Investigation of the complex character of the spin-wave relaxation at low temperatures

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The time dependences of the number of magnons and the oscillation amplitude of the magnon-related magnetization during the relaxation of parametrically excited magnons after the pump has been switched off have been determined. The data of these measurements indicate that magnon relaxation in the antiferromagnetic crystals $CsMnF_3$ and $MnCO_3$ at $T\sim1.5$ K has a complex character: besides a decrease in the number of magnons, there occurs a destruction of the initially existing phase correlation. The magnon lifetimes and the phase correlation destruction time are determined. The effect of the complex character of the relaxation on the parametric magnon-excitation threshold is studied.

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1. INTRODUCTION

Spin-wave relaxation in magnetically ordered crystals has been studied both theoretically and experimentally in a number of papers (see, for example, Refs. 1–4). In the experimental investigations the relaxation rate of the spin waves was usually determined from the strength of their parametric excitation threshold field. During the parametric excitation wave pairs with wave vectors k and −k are excited whose frequency ω_k satisfies the parametric-resonance condition $\omega_k=\omega_p/2$ (ω_p is the microwave-pump frequency). For this excitation to be possible, it is necessary that the microwave-field amplitude h exceed the threshold value h_c. The relation between the relaxation rate, $\Delta\nu_k$, of the excited waves and h_c was established theoretically in a phenomenological analysis of magnon damping in the τ approximation (see, for example, Ref. 5):

$$h_cV_k=\Delta\nu_k, \quad (1)$$

where V_k is the spin wave-pump coupling constant, which depends on the frequency of the excited waves, the parameters of the material, and the external conditions (e.g., the magnetic field).

Thus, the method of determining $\Delta\nu_k$ from the value of h_c is an indirect one, and is based on certain assumptions. A more direct method was used in subsequent investigations.[6,7] The spin waves were parametrically excited up to some amplitude, then the pump generator was switched off, and the damping of the microwave signal emitted by the spin waves in the course of the relaxation was studied. Relaxation-rate values obtained with the aid of these two methods for one and the same sample (the antiferromagnet $MnCO_3$ in the investigation by Prozorova and one of the present authors[6] and a YIG-ferrite sphere in Zhitnyuk and Melkov's investigation[7]) are found to differ greatly from each other (by a factor of 4–7).

To explain this inconsistency, it was proposed in Ref. 6 that a significant contribution to the damping of the microwave signal is made by those interactions of the spin waves which result only in the dislocation of the phases of the spin waves, and leave the frequency and the wave vector unchanged. In other words, it is assumed that the phase correlation that arises in the spin-wave system under the action of the pump is destroyed after the microwave field has been switched off at a rate faster than the rate of variation of the number of spin waves. Then the situation arises in which magnons still exist, but no longer emit a coherent signal. These interactions should affect the threshold-field strength h_c to a lesser extent, since for an ensemble of waves with broken phase correlation, the coupling to the pump weakens, but does not cease entirely. The effect of this type of interaction of the spin waves on their parametric excitation has been theoretically analyzed by Zakharov and L'vov.[8] The scattering of spin waves by point defects is considered as such an interaction.

In order to be able to say with certainty that the randomization of the magnon phases does indeed occur, we must carry out an experiment during which we measure the time dependence of the number $n_{k'}$ of magnons with a given wave-vector value k′ while the excited crystal relaxes to the equilibrium state, and compare this dependence with the time dependence of the emitted-microwave signal intensity during the same relaxation process. If the characteristic relaxation times obtained in these two experiments turn out to be different, then the phase randomization occurs. The purpose of this work was to set up such an experiment.

2. PROCEDURE OF THE MAIN EXPERIMENT

a) Measurement of the decrement of the number of nonequilibrium magnons

To measure the $n_{k'}$ dependence, we use the phenomenon whereby the spin-wave spectrum changes during the interaction of the magnons,[9,10] a phenomenon which has been experimentally studied by Prozorova and one of the present authors.[11] This phenomenon consists in the fact that the natural frequency $\tilde\omega_k$ of a magnon with wave vector k in a crystal in which some ensemble of spin waves has been excited differs from the frequency ω_k of a magnon with the same k value in an unexcited crystal by the amount

$$\Delta_k=\tilde\omega_k-\omega_k=2\sum_{k'}T_{kk'}n_{k'}=\sum_{k'}\Delta_{kk'}. \quad (2)$$

Here $T_{kk'}$ is the amplitude of a four-magnon interaction in which two initial magnons with wave vectors **k** and **k**′ are transformed into two final magnons with the same wave-vector values (nondissipative interaction). The quantity $\Delta_{kk'}$ naturally depends only on the number $n_{k'}$ of magnons with wave vector **k**′, and does not depend on the presence of phase correlation in the investigated magnon ensemble.

Thus, to measure the $n_{k'}(t)$ dependence, we only need to measure the time dependence of the contribution of these magnons to the shift in the natural frequency of magnons with another k value, i.e., the quantity

$$\Delta_{kk'}=2T_{kk'}n_{k'}.$$

The frequency shift $\Delta_{kk'}$ was measured with the setup described in Ref. 11, but the measurement procedure was slightly changed. A crystal of antiferromagnetic $CsMnF_3$ or $MnCO_3$ is subjected to the action of two microwave pumps with frequencies ω_{p1} and ω_{p2}, which parametrically excite in the sample magnons with wave vectors k_1 and k_2 and frequencies

$$\tilde{\omega}_{k1}=\omega_{p1}/2, \tag{3a}$$

$$\tilde{\omega}_{k2}=\omega_{p2}/2. \tag{3b}$$

The number of excited magnons (~10^{16} per cubic cm) is roughly six orders of magnitude higher than that of the thermal magnons with the same wave vectors at a temperature $T\approx 2K$. We shall denote by PM1 the magnons parametrically excited by the pump with frequency ω_{p1} and by PM2 the magnons that arise under the action of the second pump (as is done in Ref. 11). The pump frequencies are $\omega_{p1}/2\pi=22400$ MHz and $\omega_{p2}/2\pi=35500$ MHz. In this case the wave vectors of the excited magnons are determined by the relations (3) and by the dispersion law [see formula (4) below], and, depending on the external magnetic field, range from zero to a value of the order of 10^5 cm^{-1}. For more details about the parametric excitation of spin waves in antiferromagnets see Refs. 4, 6, 10, 11.

We shall study the relaxation of the PM2 magnons after the pump exciting them has been switched off. Let us try to determine the time dependence of the number $N_2(t)$ of these magnons. For this purpose, let us consider PM1-magnon shift natural-frequency resulting from the presence of the PM2 magnons, i.e., the quantity $\Delta_{12}=2T_{12}N_2$. Before the beginning of the experiment the two pumps are switched on, and a steady-state absorption level is established at the two frequencies. Then, after the second pump has been switched off, Δ_{12} decreases to zero. This leads to a change in the natural frequency $\tilde{\omega}_{k1}$ of the PM1, and the parametric-resonance condition (3a) is violated. As a result, the steady-state power-absorption regime for the first pump is perturbed, and, by making use of the onset of the characteristic transient process, we can register the spectral shift Δ_{12}. In the course of the transient process, the nonresonant magnons attenuate, and magnons with a new resonance k value are excited, which leads to the reestablishment of the steady-state absorption level.

The relatively weak attenuation of the spin waves allows the registration of a shift $\Delta_{12}\sim 10^{-5}\omega_{k1}$. During the transient process caused by the switching off of the second pump, the natural frequency of the PM1 varies according to the law

$$\tilde{\omega}_{k1}=\tilde{\omega}_{k1}(0)-\Delta_{12}(0)+\Delta_{12}(t).$$

The $\Delta_{12}(t)$ dependence is measured by cancelling this change with an artificial shift of $\tilde{\omega}_{k1}$ in the opposite direction [i.e., toward $\tilde{\omega}_{k1}(0)$]. The reverse spectral shift is produced by changing the external magnetic field by a small amount. The spin-wave spectrum in an unperturbed crystal of an antiferromagnet with the "easy-plane" type of anisotropy depends on the magnetic field H in a known fashion[12]:

$$\omega_k^2=g(H(H+H_D)+H_\Delta^2/T_n+\alpha^2k^2), \tag{4}$$

where g is gyromagnetic ratio, H_D is the Dzyaloshinskiĭ field, H_Δ^2 is a constant describing the interaction between the elecronic and nuclear spins, and T_n is the temperature of the nuclear spin subsystem. The values of g, H_D, H_Δ^2, and α for our samples are known.[4,13]

Thus, if simultaneously with switching off the second pump we begin to vary the external magnetic field in such a way that at each moment of time

$$\omega_{k1}(t)-\omega_{k1}(0)=\Delta_{12}(0)-\Delta_{12}(t), \tag{5}$$

then the resonance condition (3a) will not be violated, and no transient process should be observed. Thus, we must choose in the course of the experiment that $H(t)$ dependence which guarantees the fulfillment of (5). If we are able to do this, then, using (4), we can find $\Delta_{12}(t)$ and, consequently, both the time dependence of N_2 and the PM2 lifetime. We vary the external field with the aid of a small coil wound around the sample located inside a two-mode microwave cavity resonator. The reaction of the PM1 to the switching off of the second pump is compensated for by a current pulse fed to the coil via a small adjustable RC circuit. By appropriately choosing the current strength and the time constant of the RC circuit, we can indeed effect this conpensation.

This is illustrated by the oscillograms of the power of the first pump passing through a resonator with a sample after the second pump has been switched off in the absence of a current in the coil (i.e., simply the response of the PM1 to the spectral shift Δ_{12}) and upon the passage of a current through the coil (Fig. 1). The compensation occurs when the leading edge of the current pulse fed to the coil has an exponential form, and allows the determination of the characteristic time of this exponential function to within 15%. When the time constant of the RC circuit deviates by 10–15% from the value corresponding to the optimal compensation, the compensation becomes unattainable at any amplitude of the current pulse in the coil. Since the spectral shift Δ_{12} is small (~$10^{-5}\omega_{k1}$), the change in ω_k that offsets it is also small and, hence, proportional to the change in H. Then at compensation the growth rate of the current in the coil is equal to the damping constant of the spectral shift Δ_{12}. We have thus determined the characteristic relaxation time τ_Δ of the spectral shift.

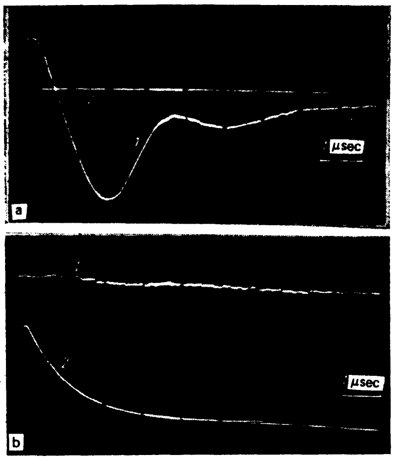

FIG. 1. Compensation of spectrum shift: trace 1) power passing through the resonator, trace 2) current in the coil; a) response of the PM1 to the switching off of the second pump, b) compensation of this response with the aid of the current in the coil.

A somewhat different method of measuring Δ_{12} was used earlier.[11] A transient process similar to the response of the PM1 to the switching off of the second pump was initiated by a small change in the frequency ω_{p1} of the first pump, and this also led to the violation of the parametric-resonance condition (3a). But the change in ω_p does not merely reduce to a change in the difference $\tilde{\omega}_{k1} - \omega_p/2$, as we thought,[11] but also leads to some other changes in the equations describing the parametric excitation of waves [Eq. (7b) of Ref. 11 acquires a term proportional to $t\partial\omega_p/\partial t$]. Therefore, the same changes in $\tilde{\omega}_{k1}$ and $\omega_{p1}/2$ can, generally speaking, lead to different reactions of the PM1.

The method used in the present work to offset the frequency shift does not have this disadvantage. We performed control experiments in which the shift Δ_{12} was measured by the method described in Ref. 11 and the method proposed in the present paper. The Δ_{12} values and the characteristic magnon-damping times obtained by these two methods do not differ from each other within the limits of the measurement error (15%). This fact allows us to believe that the experimental data on the magnitude of the spectral shift given in Ref. 11 remain valid.

b) Measurement of the characteristic destruction time of the magnon phase correlation

To measure the characteristic phase-correlation-destruction time, we must measure the time dependence of the oscillation amplitude of the spin-wave-related magnetic moment m of the sample. The nonlinear coupling of the magnetic field with the magnon, which makes the parametric excitation possible, leads to a situation in which the parametrically excited spin waves are accompanied by a magnetic-moment oscillation that is uniform over the sample, and has a frequency equal to the frequency of the pump. The amplitude m_0 of this oscillation is proportional to the number of PM, and is due to the presence of phase correlation in the magnon system.[10] The damping of the oscillations of the PM2-related magnetic moment m was studied, by the method of beats described in Ref. 6. The essence of this method consists in the following. After the pump that excites parametrically the magnons has been switched on, and the steady-state absorption level has been attained, the pump frequency is changed quickly (i.e , within a time interval short compared to the PM2 lifetime) by an amount several times greater than the magnon relaxation frequency. The power absorbed then executes beats near the zero level with frequency equal to the difference between the pump frequencies before and after the frequency shift. An example of an oscillogram of such beats is shown in Fig. 2. Depicted here is the time dependence of the microwave power passing through a resonator with a sample (the voltage of the crystal microwave detector). A measure of the power absorbed in the sample is the difference between the voltages generated by the detector in the absence and presence of absorption.

The beats are observed because there still exist in the crystal, for some time after the of the pump-frequency shift, magnetic-moment oscillations with frequency equal to the initial pump frequency. As a result, the absorbed power $W = h\partial m/\partial t$ will undergo beats until the oscillations excited in the sample by the initial pump die down. Magnetic-moment oscillations with a new frequency begin to build up out of the thermal background, but do not attain an appreciable amplitude for some time after the beats have completely died down (for an oscillogram of the entire process with a slow time base, see Ref. 6). Since the change in the frequency is significantly greater than $\Delta\nu_k$, the "new" pump does not enter into resonance with the "old" PM2's, and has practically no influence on their damping, which thus occurs in the same way as it does in the absence of the new pump. Therefore, the envelope of the beats is a plot of $m_0(t)$ for the case of free damping of the PM2. In our experiments this envelope had the shape of an exponential function of the time. The characteristic damping time τ_m of m was defined to be as the characteristic time of this exponential function.

The characteristic sensitivity of the crystal microwave detector is quadratic in the microwave-field amplitude. Therefore, the method of beats guarantees a higher sensitivity in the m_0 measurement than the direct observation of the microwave emitted by the sample after the pump has been switched off. The control experiments on the direct observation of the signal emitted by the sample yielded the same τ_m values as the experiments on the observation of the

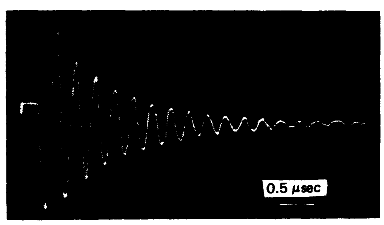

FIG. 2. Beats of the absorbed power after a change in the pump frequency.

beats.

In order to excite magnons in a sufficiently narrow interval of k space, we performed the τ_m measurements with a pump power that barely exceeded the threshold power. As is well known, parametric excitation leads to buildup of those oscillations whose natural angular frequencies fall in an interval of length

$$\tau^{-1}[(h/h_c)^2-1]^{1/2}$$

with its center at the point $\omega_p/2$; here τ is the magnon lifetime in the τ approximation for the relaxation. The finite range of the natural-frequencies of the excited oscillations is itself a cause of dephasing of these oscillations after the exciting force has been switched off. The τ_m values given below were obtained for $(h/h_c)^2-1\leq 0.1$. In this case the above-cited length of the excitation interval turns out to be such that over the period of time τ the phases of the individual isochromats differ insiginficantly from each other: the cosine of the maximum phase-difference angle is not less than 0.95. It should be noted that the appearance of a dephasing of the magnetic-moment oscillations in the sample can occur also in the case in which a pump generator with a fairly large spectral width (i.e., with a poor frequency stability) is used in the above-described experiment.

The frequency stability of the pump generator used, measured by beating with a signal from another generator of the same type, is not worse than 20 kHz/μsec. This is adequate for the analysis of those variations of the m-oscillation phase in which an appreciable phase change occurs over a period of time not longer than on the order of 10 μsec. Since the transient in question lasts not more than 2–3 μsec, our generator should from the point of view of "monochromaticity," be considered to be satisfactory.

3. RESULTS OF THE MAIN EXPERIMENT

Figures 3 and 4 show the values of the relaxation rates $\Delta\nu_m$ and $\Delta\nu_\Delta$ obtained by the beat and frequency shift-compensation methods at different magnetic-field values and temperatures. (The relaxation rate is connected with the characteristic exponential-damping time τ by the simple relation $\Delta\nu=1/2\pi\tau$.) It can be seen that the frequency shift Δ_{12} relaxes roughly two times more slowly than the high frequency magnetic-moment oscillations connected with the phase correlation in the PM2-magnon group

Let us note that the deviation of $\Delta\nu_\Delta$ from $\Delta\nu_m$ may be due not only to dephasing, but also to the presence of secondary magnons that can be generated in the course of the relaxation of the PM2. These secondary magnons can make a contribution to Δ_{12} at a time when a significant part of the PM2 system has already relaxed. Thus, the frequency-shift-compensation experiments yield the upper limit of the magnon lifetime τ_N.

4. CONTROL EXPERIMENT

For an indication of the randomization of the PM phases in the course of the relaxation, we performed

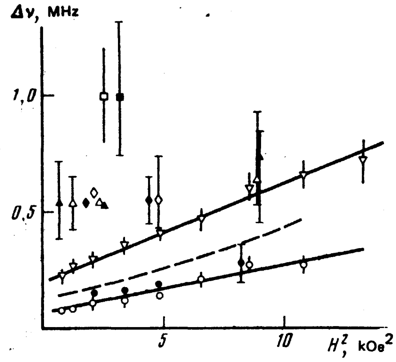

FIG. 3. Results of the magon-relaxation frequency measurements at $T=1.63$ K: the symbols ○, ∇, and ● correspond to the quantities $\Delta\nu_\Delta$, $\Delta\nu(h_c)$, respectively, for the original $CsMnF_3$ sample; ▲ and Δ, to the quantities $\Delta\nu_\Delta$ and $\Delta\nu_m$ for a sample with excess Mn content. The symbols ♦ and ◇ denote $\Delta\nu_\Delta$ and $\Delta\nu_m$ for a powder; while □ and ■ denote the same quantities for a sample irradiated in a microtron. The dashed line represents the values of $\Delta\nu(h_c)$ computed from the formula (7) with the use of the experimental values of $\Delta\nu_p$ and $\Delta\nu_N$.

the following control experiment. We rapidly varied the pump's phase in the entire range from 0 to 2π at the initial stage of the PM buildup (after the pump had been switched on for some time), as well as after interrupting the pump for some time δ (during which the PM attenuated freely in the absence of the pump), and compared the PM2's reactions to the rapid phase variation in both cases. The procedure for the rapid variation of the pump's phase is described in Ref. 6. Figure 5 shows a schematic drawing of the oscillogram of the pump power passing in this case through the resonator. That the phase correlation can be exhibited in this way is due to the fact that the phase-correlated system of oscillations naturally reacts strongly to a change in the pump's phase, while an ensemble of oscillations with randomly distributed phases in no way reacts to such an action. The sequence of our actions in time is as follows. At the moment of time $t=0$ we switch on the pump, whose power slightly exceeds the threshold power ($h/h_c-1\sim 0.1-0.2$). If the pump is not manipulated, by the moment of time t^* the number of excited PM will become sufficient for our apparatus to be able to register the power absorbed by them, and after quite a long flat section the oscillogram will show a rapid growth of the absorbed power (a steep drop of the pulse) and, subsequently, the approach to the steady-state regime.

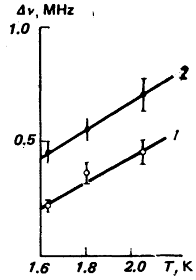

FIG. 4. Temperature dependence of $\Delta\nu_\Delta$ (1) and $\Delta\nu_m$ (2) for the $CsMnF_3$ sample.

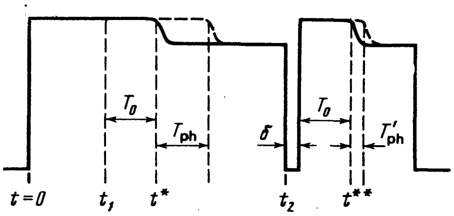

FIG. 5. Schematic drawing of the oscillogram of the microwave power passing through the resonator in the control experiment.

For more details about the kinetics of the parametric-excitation process, see Refs. 13 and 14.

If, without waiting for the appearance of the drop, we carry out, during a period of time T_0 before its appearance, a rapid variation of the phase of the pump at the moment t_1, then the chip appears at a later time. The lengthening of the flat part depends on the magnitude of the phase change, but the maximum lengthening (T_{ph}) is of the order of $t^*/2$. Such a strong reaction to a change in the phase of the pump indicates the presence of a fully correlated state at the growth stage. The rapid variation of the phase of the pump in the steady-state stage of the process (after the drop) also leads to a strong perturbation of the PM (see Ref. 6). Now, after the PM system has reached the steady state, at the moment of time t_2 we interrupt the action of of the pump on the crystal (without switching off the generator itself) for a period of time, δ, such that the time interval $t^{**} - t_2 - \delta$ necessary for the appearance of a new drop after the resumption of the action of the pump is again equal to T_0. In this case if the phase correlation of the magnons is not destroyed during the free attenuation, then the PM should be in identical states at the moments of time t_1 and $t_2 + \delta$, and should react in identical fashion to the phase changes. Experiment shows, however, that, when the phase of the pump is varied within the limits from 0 to 2π, the maximum change in the position T'_{ph} of the drop at the moment of time $t_2 + \delta$ becomes significantly smaller than T_{ph} even for $\delta = 1$ μsec, while for $\delta > 2$ μsec T'_{ph} practically vanishes. Thus, the destruction of the phase correlation during the PM attenuation is obvious.

Let us note that the effect of the action of the pump in the period prior to the interruption on the duration of the oscillogram's flat section arising after the pump has been switched on again persists right up to $\delta \approx 4-5$ μsec. As an example, let us give values for the quantities characteristic of such experiments (all the times are in μsec):

Experiment Number	t^*	t_1	T_{ph}	δ	T'_{ph}	H, kOe^2	T, k
1	12	10	6	2.5	0.4	1	1.6
2	25	20	10	1.5	1	1	1.6

These data allow us to believe that the phase correlation in the PM system is destroyed with a characteristic time τ_{ph} not exceeding 1–1.5 μsec. The same τ_{ph} estimate is obtained for other magnetic-field values and temperature in the range from 1.6 to 2.1 K.

5. ANALYSIS OF THE DATA AND THE MAIN RESULT

We shall characterize the magnon relaxation by two relaxation frequencies: $\Delta\nu_N = 1/2\pi\tau_N$, where τ_N is the lifetime of the magnon irrespective of its phase, and $\Delta\nu_{ph} = 1/2\pi\tau_{ph}$, where τ_{ph} is the phase correlation destruction time for $\tau_N = \infty$. Then we obtain for the lifetime of the HF magnetic moment m associated with the spin waves the relation

$$\frac{1}{\tau_m} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_N}, \quad \Delta\nu_m = \Delta\nu_{ph} + \Delta\nu_N. \tag{6}$$

The above results determine these quantities through the following relations:

$$\Delta\nu_m = \Delta\nu_{ph} + \Delta\nu_N, \quad \Delta\nu_\Delta \leqslant \Delta\nu_N, \quad \Delta\nu_{ph} \geqslant 0.1 \text{ MHz}.$$

Under those conditions when the lowest magnon relaxation rate is attained in our experiments ($T = 1.6$ K, $H \leq 1$ kOe), these relations determine the intervals in which $\Delta\nu_{ph}$ and $\Delta\nu_N$ have their true values:

$$0.1 \leqslant \Delta\nu_{ph} \leqslant 0.13, \quad 0.1 \leqslant \Delta\nu_N \leqslant 0.13 \text{ MHz}.$$

At all the remaining magnetic-field and temperature values the values of $\Delta\nu_N$ also turn out to be close to the values of $\Delta\nu_\Delta$, and, consequently,

$$\Delta\nu_{ph} \approx \text{const}(H, T) \approx (0.2 \pm 0.05) \text{ MHz}.$$

For the $MnCO_3$ sample, the difference $\Delta\nu_m - \Delta\nu_\Delta$, which indicates the randomization of the phases, turned out to be even greater: at $T = 1.6$ K and $H = 0.5$ kOe, $\Delta\nu_\Delta = (0.1 \pm 0.02)$ MHz and $\Delta\nu_m = (0.35 \pm 0.05)$ MHz. Thus, the randomization of the magnon phases occurs roughly with the same characteristic time as the decrease in the number of magnons, and therefore the role of the loss of phase coherence is important in all the phenomena in which a particular phase correlation manifests itself in the magnon system.

The virtually exact equality of the quantities $\Delta\nu_\Delta$ and $\Delta\nu_N$ indicates that the secondary nonequilibrium quasiparticles produced during the relaxation of the magnons in question either make no contribution to the frequency shift Δ_{12}, or die down significantly faster than the PM2.

6. INVESTIGATION OF THE ROLE OF THE DEFECTS

To elucidate the nature of the randomization of the magnon phases, we investigated a number of samples containing artificially produced defects, since one of the mechanisms leading to this phenomenon is the elastic scattering of magnons by all kinds of point defects in the volume or on the surface of the crystal. As samples with volume point defects, we investigated: 1) a $CsMnF_3$ sample with nonstoichiometric Mn content (the Mn excess over the content in the stoichiometric composition was ~1%; the distribution of this excess over the volume of the sample was not monitored), and 2) a sample of stoichiometric composition, but irradiated with 8-MeV electrons in an accelerator of the microtron type (the radiation dose was 10^{-5} C/mm^3). The results of the $\Delta\nu_\Delta$ and $\Delta\nu_m$ measurements on these samples are presented in Fig. 3.

To analyze the effect of the boundaries on the difference between the quantities $\Delta\nu_\Delta$ and $\Delta\nu_m$, we investigated a sample composed of a great number of arbitrarily-oriented small crystals with the dimensions of the individual particles ranging from 0.1 to 0.2 mm, i.e., the dimension of the individual particles did not exceed 1/5 of the dimensions of the parent sample. The result of the investigation of this sample is also shown in Fig. 3. Because of the large experimental errors, these data do not allow the determination of the difference $\Delta\nu_m - \Delta\nu_\Delta$ with the same accuracy with which this difference was determined for the original perfect sample, but it is clear that the difference at least does not increase as a result of the introduction of these defects. Consequently, the above-described defects have no effect on the processes randomizing the magnon phases, although they significantly increase the rate of relaxation of the magnon number.

The negative result of the experiment on the observation of the effect of crystal defects on the magnon-phase randomization compels us to postulate the existence of some intrinsic phase-modifying magnon-interaction processes. It is possible that in the antiferromagnets investigated by us such a process is the scattering of the magnons by the nuclear spin subsystem, which behaves in the interaction with the magnons like paramagnetic impurities.[15]

7. THE THRESHOLD FOR PARAMETRIC EXCITATION

Of importance in connection with the establishment of the existence of two types of magnon relaxation is the question of the threshold for parametric excitation of magnons under such conditions. To measure the parametric-excitation threshold field h_c, we used the procedure employed in the earlier experiments described in Refs. 4, 6, and 13 with slight modifications. These modifications were made necessary by the following circumstances. As it turned out, the permittivity of $CsMnF_3$ and $MnCO_3$ single crystals at microwave-pump frequencies in the centimeter-wave band is quite high: $\varepsilon = 4 \pm 0.2$ for $MnCO_3$ and 5.5 ± 0.5 for $CsMnF_3$. Therefore, the wavelength of a plane electromagnetic wave in such a medium is comparable to the sample dimensions $l \approx 1$ mm. The presence of such an extended dielectric in the microwave cavity resonator used to produce at the sample a microwave magnetic field stronger than h_c can appreciably distort the microwave-field distribution as compared to the distribution in the empty resonator (see, for example, Ref. 16). This circumstance was not taken into consideration in the cited investigations, and the field h_c was computed from the magnitude of the microwave power entering the resonator under the assumption that the sample did not severely distort the field distribution. In order that the microwave field at the sample could be computed more accurately, the sample, in the form of a cylinder, was placed in a cylindrical hole in a quartz disk, completely filling this hole. The permittivity of quartz is 3.8, i.e., close to that of the sample. The diameter of the quartz disk was equal to that of the cylindrical cavity of the resonator, and the disk with the sample was placed at the bottom of the resonator. The electromagnetic field in such a resonator with the disk can be calculated exactly (see, for example, Ref. 16). Furthermore, a factor $\sqrt{2}$ was omitted in the earlier[4,6,13] computations of h from the magnitude of the microwave power, and the h_c value was accordingly too low.

The measurements of h_c with the aid of the quartz disk showed that the distortion of the electromagnetic field in the resonator led to an underestimate of h_c's by roughly a factor of two. Thus, the relaxation rates determined from the beat damping and the h_c value[6] do not in fact differ from each other as greatly as the data of Ref. 6 indicate (by a factor of 7), but, apparently, by a factor of 1.5–2. The relaxation frequency $\Delta\nu(h_c)$ determined from h_c by the described procedure is presented in Fig. 3. The absolute accuracy of these measurements is not high, since it is connected with the absolute microwave-power measurements; it is ~30%. The value of $\Delta\nu(h_c)$ lies between $\Delta\nu_\Delta$ and $\Delta\nu_m$, which qualitatively corresponds with the idea that the randomization of the phases of the magnons affects the threshold for the parametric excitation of these quasiparticles: $\Delta\nu(h_c)$ should be greater than $\Delta\nu_\Delta$, since the phase randomization impedes the buildup, and smaller than $\Delta\nu_m$, since the loss of phase coherence of a pair of magnons does not mean that they completely stop interacting with the pump, for the phase gets readjusted after some time to a value at which the energy absorption is maximal. Our data on the quantity $\Delta\nu(h_c)$ are in agreement with the dependence, obtained by Zakharov and L'vov,[8] of $\Delta\nu(h_c)$ on the relaxation frequencies $\Delta\nu_N$ and $\Delta\nu_\phi$:

$$\Delta\nu(h_c) = (\Delta\nu_N^2 + \Delta\nu_\phi \Delta\nu_N)^{1/2}, \tag{7}$$

where $\Delta\nu_\phi$ is assumed to be due to scattering by the inhomogeneities.

Thus, we have shown that the relaxation of magnons at low temperatures has a complex character, and is described by two characteristic times: the phase-correlation-destruction time and the magnon lifetime proper. The values of these times have been determined. The effect of the complex character of the relaxation on the parametric magnon-excitation threshold has been studied.

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