THE PHENOMENON OF LONGITUDINAL MAGNETIZATION OF AN ANTIFERROMAGNET BY A TRANSVERSE CIRCULARLY POLARIZED MAGNETIC FIELD

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IN ferromagnetic resonance (as also in paramagnetic electron resonance or nuclear resonance), there occurs a nonlinear effect consisting of a resonance diminution of the longitudinal magnetization M_z by a transverse high-frequency magnetic field.[1] The order of magnitude of the effect is determined by the equation

$$\Delta M_z/M_z = -(h_0/\Delta H)^2, \quad (1)$$

where h_0 is the amplitude of the hf field, and ΔH is the width of the resonance line. A similar effect should occur also in antiferromagnets; in this case, however, a circularly polarized hf field, perpendicular to the axis of antiferromagnetism z, can cause the appearance of a constant component of magnetization along the axis mentioned, in the absence of any constant magnetic biasing field ($H_z = 0$). It is of interest to estimate the order of magnitude of this effect.

We consider a uniaxial antiferromagnet, with the axis of antiferromagnetism coincident with the principal crystal axis z. We solve by the usual method[2] the equations of motion of the magnetic moments $\mathbf{M}_j$ ($j = 1, 2$) of the sublattices in an external field

$$H_x = h_0 \cos \omega t, \qquad H_y = h_0 \sin \omega t, \qquad H_z = 0,$$

and obtain in the first (linear) approximation

$$M_{1,2}^{+} = \frac{\gamma M_0 (\omega \pm \gamma H_A) h_0}{\omega_0^2 - \omega^2} e^{i\omega t}, \quad M_{1,2}^{-} = \frac{\gamma M_0 (\omega \pm \gamma H_A) h_0}{\omega_0^2 - \omega^2} e^{-i\omega t},$$
$$M_{1z} \cong -M_{2z} \cong M_0, \quad (2)$$

where $\omega_0 = \gamma\sqrt{(H_E H_A)}$ is the resonance frequency, H_E is the "exchange" field, and H_A is the magnetic anisotropy field ($M_j^{\pm} = M_{jx} \pm iM_{jy}$).

In order to take account of the finite value of the width $\Delta\omega$ of the resonance line, it is necessary in Eqs. (2) to make the substitutions* $\omega_0 \to \omega_0 - i\Delta\omega/2$ for M_j^+ and $\omega_0 \to \omega_0 + i\Delta\omega/2$ for M_j^-. By use of the formulas thereafter obtained, it is not difficult to find in the second (nonlinear) approximation the longitudinal magnetization $M_z = M_{1z} + M_{2z}$, if we use the relations

$$M_{1z} \cong M_0 - M_1^+ M_1^- / 2M_0, \quad M_{2z} \cong -M_0 + M_2^+ M_2^- / 2M_0.$$

In particular, at resonance ($\omega = \omega_0$) we have

$$M_z / M_0 = -2 (\gamma H_A / \omega_0)(h_0 / \Delta H)^2 \text{ or}$$
$$-2 (H_A / H_E)^{1/2} (h_0 / \Delta H)^2, \quad (3)$$

where $\Delta H = \Delta\omega/\gamma$.

Thus, as in the case of a ferromagnet, observation of the effect requires crystals with a quite narrow resonance line. Here, it is true, in comparison with formula (1), the coefficient $(H_A/H_E)^{1/2}$ is small; but on the other hand, the quantity M_z that interests us emerges in the present case against a "zero" background, whereas for a ferromagnet it appears against the background of the large spontaneous magnetization existing in the specimen.† Suppose, for example, that $H_A/H_E \sim 10^{-2}$ and $M_0 \sim 10^3$ G: then in order to get a magnetization M_z of order 1 G, it is necessary to have the ratio $h_0/\Delta H \sim 10\%$. When we consider that even at the present time (in the almost complete absence of work in search of antiferromagnets with a narrow resonance line) resonance curves with $\Delta H \sim 10$ Oe have already been obtained (Borovik-Romanov[3]), we may hope for experimental observation of the phenomenon considered.

We remark that exactly the same effect should occur in nuclear magnetic resonance in antiferromagnets. Here the role of a magnetic anisotropy field H_A of alternating sign will be played by the effective field on the nuclei, $H_{eff} = AM_0$, where A is the hyperfine-interaction constant. For the relative value of the resulting longitudinal magnetic moment of the nuclei, I_z/I, the first of formulas (3) will again be applicable, but it will be necessary to replace γH_A by $\gamma_n H_{eff}$ and to interpret ω_0 as the nuclear resonance frequency. Since $\omega_{0n} \cong \gamma_n H_{eff}$, and since $I = \chi_n H_{eff}/2$, in this case

$$I_z \cong -\chi_n H_{eff} (h_0/\Delta H_n)^2,$$

where χ_n is the magnetic susceptibility of the nuclei, and ΔH_n is the width of the nuclear resonance line.

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*The same result for the frequency region near resonance is also obtained by direct solution of the equations of motion with inclusion of damping terms (in the manner of Bloch or of Landau and Lifshitz).

†In the presence of a constant longitudinal field $H_z = H \neq 0$, the value of M_z determined by formula (3) (in unaltered form, if $H \ll \sqrt{(H_E H_A)}$,) enters as a term along with $\chi_{\parallel} H$, where $\chi_{\parallel}$ is the longitudinal susceptibility of the antiferromagnet.

[1] A. G. Gurevich, Ferrity na sverkhvysokikh chastotakh (Ferrites at Microwave Frequencies), Fizmatizdat, 1960, p. 311.

[2] M. I. Kaganov and V. M. Tsukernik, JETP **34**, 524 (1958), Soviet Phys. JETP **7**, 361 (1958).

[3] A. S. Borovik-Romanov, Proceedings, International Conference on Magnetism, Kyoto, Japan, 1961.

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A METHOD OF MEASURING THE MOMENTUM OF ELECTRONS IN A METAL

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A series of size effects, which are determined by the relationships between the size of electron orbits and the size of a metallic sample, can be observed when a sample having a long free path is placed in a constant magnetic field. Phenomena of similar type were discovered a relatively long time ago in dc measurements of conductivity. They can be observed, however, in much more distinct form in measurements of high-frequency impedance, owing to the presence of a supplementary parameter with the dimensions of length—the skin depth δ. A similar effect was first found by Khaĭkin,[1] who discovered the disappearance of cyclotron resonance upon decrease of the field, starting with that field for which the diameter of the electron orbit is comparable with the thickness of the sample.

For observation of the size effects, however, one can also use frequencies much lower than in Khaĭkin's experiment, on the order of 10^6 cps, at which there is no cyclotron resonance, but the condition $d \gg \delta$ is well satisfied (d is the diameter of the electron orbit).

Let us consider a flat slab with a constant magnetic field parallel to its surface. The electrons move along helices with axes parallel to the surface of the metal; the major part of the electron trajectories passes deep in the metal, where there is no high frequency field; on returning to the skin layer, the electrons find there a high frequency field in the same phase as it was during the preceding passage through the skin layer. The reason for this is that the field does not have time to change significantly during the time of rotation of the electron in orbit ($\sim 10^{-9}$ sec). The dependence of the impedance on the field does not have, however, a resonance character, since the condition of constant phase of the electric field for all passages of the electron through the skin layer is fulfilled for all fields. When the field is increased the radius of the electron orbit decreases, and the number of returns of the electron through the skin layer during the free path time increases. However, the electron returns to the skin layer only if the diameter of its orbit is less than the thickness of the sample. In the contrary case, it is scattered on the surface of the crystal. Thus for that value of the field at which the orbit diameter of the electron on the extremal section of the Fermi surface becomes equal to the thickness of the slab, a certain singularity should be observed in the field dependence of the impedance. The character of this singularity depends on the variation of the dispersion in the vicinity of the extremal section. For example, using a method analogous to that used by Heine,[2] it is easy to show that for a quadratic dispersion law the curve has a kink, and if the part of the Fermi surface under consideration is a tube of constant cross section, then the singularity is a discontinuity.

We observed this phenomenon experimentally. A flat sample was inserted into the coil of the tank circuit of an oscillator. The cross section of the coil was an elongated rectangle. A constant magnetic field was applied parallel to the surface of the sample. The oscillation frequency varied with the magnitude of field, owing to the variation of the reactive component of the impedance of the sample. The dependence of the frequency on the magnitude of the field was measured by a modulation method; the modulation frequency was 20 cps.

The samples were highly purified monocrystalline tin (about 10^{-4}% impurities), grown from a melt in dismountable crystal molds. At helium temperatures the mean free path of the electrons in the samples reached apparently $(1-3) \times 10^{-1}$ cm: the skin depth at 1—5 Mcs was about 10^{-4} cm.

One of the curves obtained is shown in the figure. The sample had a thickness of 0.54 mm. The [100] axis was perpendicular to the surface of the slab; a high-frequency and a constant magnetic field were directed along [001] axis. The temper-