lect contribution from the $V_S{}^2$ term which is very small for the fields achieved in our experiments.

(2) The magnitude of the splittings is expected to be the same for the R_1 and R_2 excited states because the Stark term is independent of spin. The same is true for the initially split ground levels having $M_S = \pm 3/2$ and $M_S = \pm 1/2$.

(3) Optical anisotropies associated with the split components are identical with each other and also with the anisotropy of the original unsplit line. All these points are in agreement with our experiments.

Although we have not given any detailed discussion on the local electric field, experiments of this type are very important because they allow a direct investigation of the local electric field. The quantitative discussion on the local field is only possible after the detailed knowledge of the odd-parity excited states is obtained.

The effect discussed here is expected to be extremely fast (comparable to the optical frequencies of the lattice), and high-frequency modulation of the ruby emission can be anticipated. The application of an ac electric field should allow frequency modulation of the output of a ruby optical maser.[5]

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ANISOTROPY OF THE MAGNETOELECTRIC EFFECT IN Cr_2O_3

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(Received May 8, 1961)

On the basis of earlier considerations of magnetic crystal symmetry effects by Landau and Lifshitz,[1] Dzyaloshinskii[2] showed that a magnetoelectric effect (i.e., a magnetic moment produced by an externally applied electric field or an electric moment produced by an externally applied magnetic field) may exist in antiferromagnetic Cr_2O_3. In his development of the thermodynamic potential which is compatible with the magnetic symmetry, Dzyaloshinskii obtained the relation[2]

$$4\pi\phi_{me} = -\alpha_{\parallel} E_z H_z - \alpha_{\perp}(E_x H_x + E_y H_y), \qquad (1)$$

where ϕ_{me} is the magnetoelectric part of the thermodynamic potential, and $\alpha_{\parallel}$ and $\alpha_{\perp}$ are the magnetoelectric parameters for the directions parallel and perpendicular to the crystallographic c axis, respectively. From this potential, one obtains (using $4\pi\partial\phi/\partial\vec{H} = -\vec{B}$) the linear relations

$$B_z = \alpha_{\parallel} E_z,\ B_x = \alpha_{\perp} E_x,\ \text{and}\ B_y = \alpha_{\perp} E_y. \qquad (2)$$

As a result of measurements on a nonoriented Cr_2O_3 single crystal, Astrov[3] obtained evidence that the magnetoelectric effect does exist in Cr_2O_3, and that the effect is a linear function of the electric field in accord with Eq. (2).

In this Letter, we report measurements of the magnetoelectric effect (resulting from an applied electric field) in two x-ray-oriented single-crystal disks of Cr_2O_3, and show that a large anisotropy exists both in the magnitude and temperature dependence of this effect. One of the disks was fabricated with its plane surfaces parallel to the crystallographic c axis, and the second disk with its plane surfaces perpendicular to the c axis. In the former case, the surfaces were parallel to the (110) plane. The plane surfaces were coated with silver paint to provide uniform electrical contact with the specimen. The apparatus used to measure the magnetic moment was similar to that used by Astrov.[3] However, we found it necessary to make the measurements in vacuum in order to avoid electrical breakdown in the vicinity of the electrodes. The magnetic moment was obtained by applying to the sample a 1000-cps alternating electric field and using a narrow-band amplifier of approximately 0.15-μv sensitivity to measure the voltage induced in a 10 000-turn pickup coil surrounding the sample. The largest values of $\alpha_{\perp}$ and $\alpha_{\parallel}$ correspond to induced rms voltages of

8.35 μv and 124.7 μv, respectively. Electrostatic shielding was provided by inserting a grounded brass cylinder between the pickup coil and the assembly consisting of the sample and electrodes. A Lavite disk having approximately the same conductivity as the Cr_2O_3 disks was used to show that the electrostatic shielding is adequate and that extraneous current effects are absent. Low temperatures were obtained by immersing a cylinder containing the sample and electrodes into a liquid nitrogen bath. High temperatures were obtained with a furnace or heated water bath. In all the measurements the temperature was determined by means of a copper-constantan thermocouple in thermal contact with one of the silver electrodes on the sample. The copper thermocouple wire also served as the ground connection for this electrode. Considerable care had to be taken to avoid electrical breakdown in the vicinity of the electrodes, particularly at the lower temperatures. Such breakdown even occurred when a helium atmosphere was used in the apparatus, and consequently the measurements had to be made in vacuum so that no breakdown occurred.

Figure 1 shows the results of our measurements on the temperature dependence of $\alpha_\perp$ and $\alpha_\parallel$. It is seen that there is a large anisotropy of the magnetoelectric effect. The magnitude of $\alpha_\perp$ and its temperature dependence is similar to that obtained by Astrov.[3] His measurements (which were made on a nonoriented crystal) extended down to 250°K only. The curve $\alpha_\parallel$, on the other hand, shows that the magnetoelectric effect goes through a maximum and then becomes zero at 97°K. At slightly lower temperatures it appears to rise again. In both samples, the magnetoelectric effect is zero at 306°K, and remains approximately zero at higher temperatures. Since antiferromagnetic susceptibility measurements by McGuire et al.[4] show the Néel temperature to be 307°K, it appears that the magnetoelectric effect does not exist in the paramagnetic region, in accord with the symmetry considerations of Landau and Lifshitz.[1] Measurements of the magnetoelectric effect in the two disks as a function of applied electric field showed that the effect is linear [in accord with Eq. (2)] for fields ranging from zero to 3200 rms volts/cm. The values of E_z and E_x used in obtaining the results shown in Fig. 1 were 2160 and 2050 rms volts/cm, respectively.

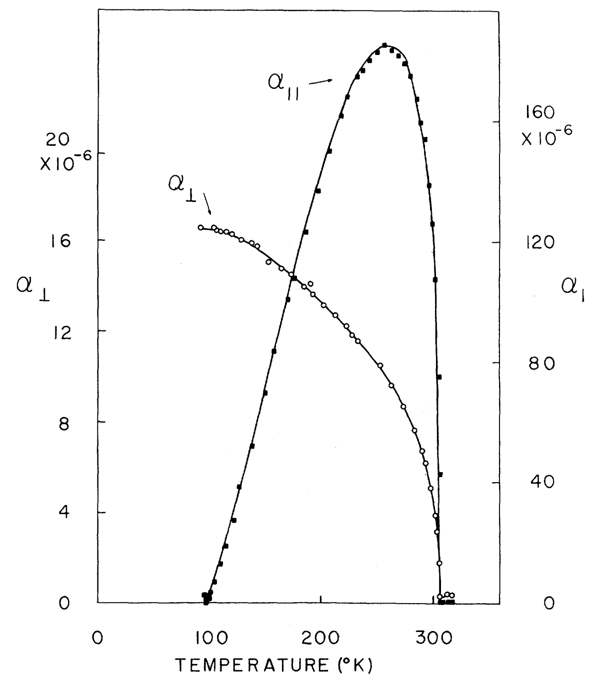

FIG. 1. Temperature dependence of the magnetoelectric parameters $\alpha_\perp$ and $\alpha_\parallel$. The α's are dimensionless in the Gaussian units used.

A theoretical discussion of the temperature dependence of the α's is given in reference 5.

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