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SCATTERING OF LIGHT BY COHERENT SPIN WAVES

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Submitted 10 January 1967
JETP Pis'ma 5, No. 7, 242-244 (1 April 1967)

A study of the scattering of light in magnetically-ordered crystals yields important information on the dynamics of a spin system. Raman scattering of light was recently observed [1] in antiferromagnetic FeF_2. This effect, however, is quite weak, owing greatly to the smallness of the amplitude of the thermal spin waves.

We consider in this letter Raman scattering of light by coherent spin waves excited, for example, in parametric fashion. An important fact is that in such an excitation method the experimentally attainable energy of the monochromatic spin waves exceeds kT by 15 - 16 orders of magnitude [2].

In addition, the length of such spin waves can be varied in a wide range ($0 < k_m < 10^5$ cm^{-1}) with the aid of a magnetic field, and is comparable with the wavelength of light. All this makes it possible to observe intense scattering of light at any angle ($0 - \pi$), whose magnitude depends on the external magnetic field.

Let us consider for simplicity a standing spin wave

$$\vec{m}(\vec{r}, t) = \vec{m} \cos(\vec{k}_m \vec{r}) \cos \Omega t, \qquad (1)$$

where $\vec{k}_m \perp \vec{H}_0$ and $\Omega = \Omega_H/2$. This corresponds to the case of "parallel pumping" with frequency Ω_H. Let light with frequency $\omega \gg \Omega$ and wave vector $\vec{k}_p$ be incident on a ferromagnet in which the wave (1) is excited. We shall assume that either of the two Raman-scattering mechanisms - the "magnetic" or "electric," proposed respectively by Bass and Kaganov [3] and by Elliott and London [4] - predominates. Then the differential scattering cross section, obtained by one of the authors [6] takes the form

$$\frac{d\sigma}{d\theta} = \frac{\Phi^2 k_p^2}{(4\pi)^2} \sum_{j=1}^{3} \left| \int d^3r \, \frac{m_j(r) e^{-iqr}}{M} \right|^2 . \qquad (2)$$

Here Φ is the angle of rotation of the polarization plane per unit length of sample when the light propagates along the magnetization $\vec{M}$ (Faraday effect), $\vec{q} = \vec{k}_p - \vec{k}'_p$, $\vec{k}'_p$ is the wave vector of the scattered light, and

$$m_1(\vec{r}) = \vec{\alpha}\cdot\vec{m}(\vec{r}),\; m_2(\vec{r}) = \vec{\beta}\cdot\vec{m}(\vec{r}) \quad\text{and}\quad m_3(\vec{r}) = [\vec{\alpha}\times\vec{\beta}]\vec{m}(\vec{r}), \tag{3}$$

where $\vec{\alpha} = \vec{k}'_p/k_p$, $\vec{\beta} = \vec{k}_p/k_p$, and $\vec{m}(\vec{r})$ describes the spatial variation of the magnetization in the sample. In our case

$$\vec{m}(\vec{r}) = \frac{\vec{m}}{2}(e^{i\vec{k}_m\vec{r}} + e^{-i\vec{k}_m\vec{r}}) \tag{4}$$

and the scattering cross section (2) has sharp maxima in one of the directions

$$\vec{\alpha}^{\pm} = \vec{\beta} \pm \vec{k}_m/k_p, \tag{5}$$

corresponding to the momentum conservation law for elastic scattering ($\omega \gg \Omega$) of a photon by magnons.

Integrating (2) over the solid angle θ, in analogy with the procedure used in the theory of x-ray diffraction [5], we obtain the scattering cross section for the diffraction maximum (5) of interest to us

$$\sigma = \frac{\Phi^2}{16}\int z^2 df \sum_{j=1}^{3}\left(\frac{m_j}{M}\right)^2, \tag{6}$$

where z is the dimension of the sample in the α direction, and df = dx dy.

For comparison we present the cross section for scattering by thermal spin waves [6]:

$$\sigma_T = \left[1 - \frac{\cos^2(\vec{\beta}\vec{M})}{3}\right]\frac{\gamma M}{\Omega_{res}}\frac{2kT}{\pi M^2}V\Phi^2 k_p^2,$$

where γ is the gyromagnetic ratio, Ω_{res} the frequency of ferromagnetic resonance, and V the volume of the sample. In order of magnitude,

$$\frac{\sigma}{\sigma_T} = \left(\frac{m}{M}\right)^2 \frac{\pi M^2 k_p^{-3}}{2kT}\,\frac{\Omega_{res}}{4\gamma M}\,\frac{k_p\int z^2 df}{4V}.$$

Let us estimate this ratio for an yttrium garnet crystal, which has a low parametric-excitation threshold and high transparency in the near infrared. We put $k_p \sim 2 \times 10^4$ cm^{-1}, $(m/M)^2 \sim 10^{-5}$, $k_p\int z^2 df/4V \sim 10^2$, $\Omega_{res}/4\gamma M \sim 2$, and M = 140 G/cm^3 at T = 300°K. Then $\sigma/\sigma_T \sim 10^5$.

We note that the foregoing considerations are merely estimates, since we have considered an excessively idealized scattering case in which both waves - light and spin - are assumed to be plane and monochromatic. An analysis of a more realistic situation will modify somewhat the value of the scattering cross section, but will not affect the validity of the conclusion that Raman scattering of light by spin waves in the case of parametric excitation is much more intense than scattering by magnetization fluctuations at thermodynamic equilibrium.

An experimental study of light scattering by powerful coherent spin waves is a very interesting and fascinating problem. This effect can be used to study the instability of spin waves, the dependence of their amplitude on the pump power, the distribution of the spin waves with respect to $\vec{k}_m$, etc. In addition, it enables us to measure directly the wave vector of the spin waves as a function of their frequency and of the external magnetic field, i.e., the spin-wave spectrum.

We are grateful to A. G. Gurevich and V. L. Gurevich for fruitful discussions and useful advice.

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