MAGNETO-OPTICAL RESONANCE IN NICKEL AT INFRARED FREQUENCIES

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Resonance absorption of infrared light in nickel has been detected by a magneto-optical method. The resonance wavelength of $4 \pm 0.5\,\mu$ corresponds to the reorientation energy of the electron spin magnetic moment in the exchange field of a ferromagnet.

RECENT measurements of the magneto-optical characteristics of nickel in infrared, visible, and ultraviolet light[1-3] have made it possible to detect resonance effects in the region of 1 and $5\,\mu$. The first of these resonances is due, apparently, to electron transitions between the 3d and 4s bands. Such a possibility was predicted theoretically in a formulation of the quantum theory of magneto-optical phenomena.[4*]

More interesting is the second resonance, observed at $5\,\mu$. Firstly, such low-energy transitions cannot be investigated by the x-ray method or by the method of discrete electron energy losses. Secondly, the natural frequency of this resonance corresponds to the energy of spin flip in the molecular field of the ferromagnet, and we may be dealing here with exchange resonance. We therefore undertook more precise measurements in the region of second resonance.

In this investigation we measured, as previously, the change in the intensity of reflected light upon reversal of magnetization of the ferromagnet. The principal apparatus used for such measurements is described in reference 2. Light, polarized in the plane of incidence (p wave) is reflected from the specimen and strikes one of the junctions of a vacuum thermocouple. A portion of the light from the same source is aimed with a system of mirrors onto the second, compensating junction of the thermocouple. Before each measurement, the intensities of the two beams are equalized. When the magnetization of the specimen is reversed, the intensity of the first beam changes by an amount $2\Delta I$, which is registered by an M21/4 galvanometer connected to the output of an FEOU-15 photoelectron-optical amplifier. Knowing the intensity of the light reflected from the specimen, we obtain the relative change in the intensity of the light during magnetization, $\delta = \Delta I/I$.

The specimen was a mechanically polished plate of electrolytic nickel, $40 \times 40 \times 3$ mm, placed between the poles of a small electromagnet. The specimen was magnetized to saturation, i.e., the so-called equatorial magnetization was produced. This effect can be analyzed phenomenologically by assuming the ferromagnet to be a gyrotropic medium. The dielectric-constant tensor is then

$$[\varepsilon] = \begin{vmatrix} \varepsilon & -i\varepsilon M & 0 \\ i\varepsilon M & \varepsilon & 0 \\ 0 & 0 & \varepsilon_0 \end{vmatrix}.$$

For a gyromagnetic medium, the magnetic permeability has a similar form. The magneto-optical parameter $M = M_1 - iM_2$ is a constant of the substance and determines the magnitudes of all the magneto-optical effects. M_1 and M_2 can be determined from two independent measurements made on any magneto-optical effect for light of a given frequency. In reference 1 the following formula was obtained for the relation between δ and M_1 and M_2

$$\delta = 2\sin 2\varphi\,(M_1A - M_2B)/(A^2 + B^2), \qquad (1)$$

where $A = \epsilon_2 \cos^2\varphi - q$, $B = \epsilon_1 \cos^2\varphi - 1 + p$, $p = \epsilon_1 \sin^2\varphi/(n^2+k^2)^2$, $q = \epsilon_2 \sin^2\varphi/(n^2+k^2)^2$, $\epsilon_1 = n^2 - k^2$, $\epsilon_2 = 2nk$, and φ is the angle of incidence. Bonetti et al.[5] considered the general case of a bi-gyrotropic medium and obtained an analogous formula for a gyromagnetic medium.

Figure 1 shows the measured values of δ for nickel at various angles of light incidence. Each point on the curve was obtained by averaging 40 readings. The mean-squared measurement er-

*In connection with this, it would be desirable to find an analogous resonance at ultraviolet frequencies, where the presence of inter-band electron transitions in nickel were established by the x-ray method and by the method of discrete electron energy losses. However, progress in the ultraviolet region down to $0.3\,\mu$ is still insufficient to observe the expected resonance with certainty.[3]

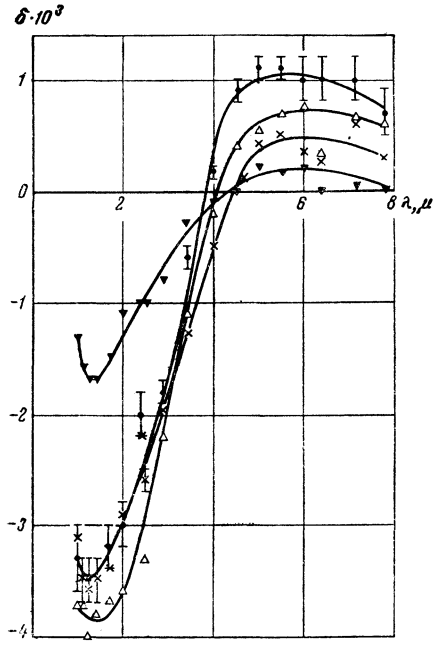

FIG. 1. Variation of the intensity of reflected light during magnetization of nickel, for various angles of incidence: • – 85°, Δ – 80°, × – 75°, ▼ – 60°.

ror, which was determined for all cases, is shown for only one of the curves.

A singularity is observed on these curves in the region from 4 to 8 μ: the effect reverses its sign and reaches a considerable magnitude. This is particularly interesting since, according to (1), δ is inversely proportional to n^2 and k^2, while n and k increase strongly with increasing wavelength.

Figure 2 shows curves of M_1 and M_2, calculated by formula (1) for the values of δ obtained at $\varphi = 75°$ and $\varphi = 85°$. The values of n and k used in these calculations were determined from the curves for ϵ_1 and ϵ_2, obtained in reference 6. This is the principal source of the possible systematic errors, since the optical constants of our specimen may differ greatly from the foregoing ones. As a check, measurements were made on less pure, non-electrolytic nickel, and the results, although lower, were qualitatively the same. As can be seen from the curves of Fig. 2, the resonance region is clearly shown, although the error in the determination of M_1 and M_2 increases with increasing λ. The resonant frequency can be determined from the position of the maximum of M_2, i.e., it equals $4 \pm 0.5\,\mu$. At this frequency M_1 apparently reverses its sign.

The origin of the observed resonance is still not clear. One can assume that it is due either to electronic transitions between 3d and 4s bands, or to spin reorientation in the volume under the influence of the light wave. The first explanation

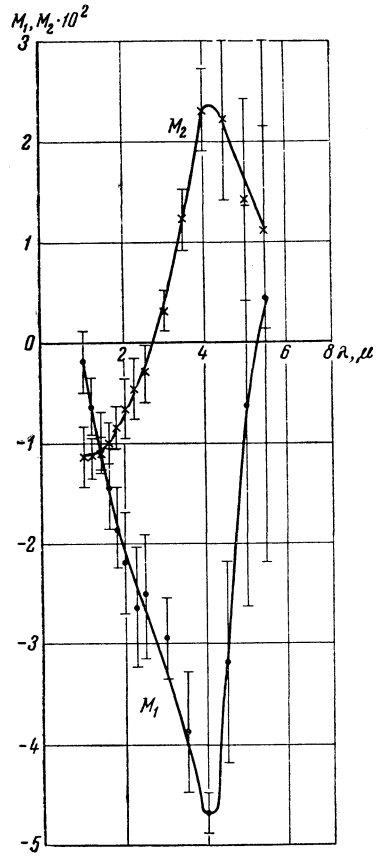

FIG. 2. Real and imaginary components of the magneto-optical parameter of nickel in the infrared region.

is generally accepted and the theory based on it gives the required order of magnitude for the magneto-optical effects.[4] However, the value of the transition energy in our case is ~ 0.3 ev, while theoretical estimates of this energy, made from the widths of the energy bands, give a value of several electron volts. The second explanation leads directly to a correct numerical value of the resonant frequency,[1] but no further comparison with experiment can yet be made for lack of a theory. The calculation of the exchange resonance on the base of a model of two interacting "sublattices" of s and d electrons gave too small a value for the effect,[1] and exchange resonance in a ferromagnet with one sublattice is generally considered impossible.[7] But it has been shown recently[8] that resonant absorption of light should be observed at the exchange frequency in

λ, μ	n	k	λ, μ	n	k
1	2.6	5.3	3.5	4.7	11.8
1.2	2.9	6.0	4.0	4.8	13.4
1.4	3.1	6.7	4.5	4.8	15.5
1.6	3.3	7.3	5.0	4.9	17.6
1.8	3.6	7.9	5.5	5.1	19.0
2.0	3.7	8.5	6.0	5.4	20.6
2.25	3.9	9.2	6.5	5.8	21.8
2.5	4.0	9.3	7.0	6.1	23.0
3.0	4.4	10.4			

any ferromagnet. Further calculations will show whether this mechanism can ensure the observed value of the effect in the infrared region. If this is so, then it is possible, with the aid of the observed effect, to study the exchange interaction in the ferromagnets, and, in particular, to measure the exchange integral by direct methods.

[1] G. S. Krinchik, Вестник МГУ (Bull. Moscow State Univ.) No. 6, 87 (1957).

[2] G. S. Krinchik and R. D. Nuralieva, Физика металлов и металловед. (Physics of Metals and Metal Research) **7**, No. 5 (1959).

[3] G. S. Krinchik and I. S. Stroganova, Физика металлов и металловед. (Physics of Metals and Metal Research) **7**, 460 (1959).

[4] H. R. Hulme, Proc. Roy. Soc. **135**, 237 (1932); P. N. Argyres, Phys. Rev. **97**, 334 (1955).

[5] G. S. Krinchik and M. V. Chetkin, J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1924 (1959), Soviet Phys. JETP **9**, in press.

[6] J. R. Beattie and G. K. T. Conn, Phil. Mag. **46**, 989, 1002 (1955).

[7] C. Kittel and C. Herring, Phys. Rev. **77**, 725 (1950), J. Kaplan and C. Kittel, J. Chem. Phys. **21**, 760 (1953).

[8] N. M. Potapkov, J. Exptl. Theoret. Phys. (U.S.S.R.), in press.

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