OBSERVATION OF BOUND ELECTRON-NUCLEAR OSCILLATIONS IN FERROMAGNETIC FILMS

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Submitted 19 July 1971
ZhETF Pis. Red. 14, No. 5, 305 - 307 (5 September 1971)

Effects caused by dynamic interaction of the electronic and nuclear spin systems in ferromagnetic films were analyzed in [1], and the possibility was noted of the existence of bound electron-nuclear oscillations in the region of intersection of the unperturbed spin branches. Their entanglement occurs in the presence of magnetic asymmetry in the plane perpendicular to the direction of the magnetic field, for only in this case do the alternating components of the electron and nuclear moments have the necessary circular components. These conditions are realized in a magnetic film magnetized in its plane. The magnetic asymmetry for such an orientation is due to demagnetizing factors. In addition, a thin film is the only known ferromagnetic material in which a very low ferromagnetic-resonance (FMR) frequency can be realized [2], and consequently intersection of the electron and nuclear branches can be easily realized.

The object of the investigation was chosen to be a film with thickness about 1000 Å of iron-nickel-cobalt alloy containing about 40% of the latter. The film had a clearly pronounced uniaxial anisotropy in the plane, with angular dispersion ~1.5° and an anisotropy field (H_c) ~ 18 Oe. FMR with a sufficiently narrow line (2 Oe) was observed to frequencies on the order of 1 MHz; NMR from the cobalt nuclei could be observed in the frequency range 190 - 200 MHz.

It is known that when a thin film is magnetized in the plane and perpendicular to the anisotropy axis, the condition for unperturbed FMR can be written in the form

$$\omega_e = \gamma_e \sqrt{4\pi M(H - H_c)}\,, \tag{1}$$

where $\omega_e = 2\pi f$ is the circular frequency, γ_e the electron magnetomechanical ratio, M the saturation magnetization, and H the external field. It is easily seen that as $H \to H_c$ we have $\omega_e \to 0$. On the other hand, the unperturbed NMR frequency ω_n is practically independent of the external field [3] and is determined by the hyperfine field H_{hfi}:

$$\omega_n = \gamma_n |H_{hfi}|\,, \tag{2}$$

where γ_n is the nuclear magnetomechanical ratio. In the region $\omega_e \simeq \omega_n$, without allowance for the damping, calculation gives for the perturbed frequencies two non-intersecting diverging branches (see Fig. 2 of [1]). Allowance for the damping apparently (just as in the case of other "crossings") can lead to a characteristic kink on the electronic branch (Fig. 1), observed experimentally in the frequency region corresponding to NMR. When the power of the high-frequency field is increased (by approximately 10 times), one observes a straightening and a certain shift of the kink, probably as a result of nonlinear phenomena. The same figure shows, for comparison, the frequency dependence of the FMR of a film containing no cobalt. We note also that a distortion of the FMR line is observed in the region of the "crossing." Figure 2 shows the dependence of the NMR intensity on the external field, which is applied, as before, perpendicular to the easy axis. The curve has a clearly pronounced resonance character with a maximum at field values corresponding to FMR. With increasing power, the curve broadens, owing to saturation (upper curve). An interesting fact is that the observed NMR intensity in the region of the "crossing" greatly exceeds the intensity in the absence of a magnetic field when the high-frequency field is oriented perpendicular to the easy axis.

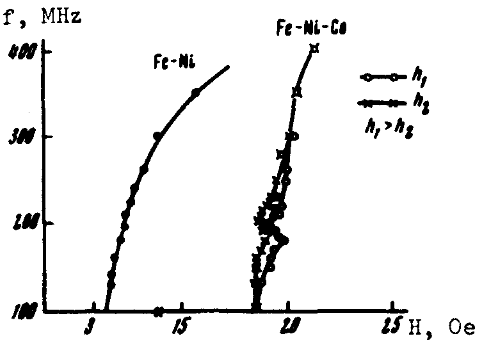

Fig. 1

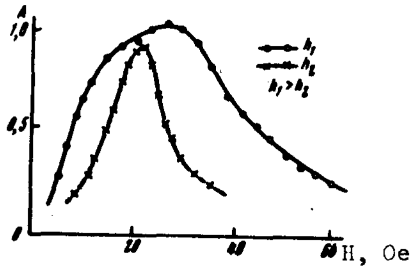

Fig. 2

Fig. 1. Frequency dependence of FMR of thin films of two compositions. The magnetic field is applied in the plane of the film and perpendicular to the anisotropy axis.

Fig. 2. NMR signal of a thin film containing Co^{59} vs. the external magnetic field applied perpendicular to the easy axis.

This is, in our opinion, direct evidence of the presence of coupled oscillations, since energy is transferred more effectively from the electron system to the nuclear one (the gain of the radio-frequency field at the nucleus is sharply increased, since the susceptibility of the electron system is increased in the FMR). Of course, such a simplified treatment of the observed effects is not quite correct, since it is difficult to distinguish between NMR and FMR in the region of coupled oscillations. One can hope that further development of the theory of coupled electron-nuclear oscillations with allowance for the damping and for the nonlinear phenomena will afford a more accurate explanation of the experimental facts.

The authors are grateful to V.A. Ignatchenko and M.P. Petrov for interest in the work.

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SCATTERING BY QUASISTATIONARY STATE IN TELLURIUM

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Submitted 22 July 1971
ZhETF Pis. Red. 14, No. 5, 307 - 310 (5 September 1971)

It was noted in an investigation of the galvanomagnetic properties of tellurium at ultralow frequencies [1] that the temperature dependence of the electric conductivity has a nonmonotonic character below 4°K [2]. A nonmonotonic behavior of $\sigma(T)$ in the same temperature region was observed recently by other authors [3]. A careful investigation of the electric conductivity of a number of longitudinal tellurium samples ($j \parallel C_3$) with minimum impurity concentration (from 6.5×10^{13} cm^{-3} at 77°K) has revealed the presence of a minimum of $\sigma(T)$ at 1.4 - 2.8°K. The figure shows the $\sigma(T)$ dependence for the most perfect crystal (with maximum mobility at T = 4.2°K). The appearance of this minimum cannot be explained within the framework of the models of the known scattering mechanisms. If it is assumed that the maximum of the electric conductivity in the region 4 - 6°K is due to the replacement of the acoustic scattering mechanism by scattering from ionized impurities, then the electric conductivity