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1994 J. Phys.: Condens. Matter 6 8051

(http://iopscience.iop.org/0953-8984/6/39/024)

J. Phys.: Condens. Matter 6 (1994) 8051–8063. Printed in the UK

Detection of UHF sound in the antiferromagnet $FeBO_3$ by a SQUID magnetometer

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Received 17 January 1994, in final form 13 May 1994

Abstract. The effect of ultra-high-frequency sound on the magnetic moment of an antiferromagnet with strong magnetoelastic interaction is studied. Quasiphonons of frequency ~ 1 GHz were excited by an external piezotransducer or by a microwave field. At liquid nitrogen temperatures the total magnetic moment of the sample is found to decrease with increasing number of quasiphonons, whereas at liquid helium temperatures the magnetic moment increases. This increase can be considered as an effect of dynamic polarization induced by hypersound excitation, which is observed for the first time. The dynamic polarization can be explained in terms of a three-particle process: a quasiphonon and a quasimagnon are annihilated and a new quasimagnon with smaller magnetic moment is created.

1. Introduction

The elementary excitations of an elastic solid are phonons, and those of an ordered magnetic system are magnons. Magnetoelastic interactions give rise to a coupling of magnetic and elastic oscillations. The resulting normal modes (quasimagnons and quasiphonons) contain both magnetic and elastic components. This means that such quasiparticles can be excited, in principle, by either an alternating magnetic field or by elastic vibrations. Magnetoacoustics, a science devoted to the study of coupled magnetoelastic excitations, has been one of the developing directions in research on magnetic solids since the 1950s, and the state of the art has been reviewed in several articles (LeCraw and Comstock 1965, Bar'yakhtar and Turov 1988, Ozhogin and Preobrazhenskii 1988, 1990).

In the present paper we study the possibility of the magnetic detection of elastic vibrations in a crystal with a strong magnetoelastic interaction. $FeBO_3$, an antiferromagnet with easy-plane anisotropy and a high Néel temperature ($T_N = 348$ K) is one of the most convenient objects for this purpose. It has rhombohedral crystalline symmetry with the C_3 axis perpendicular to the easy plane. The magnetoelastic phenomena in $FeBO_3$ give rise to the so-called exchange enhancement.

The excitation of non-equilibrium quasiphonons is accompanied by non-uniform magnetic oscillations, which can be detected through their radiation field. The sensitivity of this method rapidly decreases with increasing quasiphonon wavevector and depends on the quality of the sample surface. Such a type of detection was usually used in the frequency range 1–100 MHz. In our experiments we detected non-equilibrium quasiphonons by measuring the change of the *total magnetic moment* of the sample. An analogous method was used for investigations of non-equilibrium electronic magnons (Kotyuzhanskii

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and Prozorova 1983, Svistov 1991) and nuclear magnons (Svistov *et al* 1993). Here we develop a method for detecting ultra-high-frequency phonons in the 1 GHz range, where detection with standard piezo or magnetoacoustic resonance techniques is difficult. The method is based on the fact that a single quasiparticle has a magnetic moment

$$\mu_k = -\partial\varepsilon_k/\partial H \tag{1}$$

where ε_k is the energy of a quasiparticle with wavevector k and H is the external magnetic field.

The spectra of low-frequency quasimagnons (ω_k) and quasiphonons (Ω_k) in $FeBO_3$ have the form

$$\omega_k = \gamma[H(H + H_D) + H_\Delta^2 + (\alpha k)^2]^{1/2} \tag{2}$$

$$\Omega_k = c_e k[1 - (\gamma H_\Delta \xi/\omega_k)^2]^{1/2} \tag{3}$$

where $\gamma = g\mu_B/\hbar = 17.8 \times 10^9\,s^{-1}\,kOe^{-1}$ is the gyromagnetic ratio, $H_D \simeq 100\,kOe$ is the Dzyaloshinskii field, γH_Δ is the so-called magnetoelastic gap in the spin-wave spectrum (Borovik-Romanov and Rudashevskii 1964, Turov and Shavrov 1965) with $H_\Delta \simeq 2.2\,kOe$, and $\alpha \simeq 0.8 \times 10^{-3}$ Oe cm is the phenomenological exchange constant, which is proportional to the exchange field $H_E = 2.6 \times 10^6$ Oe. The sound velocity c_e and the coefficient ξ describing the efficiency of the linear interaction between magnons and phonons depend on the direction of the wavevector and polarization of the quasiphonon, and are well known for $FeBO_3$ (see, for example, Andrienko *et al* 1992). Here we will focus on transverse quasiphonons with wavevector in the C_3 direction and polarization parallel to $\boldsymbol{H}$, which are most strongly coupled to the magnons. Their parameters are $c_e \simeq 4.8 \times 10^5\,cm\,s^{-1}$ and $H_\Delta\xi \simeq 2\,kOe$ (Seavey 1972, Kotyuzhanskii *et al* 1983). The spectra of quasimagnons and quasiphonons are shown in figure 1.

Substituting (2) and (3) into (1), we easily obtain the magnetic moments of a quasimagnon and a quasiphonon, respectively:

$$\mu_{m,k} = -\hbar\gamma^2\frac{(2H + H_D)}{2\omega_k} \tag{4}$$

$$\mu_{ph,k} = \frac{(c_e k)^2}{\Omega_k \omega_k}\left(\frac{\gamma H_\Delta \xi}{\omega_k}\right)^2 \mu_{m,k}. \tag{5}$$

The dependencies of $\mu_{m,k}$ and $\mu_{ph,k}$ on ω_k and Ω_k, respectively, are shown in figure 2.

Note that the magnetic moment of a quasiphonon rapidly decreases in the high-frequency range (i.e. for large wavevectors). As a consequence the total magnetic moment corresponding to thermal quasiphonons at temperatures $T > 1$ K is negligibly small. A quantitative estimate of the sensitivity for the detection of quasiphonons can be obtained from the formula

$$\Delta M = \sum_k \mu_{ph,k}(n_{ph,k} - n_{ph,k}^{(0)}) \simeq \mu_{ph,k_1} P_a \tau_{ph,k_1}/\hbar\Omega_{k_1} \tag{6}$$

where $n_{ph,k}$ and $n_{ph,k}^{(0)}$ are the non-equilibrium and thermal (equilibrium) populations of quasiphonons, respectively, P_a is the power absorbed by quasiphonons in the sample and τ_{ph,k_1} is the lifetime of an excited quasiphonon. Taking $H = 100$ Oe, $\Omega_{k_1}/2\pi = 1$ GHz, $\tau_{ph,k_1} \sim 1\,\mu s$ and $P_a = 1$ mW, one obtains a change of magnetic moment $\Delta M \simeq -10^{-5}\,G\,cm^3$.

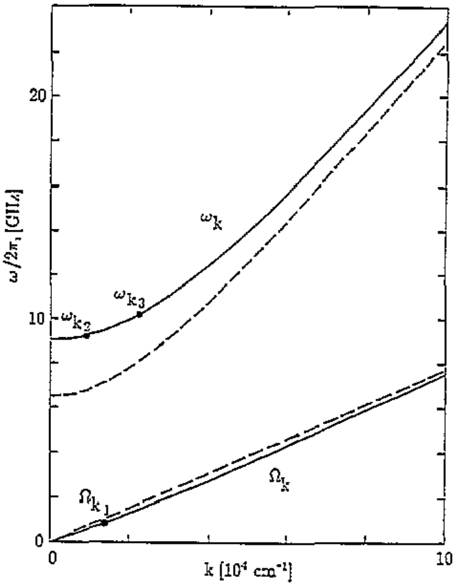

Figure 1. Quasimagnon and quasiphonon branches in $FeBO_3$ at $H = 50$ Oe. Broken curves show magnon and phonon branches without a magnetoelastic interaction. The bullets indicate a three-quasiparticle process ph + m → m ($\Omega_{k_1} + \omega_{k_2} = \omega_{k_3}$, $k_1 + k_2 = k_3$).

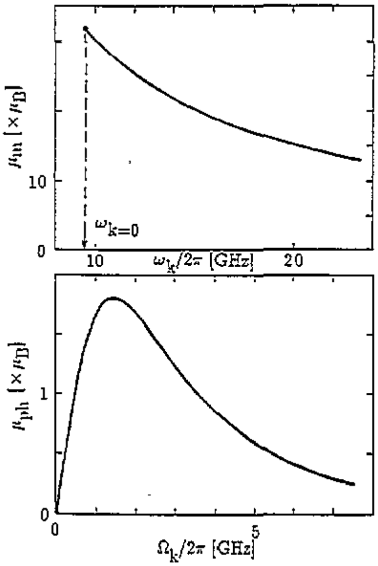

Figure 2. Magnetic moment of (*a*) quasimagnons and (*b*) quasiphonons at $H = 50$ Oe.

2. Experimental technique

In order to measure the change of magnetic moment induced by the microwave field we built a wide-band microwave spectrometer combined with a standard SQUID magnetometer (see figure 3). The device was designed to work in the frequency range from 100 kHz to 6 GHz, at temperatures from 1.4–300 K and in magnetic fields up to 500 Oe. The flux transformer was of the gradiometer type to reduce external noise. This flux transformer and the SQUID cell were placed inside a liquid helium bath at 4.2 K. The static magnetic field $\boldsymbol{H}$ was applied by a superconducting solenoid operating in persistent mode. For the thermal isolation of the sample a metal dewar was placed inside the flux transformer. The dewar also served as a screen for the microwave fields allowing high frequency (HF) and ultra-high-frequency (UHF) excitation to be applied to the sample without affecting the operating point of the SQUID. For the reduction of external noise additional superconducting screens were used. The change of the total magnetic moment was measured with an accuracy of 5×10^{-7} G cm^3. The experiments were performed at liquid nitrogen (77 K) and liquid helium (1.4–4.2 K) temperatures. In order to obtain good thermal contact, the samples were immersed into the coolant bath.

The $FeBO_3$ single crystal was a small platelet of $0.8 \times 2 \times 3$ mm^3 with the largest natural dimensions corresponding to the magnetic easy plane. From the field dependence of the magnetic moment $M(H)$ we checked that the sample was in the monodomain state for $H > 80$ Oe. However, it is possible to obtain a monodomain state at lower magnetic fields by cooling the sample in the presence of a stronger magnetic field, which is afterwards decreased.

The quasiphonons were excited either elastically by means of a piezotransducer (see the

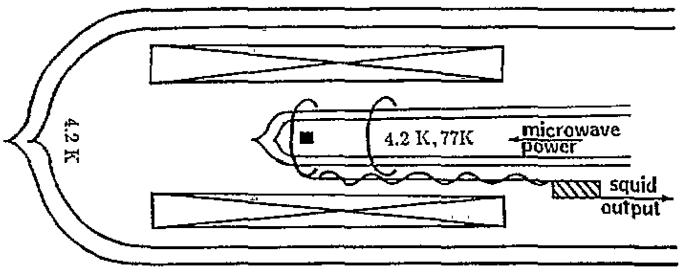

Figure 3. Scheme of the low-temperature part of the measuring device.

insert in figure 4) or magnetically by a microwave field with the help of a helix resonator (see the insert in figure 5). In the first case the $FeBO_3$ sample was glued on the surface of a $LiNbO_3$ piezotransducer designed for the excitation of transverse phonons. The orientation of the static magnetic field $\boldsymbol{H}$, the polarization e of the excited phonons, the crystal axis C_3 and the measured projection of ΔM are shown in figure 4. The amplitude of ΔM sensitively depends on the efficiency of the transducer. Comparing the data for ΔM with those for the UHF power P_r reflected by the transducer and detected by a diode, we found that there is an amplification of ΔM at the acoustic resonance frequencies of the transducer, as indicated by the inverted peaks in P_r (see figure 4). Varying the magnetic field H, we observed a pronounced change of ΔM and practically no change of P_r. From this we conclude that the elastic coupling between the transducer and the sample is weak enough to avoid a marked feedback of the response of the sample to the source of excitation. Thus, qualitatively we are confident that the observed change of magnetic moment is due to the excitation of quasiphonons. However, a quantitative evaluation of the power of phonon flux transmitted to the $FeBO_3$ crystal is complicated because of unknown contact losses.

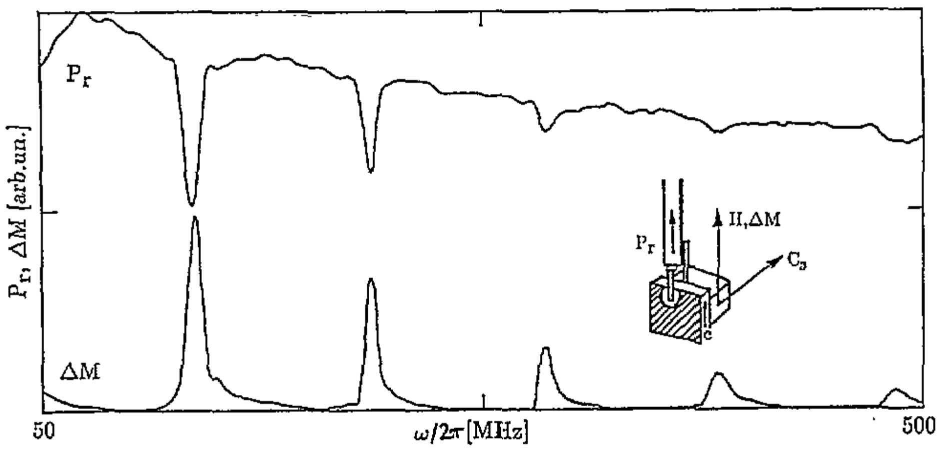

Figure 4. Power P_r reflected from the transducer and observed change of magnetic moment ΔM as a function of the excitation frequency $\nu = \omega/2\pi$. Peaks correspond to acoustic resonances inside the piezotransducer. The orientation of the magnetic field $\boldsymbol{H}$, the polarization e of excited phonons, the crystal axis C_3 and the measured projection of ΔM are shown in the insert.

In the second case, magnetic excitation was used to determine the obtainable sensitivity for phonon detection. Quasiphonons were directly excited in the $FeBO_3$ sample by means of

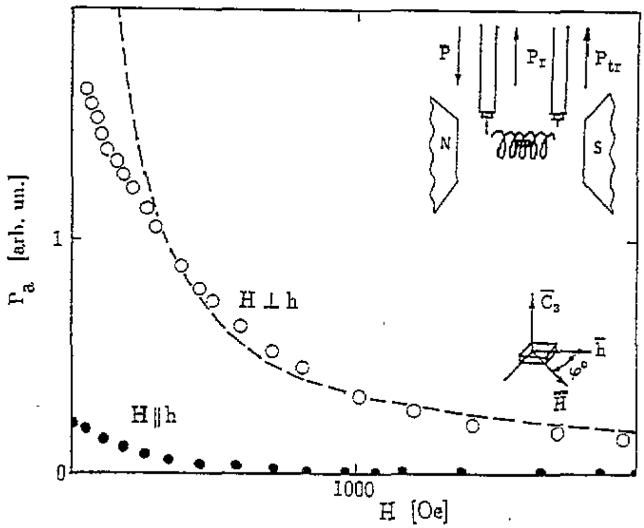

Figure 5. Magnetic field dependencies of absorbed power P_a for parallel ($h \parallel H$) (•) and perpendicular ($h \perp H$) (○) microwave pumping, $T = 4.2$ K, and $\Omega_k/2\pi = 900$ MHz. Dashed line denotes the theoretical course. The orientation of static magnetic field H, microwave field h and crystal axis C_3 is shown in the insert.

the microwave field. The orientations of the static field H and the microwave field $h(t)$ with respect to C_3 were chosen in a way to support the most efficient excitation of phonons of the same polarization and wavevector as in the experiments with piezotransducers (Seavey 1972, Kotyuzhanskii *et al* 1983).

So far, magnetic excitation of acoustic resonances has been reported only for very thin platelets of $FeBO_3$ up to frequencies of 800 MHz (Wettling *et al* 1980). In our largest sample we did not observe such resonances, probably because of their small frequency spacings. But from the microwave power transmitted (P_{tr}) and reflected (P_r) by the sample and from the parameters of the resonator we calculated the power P_a absorbed in the crystal. In figure 5 we have compared the observed field dependencies of P_a at constant transmitted power P_{tr} (i.e. at constant amplitude h of the microwave field) for two different configurations $h \parallel H$ and $h \perp H$. We found the following.

(i) The configuration $h \perp H$ shows a much stronger absorption, which results from a linear coupling of the alternating magnetic field with magnetoelastic oscillations. Such a coupling does not exist for the configuration $h \parallel H$.

(ii) P_a is proportional to P_{tr} in the low-power regime. This linear dependence and the strong anisotropy of P_a on the magnetic field at all temperatures (1.4–4.2 K, 77 K) support our supposition that P_a arises from the resonant excitation of quasiphonons (i.e. the system of quasiphonons is below the threshold of their parametric resonance).

(iii) P_a decreases with increasing magnetic field. This fact is in agreement with theoretical results of Evtikhiev *et al* (1981) (see the broken curve in figure 5) obtained for standing acoustic waves.

Therefore, we assume that all UHF power absorbed in the sample is due to the direct excitation of quasiphonons.

3. Experimental results

The excitation of phonons by means of the piezotransducer leads to a distinct change of the magnetic moment. Taking advantage of the increased sensitivity, we have measured ΔM on the top of the second harmonic of the acoustic resonance (140 MHz) of the transducer. The change of the magnetic moment on variation of the generator output power P at 4.2 K and 77 K is shown in figure 6. At low powers ($P < 10$ mW) we observed a linear dependence of ΔM on P within the range of static magnetic field investigated. At high powers we observed a saturation, which indicates a non-linear relaxation process of excited quasiphonons.

The change of magnetic moment at 77 K has a negative sign, as expected. However, at 4.2 K, to our surprise, ΔM shows a positive sign. This may mean that we observed a novel type of *dynamic polarization* process.

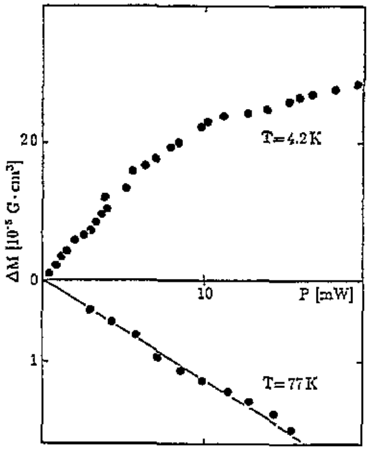

Figure 6. Dependence of the change of magnetic moment ΔM on the generator output power P at 4.2 K and 77 K ($H = 0.3$ kOe). The experimental configuration is shown in figure 5.

In order to calibrate the sensitivity of phonon detection by measuring ΔM we have excited quasiphonons directly in the sample by means of a microwave field of amplitude h. In figure 7 the transmitted power P_{tr} (at $H = 0.3$ and 5 kOe) and the change of magnetic moment ΔM (at $H = 0.3$ kOe) are shown in the vicinity of the resonance frequency (882 MHz) of the helix resonator. The P_{tr} data at 5 kOe were obtained in order to estimate the losses of the 'pure' resonator, where the excitation level of magnetoelastic waves is negligible (see (5) and figure 5). Thus the change of P_{tr} is proportional to the losses in the crystal. We found that a phonon flux of $P = 1$ mW leads to a change of magnetic moment of $-(1.2\pm0.5)\times10^{-5}$ G cm^3 at 77 K and of $+(5\pm1)\times10^{-5}$ G cm^3 at 4.2 K ($H = 0.5$ kOe). This means that the experiment allows detection of a phonon flux of 10 μW. Analogous experiments were performed in different resonators with resonance frequencies from 600–900 MHz. We obtained the same sensitivity within the experimental accuracy.

Figure 8 shows the field dependence of ΔM at a constant power of the phonon flux. The data were obtained by the methods of quasiphonon excitation mentioned above. In the case of elastic excitation the condition of constant phonon flux means constant power of the UHF generator, in the case of magnetic excitation this condition means constant absorbed power P_a (= 1 mW). For piezomeasurements ΔM is given in arbitrary units. Both methods show the reversal of the sign of ΔM, when the temperature is changed from 77 K to 4.2 K, and (within the experimental accuracy) the same magnetic field dependencies. This means

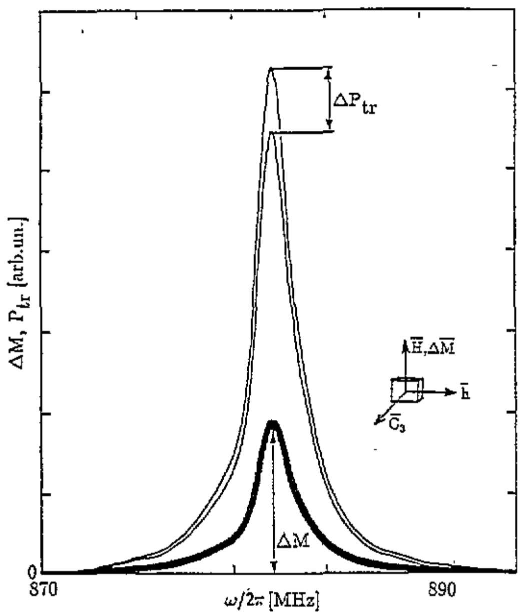

Figure 7. Transmitted power P_{tr} (lower curve: 0.3 kOe; upper curve: 5 kOe) and the change of magnetic moment (at 0.3 kOe) near the resonance of the helix resonator. The geometry of the experiment is presented in the insert.

that at a certain temperature between 77 K and 4.2 K ΔM has to vanish, but we did not study this range in detail.

In order to estimate the sensitivity of phonon detection in the frequency range 1–2.5 GHz we have used a microcoil (instead of a helix resonator) for the magnetic excitation of UHF magnetoelastic waves in the sample of $FeBO_3$ (see the insert in figure 9). This way a broad-band UHF excitation of quasiphonons could be obtained, but the microwave amplitude h inside the sample remained undefined. Figure 9 shows the frequency dependence of ΔM for the constant magnetic field H and constant UHF generator output power. The oscillations of ΔM are attributed to cable resonances in the feeding coaxial line. Although only qualitative, this experiment proves that $FeBO_3$ crystals can be used efficiently for generation and detection of phonons up to 2.5 GHz (and probably to higher frequencies).

4. Discussion

Consider first the results obtained at liquid nitrogen temperature. Using the data of figure 8(a) and equation (6), we can estimate the lifetime of the excited quasiphonons ($\Omega_k/2\pi$ = 882 MHz). Figure 10 shows the magnetic field dependence of the inverse lifetime of these quasiphonons. For comparison, the results obtained by Andrienko and Podd'yakov (1989) from parallel-pumping experiments in $FeBO_3$ for quasiphonons with $\Omega_k/2\pi$ = 570 MHz are also shown. One can see that these two different methods give reasonable agreement, both in the order of magnitude and in the character of the field dependence. The difference in the frequencies of the excited quasiphonons seems not to be extremely significant as far as the relaxation rate of UHF sound according to parallel-pumping experiments (Andrienko and Podd'yakov 1991) has a linear dependence on Ω_k, and the magnitude of τ_{ph}^{-1} depends on the quality of the sample. Thus, in addition to detection, our method can be used for the investigation of the lifetime of excited quasiphonons at high temperatures.

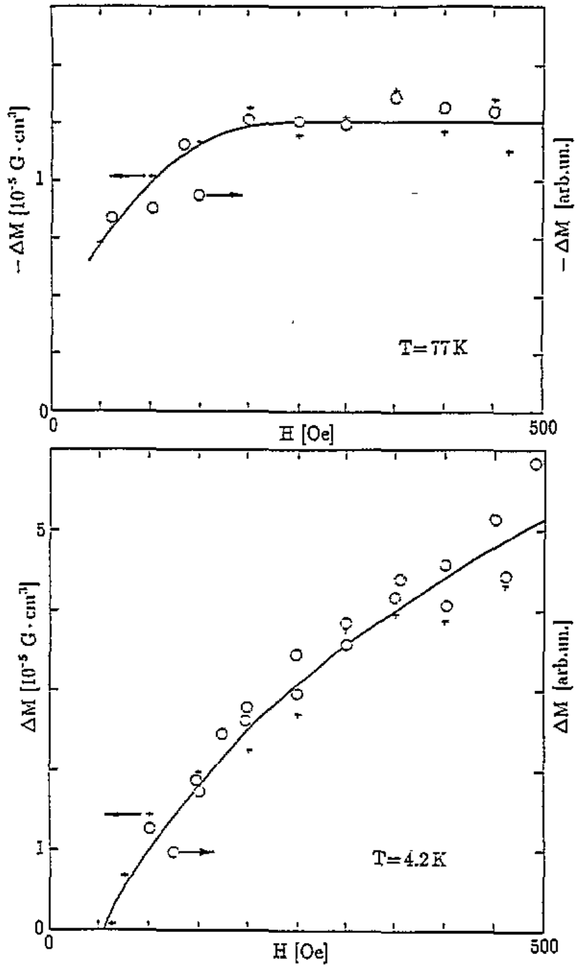

Figure 8. Dependence of the change of magnetic moment on the static magnetic field (*a*) at 77 K, and (*b*) at 4.2 K. Data obtained (o) by the piezotechnique, (+) by microwave pumping ($\Omega_k/2\pi$ = 882 MHz, P_a = 1 mW).

The above simple scheme, however, fails at helium temperatures where we observed an increase of the magnetic moment of the sample under phonon flux. This fact indicates that secondary quasimagnons and quasiphonons play an important role in the change of total magnetic moment in this case. If the population of quasiphonons and quasimagnons differs from the thermal one, then the change of magnetic moment is defined as

$$\Delta M = \sum_k \mu_{\mathrm{ph},k}(n_{\mathrm{ph},k} - n^{(0)}_{\mathrm{ph},k}) + \sum_k \mu_{\mathrm{m},k}(n_{\mathrm{m},k} - n^{(0)}_{\mathrm{m},k}). \tag{7}$$

The theoretical analysis shows that the elementary three-particle process of the annihilation of a quasiphonon and a quasimagnon and the creation of a new quasimagnon (ph + m → m) is the most probable and important process affecting the total magnetic moment. The non-equilibrium populations of magnons and quasiphonons for this process can be calculated from the following kinetic equations:

$$\frac{\mathrm{d}n_{\mathrm{ph},k_1}}{\mathrm{d}t} + \frac{(n_{\mathrm{ph},k_1} - n^{(0)}_{\mathrm{ph},k_1})}{\tau_{\mathrm{ph},k_1}} = I_{\mathrm{ph},k_1} + f_{k_1} \tag{8}$$

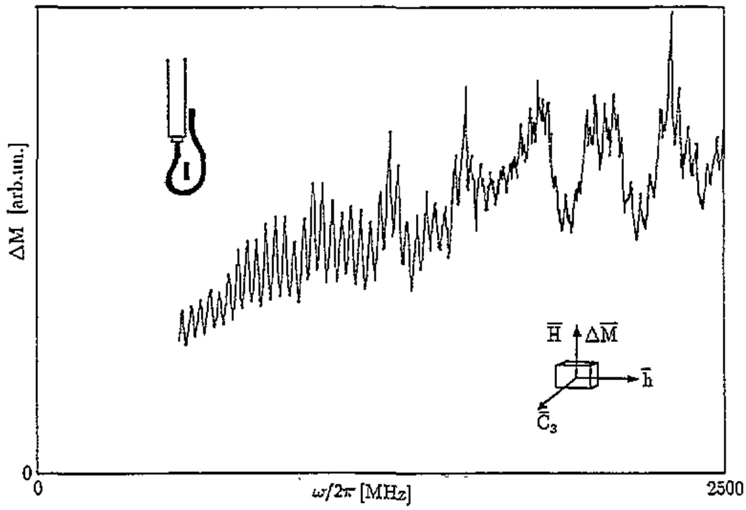

Figure 9. Frequency dependence of ΔM ($H = 0.3$ kOe and $T = 4.2$ K) at constant generator output power. Oscillations are attributed to cable resonances inside the feeding coaxial line. The microcoil and geometry of the experiment are shown in the inserts.

$$\frac{dn_{m,k_2}}{dt} + \frac{(n_{m,k_2} - n^{(0)}_{m,k_2})}{\tau_{m,k_2}} = I_{m,k_2} \tag{9}$$

$$\frac{dn_{m,k_3}}{dt} + \frac{(n_{m,k_3} - n^{(0)}_{m,k_3})}{\tau_{m,k_3}} = I_{m,k_3}. \tag{10}$$

Here f_k is an incoming term which describes the probability for the creation of quasiphonons by the external pumping; τ^{-1}_{ph,k_1}, τ^{-1}_{m,k_2} and τ^{-1}_{m,k_3} describe relaxation rates due to other processes that are not important for the change of magnetic moment. The collision integrals are defined as follows:

$$\begin{aligned} I_{ph,k_1} &= \sum_{k_2,k_3} \rho(k_1, k_2; k_3) \\ I_{m,k_2} &= \sum_{k_1,k_3} \rho(k_1, k_2; k_3) \\ I_{m,k_3} &= -\sum_{k_1,k_2} \rho(k_1, k_2; k_3) \end{aligned} \tag{11}$$

where

$$\begin{aligned} \rho(k_1, k_2; k_3) = 2\pi|\Psi(k_1, k_2; k_3)|^2[n_{m,k_3}(n_{m,k_2}+1)(n_{ph,k_1}+1) - (n_{m,k_3}+1)n_{m,k_2}n_{ph,k_1}] \\ \times\,\delta(\Omega_{k_1} + \omega_{k_2} - \omega_{k_3})\delta(k_1 + k_2 - k_3) \end{aligned} \tag{12}$$

and $\Psi(k_1, k_2; k_3)$ is the matrix element for phonon–magnon processes (see, for example, Lutovinov *et al* 1978), with $\delta(k)$ as the Kronecker delta function. We cannot solve (8)–(10) analytically, but by analysing different approximations we can obtain qualitative solutions.

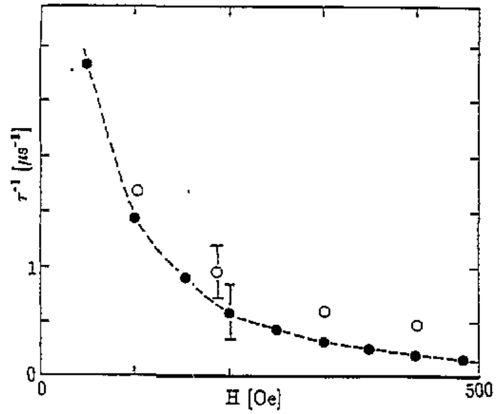

Figure 10. Magnetic field dependence of the inverse lifetime of quasiphonons at $T = 77$ K. Results obtained (o) from the data of figure 8(*a*), (•) from parallel pumping experiments.

4.1. Three-level model

The change of the magnetic moment of the sample is mainly defined by the population of quasimagnons in the vicinity of the spin-wave spectrum as far as the magnetic moment of the magnons shows a strong decrease with increasing ω_k. Equations (8)–(10) can be simplified if we assume that quasimagnons taking part in the process are distributed in narrow frequency intervals. In this case the above analysis looks like that of a 'three-level' model. For the steady state ($\mathrm{d}/\mathrm{d}t = 0$) the kinetic equations can be written as

$$\begin{aligned} &(N_{\mathrm{ph},k_1} - N^{(0)}_{\mathrm{ph},k_1})/\tau_{\mathrm{ph},k_1} = I + P_{\mathrm{a}}/\hbar\Omega_{k_1} \\ &(N_{\mathrm{m},k_2} - N^{(0)}_{\mathrm{m},k_2})/\tau_{\mathrm{m},k_2} = I = -(N_{\mathrm{m},k_3} - N^{(0)}_{\mathrm{m},k_3})/\tau_{\mathrm{m},k_3}. \end{aligned} \tag{13}$$

Here N_ν and $N^{(0)}_\nu$ are the non-equilibrium and thermal equilibrium numbers of quasiphonons and quasimagnons in the sample ($\nu = \mathrm{ph, m}$), $N_\nu \equiv \sum_k n_{\nu,k}$, $I \equiv \sum_{k_1} I_{\mathrm{ph},k_1}$. The change of magnetic moment in this case is

$$\Delta M \simeq \mu_{\mathrm{ph},k_1}(N_{\mathrm{ph},k_1} - N^{(0)}_{\mathrm{ph},k_1}) + \mu_{\mathrm{m},k_2}(N_{\mathrm{m},k_2} - N^{(0)}_{\mathrm{m},k_2}) + \mu_{\mathrm{m},k_3}(N_{\mathrm{m},k_3} - N^{(0)}_{\mathrm{m},k_3}). \tag{14}$$

Solving (13), we can rewrite (14) in the form

$$\begin{aligned} \Delta M \simeq &\left(\mu_{\mathrm{ph},k_1} + \frac{\tau_{\mathrm{m},k_2}}{\tau_{\mathrm{ph},k_1}}\mu_{\mathrm{m},k_2} - \frac{\tau_{\mathrm{m},k_3}}{\tau_{\mathrm{ph},k_1}}\mu_{\mathrm{m},k_3}\right)(N_{\mathrm{ph},k_1} - N^{(0)}_{\mathrm{ph},k_1}) \\ &- (\mu_{\mathrm{m},k_2}\tau_{\mathrm{m},k_2} - \mu_{\mathrm{m},k_3}\tau_{\mathrm{m},k_3})P_{\mathrm{a}}/\hbar\Omega_{k_1}. \end{aligned} \tag{15}$$

This equation implies that the change of magnetic moment can have either a negative or a positive sign depending on the magnitude of the parameters. Note that (15) coincides with (6) if the lifetimes of quasimagnons are very small ($\tau_{\mathrm{m},k_2}, \tau_{\mathrm{m},k_3} \to 0$).

For simplicity, we assume that

$$N_{\mathrm{ph},k_1} - N^{(0)}_{\mathrm{ph},k_1} \simeq P_{\mathrm{a}}/\hbar\Omega_{k_1}(\tau^{-1}_{\mathrm{ph},k_1} + \tau^{-1}) \tag{16}$$

where τ^{-1} is the relaxation rate which (to some extent) characterizes the magnon–phonon process of interest. Then (15) becomes

$$\Delta M \simeq (\mu_{\mathrm{ph},k_1}\tau - \mu_{\mathrm{m},k_2}\tau_{\mathrm{m},k_2} + \mu_{\mathrm{m},k_3}\tau_{\mathrm{m},k_3})\frac{\tau_{\mathrm{ph},k_1}}{\tau_{\mathrm{ph},k_1} + \tau}\frac{P_{\mathrm{a}}}{\hbar\Omega_{k_1}}. \tag{17}$$

For example, let $\tau_{m,k_2} \simeq \tau_{m,k_3} = \tau_m$, then using (2), (4) and (5), one obtains

$$\Delta M \simeq -\mu_m \left(\frac{\tau_m}{\tau} - \frac{(H_\Delta \xi)^2}{H H_D} \right) \frac{P_a \tau_{ph}}{\hbar\omega_0 (1 + \tau_{ph}/\tau)}. \tag{18}$$

In our experiment we have $(H_\Delta\xi)^2/HH_D \simeq 0.1$, so ΔM becomes positive if $\tau^{-1} > 0.1\tau_m^{-1}$. Such an order of magnitude for τ^{-1} is reasonable within the framework of the assumed simplifications. Note that the estimate $\tau_{ph}^{-1} \sim 10^3$–10^4 s^{-1}, which follows from the formula for phonon–magnon relaxation (Lutovinov *et al* 1978), is less than that obtained from the theoretical estimate $\tau_m^{-1} \sim 10^5 - 10^6$ s^{-1} for the magnon–phonon (m $\to$ m + ph) process. We also know that at 4.2 K, τ_m^{-1} approximately amounts to 10^6–10^8 s^{-1} as follows from experimental data for the electronic spin waves in $FeBO_3$ (Kotyuzhanskii and Prozorova 1981). The above facts indicate that the occupation numbers of quasimagnons and quasiphonons in our experiment differ from thermal equilibrium.

In principle, $FeBO_3$ at low temperatures is a good model system for investigating the energy flow from the pumping source to the thermostat through different degrees of freedom. As measured by the SQUID magnetometer, the distribution of this flow gives important information about non-equilibrium states of a system of non-linear waves.

We finally present data for the absorbed power and the change of magnetic moment due to the transmitted microwave power in a parallel-pumping experiment (figure 11). In the low-power regime we observe a linear absorption with a magnetic field dependence similar to the case $\boldsymbol{h} \perp \boldsymbol{H}$ (see figure 5). It can be explained as a direct excitation of quasiphonons due to the inhomogeneity of $\boldsymbol{h}$ in the helix resonator. Then the dependence $\Delta M(P_{tr})$ becomes non-linear. However, we cannot attribute the onset of parametric resonance to the beginning of this non-linearity since the threshold power P_c is higher (see the arrow in figure 11). P_c was determined from parametric resonance by means of a standard pulse technique (Kotyuzhanskii and Prozorova 1972) from the temporal evolution of P_{tr}. The non-linear dependence of $\Delta M(P_{tr})$ seems to indicate that there is an accumulation of secondary quasiphonons and quasimagnons far below the threshold of parametric resonance of the quasiphonons. However, this problem should be studied in detail in order to arrive at more definite conclusions.

5. Conclusions

By analysing the change of magnetic moment, which was probed with a SQUID magnetometer, we developed a new method of contactless phonon detection. In contrast to standard techniques, such as piezoresonance or bolometry, our method can be applied up to the GHz range, is selective in frequency and sensitive to bulk properties. The high Néel temperature antiferromagnet with easy-plane anisotropy represents an appropriate system for the detection of quasiphonons in the ultra-high-frequency range. In $FeBO_3$, for example, the experimental set-up allows us to detect a quasiphonon flux of $\sim 10^{-5}$ W at ~ 1 GHz.

Applying this technique to $FeBO_3$ at nitrogen temperature ($T \geqslant 77$ K) the change of the magnetic moment under quasiphonon pumping shows a negative sign. This change is entirely due to the total magnetic moment of excited quasiphonons. By measuring the UHF power absorbed by magnetoelastic waves and by measuring the corresponding change of magnetic moment, one can determine the lifetime of excited quasiphonons. Our new results are consistent with previous parallel-pumping data.

At liquid helium temperatures the total magnetic moment is increased ($\Delta M \sim 10^{-5} - 10^{-4}$ G cm^3) under quasiphonon pumping. This phenomenon can be considered as a dynamic

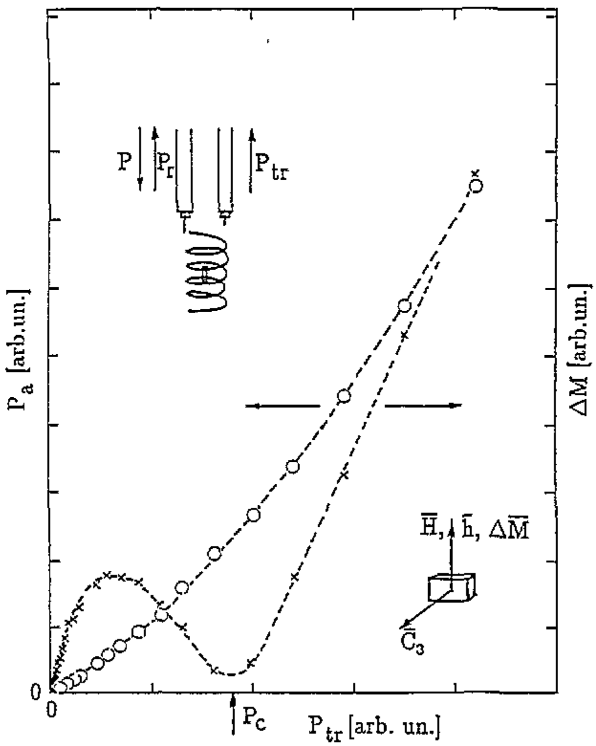

Figure 11. Excitation of quasiphonons in parallel-pumping configuration (see insert). Dependence of the change of magnetic moment ΔM (right scale) and absorbed power P_a (left scale) on the transmitted power P_{tr} (at 0.3 kOe and 1.7 K). The threshold of parametric resonance P_c obtained by the pulse technique is indicated by the arrow.

polarization of a non-linear magnetic medium. Qualitatively this effect is explained by a three-particle process where quasiphonons and quasimagnons excited near the bottom of the spin-wave band are transformed into quasimagnons of higher energy and smaller magnetic moment. In other words, there is a complex energy flow from the pumping to the thermostat through the spectrum of a system of non-linear waves.

We hope that our last result in particular will stimulate further investigations aiming at the detailed understanding of non-linear relaxation processes in other magnetoelastic materials.

Acknowledgments

The authors wish to thank Professors L A Prozorova and B Lüthi and Dr A V Andrienko for their interest in this work and for helpful discussions. We are also grateful to Professor R V Chamberlin for helpful comments on this paper. LES acknowledges the financial support of the Alexander von Humboldt-Stiftung. This investigation was supported, in pa , as a project of SFB 185 by special funds of the Deutsche Forschungsgemeinschaft and by RFFI (grant 93-02-2586).

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