Experimental observation of the fine structure of electron-nuclear magnetic resonance

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We observed experimentally in ferromagnetic films the electron-nuclear magnetic-resonance fine structure predicted in [1]. The coefficient of enhancement of the NMR signal by the ferromagnetic signal reaches 10^4 and makes it possible to investigate NMR by continuous methods.

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It was recently shown theoretically[1] that the spectrum of electron-nuclear magnetic resonance should have a fine structure, namely, when the FMR frequency ω_e is made to coincide with the NMR frequency ω_n, an inverse resonance (a transparency window), due to the NMR, should be observed against the background of the broad maximum of the ferromagnetic resonance. In a thin film magnetized in its own plane, the relative depth of the inverse-resonant peaks and its width are determined by the expressions

$$\frac{P_{max}-P_{min}}{P_{min}} = \frac{\omega_q^2}{4\Gamma_e\Gamma_n}, \quad \Delta\omega = 2\Gamma_n + \omega_q^2/2\Gamma_e, \tag{1}$$

where $\omega_q = \gamma_e\sqrt{4\pi AM\mu}$, γ_e is the electron ferromagnetic ratio, A is the hyperfine interaction constant, M and μ are the electron and nuclear magnetizations, and Γ_e and Γ_n are the half-widths of the noninteracting ferromagnetic resonance and nuclear magnetic resonance.

This resonant weakening of the absorption at the point where the NMR and FMR frequencies coincide can be conveniently illustrated with a vector diagram (Fig. 1).

The energy absorption is determined by the quantity M_x, which under the FMR conditions lags in phase by $\pi/2$ the external alternating field h_x (the X axis is directed along the easy magnetization axis). Under NMR conditions, μ_x lags the hyperfine field $H_{nx}^{hf} = -AM_x$ in phase by $\pi/2$. In turn, μ_x exerts a resonant reaction on M_x, namely an increment ΔM_x appears, lags $H_{ex}^{hf} = -A\mu_x$ by $\pi/2$, and consequently decreases M_x.

To observe this phenomenon we used a setup consisting mainly of a standard Q meter of the E9-5 type,

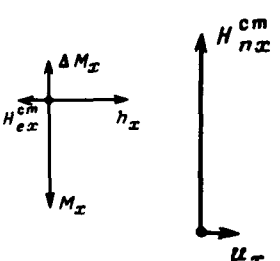

FIG. 1.

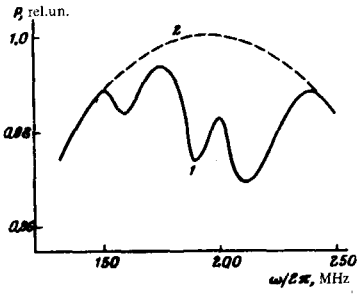

FIG. 2.

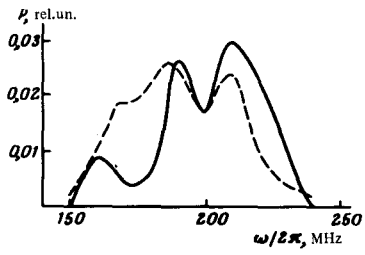

FIG. 3.

modernized to be able to register the change in the $P(\omega, H)$ losses introduced at FMR by the film in a resonant circuit whose high frequency voltage is maintained constant.

Figure 2 shows the frequency dependence of P (in relative units) at $\omega_e/2\pi \approx 190$ MHz for a film with 14% Xe, 60% Ni, and 26% Co (curve 1). The dashed curve 2 in this figure shows the form that the function $P(\omega)$ would have in the absence of a nuclear system; this curve was plotted theoretically.

The dashed line in Fig. 3 shows in arbitrary scale the NMR spectrum for the same films, plotted with a pulse spectrometer by the Hahn method. It is easily seen that the difference between curves 2 and 1 of Fig. 2 are similar in shape to this spectrum. Thus, curve 1 represents the spectrum of the inverse resonance predicted in[1]. Since the NMR spectrum in the investigated film has a large inhomogeneous broadening of complicated form, the characteristics of the inverse resonance cannot be described by the simple relations (1). For a quantitative interpretation of the observed spectrum, let us average the formulas of[1] with an arbitrary distribution function $q(\omega_n - \omega_n^0)$, where ω_n^0 is the average NMR frequency, with respect to which there is an inhomogeneous distribution of the NMR frequencies ω_n. If the natural half-width Γ_n of the NMR line is much smaller than the average scatter $\langle|\Delta\omega_n|\rangle$ of the NMR frequency, then the function $g(\omega_n - \omega_n^0$ is much smoother than the resonant factor in formula (9) of[1], and can be taken outside the integral sign at the point $\omega_n = \omega$; we thus obtain far from the point where the FMR and NMR coincide at $\omega - \omega_n^0 \ll \omega_e$

$$\langle P\rangle = 4\pi(\gamma_e Mh)^2 \frac{\Gamma_e(\omega_n^0)^2}{\omega_e^4}\left[1 + \frac{\pi\omega_q^2}{\Gamma_e} g(\omega - \omega_n^0)\right], \quad (2)$$

i.e., the frequency dependence of the NMR spectrum duplicates the form of the distribution function $g(\omega - \omega_n^0)$.

Analogously, if the relation

$$(\Gamma_n + \omega_q^2/4\Gamma_e) \ll \langle|\Delta\omega_n|\rangle \ll \Gamma_e \quad (3)$$

is satisfied, then the formula (7) of[1] can also be averaged in the vicinity of the points where FMR and NMR coincide, $\omega \sim \omega_n^0 \approx \omega_e$, and we obtain

$$\langle P\rangle = 4\pi(\gamma_e Mh)^2 \frac{\Gamma_e/4}{(\omega_e - \omega)^2 + \Gamma_e^2}\left[1 - \frac{\pi\omega_q^2}{4\Gamma_e} g(\omega - \omega_n^0)\right]. \quad (4)$$

This formula was used to determine from the experimental curves 1 and 2 of Fig. 2 the dimensionless function $\pi\omega_q^2 g/4\Gamma_e$, which is shown by the solid line in Fig. 3. We see that there is satisfactory agreement between this function and the NMR spectrum plotted by the spin-echo method (the ordinate scale of this figure corresponds to the solid curve; the scale of the echo spectrum is not indicated in the figure). The function $g\pi\omega_q^2/4\Gamma_e$ was then integrated graphically; since $\int g d\omega = 1$, the results of the integration yields the factor $\omega_q^2/4\Gamma_e$; Γ_e was determined by measuring the FMR line width. For the investigated films we obtained

$$\Gamma_e \approx 2.65\cdot 10^9 \text{ sec}^{-1}; \quad \omega_q^2 \approx 2.63\cdot 10^{16} \text{ sec}^{-2}. \quad (5)$$

From the experimentally obtained value of ω_q^2 we can calculate the nuclear magnetization $\langle\mu\rangle$, which was found to be 3.5×10^{-5} G. This agrees with the value of $\langle\mu\rangle$ calculated by the Langevin formula

$$\langle\mu\rangle = \frac{N\mu_0^2}{3kT}\langle H_n\rangle \approx 1.87\cdot 10^{-5} \text{ G}. \quad (6)$$

Here $N = 2.3\times10^{22}$ cm^{-3} is the concentration of the Co nuclei in this alloy, μ_0 is the magnetic moment of the cobalt nucleus, k is the Boltzmann constant, and T is the absolute temperature.

The discrepancy between the theoretically calculated and the experimentally determined values of $\langle\mu\rangle$ seems to be connected with the inaccuracy with which Γ_e and N are determined.

The gain of the inverse NMR signal, observed against the background of the FMR at $\omega_e \sim \omega_n^0 \sim \omega$, in comparison with the NMR signal observed far from the FMR at $\omega \sim \omega_n^0 \ll \omega_e'$, is given by

$$K = (\omega_e')^4/(2\Gamma_e\omega_n^0)^2. \quad (7)$$

Since $\omega_n^0 \ll \omega_e'$, it follows that K can reach 10^3–10^4.

Thus, by using inverse resonance, we can investigate the NMR spectrum by a simple continuous method, and also determine $\langle\mu\rangle$.

[1]V.A. Ignatchenko and V.I. Tsifrinovich, Zh. Eksp. Teor. Fiz. 68, 672 (1975) [Sov. Phys.-JETP 41, No. 2 (1975)].