Localization of charged-particle tracks in a self-shunted helium streamer chamber

L. Busso,[1)] M. M. Kulyukin, É. D. Lozanskiĭ, V. I. Lyashenko, Nguen Minh Kao, G. Piragino,[1)] G. B. Pontecorvo, T. M. Troshev, I. V. Falomkin, and Yu. A. Shcherbakov

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Some operating characteristics of a helium self-shunted chamber with various admixtures (H_2, Xe, Ne, α-pinene, H_2O and CH_4) are investigated. A qualitative explanation of the mechanism of localization of charged-particle tracks in such chambers is presented.

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1. INTRODUCTION

Beginning in 1971, systematic studies of pion scattering by helium[1,2] and carbon[3] have been carried out successfully with self-shunted helium streamer chambers[4,5] at the Joint Institute for Nuclear Research and at the Physics Institute of Torino University. These chambers operate at increased pressure (up to 6 atm),[6–8] and under certain conditions in a magnetic field.[9]

As was emphasized in our earlier work,[4] the main feature of the self-shunted regime is the fact that localized tracks are obtained not as the result of limitation of the development of a discharge in the chamber, but by controlling the distribution of luminous intensity of the discharge channels located along the particle trajectories. This is achieved by introduction of appropriate impurities into the chamber working volume. Good results were obtained with small concentrations of heavy hydrocarbon impurities[4] and also of xenon.[10] It is true that the hydrocarbons can take part in chemical reactions in the discharge, and therefore with time the "localizing ability" of the impurity may change. We have obtained localized tracks successfully with an impurity (at the level 0.1–0.4%) of nitrogen and xenon in a helium chanber operated in a magnetic field of the order 5 kG.[5] Inorganic impurities provide greater stability of operation of a helium streamer chamber than do hydrocarbon impurities.

In the present work we have investigated some of the operating characteristics of a helium self-shunted chamber with various impurities (CH_4, H_2, Xe, α-pinene, Ne, H_2O) and we give a qualitative explanation of the mechanism of charged-particle track localization.

2. EXPERIMENTAL APPARATUS

The experiments were carried out in a streamer chamber with a diameter of 22 cm and a discharge gap of 7 cm. The inner volume of the chamber was separated from the electrodes by glass plates 1.2 cm thick which were attached with silicone rubber adhesive. An exponential pulse with a rise time of ~10 nsec, a fall time ~1.5 μsec, and a height of 280 kV was fed directly to the chamber electrodes from an Arkad'ev–Marx generator.[11] The chamber was triggered by means of a single scintillation counter which recorded electrons emitted by an Sr^{90} source and passing through the chamber. The minimum instrumental delay in the high-voltage pulse was 0.4 μsec. Type 29 film with a speed $S_{0.85}$ = 2000 GOST units was used to photographs electron tracks in the chamber.

Before filling with the working gas, the chamber was pumped through a nitrogen trap to a pressure of 10^{-3} mm Hg. In order to reduce the concentration of uncontrolled impurities released from the chamber walls, the experiments were carried out immediately after filling the chamber with a given gas mixture. We also made a determination of the rate of change of the characteristics of a chamber filled with pure helium. The time interval during which experiments were carried out was chosen significantly shorter than the time in which the effect of uncontrolled impurities on the discharge configuration became noticeable (~3 days).

3. EXPERIMENTAL RESULTS

Figure 1 shows photographs of electron tracks in helium with different impurities (all tracks were photographed in a direction perpendicular to the electric field; the gas pressure P, the amount of impurity, and the electric field strength E are given in the figure caption). It is very readily seen how the impurities affect the quality of the tracks in a streamer chamber operating in the self-shunted regime. In essence, as was said above, the action of the impurities reduces to a change in the intensity distribution of visible (i.e., photographable) radiation along the discharged channels, which leads accordingly to various degrees of localization of the tracks in the chamber.

To obtain a quantitative estimate of the degree of localization of the tracks, by means of a microphotometer we obtained distributions of the film density (i.e., of the intensity of visible light radiated by the discharge) along the images of discharge channels. For the length of the visible part of the discharge channel d we arbitrarily took the average width at half-height of the distribution curve. This length was determined from 30 different distributions corresponding to the same conditions for production and photography of tracks in the chamber. The quantity d actually characterizes ex-

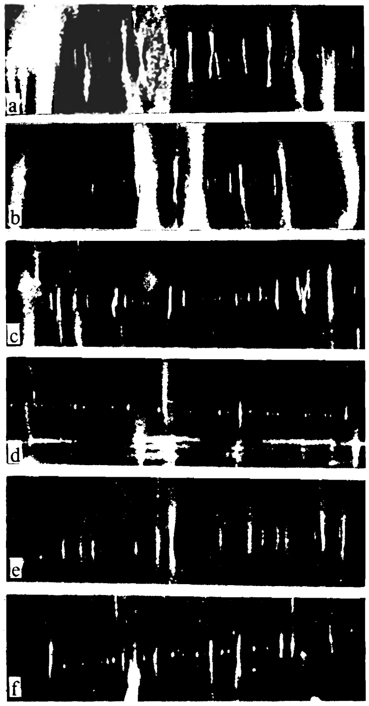

FIG. 1. Photographs of electron tracks in helium with various impurities (for a pressure of the gas mixture $P=1$ atm): a) pure helium, $E=15.7$ kV/cm, objective aperture 5.6; b) He $+0.4\%$ CH_4, $E=12.9$ kV/cm, aperture 2.5; c) He $+0.6\%$ H_2, $E=22.7$ kV/cm, aperture 5.6; d) He $+0.1\%$ H_2O, $E=22.7$ kV/cm, aperture 5.6; e) He $+0.3\%$ α-pinene, $E=22.7$ kV/cm, aperture 5.6; f) He + uncontrolled impurity, $E=22.7$ kV/cm, aperture 5.6.

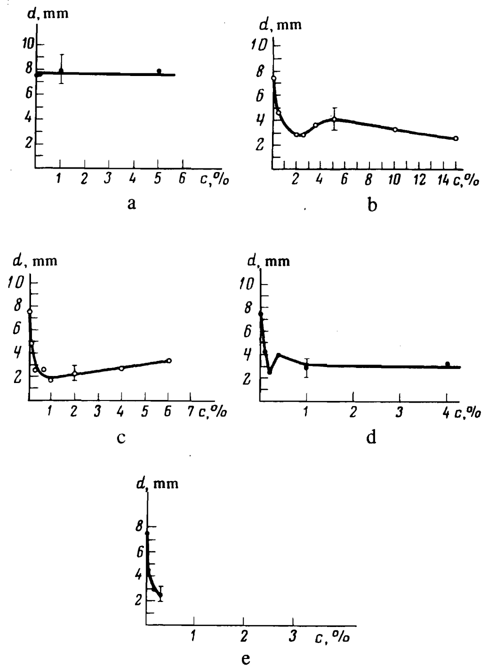

FIG. 3. Plots of length of bright part of streamer channel as a function of impurity concentration c ($P=1$ atm): a) Ne, b) Xe, c) H_2, d) CH_4, e) α-pinene.

actly the degree of localization of particle tracks in a given gas mixture.

In Figs. 2a and b we have shown distributions of the intensity of radiation of the discharge channel in pure helium and in a mixture of helium plus 2% hydrogen. As can be seen, the width of the curve is significantly less (and correspondingly the localization of the highly luminous part of the discharged channel is better) in the presence of an impurity in the helium.

1. Dependence of degree of localization of a particle track on impurity concentration

In Fig. 3 we have shown plots of the value of d as a function of the impurity concentration c for H_2, Xe, CH_4, α-pinene, and Ne at $E\approx 23$ kV/cm. For each impurity except Ne, as can be seen from these plots, there is an optimum concentration at which the average size of the bright region (or point) of the discharge channel is minimal. The term point refers to a discharge channel of characteristic appearance when there is visible in the center of the channel a bright portion whose length does not exceed its width by more than a factor of 2–3.

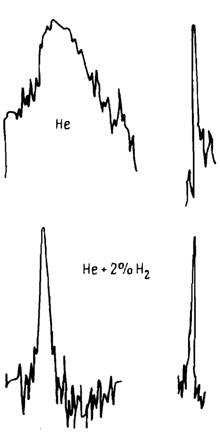

FIG. 2. Distribution of radiation intensity in a discharge channel in pure helium and in helium with 2% hydrogen ($P=1$ atm): a) along the channel; b) across the channel.

A special interest is presented by use as an additive of hydrogen, which forms with helium the well studied Penning mixture.[12] For low concentrations of H_2 ($\sim 3\%$) the discharge channel has a brush form as in pure helium, the length of the bright portion d being 7–8 mm. With increasing hydrogen concentration, d decreases and reaches a minimum value of ~ 1.7 mm for concentration of $\sim 1\%$. Further increase of the amount of H_2 leads to a slow rise in the value of d.

Recently we demonstrated the possibility of making a hydrogen self-shunted streamer chamber.[13] The electron tracks obtained in that work do not differ in their degree of localization from the tracks obtained by Rohrbach.[14] At the same time the luminosity of the tracks in the self-shunted chamber is significantly greater.

In the case of molecular impurities the optimum concentration is displaced toward lower values. Molecular impurities are also distinguished by the fact that they absorb photons and thus decrease photoionization in the working region of the chamber and discharges along the walls. This leads to a reduction in the total radiation of the chamber working volume and to an increase in the contrast of particle tracks. High quality tracks are

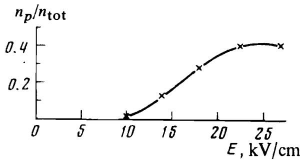

FIG. 4. Plot of the ratio of the number of points n_p to the total number of discharge channels n_{tot} as a function of the electric field E for a mixture He + 0.3% CH_4 (P = 1 atm).

obtained with addition of water (~ 0.1%) and α-pinene (~ 0.3%). The track in Fig. 1f was obtained in the presence of uncontrolled impurities.

The data presented are for impurities which are characterized first of all by low levels of excitation and ionization in comparison with helium. As a rule, in a mixture of helium with such impurities the Penning effect[15] is observed. However, for track localization it is apparently more important (as is shown below) that the probability of collisions of electrons with atoms or molecules of the impurity is significantly greater than in helium, Accordingly, in a mixture of helium and neon no track localization effect is observed (the probability of collisions of electrons with Ne atoms is less than with He[15]).

2. Dependence of track quality on the ratio E/p

The dependence of the localization of a particle track and the density of points along the track on the electric field strength agrees on the whole with the data obtained previously.[4] As an example we have given in Fig. 4 a plot of the corresponding dependence for a mixture of helium and 0.3% methane.

As it turned out, the localization of the discharge radiation takes place in a definite region of values of E/p. A plot of the length of the bright portion of the discharge channel as a function of the ratio E/p for the mixture He + 1% H_2 is given in Fig. 5. A similar dependence is observed for the ratio of the number of points n_p to the number of discharge channels n_{tot} along the track. The corresponding plot is also shown in Fig. 5. Each experimental point in the graphs corresponding to a single value of E/p was obtained for several different values of E and p.

As can be seen, there is a certain optimal range of E/p values (for the mixture He + 1% H_2 the ratio is E/p = 30–60 V/cm-torr) at which optimal values of the parameters d and n_p/n_{tot} are achieved.

4. CHARGED-PARTICLE TRACK FORMATION IN A SELF-SHUNTED STREAMER CHAMBER

In operation of a streamer chamber in the self-shunted mode, i.e., without external shaping of the high-voltage pulse, the variation of the electric field in the chamber after voltage is applied to it is determined by the discharge in it.[4] The process of charged-particle track formation in a self-shunted streamer chamber passes through three rather distinctly different steps.

1. Development of the primary electron avalanches from electrons located along the path of the charged particle. The time of development of the avalanches in an exponentially rising external field is ~ 10^{-8} sec. The current of the avalanches cannot exert an appreciable effect on the shape of the voltage pulse in the chamber.

2. Development of a streamer discharge and propagation of it over the entire discharge gap. Here[16,17] the electric field gradient inside the discharge channel drops, the current in the circuit increases, and correspondingly the voltage on the chamber decreases (the time of streamer development in a discharge gap of the order of 10 cm is of the order 10^{-8} sec[18–20]).

3. Discharge of the capacitance of the high-voltage pulse generator and discharge of the capacitance of the glass plates which separate the chamber volume from the electrodes. The current discharging the capacitance of the glass plates flows through the prepared discharge channels in the chamber. The power dissipated determines the intensity of radiation of the particle tracks. Here the electric field in the chamber is already small, so that the appearance of new discharge channels is impossible.

Some qualitative estimates of the radiation intensity distribution along discharge channels.

We shall attempt to give a qualitative explanation of the observed localization of tracks in the streamer chamber on addition to helium of impurities of xenon, hydrogen, and certain heavy hydrocabons. First, consider a discharge in pure helium. From streamer theory[21,22] it follows that the streamer channel at the place of the avalanche-streamer transition has a neck, i.e., a comparatively narrow place. For purposes of estimation we can assume that the dependence of the streamer channel radius on the coordinate z along which the electric field E_0 is directed has the form

$$r=r_0+C|z|^n, \tag{1}$$

where r_0 is the radius of the avalanche head at the moment of the avalanche-streamer transition, C is a constant, and the origin is chosen at the center of the avalanche head.

The value of the exponent n is unknown, but numerical calculations of the shape of a streamer channel[22] show that it is significantly greater than unity. As a result, after short-circuiting of the spark gap by a streamer channel the discharge current density will also depend on z and will be maximal in the vicinity of the

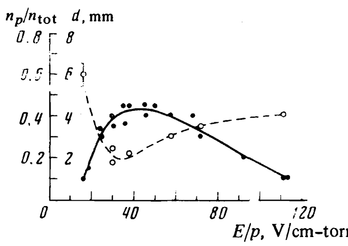

FIG. 5. Plots of the ratio n_p/n_{tot} and d as a function of E/p for a mixture He + 1.0% H_2: ○—d; ●—n_p/n_{tot}.

neck. The concentration of electrons will also be maximal in just this region. In fact, the electron concentration can be evaluated from the formula

$$N_e \sim i/eUr^2k. \tag{2}$$

Here i is the discharge current, U is the electron drift velocity, k is the number of discharge channels, and e is the charge of the electrons. Under our conditions estimated parameter values are: $i \approx 10^3$ a, $U \approx 10^6$ cm/sec, $r \approx 10^{-1}$ cm sec, and $k = 10-100$. Substituting these parameter values into Eq. (2), we find that in the region of the neck the concentration is $N_e \sim 10^{16}-10^{17}$ cm^{-3} and falls rather rapidly with departure from this region.

Let us now compare the frequency of collisions of electrons with ions and with neutral helium atoms. The frequency of collisions of electrons with ions can be estimated from the formula[23]

$$\nu_{ei} \sim N_e \frac{e^4 \ln \Lambda}{\bar{\varepsilon}^2} \left(\frac{\varepsilon}{m}\right)^{1/2}. \tag{3}$$

Here $\bar{\varepsilon}$ is the average electron energy, $\ln\Lambda$ is the Coulomb logarithm, m is the electron mass, and M is the mass of the helium atom. Under our conditions $\varepsilon \approx 1$ eV and $\ln\Lambda \approx 10$. Consequently, $\nu_{ei} \approx 10^{-4} N_e$ sec^{-1}.

The frequency of elastic collisions of electrons with helium atoms is

$$\nu_{ea} = N_a \left(\frac{\varepsilon}{m}\right)^{1/2} \sigma_e \approx 10^{19} \cdot 10^8 \cdot 10^{-15} \approx 10^{12}\ \text{sec}^{-1}, \tag{4}$$

where σ_e is the cross section for elastic collisions and N_a is the density of helium atoms. Thus, for a concentration of electrons and ions in the plasma $N_e \sim 10^{16}$ cm^{-3} the two frequencies turn out to be comparable. From this one can draw the important conclusion that in the neck, where the electron concentration is $N_e \gtrsim 10^{16}$ cm^{-3}, the main role in establishment of the equilibrium parameters of the plasma will be played by collisions of charged particles, while outside the neck, where $N_e \lesssim 10^{16}$ cm^{-3}, elastic collisions of electrons with neutral helium atoms will be dominant.

Let us consider in more detail the region outside the neck. Here the degree of ionization is small, but nevertheless sufficient for us to speak of an electron temperature. In fact, the appropriate criterion for introduction of an electron temperature[23]

$$N_e \gg N_a \frac{m}{M} \frac{\sigma_e \bar{\varepsilon}^2}{e^4 \ln \Lambda} \sim 10^{13}\ \text{cm}^{-3} \tag{5}$$

is clearly satisfied here as a result of the smallness of the factor m/M. In this case the energy-balance equation has the form[23]

$$\frac{d\bar{\varepsilon}}{dt} = \frac{e^2E^2}{m\nu_e} - \frac{2m}{M} \nu_e \bar{\varepsilon}. \tag{6}$$

From this equation it follows that the relaxation time of the electron energy is of the order $M/m\nu_e \sim 10^{-8}$ sec. Consequently, we can assume that under our conditions relaxation sets in. Here Eq. (6) has a solution

$$\bar{\varepsilon} = Me^2E^2/2m^2\nu_e^2. \tag{7}$$

If we now add to the helium an admixture of a molecular gas, we must take into account inelastic energy loss due to excitation of the vibrational-rotational structure of the molecules and also to excitation of electronic states of the molecules and ionization of the molecules. However, it is well known that for an average electron energy of ~1 eV the main role will be played by inelastic loss in excitation of vibrational levels. The average electron energy in this case can be estimated from the energy-balance equation in which we have added a term describing the inelastic loss,

$$\frac{d\bar{\varepsilon}}{dt} = \frac{e^2E^2}{m\nu_e} - \frac{2m}{M} \nu_e \bar{\varepsilon} - \hbar\omega\nu_i. \tag{8}$$

Here $\hbar\omega$ is the average energy of excitation of vibrational levels and ν_i is the frequency of inelastic collisions. The solution of Eq. (8) has the form

$$\bar{\varepsilon} = \frac{Me^2E^2}{2m^2\nu_e^2} - \frac{M}{2m} \hbar\omega \frac{\nu_i}{\nu_e}. \tag{9}$$

In spite of the fact that $\nu_i \ll \nu_e$ and $\hbar\omega \ll 1$ eV, the presence of the large factor M/m in the second term has the result that the average energy of the electrons is appreciably reduced. In addition, some reduction in the average energy can occur as the result of the increase in the frequency of elastic collisions, since the cross sections for elastic collisions of electrons with molecules of the impurities used by us are significantly greater than the cross sections for He.

A monatomic gas as an impurity can lead to the same effect only in the case where it has a high frequency of collisions with electrons (both elastic and inelastic) and also a low potential for excitation and ionization. From analysis of the properties of the inert gases it follows that xenon has the properties enumerated. In fact, the cross sections for elastic and inelastic collisions of electrons with xenon atoms are 4–5 times the similar cross sections for He. In addition, the first excitation potential of xenon is only 8.3 eV. Calculation of the average energy of electrons in a mixture of He and Xe requires solution of the kinetic equation, since in an inelastic collision with an Xe atom an electron loses practically its entire energy and therefore the concept of a continuous energy change $d\varepsilon/dt$, which is utilized in Eqs. (6) and (8), is not justified here. However, since we are interested only in the qualitative aspect of the question, in a rather crude approximation we can write an equation similar to (8) with replacement of the term describing inelastic loss due to excitation of vibration levels by a similar term describing inelastic loss to excitation and ionization of Xe. It is clear that here also we obtain a decrease in the average electron energy.

Thus, addition of the impurities discussed will lead to a decrease in the average electron energy in the region outside the neck. This decrease in turn will lead to a substantial decrease in the radiation of the channel in this region, since the intensity of a spectral line is proportional to $\exp(-\varepsilon^*/\varepsilon)$, where ε^* is the excitation energy of the corresponding level. At the same time the average energy of the electrons in the region of the neck is practically unchanged on addition of the impurity, since here the electron energy is determined by the energy balance equation, in which, as we have shown above, the parameters of collisions of the electrons with neutral atoms do not appear. We note that the absence of track localization in He with Ne impurity serves as a confirmation of the qualitative estimates which we have made, since the frequency of elastic and inelastic collisions of electrons with Ne atoms is somewhat smaller than in He, and the excitation potential of Ne is rather high: 16.5 eV.

In conclusion we should note that both the experimental data obtained and the estimates carried out show that the process of track localization in a streamer chamber is highly sensitive to the parameters of the discharge. In fact, the electron concentration in the region of the neck, it can be said, satisfies in the limit the criterion $\nu_{ei} \gg \nu_{ea}$. A small deviation of the discharge parameters can lead to violation of this criterion and also to a spreading of the luminous points.

[1)] Physics Institute, Torino University, Italy.

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