Scattering of light by magnons in two branches of the spectrum of antiferromagnetic EuTe

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(Submitted 20 February 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 6, 312–314 (25 March 1986)

A single-magnon inelastic scattering of light by thermal magnons belonging to both branches of the excitation spectrum has been detected in a classical Heisenberg antiferromagnet EuTe. The dependence of the magnon frequency on the magnetic field is studied in the entire existence domain of the antiferromagnetic phase at $T = 2$ K.

The Brillouin scattering of light (in the USSR it is known as "Mandel'shtam-Brillouin scattering") is one of few experimental methods that makes it possible to directly study the low-frequency component of the spectrum of elementary excitations in a solid. The principal difficulty that arises when this method is used to study the spin-wave spectrum in magnetic materials is the low scattering intensity in these materials. The progress achieved during the past decade in the development of the technology of Brillouin scattering has made it possible, however, to study the spin-wave spectra in some ferro-, ferri-, and antiferromagnetic materials.[1,2]

In the present letter we report the results of a study of Brillouin scattering in a classical Heisenberg antiferromagnet (EuTe) with thermal magnons belonging to both branches of the excitation spectrum. The experiments were carried out at $T = 2$ K over a broad interval of magnetic fields (0–70 kOe) corresponding to the entire existence domain of the antiferromagnetic phase.

At temperatures below $T_N = 9.6$ K, cubic europium chalcogenide[3] EuTe becomes an easy-plane two-sublattice antiferromagnet in which the spins lie in the (111) plane. The corresponding effective anisotropy field H_A is ~ 10 kOe. Because a cubic crystal has four equivalent (111) planes, below T_N it breaks up into antiferromagnetic T domains. The external magnetic field cannot bring about a transition of the sample to a single-domain state. In the (111) easy plane there is a weak intraplane anisotropy H_a which aligns the spins in the $[11\bar{2}]$ direction. This anisotropy corresponds to an effective field ~ 10 Oe. EuTe undergoes a transition from the antiferromagnetic phase to the ferromagnetic phase (a spin-flip transition) in an external magnetic field $H_C = 2H_E = 72$ kOe (at $T = 0$ K).

The EuTe crystals are relatively transparent to the wavelength of light, $\lambda = 632.8$ nm, used by us in the experiment: the penetration depth is ≈ 200 μm. At this wavelength of light, EuTe in the ordered state has strong magnetooptical effects: the Faraday effect and the magnetic isotropic refraction. At $T = 2$ K the Faraday effect[4–6] is $\sim 2 \times 10^5$ deg/cm (or $n_+ - n_- = 0.07$). The magnetic isotropic refraction accounts for the quadratic dependence of the magnetic part of the refractive index on the magnetization of the crystal. At $T = 2$ K a change in the refractive index, Δn, of EuTe in the saturated state is ~0.05, according to the estimates given in Ref. 6. Both of these magnetooptical effects (and also the magnetic birefringence, a much weaker effect) account for a relatively higher intensity of Brillouin scattering by the spin waves in EuTe (Ref. 6). As the spectral instrument in the study of Brillouin scattering in EuTe we used a five-pass Fabry-Perot interferometer (manufactured by Burleigh) with a contrast $> 10^8$. The general schematic diagram of the experimental apparatus and the specific details of the measurement procedure were reported in Refs. 1 and 7. The experiments were carried out in the backward-scattering geometry with the use of magnons with a wave vector $|\mathbf{q}| = 3\times10^5$ cm^{-1}, propagating along the [100] axis of the crystal. The magnetic field was applied along the [100] axis parallel to the direction of propagation of light. At this orientation all T domains are in the equivalent position with respect to the field. Since the excitation spectrum of an easy-plane antiferromagnet depends on the angle of inclination of the magnetic field relative to the (111) "easy" plane, the magnon spectra of the different domains are the same for the experimental geometry used by us. Accordingly, it is important to align the sample correctly with respect to the magnetic field. In our experiments the alignment error was $< 1°$.

Figure 1 is a trace of the scattering spectrum at a constant magnetic field. The strong peak with a zero frequency shift (the principal line) is attributable to the eastic scattering of light by the crystal defects. The displaced satellites correspond to the inelastic scattering of light by magnons. As can be seen in Fig. 1, the magnons belonging to each branch of the spin-wave spectrum of the easy-plane antiferromagnet were detected by the Brillouin-scattering method. The satellites with a shifted frequency $\Delta\nu_1 = \pm(50\pm0.5)$ GHz(S_1 and AS_1) correspond to the scattering by magnons belonging to the low-frequency branch of the spectrum and the satellites with $\Delta\nu_2 = \pm(94\pm0.5)$ GHz (S_2 and AS_2) correspond to the scattering by magnons belonging to the high-frequency branch. The high-frequency branch of magnon spectrum was detected previously by the method of Brillouin scattering in a slightly ferromagnetic[8] FeBO$_3$.

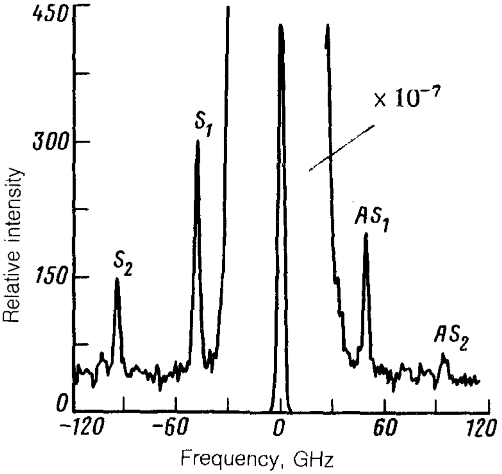

FIG. 1. The spectrum of light scattered in the crystal $T = 2$ K; $\lambda_l = 632.8$ nm, $|\mathbf{q}| = 3\times10^5$ cm^{-1}, $\mathbf{H}\|[100]$, $H = 25$ kOe.

In the spectrogram shown in Fig. 1, we see that the intensity of the Stokes satellites (*S*) is different from the intensity of the anti-Stokes satellites (*AS*) for each branch of the magnons. We assume that this difference stems from the different probabilities of the absorption and emission of a magnon by a photon during scattering under conditions where $\hbar\omega_{\mathrm{magn}} \sim kT$. In this case, the ratio of the intensities of the *S* and *AS* satellites can be written in the form

$$\frac{I_S}{I_{AS}} = \frac{n_\omega + 1}{n_\omega} = e^{\hbar\omega/kT}$$

where

$$n_\omega = \frac{1}{e^{\hbar\omega/kT} - 1}$$

is the number of excited magnons with a frequency ω for a given T. For the data corresponding to the spectrum in Fig. 1, this ratio calculated from a formula is 2.3 for magnons of the lower branch and 4.8 for magnons of the upper branch. A slight difference between the values measured experimentally and the calculated data seems to be due to a slight ($\sim$0.5 K) superheating of the crystal being studied relative to the helium bath. The ratio I_S/I_{AS} changes as the magnetic field and hence the magnon frequencies are changed.

In our experiment we have studied in detail the dependence of the magnon frequency in each branch on the magnetic field. The results of the experiment are shown in Fig. 2. Because of the large scattering intensity, the low-frequency branch of the spectrum is seen up to the field $H = 68$ kOe, i.e., virtually in the entire existence

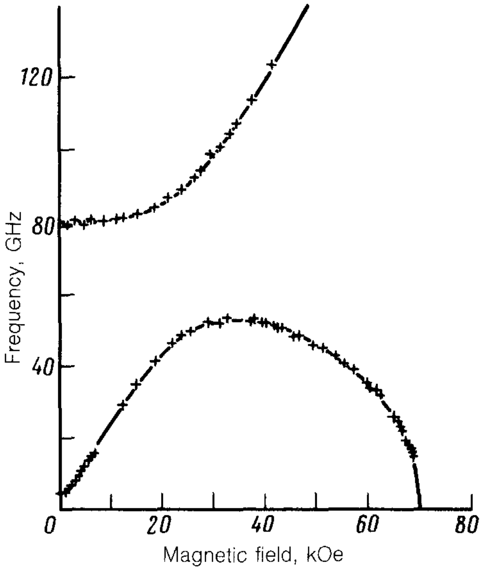

FIG. 2. The spectrum of spin waves in EuTe for **H**||[100]. + —Experimental data; ——— —the result of a theoretical calculation.

domain of the antiferromagnetic phase. The magnons of the high-frequency branch can be seen only to $H = 42$ kOe because of the small scattering intensity. The solid curves in Fig. 2 are the result of a calculation of the magnon spectrum of an easy-plane antiferromagnet, carried out with allowance for the magnetic-dipole interaction. The constants required for the calculation were taken from Refs. 3 and 9. The theoretical curves are in good agreement with the experimental results. These results show that each branch of the spectrum has a gap in the absence of a magnetic field. The gap in the low-frequency branch, $\Delta_1 = \sqrt{2H_E H_a}$, is caused by the interplane anisotropy H_a and the gap in the high-frequency branch, $\Delta_2 = \sqrt{2H_E H_A}$, is caused by the easy-plane anisotropy H_a. The following values were determined from the experimental data: $H_a = 15 \pm 1$ Oe and $H_A = 10.4 + 0.2$ kOe.

We are sincerely grateful to A. S. Borovik-Romanov for valuable suggestions and for the discussions. We also thank L. A. Klinkova (Institute of Solid-State Physics) for graciously furnishing the EuTe crystals.

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Translated by S. J. Amoretty