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SPONTANEOUS MAGNETIC MOMENT IN THE DIRECTION OF THE TRIGONAL AXIS IN $CoCO_3$

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According to the theory developed by Dzyaloshinskii [1] for the weak ferromagnetism of antiferromagnets, there can exist in rhombohedral crystals, besides the thoroughly investigated spontaneous ferromagnetic moment σ_D in the basal plane of the crystal, also a spontaneous moment σ_z directed along the threefold axis. The value of σ_z depends strongly on the direction of the antiferromagnetic vector $\vec{\ell}$ relative to the binary axes in the basal plane of the crystal. Such a moment was recently observed by Flanders in hematite (α-Fe_2O_3) [5]. We have observed in the present investigation the spontaneous moment σ_z in the rhombohedral antiferromagnet $CoCO_3$[1]. Its value turned out to be larger by approximately two orders of magnitude than in the case of hematite.

The existence of σ_z follows directly from the general form of the thermodynamic potential, which for rhombohedral crystals with symmetry D_{3d}^6 can be written, following Dzyaloshinskii [1] in the form

$$\begin{gathered}\Phi = \frac{a}{2}\cos^2\theta + \frac{B}{2}m^2 - q\sin\theta\,(m_y\cos\phi - m_x\sin\phi) + \frac{D}{2}(\vec{\gamma}m)^2 - \\ - fm_z\sin^3\theta\cos 3\phi + d\cos\theta\sin^3\theta\sin 3\phi + e\sin^6\theta\cos 6\phi + \\ + \frac{g}{4}\cos^4\theta - mH,\end{gathered} \tag{1}$$

where ϕ is the angle between the vector $\vec{\ell}$ and the C_2 axis, and θ is the angle between $\vec{\ell}$ and the C_3 axis.

Minimizing this potential at a specified angle ϕ we obtain for the magnetization along the z axis

$$\sigma_z = \frac{f}{B}\sin^3\theta\cos 3\phi\,. \tag{2}$$

From the results of magnetic measurements [2] it is known that if a field H > 2 kOe is applied in the basal plane, then the antiferromagnetic vector $\vec{\ell}$ is

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[1] According to neutron diffraction data [3], in the absence of a magnetic field, the vector $\vec{\ell}$ in $CoCO_3$ is deflected from the basal plane by an angle $\beta = 44 \pm 4^\circ$. We do not know whether this angle changes with changing angle ϕ. However, from the isotropy of the magnetic properties of $CoCO_3$ in the plane it follows that the projection of the antiferromagnetic vector $\vec{l}$ on the basal plane is practically independent of the angle ϕ.

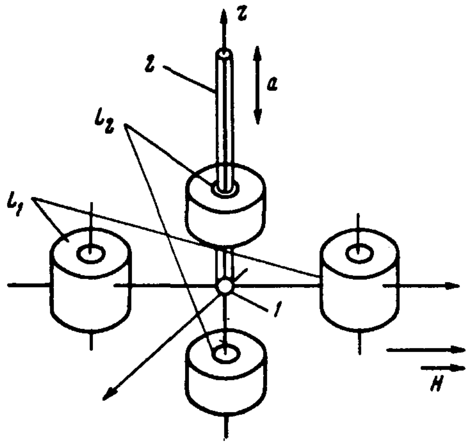

Fig. 1

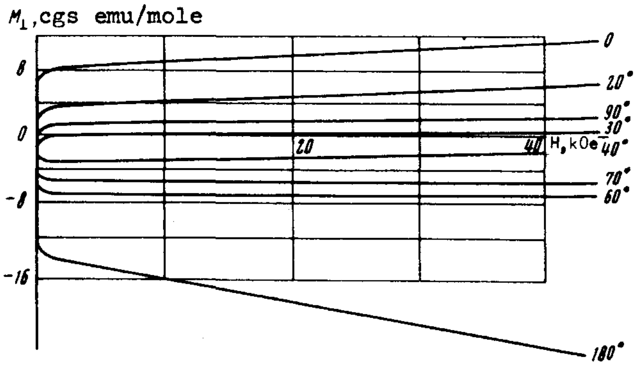

Fig. 2

always established perpendicular to the applied field[2]. By virtue of this, the angle ϕ in formula (2) can be replaced by the angle ψ between the applied magnetic field and the vertical symmetry plane.

To observe weak ferromagnetism along the threefold axis in $CoCO_3$, we developed a modification of Foner's vibration magnetometer [4]. A distinguishing feature of the magnetometer scheme (see Fig. 1) is the presence, in addition to the usual pair of coils L_1, in which the signal proportional to the sample magnetization $M_\parallel$ parallel to the magnetic field is induced, of another pair of coils L_2, in which the signal is proportional to the sample magnetization $M_\perp$ in the vertical direction. The magnetic field was directed horizontally. The $CoCO_3$ single-crystal sample 1 was fastened to the bar of the vibrating system 2 in such a manner that the C_3 axis was vertical. The vibrating system together with the sample could be rotated around a vertical direction relative to the fixed superconducting magnet producing the magnetic field and the fixed receiving coils L_1 and L_2. The magnetization M(H) as a function of the field, was received by both pairs of coils and plotted with an x-y recorder. The measurements were carried out at 4.2°K (T_N = 18.1°K for $CoCO_3$ [2]). The magnetic field remained, with the same accuracy as the orientation of the sample in the instrument (~0.5°), in the basal plane of the crystal at all times. The magnetization $M_\parallel(H)$ along the field is independent of the angle ψ within the limits of the measurement accuracy, and in fields above 2 kOe is well described by the straight line

$$M_\parallel(H) = \sigma_D + \chi_\perp H. \qquad (3)$$

The values σ_D = 1400 ± 30 cgs emu/mole and χ = 53 ± 1 cgs emu/mole coincide within 2% with those obtained in [2].

Figure 2 shows the results for $M_\perp(H)$ at several angles ψ between the magnetic field and the symmetry plane. It should be noted first of all that $M_\perp$ is smaller by approximately two orders of magnitude than $M_\parallel$. When the angle ψ changes, a significant change takes place both in the moment $M_\perp(0)$ extrapolated to H = 0, and in the slopes of the $M_\perp(H)$ lines. When discussing the results, it should be borne in mind that when the sample was rotated its position could change slightly. When the sample was displaced from the central position in the coil system, a parasitic signal proportional to the magnetization of the

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[2] The authors thank N.Yu. Ikornikov and V. Egorov (Crystallography Institute of the USSR Academy of Sciences) for kindly supplying the $CoCO_3$ samples.

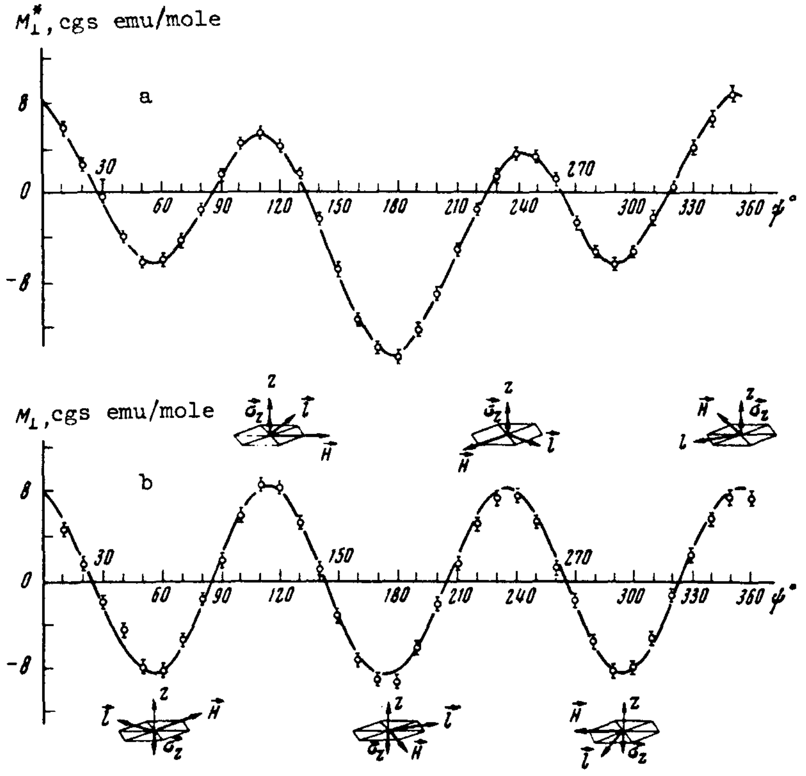

Fig. 3

sample in the basal plane could be induced in the coils L_2. This results in a linear dependence of $M_\perp$ on the magnetic field at certain angles ψ.

Figure 3a shows the moment $M_\perp(0)$ extrapolated to $H = 0$ on the angle ψ, obtained in one of the experiments. Although this dependence does not have a regular form, it reveals clearly the presence of a component with a period of 120°. Taking into account the statement made above concerning the displacement of the sample, we have corrected the experimental values of $M_\perp(0)$ by subtracting from each angle ψ the quantity $K\sigma_D$. The magnitude and sign of the coefficient K was determined from the paramagnetic moment $M_\perp(H) - M_\perp(0) = K\chi_\perp(H)$. The results corrected in this manner are shown in Fig. 3b. Within the limits of errors, the experimental points fit the curve $y = A \sin 3\psi$ (continuous curve in Fig. 3b). The existence in $CoCO_3$ of the spontaneous ferromagnetic moment in the direction of the threefold axis, predicted by Dzyaloshinskii, can thus be regarded as proved. In accordance with formula (2), this moment oscillates when the vector $\vec{l}$ (which is perpendicular to the magnetic field $\vec{H}$) is rotated in the basal plane, as is shown arbitrarily by the arrows in Fig. 3. The amplitude σ_z amounts to 9 ± 2 cgs emu/mole, i.e., is smaller by a factor 200 than σ_D. This error is a reflection of the scatter of the values of σ_z obtained in different series of experiments, and of the error in the absolute calibration of the apparatus. The obtained value of σ_z corresponds to an angle $\sim 10^{-4}$ rad between the magnetic moments of the sublattices and the basal plane.

On the basis of the foregoing numerical values of σ_z and $\chi_\perp$ for $CoCO_3$ we can estimate the effective field causing the appearance of the spontaneous magnetic moment along the trigonal axis, namely $H_{eff} = 0.17 \pm 0.04$ kOe.

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DESTRUCTION OF A SOLID BY SUPERDENSE EXCITATION OF ITS ELECTRONIC SUBSYSTEM

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1. The processes occurring in the track of a heavy ionizing particle were simulated in macroscopic solid volumes. The samples were irradiated for a short time ($\sim 10^{-8}$ sec) by a powerful flux of electrons in such a way that the average excitation-energy density reached, as in the center of the track, $W \sim 10^{20} - 10^{22}$ eV/cm^3 [1]. For this purpose, we prepared and adapted an accelerator with the following parameters of the electron momentum: upper particle energy 0.3 MeV, duration in the interval $(7 - 30) \times 10^{-9}$ sec, and current density in the range $(0.01 - 1) \times 10^3$ A/cm^2. The accelerator was developed by Mesyats and Koval'chuk; it employs the phenomenon of explosive field emission from a sharply pointed cathode in strong electric fields [2]. We observed that irradiation by single pulse causes destruction of the solid if the average energy density absorbed during the time of the pulse exceeds a threshold W_{des} characteristic of this substance. The effect becomes manifest in the following manner:

1) Thin plates (0.01 - 0.5 mm) of ionic (LiF, NaF, NaCl, KCl, KBr, CaF_2) and covalent (Ge, Si) crystals experience brittle damage and break apart. The number of fragments is large and depends on the beam density Φ. The values of Φ_{des} and W_{des} were determined from the condition required to break the sample into two fragments.

2) In thick samples, Lichtenberg figures consisting of cracks 0.1 - 1 μ thick are produced.

3) In plastic bodies, tracks of explosive radiolysis are observed, namely gas bubbles and swelling or erosion of the surface. The electrons employed for the irradiation transfer practically the entire energy lost in the medium directly to its electronic subsystem (ES) and only an insignificant fraction $\sim 10^{-4}$ directly to the nuclear subsystem (NS). Our experiments have thus demonstrated that direct excitation of only the ES of a solid can produce brittle damage, and established the threshold W_{des} necessary for this purpose.

	Ge	LiF	NaF	NaCl	KCl
Φ_{des}, 10^{13} electron/cm^2	3,0	1,7	1,3	1,1	0,7
W_{des}, 10^{20} eV/cm^3	15,0	3,0	2,3	2,0	1,1