

RESONANT SINGULARITIES OF THE DISPERSION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF OXYGEN IN PARALLEL CONSTANT AND ALTERNATING MAGNETIC FIELDS

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The previously observed singularities in the frequency dependence of the Scott effect [4, 5] (the rotation of a heated cylinder placed in a molecular gas following application of a magnetic field) were explained theoretically in [1 - 3], where a resonant character of the behavior of the transport coefficients of the molecular gases in parallel constant and alternating magnetic fields was predicted. In the present paper we report results of experiments which revealed for the first time resonant singularities of the dispersion of the thermal conductivity coefficient of  $O_2$  molecules with electron-spin projections  $\sigma = \pm 1$  and  $\sigma = 0$  on the direction of the angular momentum. An investigation of the behavior of the transport coefficients in such fields is of considerable interest, since, as shown earlier [2], the character of the resonance of the transport coefficients is connected with the anisotropy of the nonequilibrium distribution function in the space of the angular momenta of the molecules.

The thermal conductivity in a magnetic field was measured by a procedure somewhat analogous with that described in [6]. The pickup consisted of two cylindrical glass chambers with platinum wires stretched along their axes and serving as the heat-sensitive elements. The wires were connected in opposite arms of a dc bridge. One of the chambers was placed in a high-frequency solenoid producing an alternating magnetic field ( $H_1$ ) along its axis. Both chambers were placed inside Helmholtz coils producing a constant magnetic field ( $H_0$ ) parallel to the alternating field. The entire installation was so oriented that the magnetic fields  $H_1$  and  $H_0$  were parallel to the earth's magnetic field  $H_e$ . In the experiments described below, we measured the unbalance of the bridge with the alternating field turned on, due to the change in the thermal conductivity when the constant field was turned on. The absolute values of the relative change of the thermal-conductivity coefficient ( $\epsilon_\nu = -\Delta\kappa_\nu/\kappa_0$ ), due to the influence of the alternating field, were determined by comparing the Senftleben effect in  $O_2$ , measured during the course of the experiments, with the data given in [7]. The relative error in the calibration was less than 10%.

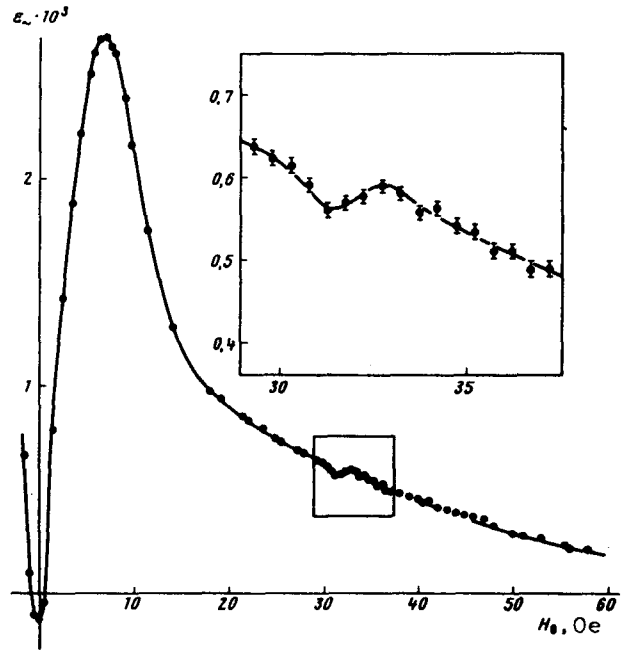


Figure 1 shows the experimental dependence of  $\epsilon_\nu$  on the intensity of the constant field  $H_0$  at an

Fig. 1. Plot of  $\epsilon_\nu = f(H_0)$  at  $H_1 = 8.6$  Oe,  $f = 0.565$  MHz, and  $p = 0.4$  mm Hg.

alternating-field amplitude  $H_1 = 8.6$  Oe, alternating-field frequency  $f = 0.565$  MHz, and pressure  $p = 0.4$  mm Hg. The value of  $\epsilon_{\nu}$  at  $H_0 = 0$  is due to the high-frequency field  $H_1$ . An increase of  $H_0$  leads to a change in the sign of  $\epsilon_{\nu}$ . At  $H_0 = 6.6$  Oe,  $\epsilon_{\nu}$  reaches its maximum  $(\epsilon_{\nu})_{\text{res}} = 2.69 \times 10^{-3}$ . A second maximum  $(\epsilon_{\nu})_{\text{res}} = 0.59 \times 10^{-3}$  is observed at  $H_0 = 32.5$  Oe.  $\epsilon_{\nu}$  tends to zero with further increase of  $H_0$ . Such a behavior of  $\epsilon_{\nu}$  agrees with the theoretical predictions.

Following [2], we can write the expression for  $\epsilon$ , for the case of diatomic molecules and  $\nabla T \perp H$ , in the form

$$\epsilon = \epsilon_- + \epsilon_{\nu}, \quad \epsilon_- = \sum_{\substack{m_2=1,2 \\ \sigma=0,\pm 1}} \Psi_{m_2} \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \left[ 1 + \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \right]^{-1},$$

$$\epsilon_{\nu} = \sum_{\substack{m_2=1,2 \\ \sigma=0,\pm 1}} \Psi_{m_2} \times$$

$$\frac{\frac{1}{2} \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2 \left[ 1 + \left( \frac{\omega}{\lambda} \right)^2 + \frac{1}{2} \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2 - 3 \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \right]}{\left[ 1 + \left( \frac{\omega}{\lambda} \right)^2 + \frac{1}{2} \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2 - 3 \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \right]^2 + \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \left[ 3 + \left( \frac{\omega}{\lambda} \right)^2 + \frac{1}{2} \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2 - \left( \frac{m_2 \gamma_{0\sigma}}{\lambda} \right)^2 \right]^2} \quad (1)$$

where  $\gamma_{\alpha\sigma}$  is the precession frequency of the magnetic moment of the molecule in the magnetic field  $H_{\alpha}$  ( $\alpha = 0$  or  $1$ );  $\omega$  is the circular frequency of the alternating field;  $\lambda$  is the collision frequency of the molecules;  $\sum_{m=1,2} \Psi_{m_2}$  determines the limiting value of  $\epsilon$  as  $H_0/p \rightarrow \infty$ .

Although formula (1) has been written out for non-paramagnetic molecules (in the case of paramagnetic molecules it must be averaged over the angular momentum  $M$ ), for a qualitative description of the behavior of  $\epsilon$  it can be used also for paramagnetic molecules, provided the angular momentum of the molecules in the expression  $\gamma_{\alpha\sigma} = [2\mu_0\sigma/M + 2\mu_0\hbar\delta_{\sigma 0}/M^2]H_{\alpha}$  for  $O_2$  is replaced by the average angular momentum  $\bar{M} = \hbar\bar{J}$  ( $\bar{J}$  is the average rotational quantum number). For paramagnetic molecules, the resonance should be more diffuse than in the case (1), since the precession frequencies for such molecules are different (Maxwellian distribution over the momenta). The chosen measurement procedure has made it possible to separate from  $\epsilon$  the part ( $\epsilon_{\nu}$ ) having only a resonant character ( $\epsilon_-$  determines the relative change of the thermal-conductivity coefficient due to the Senftleben effect). It follows from (1) that the first maximum corresponds to resonance on the molecules  $O_2$  with  $\sigma = \pm 1$ , and the second on the molecules  $O_2$  with  $\sigma = 0$ . The values  $(H_0)_{\text{res}} = 5.6$  Oe for  $\sigma = \pm 1$  and  $(H_0)_{\text{res}} = 34$  Oe for  $\sigma = 0$ , are calculated from formula (1), are in satisfactory agreement with the experimental ones.

Figure 2 shows a plot of  $\epsilon_{\nu}$  for  $f = 0.590, 1.225,$  and  $1.700$  MHz at  $H_1 = 2.16$  Oe and  $p = 0.4$  mm Hg in the region of resonance on the molecules  $O_2$  with  $\sigma = \pm 1$ . It is seen from the figure that a second maximum begins to appear with increasing  $f$ . According to (1), at definite relations between  $p, H_1,$  and  $f$  for the (diatomic) molecule  $O_2$ , two maxima should be observed, corresponding to  $m_2 = 1$  and  $m_2 = 2$ . It follows from [2] that such a character of the resonance (two maxima) is connected with the form of the anisotropy of the nonequilibrium

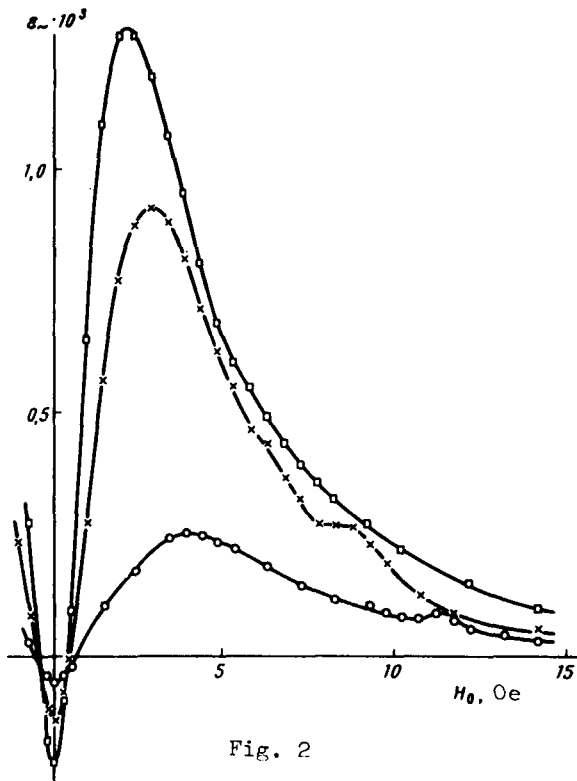


Fig. 2

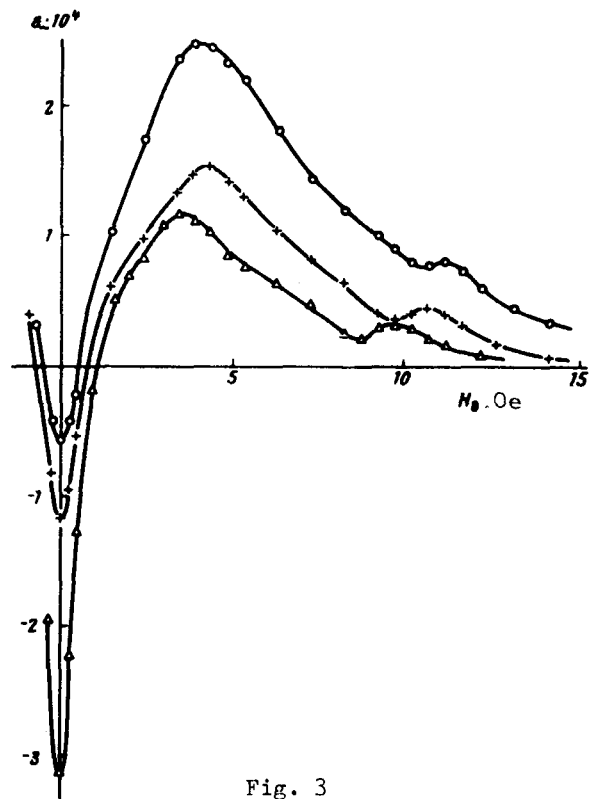


Fig. 3

Fig. 2. Plot of  $\epsilon_v = f(H_0)$  at  $H_1 = 2.16$  Oe and  $p = 0.4$  mm Hg;  $\square$  -  $f = 0.590$  MHz,  $\times$  -  $f = 1.225$  MHz,  $o$  -  $f = 1.700$  MHz.

Fig. 3. Plot of  $\epsilon_v = f(H_0)$  at  $H_1 = 2.16$  Oe and  $f = 1.7$  MHz;  $o$  -  $p = 0.4$  mm Hg,  $\times$  -  $p = 0.2$  mm Hg,  $\Delta$  -  $p = 0.1$  mm Hg.

distribution function in the space of the velocities ( $\vec{v}$ ) and momenta ( $\vec{M}$ ) of the molecules, determined by the product  $\vec{v}[\vec{M}]^2$ , where  $[\vec{M}]^2$  is a second-rank tensor made up of the components  $\vec{M}$ . Comparing the experimental values  $(H_0)_{res} = 4.0$  Oe and  $(H_0)_{res} = 11.3$  Oe with the theoretical values  $(H_0)_{res} = 4.5$  Oe for  $m_2 = 2$  and  $(H_0)_{res} = 8.8$  Oe for  $m_2 = 1$ , obtained from (1) for the experimental conditions, we conclude that the first maximum corresponds to  $m_2 = 2$  and the second to  $m_2 = 1$ .

The positions of the maxima are determined not only by the frequency but also by the amplitude of the alternating field and by the pressure, as is seen from Fig. 3, which shows plots of  $\epsilon_v$  for different  $p = 0.1, 0.2,$  and  $0.4$  mm Hg at  $H_1 = 2.16$  Oe and  $f = 1.7$  MHz. The experimental values for  $(H_0)_{res}$  agree, within the limits of experimental error, with the theoretical ones calculated from (1).

We can also conclude from the experiments that the plot of  $(\epsilon_v)_{res}$  against  $(H_1/p)$  at fixed  $(\omega/p)$  is analogous to the plot of  $\epsilon_v = f(H_0/p)$  (the Stenftleben effect). At fixed  $(H_1/p)$ , the value of  $(\epsilon_v)_{res}$  decreases monotonically with increasing  $(\omega/p)$ . Such behavior of  $(\epsilon_v)_{res}$  agrees with the theoretical one obtained from (1):

$$(\epsilon_{res})_{m_2\sigma} = -\Psi_{m_2} \frac{\frac{1}{2} \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2}{8 + 2 \left( \frac{\omega}{\lambda} \right)^2 + \left( \frac{m_2 \gamma_{1\sigma}}{\lambda} \right)^2}.$$

Thus, the experimentally observed resonant singularity in the behavior of the coefficient of the thermal conductivity of O<sub>2</sub> agrees with the theory. This confirms the correctness of the choice of the employed model of molecule collision.

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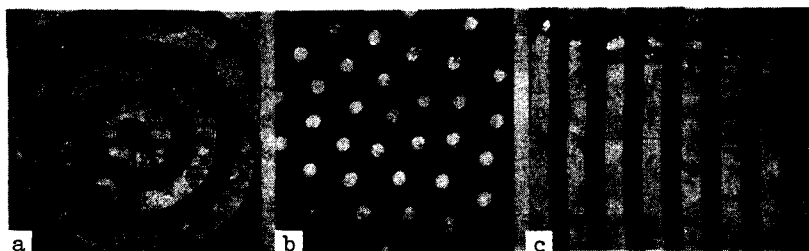
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#### CONCENTRIC DOMAINS IN SINGLE-CRYSTAL ORTHOFERRITES

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It is known that in single-crystal plates of orthoferrites cut normal to the "c" axis one can observe, besides strip domains, also a system of cylindrical domains [1]. Under certain conditions, the so-called ring domains [2] are obtained. We shall show below that all the modifications of domain configurations observed in orthoferrites can be regarded as a particular case of a regular domain structure consisting of a system of concentric ring domains (Fig. a).

The picture shown in this figure was obtained with a highly perfected TmFeO<sub>3</sub> plate measuring 7 × 10 mm and 60 μ thick. At the center of the picture is a cylindrical domain, stable in fields from H = 0 to H = H<sub>cr</sub>, where H<sub>cr</sub> is the collapse field. Thus, in the structure under consideration the range of stability of the cylindrical domains is much higher than in the known structures



Regular domain structure in single-crystal plate of TmFeO<sub>3</sub> (50×): a - system of concentric domains, H = 0; b - close-packed system of cylindrical domains, H = 30 Oe; c - system of parallel strip domains, H = 0.