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### MINIMUM OF RESISTANCE IN IMPURITY-FREE CONDUCTORS

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AS is well known, interelectronic collisions in sufficiently pure conductors, can become appreciable at low temperatures. This is connected with the fact that the frequency of the collisions between electrons decreases with the temperature much more slowly than the frequency of the electron-phonon collisions. However, collisions between electrons give rise by themselves to electric resistivity only if umklapp processes are taken into account (Peierls), for in the opposite case these collisions do not lead to a change in the summary momentum of the electrons. On the other hand, umklapp processes are possible only if certain conditions are satisfied. Roughly speaking, it is necessary that the Fermi surface reach the center of the Brillouin cell. In the opposite case the probability of a collision accompanied by an umklapp process is exponentially small. It is clear that at low temperatures umklapp processes are practically impossible in many metals and semiconductors. In this case the electric resistivity is obviously determined by the loss of momentum when the electrons are scattered by different inhomogeneities of the lattice (impurity atoms, phonons, dislocations, etc.) and on the boundaries of the specimen.

If  $l_V$  is the mean free path connected with the scattering by the inhomogeneities, and  $d$  is the characteristic transverse dimension of the conductor, then the resistance for  $l_V \gg d$  is determined essentially by collisions between the electrons and the boundaries and, it might appear, by the effective mean free path  $l_{\text{eff}} \sim d$ . Actually, however, the interelectron collisions can greatly influence the process of momentum transfer to the

boundaries. This is simplest to understand in the limiting case

$$d \gg l_{ee}, \quad l_V \rightarrow \infty, \quad (1)$$

where  $l_{ee}$  is the length characterizing the interelectron collisions without the umklapp processes. When  $l_V, l_{ee} \gg d$ , an electron situated deep in the specimen reaches the wall practically without collisions during a time  $\tau \sim d/v_0$ , and, accordingly,  $l_{\text{eff}} \sim d$  ( $v_0$  is the limiting velocity). Then, as in the case (1), the electron, moving like a Brownian particle, covers a distance  $\sim d$  during a time  $\tau \sim d^2/l_{ee}v_0$  (since  $d \sim \sqrt{\tau l} v_0$ ), and consequently

$$l_{\text{eff}} \sim d^2/l_{ee}. \quad (2)$$

This result can also be obtained by starting from a hydrodynamic description of the electron gas, introducing the kinematic viscosity  $\nu \cong v_0 l_{ee}/3$ .

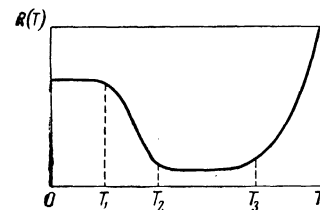
The hydrodynamic description is convenient because it is applicable for any ratio of  $l_V$  to  $d$ , provided  $l_{ee} \ll d, l_V$ ; consequently, this description enables us to take into account volume collisions, too. The corresponding equation for the average electron velocity  $v$  differs from the Navier-Stokes equation for stationary processes only in the term  $v/\tau_V$ , which describes the volume collisions:

$$eE/m = v\Delta v + v/\tau_V.$$

Let us consider by way of an example the result of the solution of this equation for a wire of radius  $r$  in a longitudinal electric field  $E$ . The electric conductivity is

$$\sigma = \frac{ne^2}{p_0} l_{\text{eff}}, \quad l_{\text{eff}} = l_V \left[ 1 - \frac{2}{x} \frac{I_1(x)}{I_0(x)} \right],$$

where  $n$  is the electron density,  $p_0$  the limiting momentum,  $x = r\sqrt{3}(l_{ee}l_V)^{-1/2}$ , and  $I_n(x)$  are Bessel functions of the imaginary argument. For  $x \ll 1$  we have  $l_{\text{eff}} \cong l_V x^2/8 = 3r^2/8l_{ee}$ , in accordance with (2). The figure shows the approximate course of the temperature dependence of the resistance  $R(T)$  for the wire. In the region of the lowest temperatures, so long as  $l_{ee} \gg r$  we have  $l_{\text{eff}} \sim d$  and the resistance is constant. Then, starting with the temperature  $T_1$ , at which  $l_{ee} \sim r$ , up to a temperature  $T_2$ , for which  $l_V \sim r^2/l_{ee}$ , the resistance decreases quadratically with increasing temperature [according to (2);  $l_{ee} \sim a(\epsilon_0/T)^2$ ,



$a$  is the lattice constant and  $\epsilon_0$  is the limiting energy]. If at a temperature  $T_2$  the electron-impurity collisions predominate over the electron-phonon collisions, namely  $l_{ef}(T_2) \gg l_{imp}$ , then the resistance remains constant from then on and remains very small (up to the value of the residual resistance of an unbounded specimen, where  $l_{eff} \sim l_{imp}$ ). Finally, at a temperature  $T_3$  ( $l_{ef}(T_3) \sim l_{imp}$ ), the usual growth in resistance begins:  $R \sim T^5 (l_{ef} \sim a(\epsilon_0/\Theta)(\Theta/T)^5$ , where  $\Theta$  is the Debye temperature). For a minimum of the resistance to occur, it is obviously necessary that at a temperature  $T_1$  the value  $l_V = (l_{imp}^{-1} + l_{ef}^{-1})^{-1} > r$ , from which follows  $a(\epsilon_0/\Theta)^{8/3} < r < l_{imp}$ . Thus, the specimen should not be too thin (for a typical metal,  $r \gtrsim 10^{-2}$  cm).

It is clear that the results obtained (and, in particular, the minimum of the resistance), are qualitatively valid for specimens of arbitrary shape. For example, for a plate of thickness  $d$  we have in the limiting case (1)  $l_{eff} \cong d^2/l_{ee}$ . An analogous situation should also occur in an unbounded conductor in the presence of macroscopic distortions (say, dislocations); in this case the role of  $d$  in the inequalities given above will be assumed by the average distance between the distortions. These considerations apparently do not apply to impurities, since the average distances between the impurity atoms is  $\lesssim 10^{-5}$  even in the purest specimens.

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### A TWO-ELECTRODE SPARK CHAMBER WITH A LARGE DISCHARGE GAP IN A MAGNETIC FIELD

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SPARK chambers with large discharge gaps have been described by many workers.<sup>[1-8]</sup> Others<sup>[9-11]</sup> have reported the results of investigations of multi-layer spark chambers in a magnetic field.

The present note reports the preliminary results of a study of the possibility of recording the trajectories of charged particles in a spark chamber with a large discharge gap, placed in a magnetic field. Figure 1 shows an external view of the chamber, placed in the gap of an electromagnet at the high-altitude cosmic-ray station Nor-Amberd of the Physics Institute of the State Commission on Atomic Energy. The side surfaces of the chamber were made of polished organic glass (Perspex) of 30 mm thickness. The Duralumin electrodes of 20 mm thickness were clamped by means of flanges with rubber spacers. The working dimensions of the chamber were  $20 \times 40 \times 21$  cm. The chamber was evacuated to a pressure of  $3 \times 10^{-2}$  mm Hg and then filled with neon to a pressure of 1.5 atm.

To avoid edge effects the chamber was fitted with outer "wings" which made it possible to obtain 100% working efficiency throughout the whole volume of the chamber.

Good records were obtained of the trajectories of particles coming at an angle of  $40^\circ$ . Moreover, it was found that particles entering from the sides of the chamber, with parts of their trajectories outside its working volume, were also recorded. Showers were recorded with high efficiency; however, detailed studies of the efficiency of recording showers have not been carried out.

Figure 2 shows the essentials of the triggering circuit of the spark chamber (S.C.). The coincidence circuit with a delay time of 0.25–0.3  $\mu$ sec was triggered by a high-voltage discharger of Marks type (M) which generated a high-voltage pulse of  $10^{-7}$  sec duration and 60–80 kV amplitude.

The tests were carried out in a magnetic field of  $5 \times 10^3$  G intensity. Photographs of the trajectories of charged cosmic-ray particles in a magnetic field are given in Fig. 3.

As indicated by the photographs, the curvature of a trajectory in the magnetic field is well reproduced by a streamer channel without visible distortions. Measurements showed that the curvature of  $\mu$ -meson tracks of a certain range, photographed with this chamber, was in good agreement with the expected value. According to our estimates in such chambers we can obtain good accuracy in determining particle momenta up to tens of BeV/c. We are carrying out detailed investigations of this problem.

The possibility of measuring the momenta of charged particles in a spark chamber of the type described considerably extends the range of applications of such chambers.

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