INDUCED NONCOLLINEAR MAGNETIC STRUCTURE IN RARE-EARTH FERRITE-GARNETS

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Measurements of the magnetocaloric effect in Gd, Dy, and Ho ferrite-garnets, made in the compensation-temperature region, made it possible to detect the occurrence of induced noncollinear magnetic structures in comparatively weak fields (up to 20 kOe). It is shown that measurements of the magnetocaloric effect provide a new possibility of investigating noncollinear spin structures induced by an external field.

IN theoretical papers of Tyablikov[1], Gusev and Pakhomov[2], and Clark and Callen[3] it has been shown that in ferrimagnets, as a result of competition between the external field and a negative exchange interaction between the sublattices, a noncollinear magnetic structure can occur in a certain field interval $H_{c1} \le H \le H_{c2}$.

Noncollinear structure induced by an external field has been observed recently in Ho garnet by study of the Faraday effect[4], in Dy garnet by measurement of the magnetostriction[5], and by measurements of the magnetization and of optical properties in Yb garnet[6]. For the majority of rare-earth ferrite garnets, in the low-temperature range, the critical fields H_{c1} and H_{c2} are very large (500 to 1000 kOe); but near the magnetic compensation temperature T_c, according to calculation[3], these fields should decrease rapidly.

In the present research, measurements of the magnetocaloric effect ΔT were used to observe the noncollinear magnetic structure induced by an external field near T_c in rare-earth ferrite-garnets. It was shown that this effect is very sensitive to the occurrence of induced noncollinear structures; this makes possible the observation of such structures in relatively weak fields (up to 20 kOe).

Earlier investigations of the magnetocaloric effect in rare-earth garnets[7,8] showed that over a wide temperature interval, far from the Curie point, the magnetocaloric effect is determined principally by the paraprocess in the rare-earth sublattice. Here $\Delta T > 0$ for $T < T_c$, where a paraprocess of the ordinary ferromagnetic type occurs, and $\Delta T < 0$ for $T > T_c$, where a paraprocess of antiferromagnetic type occurs[8]. These measurements relate to the collinear phase, that is to the range $H < H_{c1}$.

We shall consider the behavior of the magnetocaloric effect in the noncollinear phase. It has been shown[3] that in a certain range of temperatures (T_{c1} to T_{c2}), a noncollinear magnetic structure occurs in a rare-earth ferrite-garnet (considered as a Néel ferrimagnet) on application of a sufficiently strong external field. In this case, the total magnetization of the ferrite, M_{tot}, is the vector sum of the magnetization M_R of the rare-earth sublattice and the magnetization M_{Fe} of the "combined" iron sublattice and according to[3] is equal to

$$M_{tot} = M_R + M_{Fe} = H / I_{ad-c}, \tag{1}$$

where I_{ad-c} is the parameter of exchange interaction between the rare-earth and "combined" iron sublattices. Since the value of I_{ad-c} is practically independent of temperature over a wide temperature interval, it follows from (1) that M_{tot} also should be independent of temperature. In Fig. 1 the relation (1) is represented in the form of a vector diagram. The invariability of the value of M_{tot} in the noncollinear phase is determined by the fact that the values of M_R and M_{Fe} and the angles θ_R and θ_{Fe} change in such a way that M_{tot} remains constant[3].

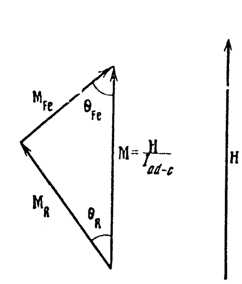

FIG. 1

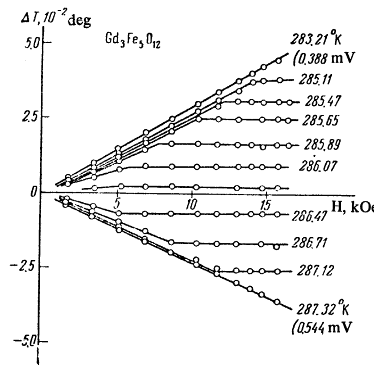

FIG. 2

FIG. 1. Vector diagram for the total magnetization in the noncollinear phase [3].

FIG. 2. Field dependence of the magnetocaloric effect ΔT in the region of the compensation temperature T_c for Gd garnet. The temperatures shown on the curves were calculated on the basis of the assumption that over a small temperature interval, the thermal emf of the thermocouple is linearly related to the temperature.

According to thermodynamics, in adiabatic magnetization

$$dT = \frac{T}{C_H}\left(\frac{\partial M_{tot}}{\partial T}\right)_H dH, \tag{2}$$

therefore in the noncollinear phase, where $\partial M_{tot}/\partial T = 0$, $dT = 0$ also; that is, the magnetocaloric effect should be absent. Thus the behavior of this effect in rare-earth ferrite-garnets during a change of the external field should be as follows: in the range $T < T_c$,

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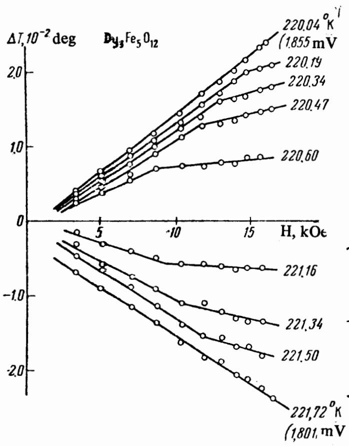

FIG. 3

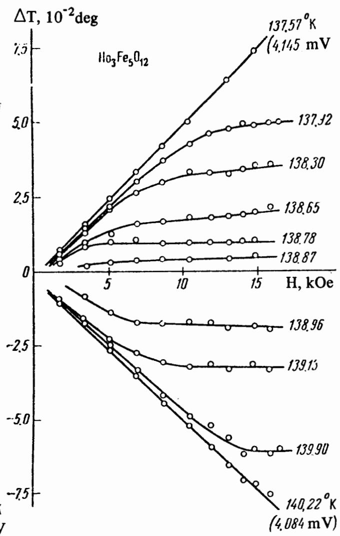

FIG. 4

FIG. 3. Dependence ΔT(H) in the T_c region for Dy garnet.
FIG. 4. Dependence ΔT(H) in the T_c region for Ho garnet.

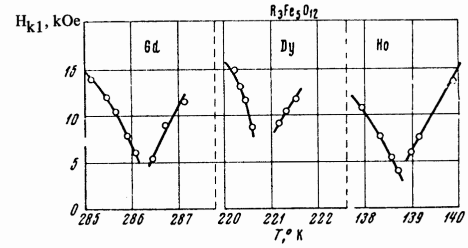

FIG. 5. Temperature dependence of critical fields for Gd, Dy, and Ho garnets.

in fields $H < H_{c1}$, where the collinear structure is preserved, an increase of ΔT should be observed; and then on transition to fields $H > H_{c1}$ (with appearance of a noncollinear structure, for which dT = 0), since we are measuring the integral effect ($\Delta T = \int_0^H dT$), saturation of the magnetocaloric effect should be observed. In the range $T > T_c$ (where $\Delta T < T$), the dependence of ΔT on H will be similar.

Figures 2—4 show the results of measurements of ΔT(H) for Gd, Dy, and Ho garnets in the immediate vicinity of T_c. The measurements were made by the method described in[7].

It is seen from Figs. 2—4 that the ΔT-effect in the range $T < T_c$ increases with increase of field, and approaches saturation with attainment of a field H_{c1}; breaks occur on the curves ΔT(H). Correspondingly, in the range $T > T_c$ the magnetocaloric effect increases with increase of field, remaining negative, and then saturates. The saturation of the magnetocaloric effect on transition to the noncollinear phase can be explained, according to[3], by the fact that the paraprocess in the rare-earth sublattice ceases in the noncollinear phase, since the increase of magnetization with field in this phase occurs without change of the degree of magnetic order in the rare-earth sublattice. In other words, the absence of a paraprocess in the rare-earth sublattice, in the range in which angular configurations exist, is explained by the fact that the total effective field acting on the rare-earth sublattice, which is the vector sum of the external field H and the exchange field of the iron sublattice $I_{ad-c}M_{Fe}$, remains constant[3].

Thus analysis of the ΔT(H) curves supports the assumption[3] that on transition to the noncollinear phase, the magnetization process of a ferrite becomes more complicated: the paraprocess in the rare-earth sublattice ceases, and there occurs a simultaneous rotation of the magnetic moments of the sublattices, M_R and M_{Fe}.

It should be noted that everything said above is, strictly speaking, valid only on the assumption of weak c-c interaction in the rare-earth sublattice and of absence of magnetic anisotropy.

From a comparison of the results of the measurements for Gd ferrite-garnet (Fig. 2) with the curves obtained for Dy and Ho ferrite-garnets (Figs. 3 and 4) it follows that the transition to the noncollinear structure takes place more abruptly in the first than in the Dy and Ho garnets. Furthermore, on the curves for the Dy and Ho garnets in fields $H > H_{c1}$ there is still observed some increase of ΔT; this is evidently due to the influence of magnetocrystalline anisotropy. When account is taken of the latter, M_{tot} does not remain constant in the noncollinear phase[9].

Figure 5 shows the dependence of H_{c1} on temperature for the ferrite-garnets that we have investigated. The values of H_{c1} were determined by extrapolation of the linear sections of the ΔT(H) curves, near the break, to their mutual intersection. The values of H_{c1} are smallest in the immediate vicinity of T_c and increase rapidly both on lowering and on raising of the temperature; on departing from T_c by more than one degree, these fields already exceed 16 kOe.

In[3], the following expression is given for the field H_{c1}:

$$H_{c1} = I_{ad-c}|M_R - M_{Fe}|.$$

From this formula it is seen that at the compensation point, where $M_R = M_{Fe}$, the field $H_{c1} = 0$, and the curve $H_{c1}(T)$ should go through zero. We have made an approximate estimate of H_{c1} for the T_c region, starting from[3]; for Gd ferrite-garnet, a value of H_{c1} for $T = T_c - 1°$ of the order of 10 kOe was obtained. Experiment gave 15 kOe for this temperature, which in itself is sufficiently good agreement. Allowance for magnetic anisotropy[9] leads to the result that the curve $H_{c1}(T)$ does not go through zero at the compensation point. Estimation of the value of H_{c1} at the compensation point itself (according to the formula $H_{c1} \geq \sqrt{H_a H_{eff}}$, where H_a is the anisotropy field) gave, for the garnets investigated, 3 to 5 kOe.

Thus our investigations have established that near the magnetic compensation point, application of comparatively weak magnetic fields (from 4 to 16 kOe) leads to the appearance of noncollinear magnetic structures in the Gd, Dy, and Ho rare-earth ferrite-garnets. The measurements have also shown that the magnetocaloric effect is sensitive to the occurrence of noncollinear magnetic structures in rare-earth ferrite-garnets. Such measurements provide new possibilities for study of induced magnetic structures in ferrimagnets. The magnetocaloric effect is more sensitive to the occurrence of noncollinear magnetic structures than is the magnetization, because in the field interval H_{c1} to H_{c2} the ΔT-effect saturates, whereas the magnetization increases in that field interval (changing its slope slightly at $H = H_{c1}$).

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