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TURNING OF MAGNETIC SUBLATTICES AND ANOMALIES OF THE COTTON-MOUTON EFFECT IN TERBIUM IRON GARNET AND IN HEMATITE

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We have recently proposed a new exchange-dipole mechanism of quadratic magnetooptic effects in ferro- and antiferromagnets [1], leading to unusually high values of the Cotton-Mouton effect (CME) in crystals below $T_{C,N}$ [2]. The large value of the CME, the availability of strong light sources of varying wavelengths, and the relative simplicity of observing the CME uncover interesting possibilities for the investigation, by means of a new magnetooptic method, of the exchange interactions in crystal, of the temperature dependences of the sublattice magnetizations, of the orientations of the magnetic moments, and of other phenomena.

In this paper we present the results of an investigation of the temperature dependence of the CME in terbium iron garnet $Tb_3Fe_5O_{12}$ and in the antiferromagnet α-Fe_2O_3 (hematite), and of observations of the CME anomalies connected with the reorientation of the magnetic sublattices.

The CME was investigated at a wavelength $\lambda = 1.15\ \mu$, at which $Tb_3Fe_5O_{12}$ and hematite have a transparency of several cm^{-1}. The CME was investigated in a plate of $Tb_3Fe_5O_{12}$ cut parallel to the (110) plane, with the magnetic field directed along the [100] axis. In the case of hematite, the plate was perpendicular to the optic axis and the magnetic field was in the plane of the plate.

The temperature dependence of the CME in $Tb_3Fe_5O_{12}$ is shown in Fig. 1. The sign of the effect is opposite that of the CME in yttrium iron garnet $Y_3Fe_5O_{12}$ [12]. This difference in signs indicates that the terbium sublattice and the summary iron sublattice result in opposite signs of the effect, and that the CME from the iron ions is lower than that from the terbium ions at room temperature. It can be assumed approximately that the contributions made to the effect by the rare-earth and by the iron sublattices are independent:

$$\Delta n_{CM}(Tb_3Fe_5O_{12}) = \Delta n(M_{Tb}^2) - \Delta n(M_{Fe}^2), \qquad (1)$$

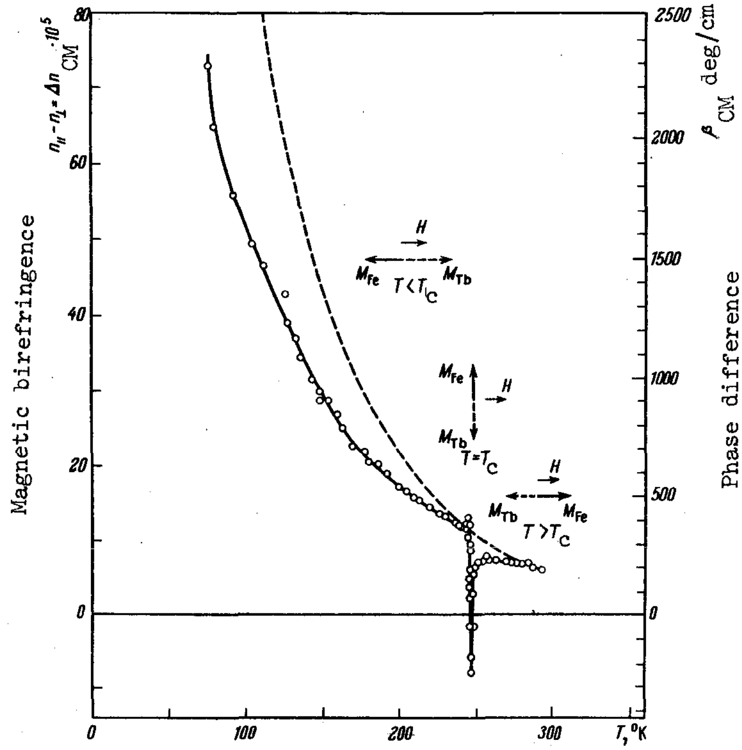

Fig. 1. Temperature dependence of Cotton-Mouton effect in terbium iron garnet in a magnetoc field H = 22 kOe. Points - experimental data; dashed line - calculated temperature dependence. The orientation of the magnetic moments in the external field are shown schematically for $T > T_c$, $T = T_c$, and $T < T_c$.

where M - magnetizations of the sublattices.

Knowing Δn_{CM} at room temperature for $Y_3Fe_5O_{12}$ and $Tb_3Fe_5O_{12}$ and the temperature dependence of the magnetization of the sublattices [3], we can calculate the temperature dependence of the CME for $Tb_3Fe_5O_{12}$. The corresponding calculated curve is shown dashed in Fig. 1. The experimental CME curve increases more slowly, but nevertheless the effect becomes quite large at 77°K: $\Delta n_{CM} = 0.73 \times 10^{-3}$, corresponding to a phase difference of 2300 deg/cm for the two waves. The discrepancy between the experimental and calculated CME curves may be due to a number of factors: 1) insufficiently strong external magnetic fields, 2) neglect of the interaction between the sublattices, 3) temperature shift of the electronic states of Tb^{3+} and Fe^{3+}, which determine the polarizability, etc.

The CME anomalies at the compensation point T_c (Fig. 2) are obviously due to the reorientation of the magnetic moments of the Tb^{3+} and Fe^{3+} sublattices relative to the external magnetic field H. Below and above T_c the sublattices are oriented parallel or antiparallel to H andby virtue of the quadratic dependence of the CME on the magnetization the effect from each sublattice retains its sign (and approximately its magnitude). However, in the immediate vicinity of T_c and at the point itself the garnet sublattices are "turned," i.e., they are perpendicular to H. The orientation of the sublattices at T_c in a plane perpendicular to H depends on the anisotropy in this plane. In the case of the CME, the following to sublattice orientations at T_c are important: 1. The sublattices are perpendicular to H and directed along the light, i.e., the case of the Faraday-effect geometry [4]. At this orientation the CME should vanish at T_c. 2. The sublattices are perpendicular to H and to the light-propagation

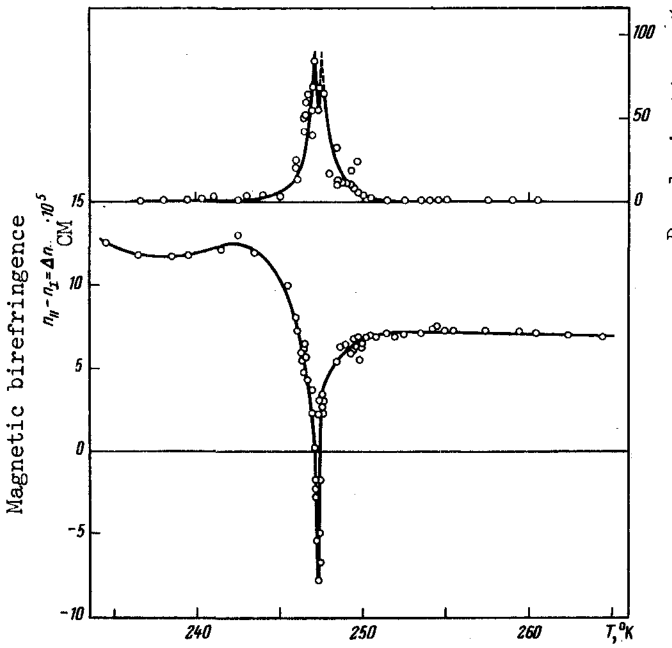

Fig. 2. Anomaly of Cotton-Mouton effect near the magnetic compensation point in $Tb_3Fe_5O_{12}$ in a field H = 22 kOe (lower curve). Upper curve - depolarization of the light passing through the crystal.

direction. In this case the magnitude of the effect should be approximately the same, but of opposite sign. The observed reversal of sign without large changes in magnitude indicates that the turning of the sublattices occurs in a plane perpendicular to the propagation of the light and parallel to the external magnetic field. It is also possible to assess the dynamics of the turning not only from the character of the CME near T_c, but also from the depolarization of the light transmitted through the crystal (upper curve of Fig. 2).

A jump of about 20% is observed in the CME on going through T_c. This jump can be attributed to the fact that the susceptibilities of the rare-earth and iron sublattices increase the CME below T_c and increase it above T_c. The jump should be proportional to χH, where χ is the combines susceptibility of the sublattices. With decreasing H, a decrease of the jump was actually observed. The same considerations make it possible to explain the observed decrease of the CME with increasing H when $T > T_c$, whereas at $T < T_c$ an increase of H leads to an increase of the CME.

The temperature dependence of the CME recals similar dependences of the magnetostriction constants of rare-earth iron garnets [5].

These two phenomena have apparently much in commen. We note, however, that if the magnetostriction is determined by the ground state of the magnetic ion in the crystal, then the polarizability (and consequently also the magnetooptic effects) depends on all electronic states of the magnetic ion.

The temperature dependence of the CME is shown in Fig. 3. Below the temperature of the magnetic transition $T_M = 353°K$, the spins of the two antiferromagnetic sublattices are oriented along the optical axis, and when the light propagates in this direction there should be no CME. Above T_M the moments of the sublattices lie in the basal plane and are oriented perpendicular to the field H and to the direction of the light. Thus, the magnetic transition

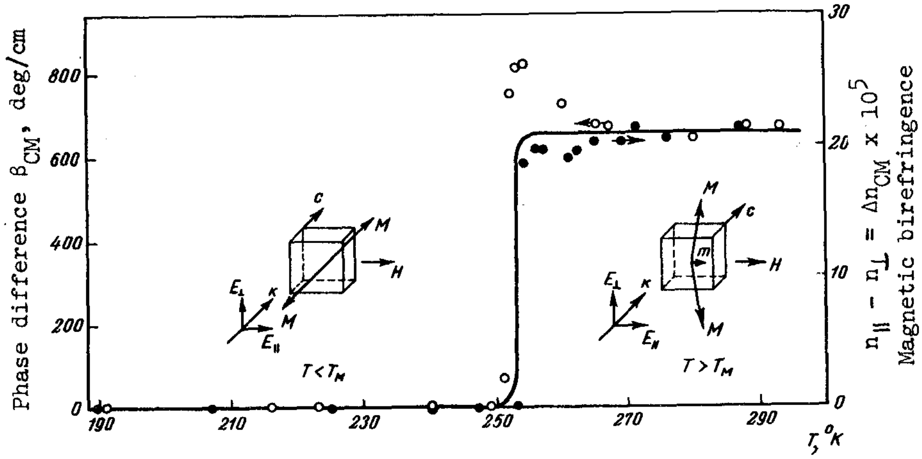

Fig. 3. Temperature dependence of Cotton-Mouton effect in hematite, in a field H = 6.7 kOe.

transition leads to the suppression of the Cotton-Mouton effect.

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CONCERNING THE GRAVITATIONAL MOMENT OF THE PROTON

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The possible existence of a proton gravitational moment violating CP-invariance was considered theoretically earlier [1 - 3].

In the presence of such a moment, the frequency of the proton magnetic resonance depends on the direction of the magnetic field, as follows from the form of the interaction Hamiltonian [3]:

$$(\mu\vec{H} + \xi\vec{g})\vec{\sigma}.$$

Here μ and ξ are the magnetic and gravitational moments of the proton, respectively, $\vec{H}$ is the magnetic field intensity, $\vec{g}$ the acceleration due to gravity, and $\vec{\sigma}$ the spin operator. The maximum change of the proton magnetic resonance frequency, which equals $4\xi g/\hbar$, should occur when the vertical magnetic field is reversed.

The author of [4] did not find this effect, but he did observe that the arithmetic mean value of the proton resonance frequencies in fields directed vertically upward and downward differs from the mean resonance frequency in horizontal fields.

According to existing notions, no such even effect should appear, accurate to terms of