Physics

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1960

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Abstract

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Physics

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On the Excitation of the Spin System of a Ferromagnet by a Spatially Inhomogeneous Electromagnetic Field

(Presented by Academician N. N. Bogolyubov, 12 IV 1960)

In the present note we consider a ferromagnet in which an inhomogeneous electromagnetic wave propagates. Such a formulation of the problem arises, in particular, in the analysis of magneto-optical phenomena, since in this case the system of spins is certainly situated in an inhomogeneous electromagnetic field.

Below it will be shown that in an inhomogeneous field, in addition to the resonant frequency

$$\Omega = \frac{\min \varepsilon_q}{\hbar} = \frac{g\mu}{\hbar} H\,(^1),$$

the frequency of infrared radiation

$$\Omega = \frac{\max \varepsilon_q}{\hbar} \sim \frac{I}{\hbar}$$

is "suspect" for resonance (ε_q is the energy of a spin wave, I is the exchange integral).

Consider the Heisenberg model of a ferromagnet, described by the Hamiltonian

$$\mathscr{H} = -\frac{I}{2} \sum_{f,\vec{\delta}} \mathbf{S}_f \mathbf{S}_{f+\vec{\delta}} - \mu H \sum_f S_f^z, \tag{1}$$

where $\mathbf{S}_f$ is the spin operator of an atom located at the site $\mathbf{f}$ ($\mathbf{S}_f$ is in units of $\hbar/2$, $S_f^z = \pm 1$). The summation is carried out over the sites $\mathbf{f}$ of a simple cubic lattice and over all $\vec{\delta}$, which connect the site $\mathbf{f}$ with its nearest neighbors. In all there are N atoms in the lattice, and they occupy a cube of volume $V = L^3 = (aN^{1/3})^3$, where a is the linear size of the elementary cell. I is the exchange integral, H is a constant magnetic field.

The Zeeman interaction energy in the alternating magnetic field

$$h^x(f_z, z) = 2h_0(f_z)\cos(\Omega t - k'_z f_z), \qquad h^y = h^z = 0 \tag{2}$$

has the form

$$\mathscr{H}'_t = \exp(-i\Omega t)V_\Omega + \exp(i\Omega t)V_{-\Omega}, \tag{3}$$

where

$$V_\Omega = -\mu \sum_f h(f_z) S_f^x; \qquad h(f_z) = h_0(f_z)\exp ik'_z f_z.$$

Under the action of the perturbation $\mathscr{H}'_t$, the component of the magnetic moment $m_g^x = \mu S_g^x$ receives an increment $\overline{\delta m_g^x}$ ([2,3]). In this case the rate of change of the energy of the spin system is expressed in the form

$$\frac{dE}{dt} = \sum_f h^x(f_z, t)\,\frac{d}{dt}\overline{\delta m_g^x(t)}. \tag{4}$$

Representing $\overline{\delta S_g^x(t)}$ in terms of the retarded Green functions found for the Hamiltonian (1) in works ([4,5]), we obtain for the average rate of change of the energy the expression

$$\left(\frac{dE}{dt}\right)_\tau = \frac{1}{\tau}\int_0^\tau \frac{dE}{dt} \quad \tau \to \infty$$

$$= -\mu^2 \frac{\Omega}{\hbar}\frac{LN}{\pi}\int_{-\pi/a}^{\pi/a} |h(q_z)|^2 \,\mathrm{Im}\left\{\frac{1}{\Omega - \dfrac{\varepsilon_q}{\hbar} + \dfrac{i}{T}} - \frac{1}{\Omega + \dfrac{\varepsilon_q}{\hbar} + \dfrac{i}{T}}\right\} dq_z, \tag{5}$$

where ε_q is the spin-wave energy, and T is the relaxation time of the spin component S_g^α $(\alpha = x, y)$ ([6])

$$h(q) = \frac{1}{N^{1/3}}\sum_{f_z} h(f_z)\exp(-if_{zq}z), \qquad h(f_z) = h_0(f_z)\exp ik_{zf}z.$$

On passing to the limit $T \to \infty$ we have

$$\left(\frac{dE}{dt}\right)_\tau = \mu^2 \Omega LN\{|h(q_{zs})|^2 + |h(-q_{zs})|^2\}\frac{1}{\left|\partial\varepsilon_q/\partial q_z\right|_{q_z = q_{zs}}}, \tag{6}$$

where $\left|\partial\varepsilon_q/\partial q_z\right|_{q_z=q_{zs}} \neq 0$.

q_{zs} is a root of the equation $\Omega - \varepsilon_q/\hbar = 0$, which in our case has the form

$$\Omega - [4I(1-\cos aq_z) + 2\mu H]\frac{1}{\hbar} = 0. \tag{7}$$

When $\left|\partial\varepsilon_q/\partial q_z\right|_{q_z=q_{zs}} \to 0$, as is evident from (6), $(dE/dt)_\tau \to \infty$. Thus, at frequencies $\Omega \simeq \operatorname{extrem}\varepsilon_q/\hbar$ the absorption may increase sharply. If

$$\Omega \simeq \frac{\min\varepsilon_q}{\hbar} = \frac{2\mu}{\hbar}H,$$

we have the classical resonance first considered by L. D. Landau and E. M. Lifshitz ([1]). For

$$\Omega \simeq \frac{\max\varepsilon_q}{\hbar} = \frac{8I + 2\mu H}{\hbar}$$

a resonance in the infrared region is possible.

An estimate of the magnitude of the effect was made under the assumption that all the calculations are also valid for the half-space $f_z \geq 0$ and that the magnetic field has the form

$$h(f_z, t) = 2h_0 \exp(-k_z'' f_z)\cos(\Omega t - k_z' f_z). \tag{8}$$

The ratio of the absorbed energy to the incident energy in the present case is

$$\left(\frac{dE}{dt}\right)_\tau \Big/ \bar{S}L^2 \simeq \frac{\mu^2 I^{1/2}}{\hbar^{3/2}a^2c}T^{1/2}, \tag{9}$$

where $\bar{S}$ is the time-averaged flux density of electromagnetic energy, and c is the speed of light.

For example, for $I \sim 10^{-14}$ erg, $a \sim 10^{-8}$ cm, and $T \sim 10^{-6}$ sec, the ratio

$$\left(\frac{dE}{dt}\right)_\tau \Big/ \bar{S}L^2 \simeq 10^{-4},$$

and the effect is still within experimental possibilities.

We note that an anomalous increase of absorption at $\Omega \simeq \max\varepsilon_q/\hbar$ was found in works ([7,8]) on nickel. However, the connection of the effect observed in ([7,8]) with that set forth above requires clarification on the basis of the theory of magneto-optical phenomena ([9]).

The author expresses his deep gratitude to L. F. Vereshchagin, S. V. Tyablikov, and G. S. Krinchik for fruitful discussion of the physical aspect of the problem, and to S. V. Tyablikov for valuable advice and comments on the formulation of the problem and its mathematical solution.

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Received
30 III 1960

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Note: Figure translations are in progress. See original paper for figures.