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ISING STATE OF FERRIMAGNET INDUCED BY HIGH MAGNETIC FIELDS

A. S. Lagutin and A. V. Dmitriev

Kurchatov Institute of Atomic Energy, 123182, Moscow, U.S.S.R.

Abstract. - Magnetization and differential magnetic susceptibility measurements are presented for single crystals of \( \text{Tb}_x\text{Y}_{3-x}\text{Fe}_5\text{O}_{12} \) \( (x < 0.5) \). Several anomalies of the magnetization were observed in fields 7-30 T indicating the appearance of a highly anisotropic state of the rare earth ions. The exchange field between rare earth and ferrous subsystems was determined.

1. Introduction and experimental

Some jumps of magnetization were observed earlier for the \( \text{Y}_3-x\text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) single crystals \( (x < 0.65) \) at \( T = 4.2 \) K in magnetic fields near 10 T [1, 2]. The model of the energy level inversion of the rare earth ions developed in [3] was used in [2] for the result explanation. If such process takes place in fields \( H_1 < H_{ex} \), than the reversal level inversion should occur at \( H_2 > H_{ex} \) \( (H_{ex} \text{- exchange field between the rare earth and ferrous subsystems of a ferrimagnet}) \). Moreover, \( H_1 \) and \( H_2 \) have to arrange relatively from \( H_{ex} \) symmetrically. The ground state inversion is accompanied usually by the jumps of a magnetization [4, 5]. But only anomalies in fields \( H_1 \) were observed at the magnetization process of the \( \text{Y}_3-x\text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) \( (x = 0.26) \) at \( T = 4.2 \) K and in fields up to 50 T [6]. It was found also in [6], that the magnetization process of the \( \text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) ions proceeds by means of several first order phase transitions. Similar behaviour is typical for the strongly anisotropic \( \text{Ising} \) magnets [7]. Experiments carried out on \( \text{Y}_3-x\text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) system [8] were shown an excellent agreement with the theory [7]. Unfortunately, our attempts to use \( Z \text{Ising model of ferrimagnet} \) [7] without an essential modification or the alternative \( X \text{Ising model for the description of the} \ (\text{Y} \text{Fe}) \text{IG properties did not reach a success.} \)

In this communication we present detailed magnetization and differential magnetic susceptibility (DMS) measurements of the \( \text{Y}_3-x\text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) \( (x = 0.1 - 0.41) \) single crystals at 4.2 K and in magnetic fields up to 40 T, oriented along the main crystal axes. In order to describe observed magnetization and DMS anomalies we have to assume an appearance of the new state of the \( \text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) ions in fields near 10 T, which is much more anisotropic, than the initial one.

The magnetic measurements in pulsed magnetic fields up to 40 T were carried out using the inductive method [9]. Data collection \( (M, x, H) \) were performed by means of transient recorder and microcomputer.

Single crystals of the \( \text{Y} \text{Fe} \text{IG} \) were prepared at Moscow State University from oxides with 99.99 % purity. The cylinder shaped samples with a diameter 2-3 and length 4-5 mm were used for the magnetic measurements. Magnetic field was oriented with an error less than 3° relatively of crystal axes.

2. Results

Magnetic moment field dependences of the \( \text{Y} \text{Fe} \text{IG} \) crystals in field up to 40 T are given in figure 1. Easy direction for all compounds is the direction [100] in fields less than 6 T. In such fields the transition to the state with maximum moments is accompanied by jump for \( x = 0.1 \) and 0.26 at \( H \parallel [111] \), but a small jump of the magnetization occurs also at \( H \parallel [110] \) for the compound with \( x = 0.1 \). The magnetization magnitudes of all substances studied at \( H < 6 \) T are in a good agreement with the values, obtained on the assumption of parallel orientation of magnetic moments in all 6 nonequivalent positions of the \( \text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) ions [10].

Some jumps of magnetization occur in fields 6-16 T, moreover their magnitudes increase with the \( \text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) concentration linearly. Such fields are well above the

Fig. 1. – Magnetization curves of the \( \text{Y}_3-x\text{H}_{0.5}\text{Fe}_5\text{O}_{12} \) single crystals at 4.2 K: solid lines – \( H \parallel [100] \), dashed lines – \( H \parallel [110] \), circles lines – \( H \parallel [111] \).
fields of technical magnetization, but the resulting magnetic moments for all crystals are less than in the pure YIG. This circumstance points out, that a change in the remagnetization of the rare earth ions does not take place in this fields region. It is also known that the magnetization anomalies in fields 6-15 T are accompanied by the jumps of magnetostriction [1].

The magnetization process of the (Y Tb)IG samples in fields above 20 T proceeds by means of several jumps, moreover their numbers and magnitudes increase linearly with Tb$^{3+}$ concentration and depend on the orientation of an external magnetic field. It is important to note that magnetization of the (Y Tb)IG crystals in the highest fields is far from the value corresponding to a ferromagnetic state of such magnetic compounds.

Experimental results of the DMS measurements shown, that the magnitude of the $\chi = dM/dH$ is very large $[1 \ldots 5] \times 10^{-2}$] at phase transitions in fields $H > 20$ T and is close to the value, corresponding to a first order phase transition.

3. Discussion

Magnetic phase diagrams of the (Y Tb)IG in the "field-concentration" plane shown in figure 2 were constructed using experimental data of the DMS measurements. Magnetic fields, marked by the points and squares, are corresponding to a maximum of the DMS. Vertical segments indicate the width of the transition. Phase transition lines converge to one point at $x = 0$, $\mu_0H_0 = 28 \pm 2$ T. Similar properties are typical for the magnetic phase diagrams of the rare earth garnets without any dependence for an order of the transition [8, 9]. In this case $\mu_0H_0$ is the exchange field between the rare earth and ferrous subsystems of the (Y Tb)IG crystals.

One can well describe the magnetization curves of the samples investigated in fields less than 6 T using a model, developed for weakly anisotropic garnets [10]. But the (Y Tb)IG properties at $H > 20$ T are typical of the Ising magnets. That is why we assume, that the transition into a strongly anisotropic state of the (Y Tb)IG takes place in fields 6-16 T, caused by the level inversion of the Tb$^{3+}$ ions. This transition is accompanied by the arising of the noncollinear and noncoplanar rare earth magnetic structure, which is similar to observed one in (HoY)IG crystals [8]. It is easy to explain on this assumption the magnetization anomalies at $H > 20$ T as the remagnetization process of the Ising liked Tb$^{3+}$ ions. Change of the Tb$^{3+}$ ions concentration leads to a change of the Ising axes direction (see Fig. 2): direction [100] becomes at first hard, than easy and finally intermediate axis of the (Y Tb)IG crystals; at $x = 0.41$ all main directions of the cubical crystal are not easy axes. This behaviour of the ferrimagnets is caused by an existence of the very strong magnetoelastic interaction.

Concentration dependence of the field values in which the level inversion occurs (squares in Fig. 2), is possible to explain as a sequence of the lattice distortion increasing due to increasing of $x$.

Model of the arising of the noncoplanar magnetic structure admits also the absence any anomalies in magnetization of crystals with $x = 0.1$ and 0.41 at $H // [111]$ in fields 6-16 T. Actually a change of the magnetic moment caused by the level inversion is completely compensated by the reducing of rare earth resulting moment, accompanied with the form of such structure.

![Fig. 2. - Phase transition fields versus concentration of the Tb$^{3+}$ ions for the $Y_{3-x}Tb_xFe_5O_{12}$ single crystals: squares - the levels inversions fields, circles - Tb$^{3+}$ magnetic moments remagnetization fields.](image-url)