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Magnetic phase transitions in erbium

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Magnetic properties of a high-purity single crystal of erbium have been investigated in magnetic fields of Oe and kOe ranges and temperature region from 4.2 to 300 K. Considerable temperature hystereses of erbium magnetization were found near each of the magnetic phase transition points Θ_1, Θ_2 and Θ_B. The data obtained are used for the analysis of magnetic structure transformations in erbium.

1. Introduction

Study of magnetic phase transitions in erbium deals with in a considerable number of works. The analysis of data on neutron scattering (see for instance refs. [1,2]) shows that below some temperature $\Theta_2 \approx 85$ K the magnetic structure of erbium turns from the paramagnetic into the antiferromagnetic state of the type of longitudinal spin density wave (LSW) oriented along the hexagonal axis c of the crystalline structure. Below the temperature $\Theta_B \approx 52$ K, additionally to the LSW the helicoidal type oscillations of magnetic moment components in the basal plane appear, forming the so-called CS structure with a period of helicoid coinciding with that of LSW.

In the low temperature range (at $T < \Theta_1 \approx 20$ K) erbium has a structure of the ferromagnetic spiral type (FS) [1,2], and at $T = 6$ K $\mu_{\parallel} = 7.8\mu_B$ and $\mu_{\perp} = 4.4\mu_B$. The value of the temperature Θ_1 ranges, according to references, from 16 to 20 K, which is apparently due to the degree of purity of the samples examined.

In ref. [3] the role of high harmonics in the spatial distribution of the order parameters is ascertained. It is shown that the data obtained in ref. [2] can be accounted for on the basis of exchange approximation considering uniaxial anisotropy.

The data on magnetic structure transformations in erbium under a magnetic field applied along various crystallographic directions differ (see for instance refs. [4–6]). Experiments [7] reveal the presence of magnetization jumps even in the field $H \approx 270$ kOe applied along the c-axis. Recent synchrotron radiation data on the erbium magnetic structure [8–10] have enabled one to state that there are a few successive commensurable phases in the magnetic structure of erbium in the temperature range below 52 K. At $T < 18$ K the magnetic structure wave vector is fixed at the 5/21 value.

Investigations of reconstruction of the magnetic structure in low magnetic fields are extremely important since the value of the field may have an essential effect on the character of magnetic phase transformations. The detailed data on similar experiments are available presently only for holmium in the series of rare-earth metals [11,12,20]. Investigations of the structure of Er and Tm are just underway [13].

The present paper is concerned with the study of specific features of magnetic structure transformations in an erbium single crystal in low magnetic fields.

2. Experimental details

The magnetization of erbium in low fields (up to 10 Oe) was measured using a SQUID-magnetometer [14] in slow cooling and heating the sample in a constant magnetic field oriented along the c-axis. A vibrating sample magnetometer was used for measurements in high fields.

Since the observational results can be significantly affected by structural perfection and sample purity, a crystal thread of high-purity erbium has been used in the work. The sample was purified by multiple vacuum sublimation in the graphite-heated furnace at a residual pressure of $\sim 10^{-6}$ Torr with deposition of the solid phase on a water-cooled copper substrate. As a result of sublimation for 2–3 h, about 200–250 g of pure erbium was deposited on the condenser, having a form of druses of crystals grown close together. The composition of sublimed erbium was controlled by spark mass spectroscopy and vacuum extraction methods. The gaseous impurities in erbium were reduced after the purification: the oxygen content compared to that of a commercially available pure metal was decreased by a factor of 35, that of nitrogen by 50 and carbon by 12.

3. Results

Fig. 1 presents temperature dependencies of magnetization $M(T)$ of erbium in the field $H = 1.6$ Oe. The results were obtained as follows. First, measurements of $M(T)$ were made in cooling the sample from 300 K down to ~ 5 K. Then measurements were made in heating the sample. The rate of heating and cooling was kept constant and it did not exceed 1 K/min.

As is evident from fig. 1, the characters of curves $M(T)$ match only at $T > 40$ K. In this temperature range two maxima are observed both in heating and cooling the sample. The high temperature maximum corresponds to the point Θ_2 of the paramagnetism–LSW structure phase transition. For sample cooling the temperature Θ_2 equals to 85.0 K, while for heating it is 90.7 K (see fig. 2). It should be noted that the temperature hysteresis in the paramagnetic region terminates only at $T \approx 150$ K.

The LSW–CS transition, i.e. the helicoidal ordering in the basal plane also forms a maximum on the curve $M(T)$. Its temperature Θ_B is equal to 48.0 and 52.8 K, in cooling and in heating, respectively.

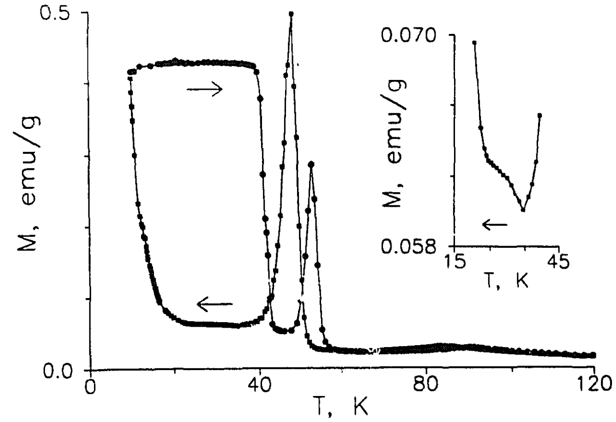

Fig. 1. Temperature dependencies of the magnetization $M(T)$ of an Er single crystal in the magnetic field $H = 1.6$ Oe parallel to the crystallographic c-axis, obtained in cooling and heating the sample. A temperature region near Θ_2 is shown in fig. 2.

As the temperature further decreases, a bend is observed on the curve $M(T)$ in the vicinity of 30 K. An abrupt increase of magnetization in the low temperature range ($T < 23$ K) points to the beginning of the transition to the ferromagnetic phase (see the inset in fig. 1).

It was of interest to find out how these properties of erbium were transformed in higher magnetic fields. For this purpose the temperature dependencies of $M(T)$ were investigated in magnetic fields up to 12 kOe. Both in the case $H \parallel c$ (see the inset in fig. 3) and $H \parallel a$ (the inset in fig.

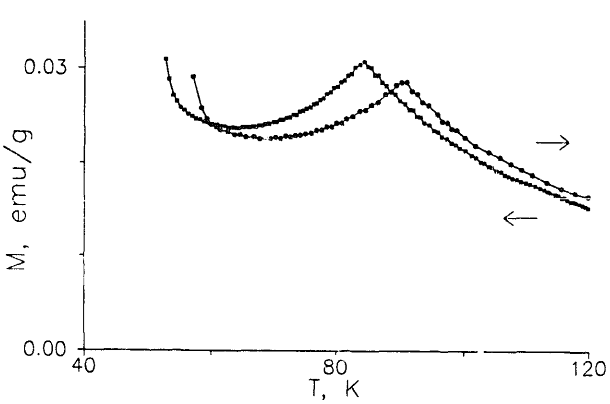

Fig. 2. Temperature hysteresis of the magnetization of an Er single crystal in the vicinity of the point Θ_2.

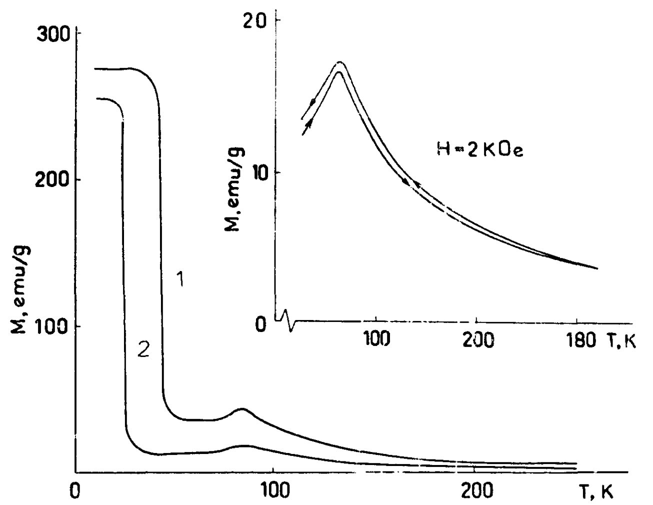

Fig. 3. Temperature dependencies $M(T)$ of erbium in the field $H \parallel c$ in cooling the sample: 1 – 12 kOe, 2 – 2 kOe. Hysteresis of $M(T)$ near the temperature Θ_2 is shown in the inset on an enlarged scale.

4) the magnetization hysteresis in the vicinity of Θ_2 does exist, terminating just at $T \approx$ 170–180 K. In the field $H \parallel c$, however, no maximum of magnetization was observed at Θ_B, and the hysteresis in the region of the temperature Θ_1 was of the order of 5 K.

For a field of 2 kOe in the case $H \parallel a$ the anomaly at the point Θ_2 was extremely weakly expressed compared to the anomalies near the temperatures Θ_1 and Θ_B, and it was lacking for a field of 12 kOe. The maximum at $T = \Theta_B$ was smoothed out and shifted towards low temperatures as the field increased.

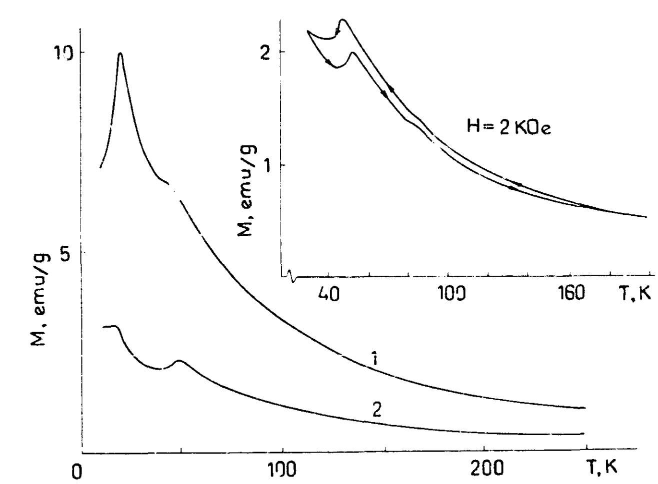

Fig. 4. Temperature dependencies $M(T)$ of erbium in the field $H \parallel a$ in cooling the sample: 1 – 12 kOe, 2 – 2 kOe. Hysteresis of $M(T)$ near the temperature Θ_2 is shown in the inset on an enlarged scale.

4. Discussion

The data obtained lead one to a conclusion that the paramagnetism–LSW phase transition in high-purity erbium both in low and high magnetic fields possesses the features of the first type phase transition and is apparently of a mixed character. We consider the presence of a rather extended hysteresis in the paramagnetic region to be an evidence of LSW clusters existing at $T > \Theta_2$. Cluster dimensions appear to decrease significantly at $T >$ 150–180 K, the paramagnetic state becoming more uniform.

The bend on the curve $M(T)$ at $T \approx 30$ K is an indication of an additional transformation of the magnetic structure of erbium. A transition of erbium to a commensurable phase with wave vector $\tau = 6/23$ [9] and corresponding anomalies of a number of physical properties were previously found in this temperature range (see for instance refs. [15,16]). In ref. [16] an attempt was made to give a theoretical description of these anomalies. According to that paper, the conduction electrons change their energy spectrum due to the spin density wave diffraction. The reconstruction of the electron spectrum consists in the appearance of a system of microslits on the planes of Bragg diffraction in the k-space. It is shown that within the framework of this model one can account for the behaviour of electrical resistance and of the wave vector of magnetic structure in the vicinity of the commensurability point. Within the same representation one can also account for the appearance of the magnetic susceptibility peak. Recent data [13] on magnetic properties and heat expansion indicate that there is a cascade of spin-slip phase transitions of various configurations in erbium over a considered temperature range, corresponding anomalies appearing as peaks and bumps on the magnetization curves.

We proceed now to the discussion of the transformation of magnetic structure near the point Θ_1. This transition is known to be the first type phase transition and it must be accompanied by a certain temperature hysteresis. The data obtained show the value of the sample magnetization to remain constant up to the temperature $T \approx 40$ K in low fields in transition from FS to CS structure (see fig. 1). As the temperature further increases there is an abrupt decrease of the sample magnetization. Such considerable temperature hysteresis extending over ~ 30 K in the vicinity of the temperature Θ_1 is observed for the first time. A field hysteresis of the magnetic structure of erbium was detected earlier in refs. [17,18]. It was accounted for by "freezing" (after application of the magnetic field) of a more homogeneous structure than the original one, and it was stated that the hysteresis had a well-defined temperature boundary of 38 K.

The analysis we made indicates that the temperature hysteresis found in the work was due to the "freezing" of the FS structure with the wave vector 5/21. Such "freezing" may be due to rather considerable energy barriers arising in the low temperature range, that separate various commensurable phases. It appears that there is a coexistence of phases with various magnetic structure wave vectors in this temperature range. The temperature boundary of this effect $T \approx 40$ K is apparently determined by the temperature range of a significant increase of magnetic anisotropy and by its reaching some critical value which is sufficient for the commensurability effects to appear [19]. It should be pointed out that we observed that effect not only in the field of 1.6 Oe but in lower and higher fields up to $H \approx 10$ Oe as well.

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References

[1] M. Habenschuss, C. Stassis, S.K. Sinha, H.W. Deckman and F.H. Spedding, Phys. Rev. B 10 (1974) 1020.
[2] M. Atoji, Solid State Commun. 14 (1974) 1047.
[3] Yu.A. Izyumov, V.M. Laptev and S.B. Petrov, Fiz. Met. Metalloved. 58 (1984) 427 (in Russian).
[4] A.S. Bulatov, V.F. Dolzhenko, V.M. Kulinich and D.A. Ogienko, Theses of the 2nd National Symposium on Nonhomogeneous Electron States (Novosibirsk, Russia) (1987) p. 50 (in Russian).
[5] S. Gama and M.E. Foglio, Phys. Rev. B 37 (1988) 2123.
[6] J.P. Burger, P. Vajda, J.N. Daou and G. Chouteau, J. Magn. Magn. Mater. 67 (1987) 343.
[7] V.L. Yakovenko, V.E. Brille, V.V. Druzhinin, R.Z. Levitin, V.M. Melnikov and P.E. Osipova, Zh. Eksp. Teor. Fiz. 78 (1980) 157 (in Russian).
[8] D. Gibbs, J. Bohr, J.D. Axe, D.E. Moncton and K.L. D'Amico, Phys. Rev. B 34 (1986) 8182.
[9] J. Bohr, J. Magn. Magn. Mater. 83 (1990) 530.
[10] J. Bohr, D. Gibbs, J.D. Axe, D.E. Moncton, K.L. D'Amico, C.F. Majkrzak, J. Kwo, M. Hong, C.L. Chien and J. Jensen, Physica B 159 (1990) 93.
[11] F. Willis, N. Ali, M.O. Steinitz, M. Kahrizi and D.A. Tindall, J. Appl. Phys. 67 (1990) 5277.
[12] G.S. Burkhanov, A.V. Volkozub, O.V. Snigirev, A.M. Tishin and O.D. Chistyakov, Fiz. Tverd. Tela 32 (1990) 2483 (in Russian).
[13] F. Willis and N. Ali, J. Appl. Phys. 69 (1991) 5697.
[14] L.Z. Avdeev, O.V. Snigirev and V.V. Khanin, IEEE Trans. Magn. MAG-21 (1985) 914.
[15] C. Schmitzer, G. Hilscher, P. Vajda and J.N. Daou, J. Phys. F 17 (1987) 865.
[16] L.A. Boyarsky and Yu.G. Peisakhovich, Theses of the 2nd National Symposium on Nonhomogeneous Electron States (Novosibirsk, Russia, 1987) p. 48 (in Russian).
[17] S.K. Godovikov, P.V. Bogdanov, M.G. Kozin and N.I. Moreva, Fiz. Tverd. Tela 23 (1981) 990 (in Russian).
[18] S.K. Godovikov, Fiz. Tverd. Tela 27 (1985) 1291 (in Russian).
[19] Yu. Izyumov, Usp. Fiz. Nauk 144 (1984) 439 (in Russian).
[20] N. Ali, F. Willis, M.O. Steinitz, M. Kahrizi, D.A. Tindall, Phys. Rev. B 40 (1989) 11414.