Investigation of the interaction of spin waves with the nuclear spin subsystem in an antiferromagnet

L. E. Svistov and A. I. Smirnov

Institute of Physical Problems, Academy of Sciences of the USSR
(Submitted 26 October 1981)
Zh. Eksp. Teor. Fiz. **82**, 941–950 (March 1982)

The spin-wave relaxation rate $\Delta\nu$ has been measured under conditions when the nuclear spin system is considerably superheated with respect to the lattice of a $CsMnF_3$ single crystal sample located in a liquid-helium bath with temperature in the range from 1.8 to 2.1 K. As the temperature T_n of the nuclear subsystem is varied from 1.8 to 8 K, $\Delta\nu$ is found to increase in proportion to T_n; then the $\Delta\nu(T_n)$ dependence saturates, and at $T_n = 100$ K the contribution of the heated nuclear subsystem to the spin-wave relaxation rate is of the same order as in a sample in the equilibrium state. The linear part of the $\Delta\nu(T_n)$ dependence is attributed to scattering of the spin waves by the nuclear spin waves; at higher T_n values there occurs no less intense scattering connected, apparently, with the collective nuclear-spin motions, which are correlated at small distances. The kinetics of the heating of a nuclear spin subsystem by a radio-frequency field is studied. A characteristic of this heating process is that the volume of the sample region with intermediate T_n values is small compared to the volumes of those parts of the sample where the nuclear system either has been heated to the highest possible temperature or is at the temperature of the lattice.

PACS numbers: 75.30.Ds, 75.50.Ee

1. INTRODUCTION

At present the spin-wave (SW) relaxation processes that occur in magnetically ordered materials are studied largely by determining the lifetime of the magnons from the measurement of the threshold field for their parametric excitation. These experiments allow us to determine the magnon lifetime due to all the possible dissipative interactions between the magnons and the thermal excitations of the crystal.

The problem of SW relaxation in antiferromagnets has been the subject of several theoretical and experimental investigations.[1-5] The results of these investigations indicate that, at temperatures of 2–4 K, and in a sufficiently strong magnetic field, the dominant contribution to the relaxation of the major portion of the magnons of the heat reservoir is made by the three-magnon coalescence process. But there is no settled opinion about the question of SW relaxation at lower temperatures and in weaker magnetic fields. This is due to the fact that the temperature and field dependences of the relaxation rate do not have a form characteristic only of any one type of scattering, as well as to the fact that the theoretical analysis of many types of relaxation processes yields roughly the same value for the relaxation rate: 0.1 MHz for SW with frequency $\sim 10^{10}$ Hz at $T\approx 1$ K (e.g., the SW-relaxation calculations for the cases in which the SW are scattered by other SW,[1] phonons,[2] and dislocations[3]). In view of this, measurements of the total relaxation rate do not answer this question. A more promising procedure, in our opinion, is the measurement of the change that occurs in the relaxation rate during the generation in the crystal of nonequilibrium excitations of a specific type. Such a method allows the determination of the SW-relaxation rate due to the scattering by these excitations, i.e., the separation of the contributions of the individual relaxation mechanisms to the total SW-damping rate. The scattering of magnons by magnons with a definite wave-vector value has already been studied.[6,7]

The purpose of the present investigation was to study the scattering of SW by the excitations of the nuclear spin subsystem. To do this, we had to simultaneously superheat the nuclear spin subsystem and measure the SW relaxation rate in the same sample. As the object of the investigation, we chose the antiferromagnet with an "easy plane" type of anisotropy (AFMEP) $CsMnF_3$, the properties of the SW in which have already been studied,[4] and whose electronic and nuclear spin subsystems interact sufficiently strongly with each other. The lower branch of the SW spectrum in the case in which the external magnetic field **H** lies in the easy plane of the sample has the form

$$(\nu_k/\gamma)^2 = H^2 + H_\Delta^2/T_n + \alpha_\parallel^2 k_z^2 + \alpha_\perp^2 k_\perp^2, \tag{1}$$

where ν_k is the SW frequency, H is the external-magnetic-field intensity, T_n is the temperature of the nuclear spin subsystem, $\gamma = 2.8$ GHz/kOe is the gyromagnetic ratio, $H_\Delta^2 = 6.3$ kOe^2-deg is the hyperfine interaction constant, $\alpha_\perp = 0.95\times 10^{-5}$ kOe-cm and $\alpha_\parallel$ are the exchange constants, and k_z and $k_\perp$ are the components of the wave vector of the SW along and perpendicular to the high-order (z) axis.

2. MEASUREMENT PROCEDURE

To observe the SW scattering by the excitations of the nuclear subsystem, we employed the following measurement procedure based on the phenomena of parametric excitation of SW and NMR saturation. The SW relaxation rate $\Delta\nu$ was determined from the strength h_c of the threshold field for parametric SW excitation in the same way as was done in the investigations of Kotyuzhanskiĭ *et al.*[4,5]: h_c is the smallest amplitude of the magnetic field of the microwave pump at which a microwave-power absorption corresponding to the parametric excitation of SW can be observed. The quantities h_c and $\Delta\nu$ are directly proportional to each other:

$$h_c = \pi\Delta\nu/V_k. \tag{2}$$

 0038-5646/82/030551-06$04.00

The coefficient V_k for AFMEP has been computed by Ozhogin,[8] and depends on the parameters of the material, the external magnetic field, and the pump frequency. Pairs of spin waves with frequency equal to one half the pump frequency and oppositely directed wave vectors are excited with the aid of the parametric method. The magnitude of the wave vector is determined by the SW dispersion law and the condition $\nu_k = \nu_p/2$ for parametric resonance. Here ν_p is the pump frequency. In our experiments $\nu_p = 36$ GHz; in this case the parameteric excitation is possible in the magnetic-field-intensity range $0 < H < 6$ kOe, and the wave vector of the excited SW varies from 0 to 6.5×10^5 cm^{-1} as the magnetic-field intensity is varied.

Welsh[9] and Tulin[10] have shown that the nuclear system can, on account of the NMR saturation phenomenon, be substantially superheated with respect to the lattice with the aid of a radio-frequency field. In our experiments the nuclear spin system was heated up to temperatures of the order of 100 K, with the lattice temperature $T_l = 1.8$ K. After the radio-frequency field had been switched off, the nuclear subsystem cooled down to the temperature of the liquid-helium bath in characteristic time $T_1 \approx 1$ sec. The long spin-lattice relaxation time of the nuclear subsystem allows us to measure the rate of relaxation of the SW during the cooling of the nuclear subsystem.

The estimates presented below show that the superheating of the electronic spin subsystem and the lattice resulting from the flow of energy from the superheated nuclear subsystem is insignificant. This allows us to assume that, if a change is observed in the SW-excitation threshold when the nuclear subsystem is heated, it is due to the change that occurs in the SW-relaxation rate as a result of the interaction with only the excitations of the nuclear subsystem. The NMR frequency in an AFMEP depends on the temperature T_n of the nuclear subsystem in the following manner:

$$\nu_n(T_n) = \nu_0[H^2/(H^2 + H_\Delta^2/T_n)]^{1/2}, \qquad (3)$$

where ν_0 is the unshifted NMR frequency: $\nu_0 = 666$ MHz for $CsMnF_3$. Thus, by measuring the NMR frequency we can determine T_n.

Figure 1 shows a diagram of the setup that allowed us to simultaneously heat the nuclear subsystem and parametrically excite the SW. The microwave-pump field with amplitude $h \sim 1$ Oe was produced with the aid of a klystron-type oscillator in a cylindrical cavity. The crystal was placed at the antinode of the microwave magnetic field. For the purpose of producing the rf magnetic field that heated the nuclear subsystem and measuring the NMR frequency, we wound around the crystal two coils, one of which contained two turns and the other one turn. These coils were separately connected to the rf oscillators Γ1 and Γ2, which operated in the 300-800 MHz band. The constant magnetic field was applied in the easy plane of the sample, the microwave field was parallel to **H** (condition for parametric excitation of SW), and the rf magnetic fields produced by the oscillators *G*1 and *G*2 were perpendicular to **H** (condition for maximum absorption of the rf power by the nuclear subsystem). The relative change occurring in the excitation threshold h_c when the nuclear subsystem was heated was determined with the aid of a precision attenuator connected in the waveguide circuit. The attainment of the threshold power was inferred from the onset of microwave-power absorption in the sample, which manifested itself in the form of a characteristic chip on the oscillogram of a pulse of microwave power that had passed through the resonant cavity.

When the oscillator Γ1, tuned to a frequency ν^* lying between $\nu_n(T_l)$ and ν_0, is switched on, the nuclear system is heated to the temperature T_n^* at which $\nu_n(T_n^*) = \nu^*$. The heating of the nuclear system leads to apparent changes in the microwave power absorbed in the sample. Figure 2 shows a scheme of oscillograms of the transmitted microwave power in the case in which the oscillator *G*1 operates in the regime of long pulses of duration 1–2 msec and repetition interval 0.5 sec. At the moment 1 the oscillator *G*1 is switched on, and when its power is sufficiently high the excitation of SW ceases almost immediately. No absorption occurs in the section 1–2. Subsequently, a new parametric-excitation process develops: the chip for it is observed at the moment 2. Then a steady level of absorption is reestablished in the vicinity of the moment 3. At the moment 4, which corresponds to the end of the pulse from the oscillator *G*1, there occurs a small, but abrupt increase in the absorbed power, after which the absorption slowly varies, and returns after a time ~1 sec to the position corresponding to the level of absorption that obtains when the oscillator *G*1 is switched off. The actual oscillogram is shown below in Fig. 6.

The shape of the oscillogram of the microwave power can be explained as follows: The rapid superheating of the nuclear system leads to a shift of the SW spectrum according to the formula (1), because of which the SW

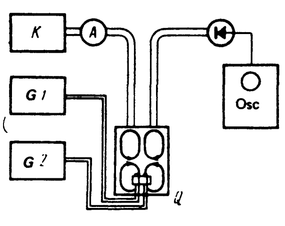

FIG. 1. Block diagram of the setup: *K*) klystron, *A*) precision attenuator, *G*1) and *G*2) rf oscillators, and *Q*) microwave resonant cavity.

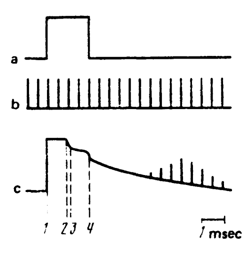

FIG. 2. Scheme of oscillator-power oscillograms: a) output power of *G*1; b) output power of *G*2; c) microwave power after it had passed through the resonant cavity.

excited before the commencement of the pulse from the oscillator $G1$ go out of parametric resonance with the microwave pump (the moment 1). Then another group of SW with frequency satisfying the condition for parametric resonance are excited. To this excitation corresponds the chip at the moment 2. The establishment at the moment 3 of an absorbed-power value smaller than the value in the initial state corresponds to an increase in the SW relaxation rate when the nuclear system is heated. The small abrupt increase occurring in the absorbed power at the end of the rf pulse (the moment 4) corresponds to the rapid switching off of part of the relaxation, this part being apparently due to the generation of nonequilibrium magnetoacoustic vibrations (see below). Then the level of absorption of the microwave power increases slowly as a result of the decrease of the SW relaxation rate as the nuclear system cools down. When T_n is slowly varied, the SW spectrum changes insignificantly over the SW lifetime (~1 msec); therefore, the condition for parametric resonance is always fulfilled after the moment 4.

To determine the NMR frequency during the heating and cooling of the nuclear subsystem, we used another oscillator $G2$ that operated in the regime of short pulses with length 1 μsec and a repetition rate of several kilohertz (Fig. 2b). Underlying the NMR-frequency measurement is the following phenomenon. When the frequency of the oscillator $G2$ coincides with the NMR frequency, a number of blips appear on the oscillogram of the transmitted microwave power at moments of time coinciding with the moments of operation of the oscillator $G2$. Figure 3 shows an oscillogram of one blip. To check precisely the coincidence of the NMR frequency and the frequency of the oscillator $G2$ at which blips appear on the oscillogram of the transmitted microwave power, we performed the following experiment. With the oscillator $G1$ switched off, we recorded on an X–Y recorder the magnetic-field dependence of a signal proportional to the radio-frequency power that was transmitted from one coil to the other and a signal proportional to the amplitude of the blips on the oscillogram of the microwave power. It turned out that the NMR and the response of the microwave pump occur at one and the value of the magnetic field. This allows us to assume that the blips on the oscillogram of the microwave power occur upon the fulfillment of the resonance conditions for the NMR.

The measurement of the NMR frequency during the cooling of the nuclear susbsystem was performed in the following manner. If the frequency ν_2 of the oscillator $G2$ is lower than the frequency ν^* of $G1$ [but $\nu^* > \nu_n(T_l)$], then blips appear on the oscillogram of the microwave power some time after the switching off of $G1$ (see Fig. 2c). It is clear that the blips of maximum amplitude occur at the moment when T_n is such that $\nu_n(T_n) = \nu_2$. When the frequency of the oscillator $G2$ is increased, the region of the oscillogram where the blips occur moves closer to the moment when $G1$ is switched off (the moment 4 in Fig. 2c); when it is decreased, the region moves away. Thus, to determine the NMR frequency at some moment of time, we must choose the frequency of the oscillator $G2$ such that the blips of maximum amplitude occur at that time. The value of T_n at that moment was subsequently determined from the known value of ν_n with the aid of the formula (3). This method of indicating NMR turned out to be effective right up to $T_n \approx 100$ K, whereas the sensitivity of the direct method (i.e., the method using the signal induced on the pickup coil) decreases rapidly with increasing T_n because of the decrease of the magnetization of the nuclear subsystem.

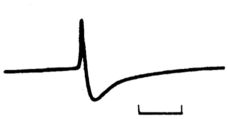

FIG. 3. Response of the parametrically excited spin waves to a pulse from the oscillator $G2$ when the conditions for NMR are fulfilled.

We suggest that the appearance of the blips on the oscillogram of the microwave power can be explained as follows. When the frequency of the oscillator $G2$ coincides with the NMR frequency, there occurs resonance absorption of the energy by the nuclear subsystem. This leads to the slight superheating of the subsystem and a shift of the SW spectrum in accordance with the expression (1). Then the parametrically excited SW go out of resonance with the pump, which is accompanied by a change in the absorbed power. In order to bring about such a response, the SW spectrum should shift by an amount of the order of the relaxation rate (i.e., by 0.1 MHz) over a period of time of the order of the magnon lifetime (1 μsec).[4,5] For this purpose, it is sufficient that we superheat the nuclear subsystem by an amount of the order of 10^{-2} K when $T_n = 10$ K. In order not to substantially superheat the nuclear system with the pulses of the detecting oscillator $G2$, it is necessary that the power of the pulses be as low as possible. That the nuclear subsystem was not superheated as a result of the action of the oscillator $G2$ was confirmed by the fact that no change was observed in T_n when the duration of the pulses of this oscillator was increased by a factor of two to three. For a more accurate measurement of the temperature we used a single measuring pulse of small amplitude. The accuracy of the measurement of the temperature was determined by the NMR-line width, which was ~2 MHz at all the nuclear temperatures. As can be seen from the formula (4), the error made in the determination of the nuclear temperature from the NMR-frequency measurements increases with increasing ν_n.

The measurements were performed in the following manner. With the aid of pulses from the oscillator $G1$ we periodically heated the nuclear system to some temperature and then cooled it. At moments of time not less than 1 msec from the ends of the $G1$ pulses, after selecting the appropriate value of the frequency of the oscillator $G2$, we measured the nuclear temperature, and, by establishing the microwave-power level at which the absorption ceased in the neighborhood of the moment in question, determined the relative change in the SW-excitation threshold.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 4 shows the dependence of the SW-relaxation rate on the temperature of the nuclear subsystem for different values of the magnetic field and lattice temperature. All the relaxation-rate values in Figs. 4a and 4b have been referred to $\Delta\nu_0$, the relaxation-rate value for $H = 2.62$ kOe and $T_l = 1.8$ K. These results indicate that, within the temperature range 1.8-8 K, the T_n-dependent part of the relaxation increases in proportion to T_n. Then this growth slows down, and in the range of T_n values from 40 to 100 K $\Delta\nu$ is practically constant.

First of all, it is necessary to explain why the SW-relaxation rate increase when the nuclear subsystem is heated. To begin with, let us deal with the question whether the increase in $\Delta\nu$ is not due to the trivial superheating of the crystal. Estimates of the superheating of the sample on account of the flow of energy from the nuclear subsystem to the lattice with the use of the known characteristics of the nuclear subsystem, the specific heat and the dimensions of the sample, as well as the clearly reduced thermal conductivity coefficient of the sample show that this superheating cannot exceed the amount $\Delta T = 10^{-2}$ K. Check experiments showed that a 10^{-2}-K increase in the sample temperature leads to a 2% increase in the relaxation rate. Such a superheating of the phonon and magnon systems cannot explain the observed increase in the SW-relaxation rate. The direct superheating of the sample by the radio-frequency power during the action of a heating pulse from the oscillator G1 was insignificant, since no response from the parametric SW was detected at a G1 frequency lower than $\nu_n(T_l)$ and higher than ν_0. Even if such superheating occurred, the sample should cool down within 0.1 msec.

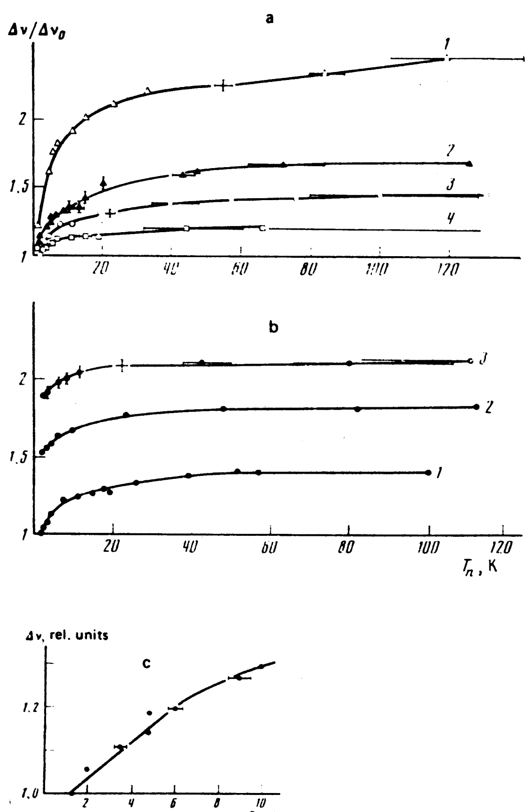

FIG. 4. Dependence of the SW relaxation rate on the temperature of the nuclear subsystem for: a) $T_l = 1.8$ K and different magnetic fields (in kOe): 1) 1.31, 2) 1.96, 3) 2.62, 4) 3.93; b) $H = 2.62$ kOe and different bath temperatures (in K): 1) 1.7, 2) 1.95, 3) 2.1. c) The initial section of the dependence 2 in Fig. 4a.

Thus, the observed increase in the SW relaxation rate is, from all appearances, due to the scattering of the SW by the nuclear subsystem. The scattering of the SW can occur on both the individual nuclear spins and the collective vibrations of the nuclear subsystem. The collective vibrations of the nuclear subsystem [nuclear spin waves (NSW)] arise as a result of the coupling of the nuclear spins to the ordered electronic spin system. These vibrations are another form of elementary excitations of the crystal. Their spectrum has the form[11]

$$\nu_{nk} = \nu_0 H (H^2 + H_\Delta^2/T_n + \alpha_\perp^2 k_\perp^2 + \alpha_\parallel^2 k_\parallel^2)^{-1/2}. \quad (4)$$

The dispersion of this spectrum at large k values is slight, and, consequently, the analysis of the wave excitations makes sense only for the long-wave part of the spectrum, i.e., for $k < k^*$. Turov and Petrov give in their monograph[11] an estimate for the limiting wave vector k^*: $|k^*| \approx H'\alpha$, so that in a field $H = 3$ kOe we have $k^* \approx 3 \times 10^5$ cm^{-1}. The excitations with wave vectors smaller than k^* can be treated as quasiparticles. The phase volume of the wave excitations is small: therefore, the contribution of these excitations to the total energy of the crystal at low temperatures is insignificant. At temperatures ~30 K the energy of all the wave excitations is comparable to the energy necessary for the total depolarization of the nuclear subsystem. Thus, it is incorrect to treat the nuclear spin waves as quasiparticles at $T_n \approx 30$ K. Notice that this temperature is a very rough estimate, since the value of k^* was estimated to within an order of magnitude. Furthermore, as pointed out in Ref. 11, the concept of long-wave excitations of the nuclear subsystem is meaningless at $T_n \sim 100-1000$ K, since the dispersion region $\nu_0 - \nu_n$ is comparable at such temperatures to the NMR line width.

The scattering of the SW by the individual magnetic moments of the nuclei cannot lead to a T_n dependence of $\Delta\nu$ as strong as the one observed in our experiment, since in this range of temperatures of the nuclear subsystem the number of nuclear spins directed along, and the number directed opposite to, the effective field of the hyperfine interaction differ by less than 1%. At the same time the number of wave excitations (NSW) increases in proportion to the temperature in accordance with the Bose distribution for $kT_n \gg 2\pi\hbar\nu_n$. Therefore, the acceleration of the SW relaxation with increasing T_n is due to the scattering by the NSW. As can be seen from the T_n dependence of $\Delta\nu$ shown in Fig. 4a, the relaxation rate due to the scattering of the SW by the NSW at $T_n = 1.8$ K constitutes ~10% of the total relaxation rate, i.e., is ~0.01 MHz. This estimate is obtained by extrapolating the linear part of the function $\Delta\nu(T_n)$ to $T_n = 0$.

As has already been noted above, the further growth of the number of wave excitations at high $T_n \gtrsim 20$ K makes no sense, since the equilibrium number of NSW would be enough for the complete depolarization of the nuclear subsystem. Furthermore, the entire dispersion region for the NSW spectrum is comparable at such temperatures to the NMR line width, which also deprives the NSW concept of any physical meaning. These circumstances apparently lead to the slowing down of the growth of the dependence of the SW relaxation rate on the nuclear temperature. But the quantity $\Delta\nu$, as T_n is increased further, does not return to the value characteristic of that state of the crystal in which the nuclear system contributes to $\Delta\nu$ only as a result of the scattering of the SW by the individual nuclear spins, but approaches a steady-state value. This result indicates that there exists at $T_n > 30$ K a relaxation mechanism that is no less effective that the one associated with the interaction with the NSW at $T_n = 10$ K. Apparently, this relaxation mechanism is connected with the scattering of the SW by the collective motions of the nuclear spins, which are correlated at small distances.

4. INVESTIGATION OF THE PROCESSES OF HEATING AND COOLING OF THE NUCLEAR SUBSYSTEM

The possibility of measuring T_n at any moment of time allows us to investigate the kinetics of the processes of heating and cooling of the nuclear subsystem. Figure 5 shows a characteristic oscillogram of the microwave power that passed through the resonant cavity during the action of the oscillator $G1$. The beginning of the sweep coincides with the moment at which $G1$ was switched on. The moment at which the oscillator was switched off lies beyond the limits of the sweep. The power level of the oscillator $G1$ established here is lower than in the case of the oscillograms in Figs. 2 and 6; therefore, the heating occurs slowly; over a period ~1 msec. The power level of the microwave pump was high enough to prevent the complete cessation of the parametric excitation. It can be seen from this oscillogram that there exists some dead time, during which no response of the SW occurs, followed by the smooth decrease of the absorbed power as a result of the increase of the relaxation rate.

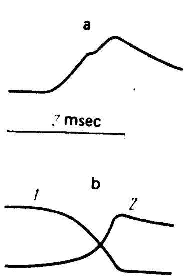

FIG. 5. Kinetics of the heating of the nuclear subsystem: a) oscillogram of the microwave power after it had passed through the resonant cavity; b) time dependence of the intensities of the NMR lines: 1) intensity of the line corresponding to $T_n = T_l$; 2) intensity of the line corresponding to $T_n(\nu^*)$.

Only two NMR frequencies existed during the heating. One frequency corresponded to $T_n = T_l$ and the second lay near the frequency of the oscillator $G1$, i.e., corresponded to the highest of the possible values of $T_n = T_n(\nu^*)$. There were no intermediate frequencies. Figure 5 also shows the variation of the NMR line intensity at these two frequencies. At first, there exists only one NMR line at the frequency corresponding to $T_n = T_l$, but it smoothly disappears, and a line corresponding to the heated nuclear system appears. The dead time decreases as the power of the oscillator $G1$ increases.

If the oscillator $G1$ is switched off at a moment when there are still two NMR lines, two lines are also observed during the cooling of the nuclei. The frequency of the NMR line corresponding to $T_n > T_l$ decreases, while the position of the line with the lower frequency remains unchanged. The threshold for parametric SW excitation has only one value during the time of existence of the two NMR lines.

The observed heating kinetics can be described within the framework of the hypothesis put forward by Witt and Portis,[12] and developed by Tulin.[13] According to this hypothesis, the heating begins in the vicinities of sample inhomogeneities of the "pinned spin" type. In these regions of the sample are localities where the NMR frequency coincides with the frequency of the rf oscillator (in our case this is the oscillator $G1$). At a sufficiently high power level of this oscillator a region absorbing the energy of the radio-frequency field begins to grow on account of the fact that the NSW excited in the vicinity of the inhomogeneity propagate into other regions of the crystal and superheat the nuclear subsystem there, as a result of which the NMR frequency in these regions changes until it becomes comparable to the frequency of the oscillator. From the fact that we do not observe NMR at frequencies lying between $\nu_n(T_l)$ and ν^*, whereas the sum of the intensities of the lines at the frequencies $\nu_n(T_l)$ and ν^* remains constant, we can conclude that the volume of those regions of the sample in which T_n has intermediate values during the entire heating process does not exceed 5% of the sample volume. This is explained by the low thermal conductivity of the nuclear subsystem, the heat-transfer processes in which do not have time to equalize the temperatures of neighboring regions in the crystal.

In fact, let us estimate the characteristic time of propagation of the energy of some superheated region of the nuclear subsystem over a distance of the order of the sample dimensions $l \approx 0.1$ cm. Excitation transfer through the nuclear subsystem occurs with the help of the NSW whose average velocity in the physically significant wave-vector range $0 < k < k^*$ is $v \approx 10^3$ cm/sec. The ability to propagate is possessed by only a part, equal roughly to $(k^*/k_{Br})^3 \sim 10^{-6}$ (where k_{Br} is the wave vector corresponding to the Brillouin-zone boundary), of the energy of the thermal excitation. Thus, even for an infinite NSW mean free path the characteristic time τ for temperature equalization over the distance l will be quite long:

$$\tau \approx (k_{Br}/k^*)^3 l/v \sim 10^2 \text{ sec}.$$

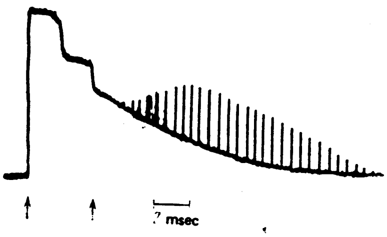

FIG. 6. Oscillogram, illustrating the method of determining $T_n(t)$, of the microwave power after it had passed through the resonant cavity.

It is clear that the relaxation of the local nuclear superheat to the lattice temperature will occur within this period.

As pointed out above in the description of the oscillogram scheme in Fig. 2, part of the SW relaxation (about 10% of $\Delta\nu_0$) is shut off within ~20 μsec after the oscillator $G1$ is switched off. This additional relaxation essentially depends on the power of $G1$. When $G1$ is switched off, there occurs, besides the decrease in the SW relaxation rate, an abrupt decrease, equal roughly to the NMR line width (~3 MHz), in the NMR frequency, which corresponds to a small but rapid increase in the magnetization of the nuclear system. Figure 6 shows an oscillogram, covering the period of action of the oscillator $G1$, of the microwave power after it has passed through the resonant cavity. The moments at which $G1$ was switched on and off are indicated by the arrows.

From the response of the microwave pump to the pulses of the oscillator $G2$, we established that the NMR frequency decreases rapidly for ~20 μsec after $G1$ has been switched off, and then the nuclear system slowly cools down in accordance with an exponential law for the quantity $1/T_n$ (the characteristic time of the exponential dependence ~0.5 sec). It is clear that part of the SW relaxation which is quickly shut off after $G1$ has been switched off is connected with some nonequilibrium excitations of the crystal that arise under the action of the rf field. It is possible that, besides heating the nuclear spin subsystem, the pulses of the oscillator $G1$ excite magnetoacoustic waves. As has been pointed out by Tulin,[14] these waves can be excited as a result of the nonlinear process in which two photons are converted into two magnetoacoustic waves with opposite wave vectors.

Thus, we have detected in the present investigation an effect of the nuclear spin subsystem of an antiferromagnet on the relaxation of spin waves, and separated out the contribution of the nuclear spin waves to the scattering of the spin waves of the electronic subsystem. It turned out that, in the temperature range 1.8–8 K, this contribution increases in proportion to the temperature. At higher temperatures, the dominant relaxation mechanism is apparently the mechanism connected with the collective nuclear-spin motions, which are correlated at small distances. We have studied the kinetics of the heating of the nuclear spin subsystem by a radio-frequency field. The principal characteristic of this heating process is the fact that the volume of the region with intermediate values of T_n is small compared to the volumes of the regions with the highest and lowest possible temperatures.

The authors are grateful to P. L. Kapitza and A. S. Borovik-Romanov for interest in the work, L. A. Prozorova for valauble advice and for a discussion of the results, and S. O. Gladkov, V. S. Lutovinov, V. A. Tulin, and Yu. M. Bun'kov for interesting discussions.

[1]V. G. Bar'yakhtar, V. S. Lutovinov, O. A. Ol'khov, and V. L. Sobolev, Fiz. Nizk. Temp. **2**, 1466 (1976) [Sov. J. Low Temp. Phys. **2**, 718 (1976)].

[2]V. S. Lutovinov, Fiz. Tverd. Tela (Leningrad) **20**, 1807 (1978) [Sov. Phys. Solid State **20**, 1044 (1978)].

[3]V. G. Bar'yakhtar and V. L. Sobolev, Fiz. Tverd. Tela (Leningrad) **19**, 3092 (1977) [Sov. Phys. Solid State **19**, 1807 (1977)].

[4]B. Ya. Kotyuzhanskiĭ and L. A. Prozorova, Zh. Eksp. Teor. Fiz. **65**, 2470 (1973) [Sov. Phys. JETP **38**, 1233 (1974)].

[5]V. V. Kveder, B. Ya. Kotyuzhanskiĭ, and L. A. Prozorova, Zh. Eksp. Teor. Fiz. **63**, 2205 (1972) [Sov. Phys. JETP **36**, 1165 (1973)].

[6]G. A. Melkov, Fiz. Tverd. Tela (Leningrad) **17**, 1728 (1975) [Sov. Phys. Solid State **17**, 1123 (1975)].

[7]A. I. Smirnov, Zh. Eksp. Teor. Fiz. **73**, 2254 (1977) [Sov. Phys. JETP **46**, 1180 (1977)].

[8]V. I. Ozhogin, Zh. Eksp. Teor. Fiz. **58**, 2079 (1970) [Sov. Phys. JETP **31**, 1121 (1970)].

[9]L. B. Welsh, Phys. Rev. **156**, 370 (1967).

[10]V. A. Tulin, Zh. Eksp. Teor. Fiz. **55**, 831 (1968) [Sov. Phys. JETP **28**, 431 (1969)].

[11]E. A. Turov and M. P. Petrov, Yadernyĭ magnitnyĭ rezonans v ferro- i antiferromagnetikakh (Nuclear Magnetic Resonance in Ferro- and Antiferromagnets), Nauka, Moscow, 1969, pp. 96–97 (Eng. Transl., Wiley, New York, 1972).

[12]G. L. Witt and A. M. Portis, Phys. Rev. **136**, 1316 (1964).

[13]V. A. Tulin, Dissertatsiya na soiskanie uch. step. kandidata fiz.-mat. nauk (Dissertation for the Degree of Candidate of the Physico-Mathematical Sciences), Institute of Physical Problems, Academy of Sciences of the USSR, Moscow, 1970.

[14]V. A. Tulin, Zh. Eksp. Teor. Fiz. **78**, 149 (1980) [Sov. Phys. JETP **51**, 73 (1980)].

Translated by A. K. Agyei