Inhomogeneous state of a system of parametrically excited nuclear spin waves

S. A. Govorkov and V. A. Tulin

Institute of Solid State Physics, USSR Academy of Sciences
(Submitted 8 February 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 6, 345–349 (20 March 1978)

Using the dependence of the position of the antiferromagnetic-resonance line on the temperature of the nuclear magnetic system in $MnCO_3$, we investigated the state of the nuclear magnetic system at a different level of parametric excitation of the nuclear spin waves. It is shown that the additional increase of the above-threshold susceptibility is due to a finite change of the temperature of the nuclear system. The distribution of the nuclear temperature (the concentration of the nuclear spin waves) in the sample is inhomogeneous in a wide range of variation of the pump-field amplitude.

PACS numbers: 75.30.Ds, 76.50.+g

We have shown in a preceding paper[1] that at a large supercriticality the nonlinear susceptibility of excited nuclear spin waves (NSW) exhibits a rather complicated behavior. Its foremost manifestation is a threshold-dependent growth of the susceptibility, which was treated in [1] as excitation of magnetoelastic waves. In the present paper we investigate the behavior of the temperature of a nuclear magnetic system at different degrees of parametric excitation of NSW. We make use of the fact that the frequency of the antiferromagnetic resonance (AFMR), for antiferromagnets with strong hyperfine interaction, depends on the degree of magnetization of the nuclear magnetic system.[2,3] Heeger, Portis, *et al.*[2] have shown that the saturation of the nuclear magnetic resonance (NMR) in antiferromagnetic $KMnF_3$ affects effectively the position of the AFMR line. A similar phenomen in the $MnCO_3$ investigated in the present paper was studied in detail in [4].

The $MnCO_3$ sample was placed in a helical resonator with natural frequency $f_r \approx 1150$ MHz. Alongside the helical resonator was placed a strip excited at the AFMR observation frequency ($f = 9.43$ GHz). The investigations were carried out at a temperature 1.4 K.

Figure 1 shows a set of absorption curves for AFMR at different values of the excitation power of the NSW at 1150 MHz. At power level above the threshold of the parametric excitation of the NSW, a small displacement of the AFMR line is observed (compare the curves marked $-\infty$ and -19.2 dB). When the second threshold is exceeded (after the additional growth of the post-threshold susceptibility of the NSW) the AFMR line broadens strongly and acquires a doublet structure. One of the lines corresponds to the old position of the AFMR, and the other broader one is shifted towards stronger magnetic fields (-15.7 and -15 dB). Further increase of the power leads to a transfer of the entire AFMR intensity into the displaced line and to motion of the displaced line towards a stronger magnetic field (10 dB). The next

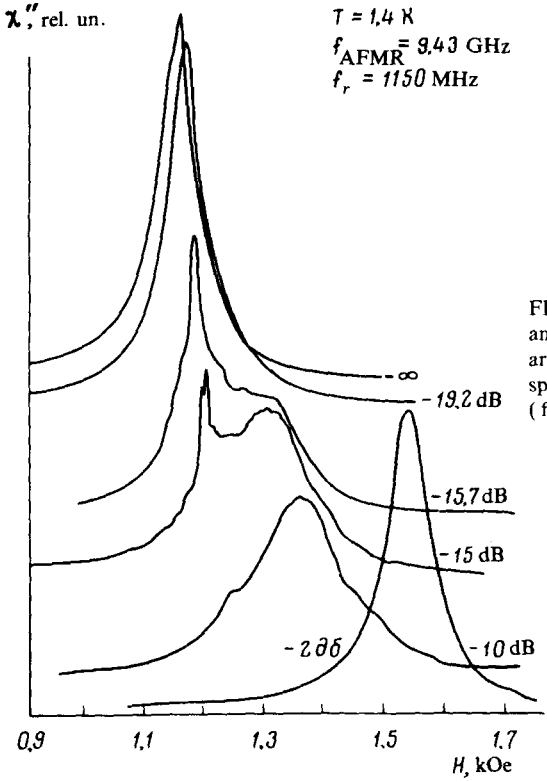

FIG. 1. Absorption curves in $MnCO_3$ sample at antiferromagnetic resonance, for different nuclear spin wave excitation power levels. 0 dB corresponds to 1 watt at a frequency of 1150 MHz (field amplitude $\tilde{h}=40$ Oe).

stage in the increase of power leads to a narrowing of the AFMR line and to stabilization of its position (the -2 dB curve).

In parallel with the study of the temperature of the nuclear system, we observed the post-threshold susceptibility in the system of parametrically excited NSW. Figure 2 shows the imaginary part of the susceptibility at the 1150 MHz for two values of the power. The lower curve corresponds to NSW excitation at low power levels and to a weak shift of the position of the AFMR line. The upper curve is a plot of $\chi''(H)$ for power above the second threshold. The broad AFMR line in the intermediate position corresponds to a state with a susceptibility to the left of the maximum, marked by the arrow. With increasing pump power this maximum shifts towards weaker magnetic fields.[1] When the position of the maximum reaches the values of the field of the displaced AFMR line, the line becomes narrower and its position becomes stabilized.

The experimentally observed AFMR broadening shows that a power above the second threshold a spatially-inhomogeneous distribution of the temperature of the nuclear magnetic system (or an inhomogeneous concentration of the parametrically excited NSW) is produced in the sample. The spectrum of the NSW in $MnCO_3$ is described by the following relation[5]

$$f_{nk}^2 = f_{n0}^2\left(1 - \frac{\gamma_e^2 H_{\Delta_0}^2/T'}{\gamma_e^2[H(H+H_D)+H_{\Delta_0}^2/T'] + v^2k^2}\right), \qquad (1)$$

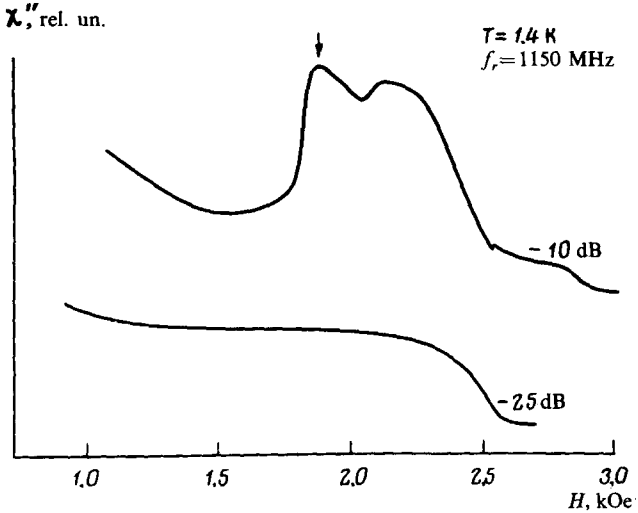

FIG. 2. Plot of the post-threshold susceptibility $\chi''(H)$ of the nuclear magnetic system. The -20 dB curve corresponds to excitation of nuclear spin waves with small amplitude. The -7.6 dB curve corresponds to excitation of spin waves through a level above the additional increase of the susceptibility (the values of χ'' are shown not to scale).

where the denominator is the spectrum of the low-frequency branch of the antiferromagnetic spin waves, γ_e is the magnetomechanical ratio for the electron, $H_D=4.4$ kOe is the effective Dzyaloshinskiĭ field, H is the external magnetic field $H_{\Delta_0^2/T}$, is the gap in the AFMR spectrum due to the hyperfine interaction, ($H_{\Delta_0^2}=5.8$ kOe^{2}C), T' is the temperature of the nuclear magnetic system, $f_{n0}=640$ MHz is the NMR frequency in the absence of dynamic coupling, v is the velocity of the antiferromagnetic spin waves, and k is the wave vector.

In parametric excitation of NSW at small power levels, this equation describes the connection between the wave vector of the excited spin wave and the external magnetic field at $f_{nk}=f_r/2$. At a sufficiently high power level, when the number of excited NSW is large ($T'\neq T_{\text{bath}}$) and at a definite value of the magnetic field, this equation gives the connection between the temperature T' of the nuclear system and the wave vector k. In contrast to NMR ($k=0$), where there is only one value of T' satisfying this equation in any given field weaker than the NMR field, in the case of NSW this equation gives the functional relation between T' and k. Realization of any particular state in the NSW system is determined by the pump power and by the behavior of the NSW relaxation rate η on the set of values of T' and k connected by Eq. (1).

The rate of relaxation of the NSW in $MnCO_3$, as determined in [6], is given by

$$\eta = akT \tag{2}$$

for a temperature lower than 3 K, where a is a certain constant. If we assume that $T\equiv T'$ in (2), then the value of η for T' and k connected by Eq. (1) has a maximum at $k=\dfrac{\sqrt{\gamma_e^2 H(H+H_D)}}{v}$ (or at the corresponding value of T'). Further decrease of k, owing to the heating of the system, will lead to a decrease of the relaxation rate

and this will cause at a certain instant of time an avalanche-like growth of the NSW. The nuclear magnetic system will then go over into a new state with a higher temperature determined by the sample irradiation power. This corresponds to the second threshold in the parametric excitation of NSW.[1] If the pump power is insufficient to heat the nuclear magnetic system to the temperature T' corresponding to the minimal relaxation rate in the entire sample, then an inhomogeneous distribution the nuclear magnetic temperature sets in.

For the magnetic field values $2H_r(H_r+H_D)>2H(H+H_D)>H_r(H_r+H_D)$, where H_r is the NMR field at the frequency $f_r/2$, the increase of the nuclear-system temperature [with decreasing wave vector, in accordance with the connection in Eq. (1)] leads to a monotonic decrease of the NSW relaxation rate. In this range of fields, the state of the system is determined only by the irradiation power, and the process develops continuously. Thus, observation of the nuclear spin temperature in parametric excitation of NSW has shown that the second threshold observed in [1] corresponds to a finite change of the nuclear spin system temperature. The NSW wave vector decreases in this case and falls in the spectral region where the phonon branches are crossed, leading to a characteristic behavior of the susceptibility. In a large range of the alternating-field amplitude, there exists a spatially inhomogeneous temperature distribution. Whether this is static or dynamic is not yet clear.

[1]S. A. Govorkov and V. A. Tulin, Zh. Eksp. Teor. Fiz. **70**, 1876 (1976) [Sov. Phys. JETP **43**, 977 (1976)].
[2]A. J. Heeger, A. M. Portis, Dale T. Teaney, and G. Witt, Phys. Rev. Lett. **7**, 307 (1961).
[3]P. G. de Gennes, P. Pincus, E. Hartman-Boutron, and T. M. Winter, Phys. Rev. **129**, 1105 (1963).
[4]V. A. Tulin, Zh. Eksp. Teor. Fiz. **55**, 831 (1968) [Sov. Phys. JETP **28**, 431, (1969)].
[5]E. A. Turov and V. T. Kuleev, Zh. Eksp. Teor. Fiz. **49**, 248 (1965) [Sov. Phys. JETP **22**, 176 (1966)].
[6]S. A. Govorkov and V. A. Tulin, Zh. Eksp. Teor. Fiz. **73**, 1053 (1977) [Sov. Phys. JETP **46**, 558 (1977)].