

FIG. 2. Magnetoresistance of a cadmium single crystal plotted as a function of  $H$  for samples with smooth (1) and damaged (2) surfaces;  $n$  is the exponent of the power dependence  $R(H)$ .

arrangement of the current flow pattern so that it is concentrated in the surface layer (curve 3).

After the production of randomly distributed grooves, 0.5–1 mm deep, on the surface of a sample (by etching with a glass fiber wetted with nitric acid), the power exponent of the dependence  $R(H)$  in the same range of fields increased to

### INFLUENCE OF A MAGNETIC FIELD ON THE THERMAL CONDUCTIVITY OF GASES WITH NONSPHERICAL MOLECULES

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IT has been shown<sup>[1,2]</sup> that the transport coefficients (viscosity and thermal conductivity) of nitrogen depend on the magnetic field. It has been suggested<sup>[1]</sup> that this effect is due to both the nuclear and rotational magnetic moments of nitrogen molecules resulting from their nonsphericity. A comparison of this effect in nitrogen with the corresponding effect in oxygen, which is due to its paramagnetism (the Senftleben effect), made it possible to estimate the effective magnetic moment  $\mu_{\text{eff}}$  of nitrogen<sup>[2]</sup> and confirm the validity of the suggestion referred to above. It is obvious that such an effect should be present in all gases whose molecules are nonspherical. The present work reports briefly the results of investigations of this effect in  $N_2$ ,  $CO$ ,  $CO_2$ ,  $H_2$  and  $D_2$ ,

1.4 (curve 2 in Fig. 2) and the ballistic measurements showed that the current was concentrated to lesser degree near the surface (curve 4 in Fig. 1).

This interrelationship between the results obtained by independent methods of measurement led us to the conclusion that we had observed one of the consequences of the static skin effect: a linear dependence of the magnetoresistance on the external field.

We take this opportunity to thank I. G. D'yakov for his kind assistance in our measurements.

<sup>1</sup>G. A. Zaĭtsev, JETP 45, 1266 (1963), Soviet Phys. JETP 18, 870 (1964).

<sup>2</sup>M. Ya. Azbel', JETP 44, 983 (1963), Soviet Phys. JETP 17, 667 (1963).

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and gives the average values of the rotational magnetic moments  $\bar{\mu}_{\text{rot}}$ , together with data on the nonsphericity of these molecules, derived from this study.

A theoretical treatment due to Yu. M. Kagan and L. A. Maksimov (private communication) shows that their theory of this effect in  $O_2$ <sup>[3]</sup> may be adapted to other molecules having moments of inertia of the same order or larger than that of  $O_2$ . For such gases, the relative reduction in the thermal conductivity  $\epsilon = -\Delta\kappa/\kappa$  is given by the formula

$$\epsilon = af(\eta), \quad (1)$$

where

$$a = b\lambda^2, \quad \eta = K\mu_{\text{eff}}H/p, \quad K = K_1K_2,$$

$$K_2 = \frac{n^2}{A^{33}} \sqrt{\frac{kT}{2I}},$$

$K_1$  is a coefficient which depends on the nature of the magnetic moment;  $K$  is a coefficient which depends on the molecular-kinetic properties of the gas (the notation is the same as in<sup>[3]</sup>);  $\lambda$  is a nonsphericity parameter; and  $b$  is a coefficient depending on the nature of the gas. The form of the function  $f(\eta)$  and more detailed data on the coefficients are given in the work of Kagan and Maksimov, according to which  $K_1 = \sqrt{\pi}/20$  for  $O_2$ .

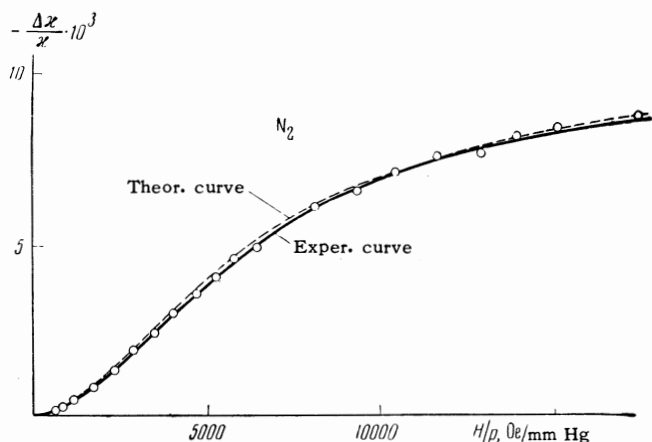


FIG. 1

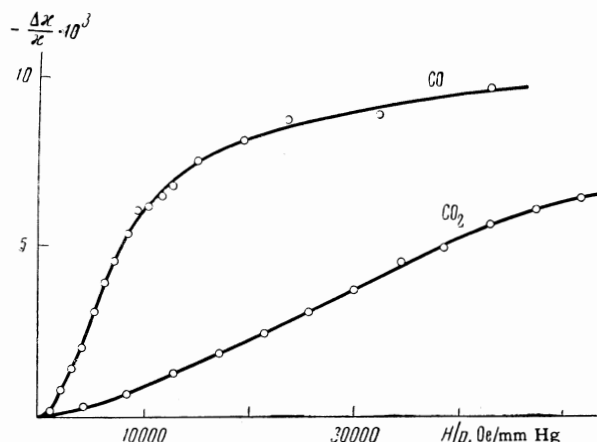


FIG. 2

As shown by L. A. Maksimov and V. Andriyako (private communication),  $K_1 = 1/15$  for diamagnetic molecules (for example,  $N_2$ ,  $CO$ ,  $CO_2$ ). For  $H_2$  and  $D_2$  molecules, Eq. (1) may be regarded only as approximate because the quantum nature of the rotational motion is not allowed for in the derivation of this equation, and allowance for this in the case of molecules with a small moment of inertia (of the  $H_2$  and  $D_2$  type) may lead to a somewhat different expression.

The basis of the apparatus was similar to that described in [2]. The measurements were carried out at room temperature over a range of pressures from  $6 \times 10^{-2}$  to 1 mm Hg, and in fields up to 3200 Oe. The curves showing the obtained dependences of  $\epsilon$  on  $H/p$  are given in the figures.

The absolute values of  $\epsilon$  were found by calibration using the known effect in oxygen [4] and allowing for the temperature discontinuity, [5] which was determined experimentally by the present authors. The measurements on  $N_2$ ,  $CO$ , and  $CO_2$  at various pressures ( $6 \times 10^{-2}$ – $4 \times 10^{-1}$  mm Hg) and fields (0–3200 Oe) showed that, in agreement with the theoretical data,  $\epsilon$  was a function of  $H/p$ .

The value of the maximum effect at saturation,  $\epsilon_{\max}$ , was determined by extrapolation of the experimental curves to higher values of  $H/p$  using the theoretical curve (1). This was possible because the relative curve (1) coincided with the experimental curves with an accuracy better than 5% for  $N_2$ ,  $CO$ , and  $CO_2$ , and 20% for  $H_2$  and  $D_2$ . The values of  $\epsilon_{\max}$  obtained in this way (with allowance for the temperature discontinuity) are given in the table (for the sake of comparison, the table also includes the data on  $O_2$  [4]). The error in the determination of  $\epsilon_{\max}$  amounted to  $\pm 10\%$  for  $N_2$ ,  $CO$ , and  $CO_2$ , and  $\pm 30\%$  for  $H_2$  and  $D_2$ .

It is evident from the table that the values of  $\epsilon_{\max}$  for  $H_2$  and  $D_2$  are relatively small. This may be explained (at least as far as the order of magnitude is concerned) by assuming that the nonsphericity of molecules is associated only with the charge distribution and that

$$\lambda \sim r_n Z, \quad (2)$$

where  $r_n$  is the distance between nuclei; and  $Z$  is the atomic number. In this case, according to Eq. (1), the values of  $\epsilon_{\max}$  for  $O_2$ ,  $N_2$ ,  $CO$ , and  $CO_2$  should be approximately two orders of magnitude larger than those for  $H_2$  and  $D_2$ , which is in agreement with the experimental data (cf. the table).

The ratio of the values of  $\epsilon_{\max}$  for  $H_2$  and  $D_2$  (2.0 : 1.0) determined with an error of less than  $\pm 30\%$ , is considerably larger than would follow from Eq. (1) on the assumption that  $\lambda_{H_2} = \lambda_{D_2}$  (1.1 : 1.0). This discrepancy may be explained either by the imperfection of the theory or by the fact that  $\lambda_{H_2} \neq \lambda_{D_2}$ .

Since, with the exception of  $\mu_{\text{eff}}$ , all the quantities occurring in the argument of  $\eta$  are known, [3, 7] this argument can be found by making the theoretical and experimental curves coincide. The values of  $\mu_{\text{eff}}$  obtained in this way are listed in the table. It is obvious that, since the  $CO$  and  $CO_2$  molecules do not have nuclear spins,  $\mu_{\text{eff}} = \bar{\mu}_{\text{rot}}$  for these molecules.

An estimate, obtained by L. A. Maksimov, shows that in the fields we used the coupling between the rotational and nuclear moments of the  $N_2$  molecule is virtually broken, i.e., the value of  $\mu_{\text{eff}}$  given for  $N_2$  is, as in the case of  $CO$  and  $CO_2$ , equal to  $\bar{\mu}_{\text{rot}}$ .<sup>1)</sup> For the same reason, the values of  $\mu_{\text{eff}}$  for  $H_2$  and  $D_2$  are equal to  $\bar{\mu}_{\text{rot}}$ . For comparison, we note that the values of  $\bar{\mu}_{\text{rot}}$

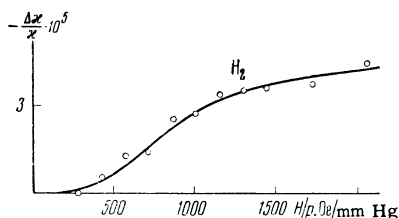


FIG. 3

for  $H_2$  and  $D_2$  at  $T = 300^\circ K$ , which we calculated from the known experimental data,<sup>[8]</sup> are, respectively, 1.1 and 0.8 nuclear magnetons (n.m.).

We shall now consider the problem of the limits of the validity of Eq. (1). It should be mentioned that the coincidence of our experimental curve for  $O_2$  (which agrees very well with Senftleben's curve<sup>[4]</sup>) with the corresponding theoretical curve (1) for  $\mu_{eff} = 1$  Bohr magneton gives a value of the coefficient  $K_1$  approximately half the theoretical value. This means that the value of  $K_1$  calculated by Kagan and Maksimov for  $O_2$  needs revision. In spite of the good agreement between the theoretical and experimental curves for  $N_2$ ,  $CO$  and  $CO_2$ , we cannot draw final conclusions about the accuracy of the theory in the case of these gases; this is because there are no other experimental data on  $\mu_{rot}$  of these molecules. However, the results of the measurements of  $\epsilon$  for  $H_2$  and  $D_2$  and the comparison of our data and published data on  $\bar{\mu}_{rot}$  of these molecules (see above) shows that the theory developed for molecules of the  $N_2$  type is approximately correct. It is obvious that, after refinement of the theory for  $H_2$  and  $D_2$ , it should be possible, depending on the degree of agreement of this theory with the experimental results for these gases, to answer the question about the limits of the applicability of the theory to other gases. At present, the data presented above show that the error in the determination of  $\bar{\mu}_{rot}$  of  $N_2$ ,  $CO$  and  $CO_2$  is probably less than  $\pm 20\%$ .

We are proposing to carry out later more accurate measurements on  $H_2$ ,  $D_2$  and other gases. Moreover, we are hoping to increase the precision of the determination of  $\bar{\mu}_{rot}$  of various molecules on the basis of an improved theory.

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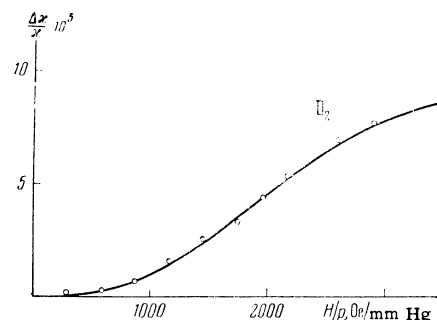


FIG. 4

A. A. Sazykin for their valuable contributions to the discussions; to V. Kh. Volkov for his interest and help in this work, to V. I. Nikolaev for his help in the making of the instruments; and to S. A. Repin for supplying the carbon monoxide gas.

<sup>1</sup>So far only the method for determining  $\mu_{rot}$  of the molecules of hydrogen isotopes and alkaline-earth elements (based on the Rabi method) has been published.<sup>[6, 8, 9]</sup>

<sup>4</sup>Beenakker, Scoles, Knaap, and Jonkman, Phys. Lett. 2, No. 1, 5 (1962).

<sup>2</sup>L. L. Gorelik and V. V. Sinitzyn, JETP 46, 401 (1964), Soviet Phys. JETP 19, 272 (1964).

<sup>3</sup>Yu. Kagan and L. Maksimov, JETP 41, 842 (1961), Soviet Phys. JETP 14, 604 (1962).

<sup>4</sup>H. Senftleben and J. Pietzner, Ann. Physik 16, 907 (1933); 27, 108 (1936), 30, 541 (1937).

<sup>5</sup>S. Chapman and T. G. Cowling, The Mathematical Theory of Non-Uniform Gases, 2nd ed., 1952 (Russ. Transl. IIL, 1960).

<sup>6</sup>N. F. Ramsey, Molecular Beams, 1956 (Russ. Transl., IIL, 1960).

<sup>7</sup>J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, Molecular Theory of Gases and Liquids, 1954 (Russ. Transl., IIL, 1961).

<sup>8</sup>N. F. Ramsey, Jr. Phys. Rev. 58, 226 (1940).

<sup>9</sup>Brooks, Anderson, and Ramsey, Phys. Rev. Lett. 10, No. 10, 441 (1963).

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Gas	$-(\Delta x/x)_{max} \cdot 10^4$	$\lambda^2$ , rel. units	$\mu_{eff}$	Gas	$-(\Delta x/x)_{max} \cdot 10^4$	$\lambda^2$ , rel. units	$\mu_{eff}$
$O_2$	120	1.00	1 Bohr magneton	$CO_2$	110	0.61	0.45 n.m.
$N_2$	105	0.58	1.30 n.m.	$H_2$	0.8	$0.45 \cdot 10^{-2}$	1.7 n.m.
$CO$	105	0.58	0.90 n.m.	$D_2$	1.6	$0.9 \cdot 10^{-2}$	0.8 n.m.