Electromagnetic excitation of ultrasound in gadolinium single crystals

A. V. Andrianov, A. N. Vasil'ev, Yu. P. Gaĭdukov, R. S. Il'yasov,
and O. D. Chistyakov
M. V. Lomonosov Moscow State University

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The temperature and field dependences of the conversion efficiency of electromagnetic and ultrasonic waves in Gd single crystals are studied. The longitudinal ultrasound excitation peak is detected at the paramagnet-ferromagnet phase transition. The conversion efficiency changes dramatically during the spin-flip transitions.

Interest in the study of the interaction of elastic, spin, and electromagnetic waves in magnetically ordered materials[1,2] has stimulated the development of new methods of studying this interaction. Additional information on the magnetoelastic interactions can be obtained from measurements of the efficiency of conversion of the electromagnetic and ultrasonic waves in magnetic materials. Theoretical[3,4] and experimental[5–10] studies in this field were carried out with 3*d* magnetic materials, in which, in particular, the efficiency of electromagnetic excitation of the longitudinal ultrasound was found to increase sharply at the phase-transition temperatures at the Curie point.[9,10]

In the present letter we report the results of the first experimental study of the temperature and field dependences of the electromagnetic and acoustic conversion in gadolinium, a 4*f* magnetic material. Although the anisotropic magnetostriction of this metal is much smaller than that of other rare-earth metals, the small magnetic-anisotropy constants and a large volume magnetostriction of Gd, which is seen most clearly at the Curie point ($T_C \simeq 290$ K), can bring about an effective conversion.

Two parallel-face plates, whose normals run in the same direction as the sixfold symmetry axis ($\mathbf{n} \| \mathbf{c}$) and the twofold symmetry axis ($\mathbf{n} \| \mathbf{a}$), were used in the measurements. The first sample was a rectangular plate, measuring $1.16 \times 0.59 \times 0.12$ cm and the second sample was a disk 0.066 cm thick and 0.91 cm in diameter. The chemical composition of the tested sample is given in Ref. 11. The samples were placed into solenoidal induction coils to which 2-kV rf pulses were applied, with a filling at 5 MHz. The strength of the alternating magnetic field h at the metal surface was $\sim 10^2$ Oe. The static magnetic field $\mathbf{H}$ was directed along the plane of the samples. Using this experimental geometry, we were able to excite in the samples longitudinal elastic waves which propagated along the normal to the plate surface and which were detected by the same coil because of the inverse electromagnetic-acoustic conversion. The detectable signal is $K = E_1 E_2 \exp(-k\Gamma d)$, where E_1 and E_2 are the efficiencies of the direct and inverse transformations, Γ is the ultrasound attenuation, d is the plate thickness, and k is the number of the echo signal. The measurements were carried out in a magnetic field up to 10 kOe at temperatures 80–300 K.

At a fixed value of the field H and fixed temperature variation, the conversion efficiency reaches the maximum values in a peak-like manner in the region where the sample undergoes a transition from the paramagnetic to the ferromagnetic state. The $K(T)$ curves for three values of H are shown in Fig. 1. We see that in a narrow temperature interval on the order of several degrees, the value increases by a factor of 10^3–10^4 and then decreases as sharply by a factor of 10^1–10^2. The maximum of the conversion efficiency and its position with respect to the temperature depend on the magnetic field. As can be seen from Fig. 2, the longitudinal ultrasound excitation peak is shifted up the temperature scale with increasing H and its value goes through a maximum at $H \sim 1$ kOe.

Below T_C the conversion efficiency in the weakest fields used experimentally remains constant up to $T_{\text{thr}} = 235$ K, after which K decreases rapidly and below T_{thr} the electromagnetic-acoustic conversion signal is virtually undetectable. The measurements in stronger fields ($H_1 = 0.5$ kOe, $H_2 = 1$ kOe, $H_3 = 3$ kOe) show that, first, the change in the slope on the $K(T)$ curve at T_{thr} becomes less pronounced as H is raised and, secondly, at $T < T_{\text{thr}}$ the ultrasound is generated again.

In the ferromagnetic region ($T < T_C$) the longitudinal ultrasound is excited after a threshold is reached: Up to a certain field H_{thr}, the conversion efficiency is low, and the ultrasound generation is detected at the limiting sensitivity of the apparatus. The generation amplitude increases sharply upon reaching the threshold field H_{thr}, and k increases ten- to one-hundredfold. The generation amplitude will then either decrease as sharply as before [the peak of the $k(H)$ curve] or will be nearly independent of H (the jog on the curve), depending on the experimental geometry. The field H_{thr} (T) curve for the sample $\mathbf{n} \| \mathbf{c}$ and $\mathbf{n} \| \mathbf{a}$ is shown in Fig. 3.

To interpret the measured field and temperature dependences of the electromagnetic-acoustic conversion in Gd, we used the data on its magnetic properties[12] and temperature evolution of the damping Γ of longitudinal ultrasound.[11] At $T = 290$ K

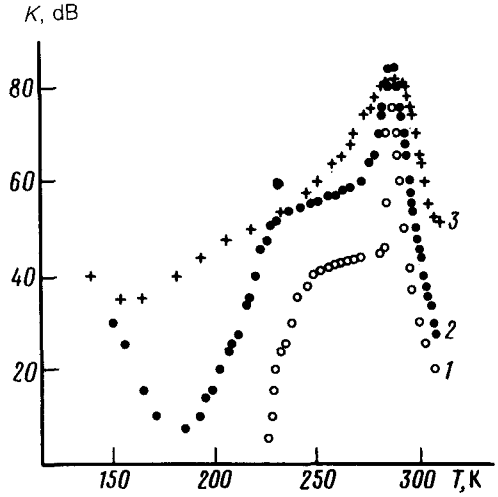

FIG. 1. Temperature dependences of a double electromagnetic-acoustic conversion signal K in Gd: $\mathbf{n} \| \mathbf{c}$, $\mathbf{H} \| \mathbf{h} \| \mathbf{a}$. $H_1 = 0.5$ kOe, $H_2 = 1$ kOe, $H_3 = 3$ kOe.

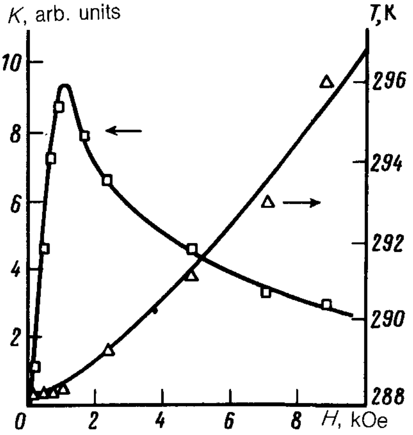

FIG. 2. Field dependences of the amplitude and temperature at the longitudinal ultrasound excitation peak at the "paramagnet-ferromagnet" transition: **n**||**c**, **H**||**h**||**a**.

gadolinium becomes a "paramagnet–easy-axis ferromagnet" with a magnetization vector parallel to the hexagonal axis of the crystal. At $T_{\mathrm{thr}} = 235$ K an easy-magnetization axis cone appears and the angle between the hexagonal crystal axis and the magnetization vector increases rapidly with decreasing temperature, reaches 70° at 190 K and then decreases to 35° at 80 K. At T_C and T_{thr} we see several damping peaks; Γ in this case varies between 0.06 and 0.3 cm^{-1} and increases to 1.2 cm^{-1} over the interval from T_{thr} to 120 K.

Analysis of the magnetic structure of Gd and of the $\Gamma(T)$ curve in the material under study shows that all important features on the $K(H, T)$ curves are attributable solely to the change in the electromagnetic-acoustic conversion efficiency.

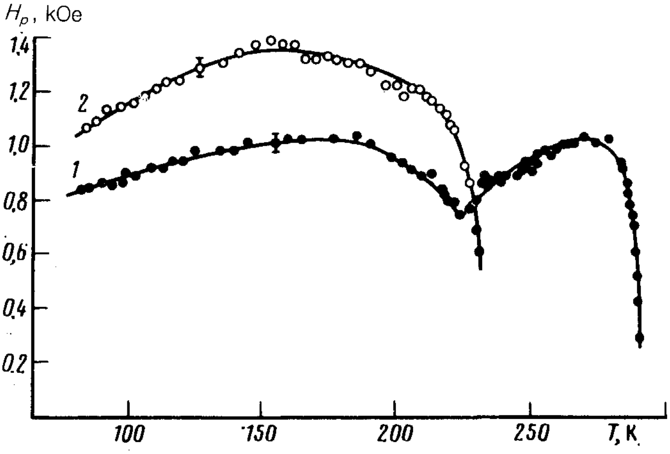

FIG. 3. Temperature dependences of the threshold field H of the sample with **n**||**c**, **H**||**h**||**a** (curve 1) and the sample with **n**||**a**, **H**||**h**||**c** (curve 2).

Since under the experimental conditions the rf magnetic field h modulates the static stress, the amplitude of the excited ultrasound is proportional to $\partial \lambda / \partial H$ (to the field derivative of the magnetostriction λ). The volume magnetostriction of Gd peaks at T_C and vanishes at T_{thr}. The magnetic field H displaces upward the temperature of the transition to the paramagnetic state and changes the value of the derivative $\partial \lambda / \partial H$. At the Curie temperature the $K(H, T)$ peak is apparently caused by the joint action of several factors. At this temperature the magnetoelastic interaction increases sharply, the magnetic susceptibility reaches a maximum value, and the depth of the magnetic field penetration decreases sharply. Each of these factors taken separately can lead to an increase in the amplitude of the generated ultrasound. The threshold nature of ultrasound generation at $T < T_C$, in our view, is a consequence of the field-induced (H_{thr}) spin-flip transitions, while the energy of the magnetic field H is equal to the energy of the anisotropy. Under the condition $T_{\text{thr}} < T < T_C$, with our experimental geometry the easy-magnetization axis of the sample $n \| a$ runs along the field **H**, and the excitation threshold in this case is absent (curve 2 in Fig. 3). Below T_{thr} the fact that $H_{\text{thr}} \neq 0$ means that a structure such as the easy-magnetization axis cone "collapses." In other words, the vertex angle of the cone in the field H_{thr} is reduced to zero. In the case of the sample with $n \| c$, the temperature evolution of H_{thr} is attributable to the fact that the spin flip to the basal plane parallel to H occurs either from the "easy-magnetization-axis" state at $T_{\text{thr}} < T < T_C$ or from the "easy-magnetization-axis cone" state at $T < T_{\text{thr}}$ (curve 1 in Fig. 3).

Any type of magnetic-field-induced or temperature-induced magnetic phase transitions can thus cause a sharp change in the efficiency of electromagnetic excitation of ultrasound in Gd. A quantitative analysis of the $K(H, T)$ curves requires a detailed consideration of the dynamics of the spin subsystem in the phase transitions.

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