MEASUREMENT OF THE RELATIVISTIC INCREASE IN SPECIFIC PRIMARY IONIZATION IN A STREAMER CHAMBER

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The possibility is demonstrated of measuring specific primary ionization in a streamer chamber. The relativistic rise in primary ionization has been with an accuracy of 2% in a chamber filled with 0.6 atm of helium.

1. INTRODUCTION

THE streamer chamber is a device in which the ionizing power of a particle can, in principle, be measured by one of the following means:[1]

a) by measurement of the number of streamers per unit length of track;

b) by measurement of the brightness of the streamers;

c) by measurement of the length of the streamers (along the electric field).

Nevertheless, in spite of the dependence of the number streamers (and also the brightness and length) on ionization, demonstrated by Asatiani et al.,[2] the possibility of measuring ionization in a streamer chamber is practically never utilized. This results from the fact that in many investigations with streamer chambers [3-6] the number of streamers per unit length of relativistic-particle track changes strongly from investigation to investigation, usually remaining several times smaller than the number of electrons produced by the particle in the chamber gas. This spread in the experimental data apparently indicates the strong dependence of the results on the conditions of the ionization measurement (the mode of chamber operation, conditions of photography, etc.), which does not permit us to count on obtaining high accuracy in such measurements.

In addition we should note two features of the streamer chamber which are of interest in regard to measurement of specific ionization. The first is the possibility of measuring the ionization in the region of the relativistic increase in ionization loss, for the density effect in the chamber gas at a normal pressure sets in near $E/mc^2 = 300-500$ (where E is the particle energy and m is the rest mass). In the second place, the streamer chamber, along with such detectors as low-efficiency Geiger counters and cloud chambers,[7] under defined conditions has the ability to record the specific primary ionization, i.e., the number of ionizing collisions per unit length of track.

The specific primary ionization produced by a charged particle in the chamber volume can be measured in the case when the electrons from secondary ionization diffuse to a distance appreciably less than a streamer radius R (i.e., the diffusion length $L \ll R$) during the time between passage of the particle and supply of the high-voltage pulse to the chamber electrodes. Under this condition the secondary-ionization electrons are not fixed in the form of individual streamers but are recorded either as a single streamer which has grown in a group of electrons (in the case of small energy transfer in the primary collision) or with a characteristic branching in the track (in the case of large energy transfer) and can easily be rejected in the analysis. As the delay time is increased up to values in which the electrons diffuse to distances considerably larger than the streamer radius $(L \gg R)$, an individual streamer grows at each electron, which permits detection of the total specific ionization.

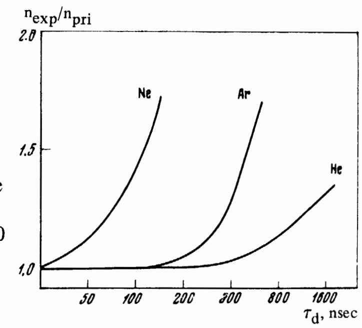


FIG. 1. Ratio of the number of streamers in the chamber to the number of primary ionizing collisions, as a function of the high-voltage pulse delay time τ_d; the calculation was made for a streamer radius R = 0.04 cm. The electron diffusion coefficients used in the calculation were 2000 cm²/sec for neon, 370 cm²/sec for argon, and 310 cm²/sec for helium.

From the point of view of accuracy in the measurement of the ionizing power of particles, a strong preference must be given to measurement of the primary ionization, since the fluctuations of the primary ionization are described by a Poisson distribution, and the relative error in the specific ionization measurement is $N^{-1/2}$, where N is the number of ionizing collisions of the particle in the track length. At the same time the fluctuations in total ionization for the case of a thin absorber such as the chamber gas are described by a Landau distribution,[7] whose width (relative to the most probable energy loss) shows practically no decrease with increasing track length of the particle in the chamber.

Figure 1 shows curves illustrating the possibility in principle of measuring primary ionization in a streamer chamber filled with various noble gases. The curves show the excess of the number of streamers in the chamber over the number of primary ionizing collisions as a function of the delay time τ_d between passage of the particle and the high-voltage pulse. The curves were calculated for a streamer radius

R = 0.4 mm, a pressure of 1 atm, and electron diffusion coefficients calculated from Ramsauer's data on the cross sections for elastic collisions of electrons.[8] It is evident from Fig. 1 that of the gases considered the most suitable for measurement of primary ionization is helium, which possesses the smallest electron diffusion coefficient (310 cm^2/sec). For helium in the region of delay times actually achievable, τ_d = 150—200 nsec, the number of streamers depends weakly on τ_d and corresponds to the number of primary collisions. On the other hand, for neon, which is most frequently used for filling streamer chambers, the expected number of streamers depends strongly on the delay time of the high-voltage pulse and is not equal to the number of primary collisions.

2. EXPERIMENT

We used a streamer chamber of dimensions 30 × 18 × 3.5 cm. The minimum-ionizing particles were electrons from a Sr^{90}(Y) source, crossing the chamber in a direction perpendicular to the electric field direction. The energy E_e of the electrons whose tracks were recorded in the chamber was determined by the maximum energy of the β spectrum, 2.26 MeV, and the absorber, which limited the electron energy to values greater than 1.3 MeV (thus, 1.3 MeV $\leq E_e < 2.26$ MeV). The delay between the passage of the electron through the chamber and the high-voltage pulse could be varied from τ_{min} = 200 nsec to tens of microseconds. The chamber did not contain any materials except metal (brass) and glass (cemented by BF-4 cement), and was filled with gases of special purity. During the operation of the chamber (except in cases where we studied the effect of impurities on operation of the chamber) the gas was in constant contact with activated charcoal which had previously been heated to 100°C and pumped to 10^{-2} mm Hg. A mass-spectrometer analysis of a sample of gas taken from the chamber showed the presence of the following impurities: Kr—less than 5×10^{-4}%, Ar and Xe—less than 5×10^{-3}%, and N_2—of the order of 1%.

The tracks were photographed by means of a three-stage image converter with an effective gain of 10^3 and a resolution of 15—20 lines/mm.

3. EXPERIMENTAL RESULTS

1. In order to confirm the usually used theoretical data on electron diffusion[9,10] we measured the electron diffusion coefficients in neon and helium in the absence of an external electric field. The results are shown in Fig. 2, where we have plotted the mean-square deviation of the streamers in a particle track as a function of delay time. From Fig. 2 it can be seen that there is good agreement of the experimentally measured values with those expected for neon and helium. On the other hand, it is apparent that presence of a small amount of molecular impurity strongly decreases the electron diffusion coefficient (presence of water or alcohol with vapor pressures corresponding to room temperature decreases the diffusion coefficient by factors of ten[1]). This phenomenon may explain the reduced values of electron diffusion coefficients measured in a streamer chamber, obtained by several investigators.[4,10]

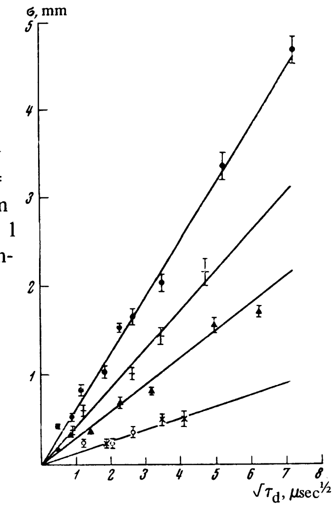


FIG. 2. Mean-square streamer deviation in the particle track as a function of high-voltage pulse delay time: ●—technically pure neon, P = 1 atm; +—neon with impurities from outgassing of ÉD-6 epoxy resin, P = 1 atm; O—neon with alcohol-vapor impurity, P = 1 atm; X—neon with water-vapor impurity, P = 1 atm; ▲—pure helium at a pressure of 0.6 atm.

2. Figure 3 shows the number of streamers per unit length of relativistic-particle track in neon for a pressure of 1 atm, as a function of delay time. The nature of the variation of the number of streamers in the track is explained by two causes: diffusion of electrons, which produces an increase in the number of streamers (see Fig. 1), and attachment of electrons to impurity molecules, which strongly decreases the number of streamers. Particularly important is the fact that the epoxy resin (in our case ÉD-6) often used to cement the chambers can appreciably decrease the number of streamers.

Thus, the impurities in a noble gas decrease the number of electrons and slow down their diffusion.

3. Under our conditions, control of the gas purity (see Sec. 2) and use of the image amplifier easily permitted us to obtain a good correspondence between the number of streamers in the particle track and the number of electrons produced by the particle in the gas. Figures 4 and 5 present data on the increase with delay time of the number of streamers per unit track length in neon at a pressure of 0.8 atm. In Fig. 4 the experimental data are compared with a theoretical curve[11] calculated with a computer. The calculation took into account electron diffusion (see Fig. 2) and

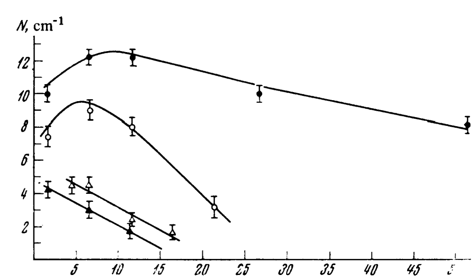


FIG. 3. Number of streamers per unit track length in neon at atmospheric pressure, as a function of high-voltage pulse delay time: ●—measurements one half hour after filling chamber with pure neon, O—six hours after filling: Δ—neon with water vapor, ▲—neon with alcohol vapor. Measurements were made in a chamber glued with ED-6 epoxy resin.

[1] A similar phenomenon has been observed by Vinogradov et al. [9]

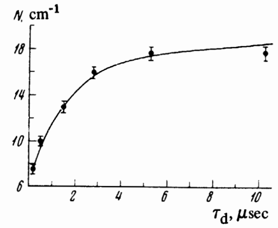


FIG. 4. Increase in number of streamers with increasing delay time. Pure neon, P = 0.8 atm. Solid curve—theoretical.

the geometrical overlap of the photographic images of the streamers.

4. On the basis of the data of Fig. 1 we made further investigations with a chamber filled with helium. Figure 5a shows a typical relativistic-particle track in a chamber filled with 0.6 atm of helium. In Fig. 5b we have specially selected a track with a δ electron possessing an energy of ~1.5 keV (large energy transfer), in order to show that such events can easily be rejected in the analysis. It should be noted that the probability of such an event is small (on the average one event in 2 m of track).

In addition to the considerations related to the small diffusion coefficient, the possibility of measuring primary ionization in helium requires further proof. As such proof we have used the shape of the distribution of the number of streamers in a particle track. Figure 6 shows the distribution of the number of streamers per unit track length for the case of minimum delay, 0.2 μsec (Fig. 6a), and for a delay of 15 μsec (Fig. 6b). It is evident that for small delays the experimental distribution is in good agreement with the Poisson distribution curve, and for large delays—with the Landau distribution.

Figure 7 illustrates the smooth transition from the primary ionization to the total ionization in the process of diffusion of the electrons in the particle track. Here

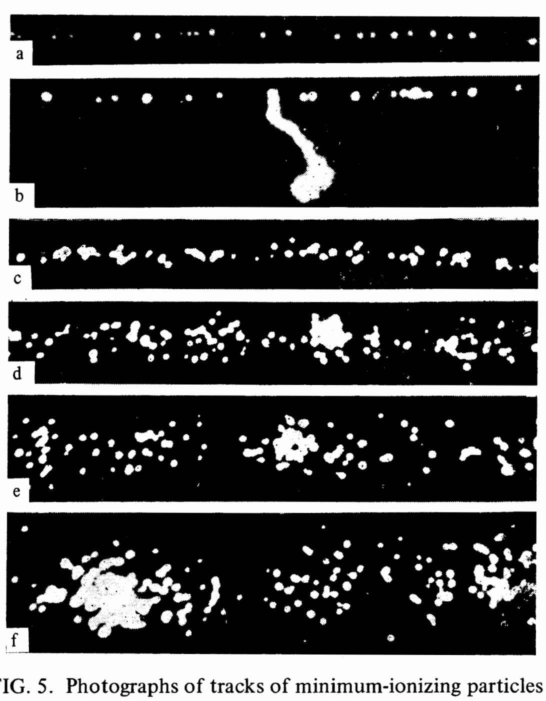


FIG. 5. Photographs of tracks of minimum-ionizing particles in a chamber filled with 0.6 atm of helium (a, b) and with 0.8 atm of neon (c–f). The track length is 5 cm, and the delay time for the tracks is: a—0.2 μsec, b—0.2 μsec, c—1 μsec, d—2.5 μsec, e—5 μsec, f—10 μsec.

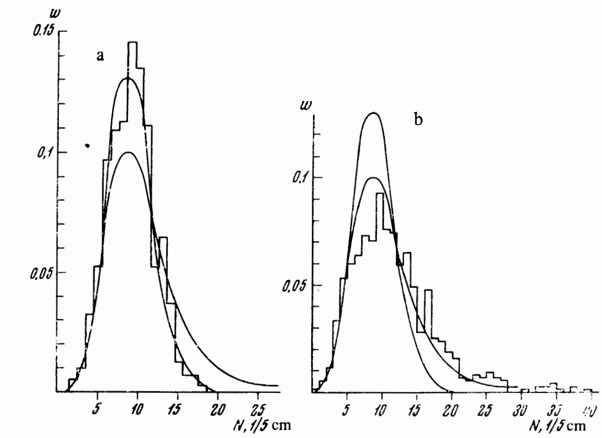


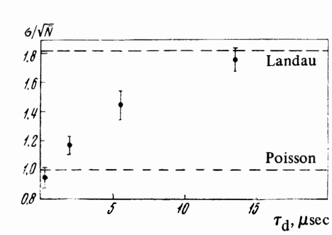
FIG. 6. Distribution of number of streamers per unit track length in a chamber filled wth 0.4 atm of helium: a–delay time 200 nsec, b–15 μsec. Smooth curves–Poisson and Landau distributions calculated for the present case. The theoretical curves and the experimentally obtained histogram have been normalized on the basis of area. The ordinate is the probability of obtaining a given number of streamers in a track length of 5 cm.

we have chosen, as the parameter characterizing the shape of the distribution of the number of streamers in the track, the mean-square deviation of the number of streamers in a given track length in units of the Poisson standard deviation. This quantity is equal to unity for a Poisson distribution and 1.8 for a Landau distribution (in our case). The data presented indicate a gradual transition from the Poisson distribution, which is characteristic of the primary ionization, to the Landau distribution, which describes the fluctuations in total ionization.

5. The possibility of measuring the primary ionization, which fluctuates in accordance with a Poisson distribution, presents real interest only in the case when the number of streamers in the particle track does not depend on the mode of chamber operation over rather wide limits. In Fig. 8 we show the results of primary-ionization measurements made over a wide range of operating conditions of a helium-filled chamber (shape and height of high-voltage pulse, delay time, and streamer length). The range of variation of chamber operating parameters is roughly an order of magnitude greater than the variations possible under conditions of actual use. Thus, it is evident from Fig. 8 that the accuracy in measurement of the number of streamers in a particle track which can be achieved under real conditions is better than 1%.

6. To measure the rise in primary ionization in the region of the relativistic increase in ionization loss, a streamer chamber filled with 0.6 atm of helium was exposed to an electron beam of known momentum. The

FIG. 7. Mean-square deviation of the number of streamers in a track length of 5 cm, in units of the Poisson standard deviation, as a function of delay time. The chamber was filled with 0.4 atm of helium.



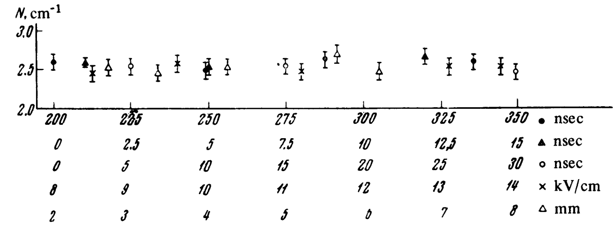


FIG. 8. Effect of change of various parameters of the chamber operating conditions on the number of streamers per unit particle track length: ●—delay, ▲—fall time, ○—rise time, ×—voltage, △—streamer length.

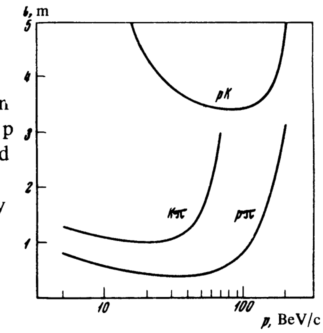


FIG. 10. Separation of particles in mass in a beam of a given momentum p in a streamer chamber of length l filled with 0.6 atm of helium. The curves correspond to a separation probability of 95%.

measurements were made in two electron accelerators at the Physics Institute of the Academy of Sciences, USSR, in the energy ranges 12.5—250 MeV (solid points in Fig. 9) and 150—570 MeV (hollow points in Fig. 9). The solid curves in Fig. 9 are theoretical calculations [12,13] in which corrections have been made for overlap of the photographic images [11] of the streamers.

During the period of use of the accelerators the chamber was repeatedly refilled and calibrated with minimum-ionizing electrons. The results of these calibrations are given below:

Time of measurement:	July	August	October
Number of streamers in 1 cm of track:	2.26 ± 0.04	2.24 ± 0.04	2.22 ± 0.03

The spread in the data serves as a measure of the systematic error of the entire experimental setup during the course of the measurements.

4. CONCLUSIONS

1. The investigations have demonstrated the possibility of precision measurements of primary specific ionization in a streamer chamber.

2. The possibility of measuring primary specific ionization in the region of the relativistic rise in energy loss permits use of a streamer chamber as a spectrometer for velocity analysis of particles. For example, with a chamber 1—1.5 m long we can obtain an accuracy of the order of several percent in determination of the ionization. This permits use of the streamer chamber for mass analysis of particles in momentum-selected beams in the region

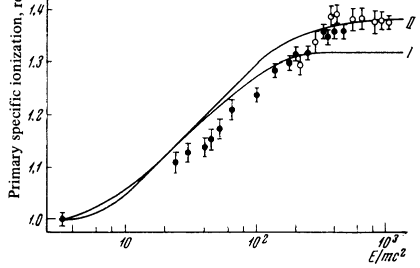


FIG. 9. Relativistic rise in primary ionization, measured in a streamer chamber filled with 0.6 atm of helium. Solid circles—measurements with 250-MeV electron accelerator, hollow circles—measurements with 570-MeV electron accelerator. Curve 1—theory according to Budini et al., [12] curve 2—calculation made by L. Kotenko, G. Merzon, and N. Chechin on the basis of formulas from Ref. 13.

$10 < E/mc^2 < 300$. We have shown in Fig. 10 as an illustration the possibility of particle separation by this means, calculated on the basis of the data obtained.

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