Transverse nuclear relaxation induced by low-frequency fields in magnetic media

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(Submitted 24 January 1983)
Zh. Eksp. Teor. Fiz. **85**, 962–966 (September 1983)

It is found that an alternating magnetic field h has a strong effect on the relaxation of Cu^{63} and Co^{59} nuclei in a ferromagnetic iron host. The effective transverse relaxation time decreases with increasing amplitude of the field h, and increases when a constant magnetic field is superimposed. It is shown that these effects are due to the motion of the micromagnetic structure of the specimen and to a nonuniform variation in the nuclear-spin precession frequency.

PACS numbers: 76.60.Es

It is known that microwave pulses[1] and pulses of constant magnetic field[2,3] have an important influence on nuclear echo signals in magnetic media. It is shown below that low-frequency magnetic fields induce transverse relaxation of nuclear spins in magnetic media and, in some cases, this effect becomes very strong. The point is that the low-frequency field produces a change in the magnetic structure, namely, motion along the dynamic hysteresis loop. This motion is accompanied by a variation in hyperfine fields in which the nuclei are located, and gives rise to additional dephasing of the nuclear spins. Of course, the strongest effects are expected in materials in which the "true" transverse relaxation time T_2, measured in the absence of the low-frequency field, is maximally high, whereas the coercive force assumes its limiting low value.

In this research, the main experiments were performed with impurity Cu^{63} nuclei in ferromagnetic iron hosts. We used polycrystalline film specimens of thickness between 0.1 and 5 μm on glass substrates. The films were produced by plasma-ion or vacuum thermal deposition techniques. The effective transverse relaxation time T_2^{eff} was measured by the spin-echo method at helium temperatures. (From the methodological point of view, the measurement of T_2^{eff} on film specimens has a number of advantages as compared with measurements on bulk specimens.[4,5])

We have found that T_2^{eff} is exceedingly sensitive even to weak alternating magnetic fields $h_0 \sin \Omega t$ of frequency $\Omega / 2\pi = 50$ Hz that are induced by currents in the power-supply system. Partial magnetic screening of the circuit containing the specimen results in an appreciable increase in T_2^{eff}. Conversely, when an additional alternating magnetic field $h \sin \Omega t$ is imposed, the effective time T_2^{eff} is found to fall sharply. Figure 1a shows the echo amplitude A (or, more precisely, $\ln A$) as a function of the delay τ between resonance pulses used to excite the echo signal for $h = 0, 0.5$, and 12 Oe (straight lines 1, 2, and 3, respectively). It is clear that the reduction in the amplitude $A(\tau)$ can be described by the exponential function with good accuracy. Figure 1b shows

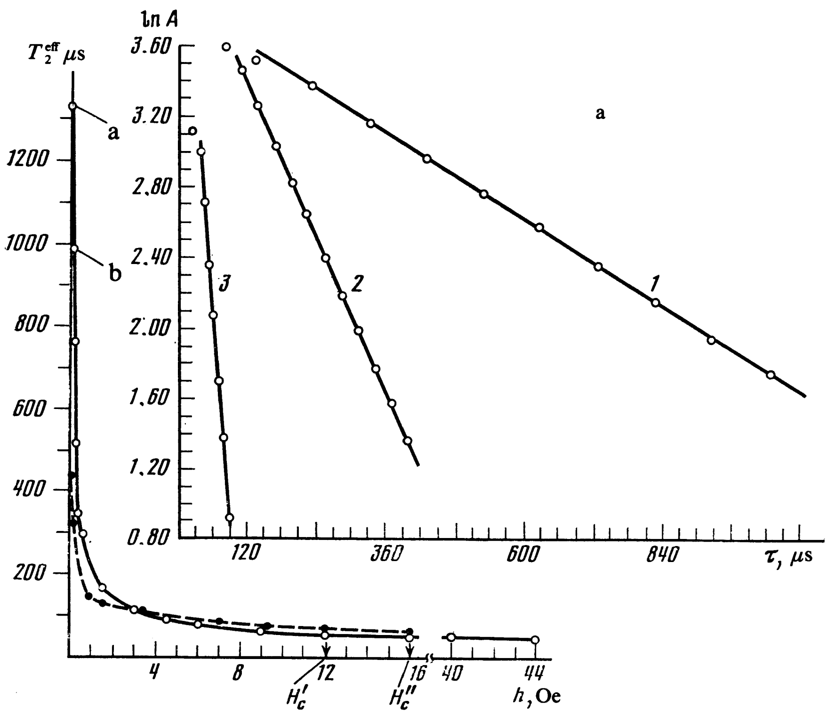

FIG. 1. a) $\ln A$ as a function of the delay time τ for $h = 0$ (curve 1), $h = 0.5$ Oe (curve 2), and $h = 12$ Oe (curve 3); b) effective transverse relaxation time T_2^{eff} as a function of h. Arrows marked H_c' and H_c'' indicate the coercive forces for the alloys FeCu and FeCo, respectively. The low-frequency field h is applied in the plane of the film at right-angles to the resonant field that generates the echo signal.

 0038-5646/83/090559-03$04.00

$T_2^{\rm eff}$ as a function of h. Point b was obtained for $h=0$ without screening the specimen, whereas point a was obtained with partial screening of the specimen. (For comparison, the dashed line in this figure shows the experimental results for Co^{59} nuclei in the alloy $Fe_{0.97}Co_{0.03}$; the other experimental curves reproduced in this paper were obtained for Cu^{63} in the alloy $Fe_{0.97}Cu_{0.03}$.) As h increases, the effective time $T_2^{\rm eff}$ first rapidly decreases, but then reaches a plateau when $h \sim H_c$ (H_c is the coercive force measured inductively). In this connection, we recall that, as h increases, the dynamic hysteresis loop becomes broader. When $h > H_s$ (H_s is the saturation field), the magnetization moves over the limiting loop which, for these particular specimens, is nearly rectangular, i.e., $H_s \approx H_c$. Thus, $T_2^{\rm eff}$ reaches its minimum value when the limiting hysteresis loop is reached, and this value for Cu^{63} is very similar to that for Co^{59}, i.e., it is determined by the properties of the host.

We emphasize that, in these experiments, the echo program is synchronized with the low-frequency field. In particular, the first resonance pulse is introduced when the voltage in the power-supply system is a maximum. The period of the low-frequency field is $T_0 = 2\pi/\Omega = 20$ ms and the delay is $\tau \leqslant 1$ ms. Thus, within the interval that includes the echo program, the phase of the low-frequency field $\psi = \omega t$ lies in the range $\psi_0 < \psi < \psi_0 + \pi/5$, where $\psi_0 = \pi/2$. This corresponds to the most slowly varying part of the hysteresis loop.

When the echo program is not synchronized with the low-frequency field (i.e., program repetition period $T \neq T_0$), the value of ψ_0 varies from program to program, and one observes an effective beat pattern for the echo amplitude. In this case, the echo program lands in different parts of the hysteresis loop, and $T_2^{\rm eff}$ varies from program to program. A similar effect is observed when a single pair of resonance pulses is introduced. In this case, the echo program lands randomly on different parts of the hysteresis loop corresponding to different values of ψ_0, and the echo amplitude varies randomly between successive pairs.

The effective time $T_2^{\rm eff}$ increases when the specimen is magnetized by a constant magnetic field H (this field is produced by Helmholtz coils fed from a TEC 88 precision source). Figure 2 shows the function $T_2^{\rm eff}(H)$. Curve 1 corresponds to $h=0$ Oe, i.e., the specimen is in the field $h_0 \sin \Omega t$ induced by currents flowing in the supply circuit. Curve 2 was obtained by superimposing a low-frequency field $h = 12$ Oe.

The appearance of the plateau for $h > H_c$ in Fig. 1b can now be explained by the competition between two processes. On the one hand, as h increases within the interval that includes the echo program, there is an increase in the magnetizing field $h \sin \psi (\pi/2 < \psi < 7\pi/10)$, which tends to cancel the micromagnetic structure and reduce its mobility. On the other hand, the rate of change in the field $h\Omega \cos \psi$ increases in the same proportion, and this accelerates the motion of the micromagnetic structure. Evidently, these two factors neutralize one another for $h > H_c$, i.e., after the limiting hysteresis loop has been reached.

We note that similar but weaker effects are observed in other magnetically-ordered materials. For example, the effective time $T_2^{\rm eff}$ for polycrystalline cobalt films falls by a factor of two when the low-frequency field amplitude $h = 60$ Oe is applied.

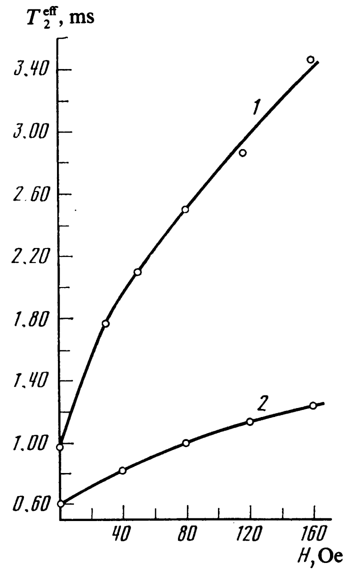

FIG. 2. $T_2^{\rm eff}$ as a function of H for $h=0$ (curve 1) and $h = 12$ Oe (curve 2). The fields H and h are applied in the plane of the film at right-angles to the resonant field.

In our experiments, we determined $T_2^{\rm eff}(h)$ for different Ω in the range 1–10^8 Hz. The following qualitative results were obtained. At low frequencies, for which $2\pi/\Omega > \tau$, the function $T_2^{\rm eff}(h)$ has a form that is similar to that reproduced for $\Omega/2\pi = 50$ Hz. At high frequencies, for which $2\pi/\Omega \ll \tau$, there is a tendency toward a reduced influence of h on $T_2^{\rm eff}$. From the qualitative point of view, this is in accordance with the model of dynamic hysteresis of micromagnetic structure. We are developing methods for the precise determination of $T_2^{\rm eff}(\Omega)$ in a broad range of Ω (for fixed h and with steps being taken to screen off laboratory stray fields with $\Omega/2\pi = 50$ Hz).

Let us now examine our data. It is clear from Fig. 2 that, in fields up to $H = 160$ Oe, the time $T_2^{\rm eff}$ has still not reached its plateau and varies appreciably with the amplitude of the low-frequency field, even though $H \gg H_s$. This means that the variation in hyperfine fields acting on nuclei is due to the motion of the micromagnetic structure which, evidently, stops in fields much higher than 160 Oe. Clearly, the motion of the micromagnetic structure is actually a variation in the orientation of magnetic moments in the specimen. Rotation of the magnetic moments leads to a change in the dipole fields due to these moments that act on the nuclei. The result of this is that the nuclear-spin precession frequency $\varkappa$ becomes a complicated function of time.

Let us consider the simplest situation, where the external magnetic field exceeds the saturation field H_s within the interval that includes the echo program. We shall suppose that the specimen is subjected to strong-enough, short, resonant field pulses, so that the nonuniformity and variation in

$\varkappa$ can be neglected. The echo signal is then proportional to[6] $\langle \exp[i(\varphi_1 - \varphi_2)]\rangle$, where

$$\varphi_1 = \int_{t_1}^{t_1+\tau} \varkappa(t')\,dt', \quad \varphi_2 = \int_{t_2}^{t} \varkappa(t')\,dt', \tag{1}$$

t_i is the time at which the ith pulse is turned off ($i = 1,2$), and the angle brackets represent averaging over the specimen.

A simple model for $\varkappa(t)$ that admits of an exact solution may be envisaged as follows. Let the spin precession frequency take the form $\varkappa = \varkappa_0 + \Delta(t)$, where $\varkappa_0$ is a random, time-independent quantity and $\Delta(t)$ is a dichotomic, random process,[7,8] i.e., $\Delta(t)$ can assume only the two values $\pm\Delta$ which follow one another randomly along the time axis. Assuming that $\varkappa_0$ and Δ are independent, and averaging $\exp[i(\varphi_1 - \varphi_2)]$ over the ensemble of realizations of $\Delta(t)$ and over the distribution of $\varkappa_0$, we obtain[9] the following results.

The dependence of the echo amplitude A on the delay τ is appreciably dependent on the dimensionless parameter $2T_c\Delta$, where T_c is the characteristic correlation time for the function $\Delta(t)$ and $2T_c$ is the average time interval between successive jumps in $\Delta(t)$. When $2T_c\Delta > 1$, the echo amplitude oscillates with increasing τ. When $2T_c\Delta < 1$, the function $A(\tau)$ takes the form of a linear combination of three exponentials:

$$A = (2\beta^2)^{-1} \exp(-\tau/T_c)$$
$$\times[\nu(\nu+\beta)\exp(2\beta\tau) - 2\Delta^2 + \nu(\nu-\beta)\exp(-2\beta\tau)],$$
$$\nu = (2T_c)^{-1}, \quad \beta = (\nu^2 - \Delta^2)^{1/2}. \tag{2}$$

When $T_c\Delta \ll 1$, the first term in (2) is the most important, and the function $A(\tau)$ can be approximately represented by a single exponential $A = A_0\exp(-2\tau/T_2')$, where $T_2' = 1/T_c\Delta^2$ is the induced transverse relaxation time. (The quantities T_2, T_2', and T_2^{eff} are related by $1/T_2^{\text{eff}} = 1/T_2 + 1/T_2'$.) Thus, the above simple model leads to the following results: the function $A(\tau)$ is an exponential when $T_c\Delta \ll 1$, and a reduction in T_2' can be connected either with an increase in the jump Δ or an increase in the mean interval of time between successive jumps.

We note in conclusion that, although we have considered relaxation induced by a low-frequency, a similar analysis would be valid for nonresonance high-frequency fields.

The effects that we have studied can be used to investigate dynamic hysteresis, and the high sensitivity of T_2^{eff} to the amplitude and phase of the alternating magnetic field may find practical applications.

The authors are indebted to V. A. Ignatchenko for useful suggestions.

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Translated by S. Chomet