MAGNETIC PROPERTIES OF A HEMATITE SINGLE CRYSTAL IN FIELDS UP TO 140 kOe

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The magnetization of hematite (α-Fe_2O_3) single crystal was measured at temperatures between 100 and 300°K in pulsed magnetic fields up to 140 kOe. It is shown that the transition from the antiferromagnetic to the weakly magnetic state in a magnetic field parallel to the basal plane takes place gradually when the field strength is varied between zero and a certain value H_0. In contrast, the transition in a field parallel to the principal axis of the crystal takes place suddenly in a certain field H_c. The results obtained are qualitatively described by a theory developed by Cinader and Shtrikman.[8]

HEMATITE (α-Fe_2O_3) has the rhombohedral crystal structure (space group D_{3d}^6). Below the Neél point (T_N = 950°K), hematite is antiferromagnetic and weakly ferromagnetic; the antiferromagnetic vector **l** and the spontaneous weak ferromagnetic moment m_s lie in the basal plane of the crystal.[1] At $T_c \approx 250$°K, hematite goes over to a different antiferromagnetic state: the antiferromagnetic vector **l** is now directed along the principal axis of the crystal (the c axis);[1] in this structure, weak ferromagnetism is impossible.[2]

Many papers have been published on the magnetic properties of the low-temperature modification of hematite and, particularly, on the field-assisted transition from the antiferromagnetic to the weakly ferromagnetic state. We may regard it as established that, when the field is directed along the principal axis of the crystal ($H_{\parallel}$), the transition from the antiferromagnetic to the weakly ferromagnetic state is a phase transition of the first kind and takes place suddenly.[3-7] The temperature dependence of the critical transition field H_c has been determined, right down to liquid helium temperatures, from measurements in pulsed[5,7] and static fields[6].

There have been far fewer theoretical and experimental investigations of the magnetic properties of the low-temperature modification of hematite in a field applied in the basal plane of the crystal ($H_{\perp}$). Kaczer and Shalnikova,[3] as well as Flanders and Shtrikman,[4] investigated the transition of hematite near the point T_c in a field lying in the basal plane ($H_{\perp}$). They demonstrated experimentally that the transition to the weakly ferromagnetic state in a field $H_{\perp}$ occurred suddenly, in a temperature range of several degrees below T_c, and was a phase transition of the first kind. However, attempts to observe the same sudden transition in a field $H_{\perp}$ at lower temperatures have not been successful.[8] This has been explained by Cinader and Shtrikman[8] as being due to the fact that a sudden change in the magnetization in a field $H_{\perp}$ should be expected only near the point T_c, where the anisotropy energy is small. At lower temperatures, the transition from the antiferromagnetic to the weakly ferromagnetic state in a field is gradual; in this case, the antiferromagnetic vector **l** rotates gradually from the principal axis of the crystal to the basal plane when the field is increased.[1)]

The main results of Cinader and Shtrikman[8] are as follows. For a magnetizing field parallel to the basal plane, the magnetization $m_{\perp}$ is

$$m_{\perp} = \chi_{\perp\,\mathrm{af}} H_{\perp} = \chi_{\perp\,\mathrm{wf}} \left[1 + \frac{H_D^2}{H_c^2}\right] H_{\perp} \quad \text{for } H \leqslant H_0; \tag{1}$$

$$m_{\perp} = m_s + \chi_{\perp\,\mathrm{af}} H_{\perp} \quad \text{for } H \geqslant H_0, \tag{2}$$

where m_s is the spontaneous weak ferromagnetic moment; $\chi_{\perp af}$ and $\chi_{\perp wf}$ are the susceptibilities in the basal plane for the antiferromagnetic and the weakly ferromagnetic states. The value of the transition field H_0 is given by the expression

$$H_0 = H_c^2 / H_D. \tag{3}$$

Here, H_D is the Dzyaloshinskiĭ field, responsible for the weak ferromagnetism and related to the spontaneous weak ferromagnetic magnetization m_s and to the susceptibility of the weakly ferromagnetic modification in the basal plane $\chi_{\perp wf}$ by the expression

$$m_s = \chi_{\perp\,\mathrm{wf}} H_D. \tag{4}$$

H_c is the critical field for the transition from the antiferromagnetic to the weakly ferromagnetic state in a field $H_{\parallel}$, parallel to the principal axis of the crystal:

$$H_c = [H_a (2H_{\mathrm{exc}} + H_a) - H_D]^{1/2}, \tag{5}$$

where H_{exc} is the effective field of the exchange interaction, and H_a is the effective anisotropy field.

The purpose of our investigation was to study in detail the magnetic properties of hematite in a wide range of magnetic fields and temperatures in order to determine the characteristic features of the transition from the antiferromagnetic to the weakly ferromagnetic state in fields parallel to the principal axis and fields lying in the basal plane of the crystal.

1)The suggestion that the transition in a field $H_{\perp}$ is a phase transition of the second kind has also been put forward by Kaczer in his paper LT10 presented at an International Conference on Low Temperatures (Moscow, 1966).

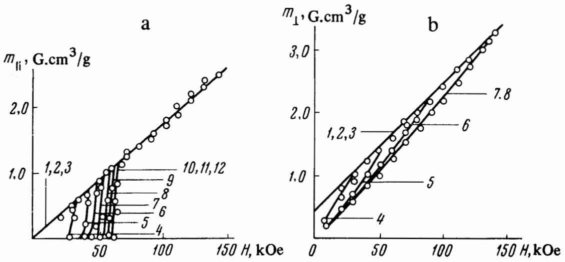

FIG. 1. Dependence of the magnetization of hematite on the field at various temperatures. a) Magnetization along the principal axis of the crystal: 1) at 291°K; 2) 273°K; 3) 257°K; 4) 245°K; 5) 230°K; 6) 220°K; 7) 205°K; 8) 185°K; 9) 165°K; 10) 145°K; 11) 120°K; 12) 110°K. b) Magnetization in the basal plane of the crystal: 1) at 290°K; 2) 273°K; 3) 257°K; 4) 245°K; 5) 230°K; 6) 205°K; 7) 145°K; 8) 120°K.

The measurements were carried out on a sphere of about 0.5 g mass, prepared from a synthetic hematite single crystal grown from a molten flux solution Bi_2O_3 + Na_2CO_3 at the Crystallography Institute of the U.S.S.R. Academy of Sciences. The sample was oriented along the various crystallographic directions by a magnetic method, whose accuracy was 2–5°.

The magnetization was measured by a ponderomotive method in pulsed magnetic fields using apparatus described earlier.[9] The accuracy of the determination of the absolute value of the magnetization was 7–10%. The dependence of the magnetization on the field and on temperature was measured with an accuracy of 3–5%.

Figure 1 shows the field dependences of the magnetization of hematite along the principal axis of the crystal and in the basal plane at various temperatures.

It is evident from Fig. 1a that, in the weakly ferromagnetic state at temperatures higher than T_c = 253°K, the magnetization along the principal axis $m_{\|}$ is a linear function of the field. Below this temperature, the magnetization in weak fields is close to zero (according to our results, when $H < H_c$ the susceptibility is $\chi_{\|af} = 0.7 \times 10^{-6}$ cm^3/g at 181°K and $\chi_{\|af} = 0.5 \times 10^{-6}$ cm^3/g at 143°K) but it increases suddenly in a critical field H_c. The susceptibility above and below the point T_c (in fields $H \geq H_c$) is, within the limits of the experimental accuracy of our measurements, independent of temperature and equal to $\chi_{\|wf} = 1.75 \times 10^{-5}$ cm^3/g, which is in good agreement with the results of other workers.[6,7,10,11] Figure 2 shows the dependence of the critical field on temperature; a similar dependence of H_c has been reported in[5-7].

The field dependence of the magnetization in the basal plane $m_{\perp}$ is different (Fig. 1b). Above the transition temperature T_c, the magnetization in fields stronger than 20 kOe obeys the standard relationship for weak ferromagnets

$$m_{\perp} = m_s + \chi_{\perp\,wf} H_{\perp},$$

where, in agreement with[6,8,9], $\chi_{\perp wf} = 1.95 \times 10^{-5}$ cm^3/g, m_s = 4.42 G·cm^3/g.

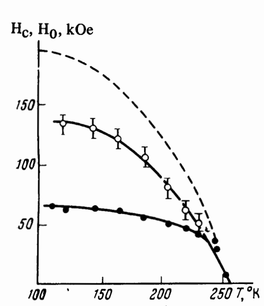

FIG. 2. Temperature dependences of the fields H_c and H_0: ● – H_c (experimental values), ○ – H_0 (experimental values), dashed curve – theoretical dependence of H_0 in accordance with Eq. (3).

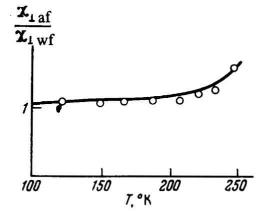

FIG. 3. Temperature dependence of the susceptibilities $\chi_{\perp af}/\chi_{\perp wf}$: ○ – experimental values, continuous curve – theoretical dependence in accordance with Eq. (1).

Below the transition point T_c, the magnetization $m_{\perp}$ in weak fields increases gradually from zero when the field is increased and in a certain field H_0, whose value depends on temperature, it reaches the value of the magnetization in the weakly ferromagnetic state; from this point onwards, the curves coincide at temperatures below and above T_c. Such a dependence of the magnetization $m_{\perp}$ on the field is in qualitative agreement with the theoretical calculations given in[8]: the transition from the antiferromagnetic to the weakly ferromagnetic state is continuous and not sudden. The experimental temperature dependence of $\chi_{\perp af}$ (Fig. 3) is also in agreement with the theoretically predicted dependence [cf. Eq. (1)]. However, the experimental values of the fields H_0 are lower than the values calculated from the theoretical formula (3) (Fig. 2). This is because, according to the theory,[8] the magnetization in the basal plane $m_{\perp}$ in fields $H \leq H_0$ should be a linear function of the field, while the experimental field dependences of the magnetization $m_{\perp}$ are nonlinear in this range of fields (Fig. 1b). The cause of this discrepancy may be the inaccuracy of the theory, namely, the fact that the magnetization near the field H_0 changes suddenly also in the basal plane. However, it is possible that the difference between the theoretical and experimental curves is due to the inaccurate orientation of the samples.

We must mention also that, in spite of the general agreement between our results and those of Kaneko and Abe,[6] we were unable to observe a second transition from the weakly ferromagnetic to the antiferromagnetic state when a hematite single crystal was magnetized in the basal plane; such a transition was reported by these workers. The cause of this disagreement is not yet clear. It may be due to the different purity of the samples investigated.

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