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

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The magnetization of hematite ($\alpha$-$\text{Fe}_2\text{O}_3$) 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 $H_s$. The results obtained are qualitatively described by a theory developed by Cinader and Shtrikman.\(^\text{[6]}\)

HEMATITE ($\alpha$-$\text{Fe}_2\text{O}_3$) has the rhombohedral crystal structure (space group $D_{3d}$). Below the Neél point ($T_N = 950\,\text{K}$), hematite is antiferromagnetic and weakly ferromagnetic; the antiferromagnetic vector $\mathbf{1}$ and the spontaneous weak magnetic moment $m_s$ lie in the basal plane of the crystal.\(^\text{[1]}\) At $T \approx 250\,\text{K}$, hematite goes over to a different antiferromagnetic state: the antiferromagnetic vector $\mathbf{1}$ is now directed along the principal axis of the crystal (the $c$ axis);\(^\text{[1]}\) in this structure, weak ferromagnetism is impossible.\(^\text{[2]}\)

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 ($H_s$), the transition from the antiferromagnetic to the weak antiferromagnetic state is a phase transition of the first kind and takes place suddenly.\(^\text{[3-7]}\) The temperature dependence of the critical transition field $H_c$ has been determined, right down to liquid helium temperatures, from measurements in pulsed\(^\text{[8]}\) and static fields.\(^\text{[9]}\)

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 ($H_L$). Kaczer and Shalnikova,\(^\text{[3]}\) as well as Flanders and Shtrikman,\(^\text{[4]}\) investigated the transition of hematite near the point $T_c$ in a field lying in the basal plane ($H_L$). They demonstrated experimentally that the transition to the weakly ferromagnetic state in a field $H_L$ 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 $H_s$ at lower temperatures have not been successful.\(^\text{[3]}\) This has been explained by Cinader and Shtrikman\(^\text{[8]}\) as being due to the fact that a sudden change in the magnetization in a field $H_s$ 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 $\mathbf{1}$ rotates gradually from the principal axis of the crystal to the basal plane when the field is increased.\(^\text{[1]}\)

The main results of Cinader and Shtrikman\(^\text{[4]}\) are as follows. For a magnetizing field parallel to the basal plane, the magnetization $m_\perp$ is

$$m_\perp = \lambda_\perp H_\perp = \lambda_\perp \frac{(1 + H_P^2)}{H_\perp^2} H_\perp \quad \text{for } H < H_c;$$

(1)

$$m_\perp = m_s + \lambda_\perp H_\perp \quad \text{for } H \geq H_c,$$

(2)

where $m_s$ is the spontaneous weak ferromagnetic moment; $\lambda_\perp$ and $\lambda_\perp$ are the susceptibilities in the basal plane for the antiferromagnetic and the weakly ferromagnetic States. The value of the transition field $H_c$ is given by the expression

$$H_c = H_L + H_B.$$

(3)

Here, $H_P$ is the Dzyaloshinskii\(^\text{[11]}\) 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 $\lambda_\perp$ by the expression

$$m_s = \lambda_\perp H_B.$$

(4)

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

$$H_c = (H_B(2H_{\text{exc}} + H_s) + H_0)^{\text{a}};$$

(5)

where $H_{\text{exc}}$ is the effective field of the exchange interaction, and $H_s$ 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 $H_L$ 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).
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 Bi₂O₃ + Na₂CO₃ 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 pomerontive method in pulsed magnetic fields using apparatus described earlier.⁶ 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 Tc = 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 the theory, m∥ = 4.42 G · cm⁻³/g, which is in good agreement with the experimental results given in 8). The transition from the antiferromagnetic to the weakly ferromagnetic state is continuous and not sudden. The experimental temperature dependence of m∥ (Fig. 3) is also in agreement with the theoretically predicted dependence [cf. Eq. (1)]. However, the experimental values of the field H0 are lower than the values calculated from the theoretical formula (3) (Fig. 2). This is because, according to the theory,⁶ the magnetization in the basal plane m⊥ in fields H ≤ H0 should be a linear function of the field, while the experimental field dependences of the magnetization m⊥ are nonlinear in this range of fields (Fig. 1b).

Below the transition point Tc, the magnetization in fields stronger than 20 kOe obeys the standard relationship for weak ferromagnets

$$m_\perp = m_s + x_{\text{Laf}} H_\perp,$$

where, is agreement with [6, 7], $x_{\text{Laf}} = 1.95 \times 10^{-5} \text{ cm}^3/\text{g}, m_s = 4.42 \text{ G · cm}^3/\text{g}$.

Below the transition point Tc, the magnetization m⊥ in weak fields increases gradually from zero when the field is increased and in a certain field H0, 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 Tc. Such a dependence of the magnetization m⊥ on the field is in qualitative agreement with the theoretical calculations given in [6]: the transition from the antiferromagnetic to the weakly ferromagnetic state is continuous and not sudden. The experimental temperature dependence of $x_{\text{Laf}}$ (Fig. 3) is also in agreement with the theoretically predicted dependence [cf. Eq. (1)]. However, the experimental values of the field H0 are lower than the values calculated from the theoretical formula (3) (Fig. 2). This is because, according to the theory,⁶ the magnetization in the basal plane m⊥ in fields H ≤ H0 should be a linear function of the field, while the experimental field dependences of the magnetization m⊥ 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 H0 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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10 P. Flanders and J. Remeika, Phil. Mag. 11, 1271 (1965).

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