translated by W. F. Brown, Jr.