INVESTIGATION OF THE MECHANISM OF OPERATION OF TRACK SPARK CHAMBERS[1)]

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The principle of operation of a new charged particle detector, the track spark chamber, is based on termination of the streamer discharges induced by primary electrons at an early stage of development. In this case the particle tracks can be discerned by the luminous centers along the particle trajectory. In contrast to the familiar spark chambers, the track spark chamber possesses isotropic properties in the sense that it records in space particles moving in any direction with respect to the electric field. The characteristics of a $100 \times 60 \times 19$ cm operating track chamber have been studied. A statistical model of development of the luminous centers is proposed for explaining the operation of the track chamber. The conclusions based on this model are in satisfactory agreement with the experimental results.

THE rapid development of experimental work in the field of high energy particle physics has necessitated the creation of new types of charged particle detectors. One of these detectors is the spark chamber, first suggested by Fukui and Miyamoto[1], various modifications of which have found wide application in experimental physics. At present many design variations of spark chambers have been developed[2,3]; however, the principles of their operation remain the same as in the first work of Fukui and Miyamoto. These authors studied spark chambers in two regimes: when the charged particle is moving in the direction of the electric field, and perpendicular to the electric field. In the first case, if definite conditions are fulfilled, the spark discharge follows the particle trajectory; in the second case, spark discharges produced by the electrons in the particle track extend from one chamber wall to the other. If we photograph the chamber along the electric field, the discharges give an image of the track consisting of its projection on the chamber wall. In the future we will designate the first regime as "track following," and the second as "projection."

In the first regime, a single spark, following a particle trajectory, arises from the joining of showers created by neighboring electrons in the track[1]. For this reason, first, chambers operating in this regime have a poor efficiency for counting particles which make an angle of more than 40° to the electric field direction, and second, fluctuation in shower development and loss of primary electrons (by attachment to impurity molecules, and recombination) can produce distortion of the track as a whole. Furthermore, great technical difficulties are encountered in obtaining tracks a meter or more in length, which is essential for accurate momentum measurements of high energy particles in a magnetic field. A chamber in the projection regime is free from these deficiencies. However, while we have satisfactory accuracy in determining a particle trajectory in the plane of the electrodes, the location of the track in the electric field direction remains undetermined.

We have achieved, for the first time, a distinctly new regime of spark chamber operation which we have proposed to call the "track regime." In our earlier papers[4,5] we designated the apparatus based on this principle as a "track spark chamber," since on the one hand it is a true track detector, and on the other hand it is a further development of the spark chamber.[2)]

A track spark chamber records equally well particles moving at any angle to the electric field. In contrast to other types of spark chambers, the development of the streamers in a track chamber is terminated at an early stage as a result of the short duration of the high-voltage pulse, and the particle tracks are obtained in the form of luminous columns or centers, oriented along the electric field and distributed along the particle trajectory. The extension of the centers along the

[1)]This work was reported at the All-union Conference on Cosmic Rays, Moscow, October, 1963.

[2)]A similar regime has been achieved by B. A. Dolgosheĭn and B.I. Luchkov (reported at the All-union Cosmic Ray Conference, October, 1963).

electric field is a few millimeters, and the diameter in the plane of the electrodes is 1.6 mm.

Long tracks can easily be obtained in a track chamber. The track chamber's ability to reproduce particle tracks in space with good resolution, together with its ability to record equally well both single particles and large groups of particles, and also particles arising in the chamber volume, makes it an extremely promising instrument for study of a broad field of problems in high energy elementary-particle physics.

In this paper we present the results of a study of the properties and operating mechanisms of the track chamber.

1. EXPERIMENTAL ARRANGEMENT

The experimental arrangement used in this work is shown in Fig. 1. It is similar to that described by us earlier[4,5]. The main element of the track chamber is a 100 × 60 × 19 cm glass container evacuated to a pressure of ~ 1 mm Hg and filled with 1 atm of neon. The evacuation and filling were carried out in a metal enclosure.

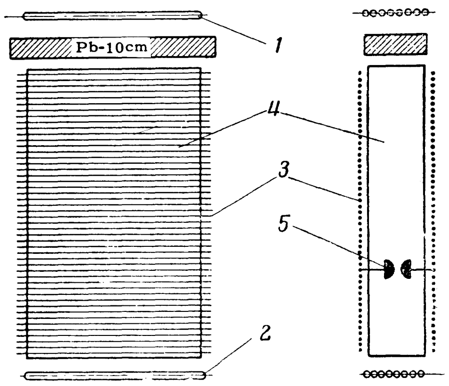

FIG. 1. Schematic view of the experimental apparatus (in two projections): 1,2) Geiger-Müller counters, 3) mesh electrodes, 4) glass vessel, filled with neon, 5) shunting spark gap.

Grids of 0.1 mm copper wire are used as transparent electrodes. The 200 kV pulse with a rise time of $(1.5-2) \times 10^{-8}$ sec which feeds the chamber is developed by a Marx-type generator with an equivalent capacitance of 2000 pF. The pulse length was adjusted by changing the spacing of the shunting spark gap. The chamber was controlled by counters connected in coincidence. A delay circuit connected between the coincidence circuit and the modulator which triggered the pulse generator allowed changing the time τ_d between the particle's passage through the apparatus and the pulse supplied to the track chamber over the range 1—200 μsec. Photography of the tracks was carried out by a stereo camera through a transparent electrode and by another camera through a side wall of the chamber.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Examination of the photographs obtained through the side wall of the chamber (Fig. 2) shows that for long durations of the high voltage pulse ($\geq 10^{-7}$ sec), the discharges are distributed from electrode to electrode (Fig. 2a) and are of the brush type with a vertex at the location of the primary electron. Decreasing the pulse length results in separation of the discharges from the chamber walls and their localization in the gas volume (Fig. 2b).

By further decrease in pulse length to $\sim 5 \times 10^{-8}$ sec we can reach a condition where the streamers have the form of short lines a few millimeters in length. This is the "track" regime. Here the track is a series of luminous centers distributed along the particle trajectory, and the chamber reproduces in three dimensions the tracks of particles moving at any angle with respect to the electric field. The streamer brightness is greater in the electric field direction and is sufficient for obtaining high quality stereo photographs with Type P-10-1000 film and an aperture of f/1.5. Further decrease in the pulse length leads to disappearance of the centers.

The pulse length for which the "track" regime exists can be varied over a very narrow interval of several nanoseconds. In order of magnitude this interval is 5—10% of the time necessary for development of the electron shower and its transition to a streamer. For a decrease in the high-voltage pulse amplitude, it is necessary to extend the pulse duration, and for an increase in amplitude, to shorten it.

All this imposes very severe requirements on the shaping of the high voltage pulse. For a pulse shape determined by an RC network, it is difficult to achieve equally good recording of single particles and groups of particles. If the chamber is adjusted to the track regime for a single particle, then for a large group of particles the rather insignificant voltage drop in the stray inductance results in very faint tracks for the shower particles. On the other hand when the chamber is adjusted to the track regime for a large group of particles, the streamers for a single particle will be overdeveloped. The method of pulse shaping by means of the shunting spark gap is free from these troubles. For the passage of a group of particles,

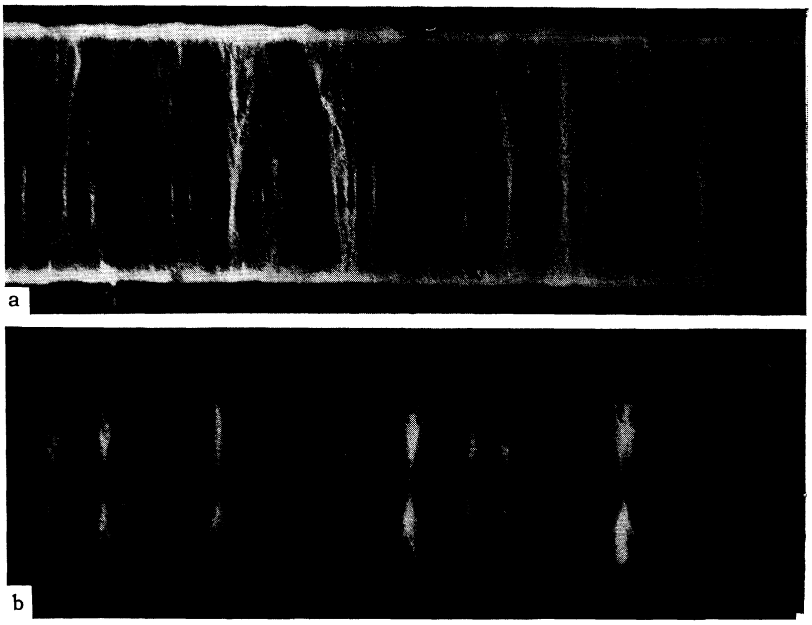

FIG. 2. Photographs of charged particle tracks in the spark chamber, taken through a side wall: a) for a high voltage pulse length of 10^{-7} sec, b) for a high voltage pulse length of $\sim 5 \times 10^{-8}$ sec (still not short enough to obtain the track regime).

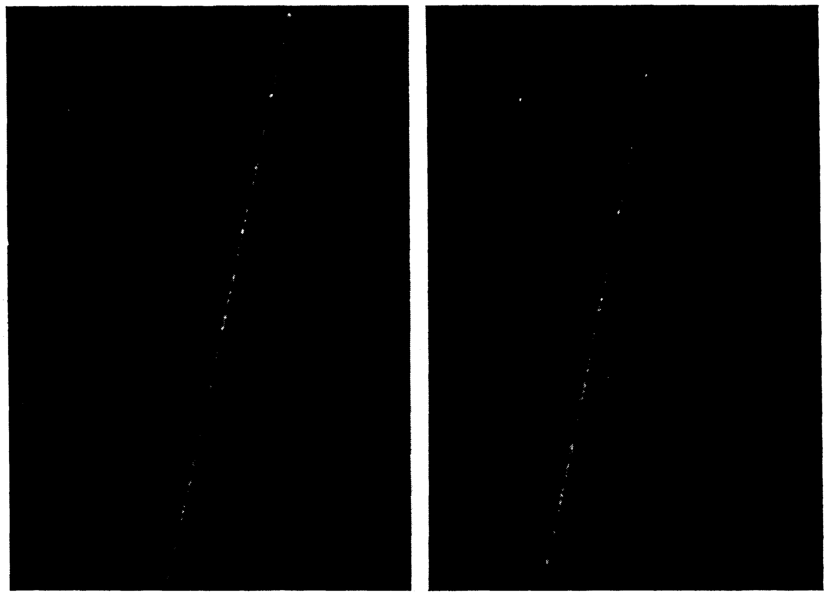

FIG. 3. Stereo photograph of the track of a single particle with the chamber operated in the track regime.

the slump in the high voltage pulse is automatically compensated by the lengthening of the pulse as a consequence of the increased delay in the spark gap breakdown. In operation with a shunting spark gap, high quality tracks are obtained in the chamber both for single particles (Fig. 3) and for groups of particles (Fig. 4).

Analysis of the stereo photographs by the method of measuring parallax has shown that the track coordinates in the electric field direction can be determined with an accuracy of a few millimeters.

We have investigated the various characteristics of track chambers, including the number of luminous centers, the width of the centers, and the root-mean-square deviation of the centers from the true trajectory, as a function of the delay time between the particle passage and the time of application of the high voltage pulse.

Good tracks are obtained in a track chamber over the range of delays studied by us, from 1 to 200 μsec. With increasing delay the brightness of the luminous centers decreases, and for obtaining good tracks it is necessary to increase somewhat the width of the high voltage pulse. Thus, for example, for an increase in the delay up to 200 μsec, the pulse length must be increased by about 5% in comparison with short delays of the order of 1 μsec.

The width of the centers for small delays fluctuates slightly, and the mean value of the diameter of the centers is 1.6 mm at a delay $\tau_d = 1\ \mu$sec.

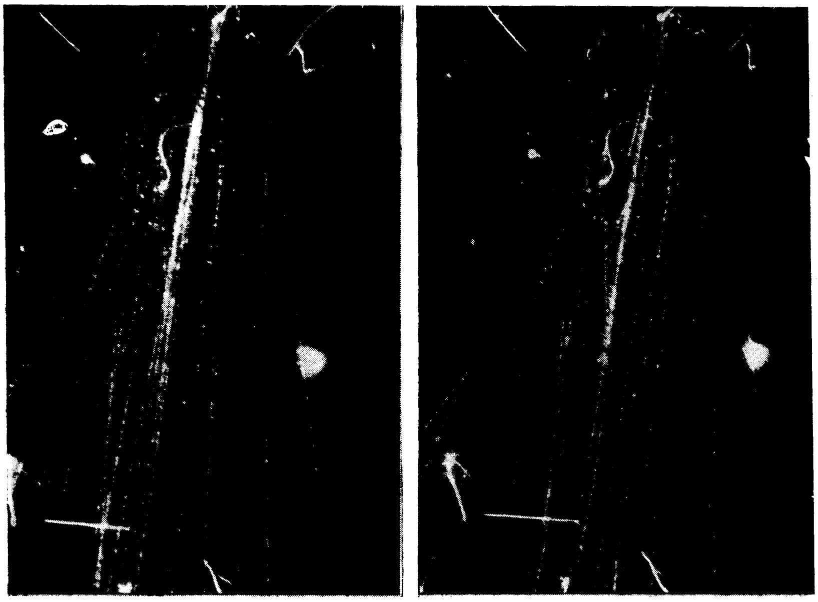

FIG. 4. Stereo photograph of a shower of particles with the chamber operated in the track regime.

With an increase in delay the fluctuation in the diameter of the centers increases somewhat, and the number of luminous centers per unit path length grows very slowly. With a change of delay from 1 to 200 μsec, the number of centers in 1 cm of track length changes from 1.4 to 2.8, and it is more than an order of magnitude less than the number of primary electrons, which in neon (at a pressure of 1 atm and for minimum ionization) is approximately 30. The observed discrepancy cannot be explained by the decrease in the number of primary electrons due to their attachment to impurity molecules. A mass spectroscopic analysis of a sample of gas taken from a chamber six months after its filling shows the presence in it of 0.1% of air (other impurities are absent). Under these conditions the mean lifetime of an electron up to its capture by impurities is about 10^{-3} sec, and the loss of electrons in a period of 200 μsec is only 20% of the initial number of electrons. For smaller delay time this effect plays a still smaller role.

The small number of luminous centers can be explained simply by the fact that a streamer inhibits the development of showers which are close to it. In fact, let us consider a small region containing several primary electrons of the track. After application of the electric field, the showers initiated by these electrons begin to develop. As a result of fluctuations, one of them will reach the critical dimensions sooner than the others and will develop into a streamer. Then the field produced by the space charge of the streamer reduces the strength of the external field in its vicinity, which leads to a "freezing" of the development of showers from neighboring electrons[6]. Thus, there must exist a definite distance r_0, closer than which only one of several growing showers can develop into a streamer.

For very large delays, τ_d = 200 μsec, the root-mean-square deviation σ of the luminous centers (from a particle trajectory reproduced by many points of the track) agrees with the deviation of the primary electrons expected from diffusion. For a delay of 1 μsec, σ = 0.3 mm, which is two times less than the value resulting from diffusion of the primary electrons. The fact that for very small delays the luminous centers are distributed very close to the trajectory of a particle is very important for measurement of its momentum in a magnetic field. For a delay τ_d = 1 μsec, the natural curvature of the track due to deviation of the luminous centers from the particle trajectory corresponds to a maximum measureable momentum of about 400 BeV/c (for a field intensity of 10^4 Oe, a track length of 100 cm, and measurement of 140 points). In Fig. 5 are plotted experimentally determined values of σ for delay times τ_d of 1—11 μsec. The errors shown correspond to two standard deviations. The solid curve corresponds to the diffusion of electrons in neon for a diffusion coefficient $D = 2 \times 10^3$ cm^2/sec.

It can be seen from Fig. 5 that the experimental points fall below the diffusion curve, and that the discrepancy cannot be explained by the experimental errors. The cause of disagreement lies in the mechanism of operation of the track chamber and indicates, apparently, that for small delay times the principal role in the creation of the luminous centers is played not by individual electrons of the

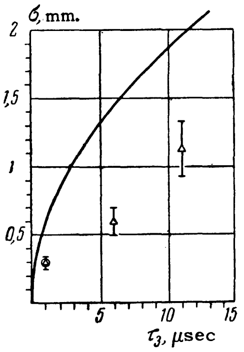

FIG. 5. Root-mean-square values of the deviation of the luminous centers from the particle trajectory, as a function of τ_d: △-experimental values (the errors shown are equal to two standard deviations), ○ – theoretical value for a group of electrons with a multiplicity of 3.9.

track but by their combined action. Therefore there must exist some definite distance $r_1 < r_0$, such that if the distance between the primary electrons is less than r_1, the showers initiated by these electrons are joined and create a single streamer. The lateral dimension in which 99% of the electrons of a shower are located, before its transition to a streamer, is very close to the width of the luminous centers, and therefore it is reasonable to assume that r_1 is equal to the lateral dimension of the luminous centers.

Proceeding from the above, it is possible to imagine a general picture of the development of the luminous centers in the following way: After the passage of the particle through the track chamber and the application of the high voltage pulse, the primary electrons created by the particle initiate Townsend showers. Townsend showers which have reached a definite stage of development, when the field created by their space charge becomes comparable with the external field, transfer to a streamer[7]. However, the number of streamers arising will be less than the number of primary electrons, since, on account of fluctuations in the development, one of the showers will transfer to a streamer earlier than the others and then, by the field of its space charge, will inhibit the development of showers arising inside a certain region and will make it impossible for them to develop into streamers. Furthermore, since the condition for transfer of a shower to a streamer is related to a definite critical number of electrons in its "head," then two or more showers located sufficiently close together can create a single condition for streamer development, that is, a streamer can arise as the result of the development of two or more closely spaced showers. It is obvious that a streamer created by such combined showers will arise earlier than a streamer created by a single shower, and, since the probability of joining of showers is much greater in the center of the particle track than at its edges, the deviation of the streamers from the particle trajectory will be less than the deviation of the primary electrons due to diffusion. The streamers which arise develop very rapidly in the electric field and become visible a few nanoseconds after their initiation. The development of the streamers is terminated by the sharp drop in the electric field, and the particle track is a succession of luminous centers, streamers located in the particle trajectory.

Thus, we see that the process of development of a visible track in a track chamber is a very complex process, in which an important part is played by a different mode of interaction of showers and also by fluctuations in their development. Construction of an exact, quantitative theory of this process at the present time is not possible; however, we can construct a qualitative model which allows us to describe the dynamics of luminous center development in a track chamber and to explain the observed experimental facts.

The model which we have proposed is described in the following section, and its comparison with experiment is described in Sec. 4.

3. STATISTICAL MODEL OF LUMINOUS CENTER DEVELOPMENT IN A TRACK CHAMBER

Before we proceed with the analysis of the mechanism of track chamber operation, let us consider the fluctuations in the number of particles contained in a shower in the Townsend stage of its development.

The probability that a shower created by a single electron traversing a distance l in the electric field will contain M electrons is given[8] by

$$P(M, l) = e^{-\alpha l}(1 - e^{-\alpha l})^{M-1}, \quad (1)$$

where α is the first Townsend coefficient, which depends both on the nature of the gas and on the electric field strength. We will designate the mean number of particles in a shower produced by a single electron in a path length l by $\overline{M}$. From (1) it follows that

$$\overline{M} = e^{\alpha l}. \quad (2)$$

According to (1), the probability that a shower which has traversed a path length l in the field contains a number of particles $\geq$ M is equal to

$$F_1(M, l) = (1 - 1/\overline{M})^{M-1}. \quad (3)$$

We will introduce a new variable $\beta = M/\bar{M}$. If we consider that $\bar{M} \geq 10^8$, then the integral distribution function of the quantity β will be given by the formula[3]

$$F_1(\geqslant \beta, l) = e^{-\beta}, \quad (4)$$

and the differential probability will be given by

$$f_1(\beta, l)\, d\beta = e^{-\beta}\, d\beta. \quad (5)$$

If instead of a single initial electron there are m electrons, then the total number of particles M_m in the shower will be

$$M_m = \sum_{i=1}^{m} M_i,$$

where M_i is the contribution to the total number of particles from the shower initiated by the i-th primary electron.

Let us define

$$\beta_m = \frac{M_m}{\bar{M}} = \sum_{i=1}^{m} \beta_i.$$

If the values of β_i are distributed according to (5), then we can show[9] that the normalized differential probability of finding the value of β_m in the interval β_m, $\beta_m + d\beta_m$ will be given by

$$f(\beta_m, l)\, d\beta_m = \frac{1}{\Gamma(m)} \beta_m^{m-1} e^{-\beta_m} d\beta_m. \quad (6)$$

The probability that a shower with m initial electrons traversing a path length l will contain a number of particles $\geq M$, according to (6), is expressed by the equation

$$\Phi_m(M, l) = \frac{1}{\Gamma(m)} \int_{M/\bar{M}}^{\infty} \beta^{m-1} e^{-\beta}\, d\beta$$
$$= \frac{1}{\Gamma(m)} \frac{1}{2^{m-1}} \int_{\sqrt{2M/\bar{M}}}^{\infty} t^{2m-1} e^{-t^2/2}\, dt. \quad (7)$$

The right hand side of (7) is well known χ^2 distribution of mathematical statistics. From (6) and (7) it follows that the number of particles M in a shower can differ considerably from the mean value $\bar{M}$.

If the number of particles in a shower during its development in the electric field reaches such a size that the field in the head of a shower due to its space charge becomes equal to the external field, then the shower will develop into a streamer. The conditions for the transfer of a shower to a streamer are given by the relations of Meek and Craigs[7]:

$$M_M = e^{\alpha l_M}, \qquad l_M \approx 20/\alpha. \quad (8)$$

Because of fluctuations, the shower can satisfy the Meek-Craigs condition at distances other than the mean distance l_M. The probability that a shower traversing a path length l will transfer to a streamer, according to (7) and (8), will be equal to

$$F_m(l) = \frac{1}{\Gamma(m)} \frac{1}{2^{m-1}} \int_s^{\infty} t^{2m-1} e^{-t^2/2} dt,$$
$$s = \sqrt{2\exp[20(1 - l/l_M)]}\,. \quad (9)$$

The function $F_m(l/l_M)$ is shown in Fig. 6 for different values of m. We can see from Fig. 6 that showers created by several initial electrons begin to develop into streamers after traversing a smaller path length in the electric field, and complete the transition to a streamer in a shorter path length, than showers created by single electrons. This fact is expressed more strongly, the larger the number of initial electrons which initiate the shower.

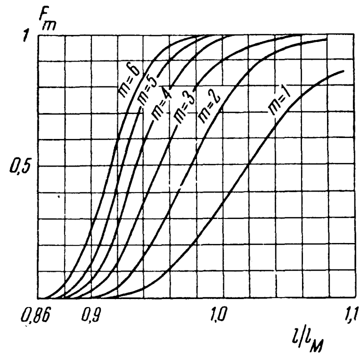

FIG. 6. Probability of the transition of a shower to a streamer as a function of the path length traversed by the shower in the electric field, for different numbers of initial electrons m.

We have discussed above the behavior of isolated showers created by one or several initial electrons. However, as a result of the fact that the electrons arising from ionization of the gas by a charged particle are spaced relatively small distances apart, neighboring showers which develop from them can interact with each other.

We have designated by r_0 the linear dimension of the region inside which an inhibition of the shower development into streamers will occur, and by r_1 the dimension of the region inside which joining of showers will occur (see Sec. 2). We will now find the number of streamers N in a unit length of track for a path length l traversed by the showers in the electric field.

The distribution of the number of electrons across the track is given by a normal probability distribution. However, for simplicity we assume that the electrons are distributed across the track with equal probability with a distribution width b, where b is chosen so that 80% of the primary electrons fall in it. We will divide a segment of track 1 cm long and of width b into square "elements" of area of dimensions $r_0 \times r_0$ (Fig. 7). We choose the position of the elements so that the central elements are bisected by the axis of the track. In each element of area, according to the definition of the quantity r_0, only one streamer can develop. A unit length of track will contain a different number of elements Δ_0 depending on the size of b:

$$\Delta_0 = \frac{1}{r_0} \text{ for } 0 \leqslant b \leqslant r_0, \quad \Delta_0 = \frac{3}{r_0} \text{ for } r_0 < b \leqslant 3r_0,$$
$$\Delta_0 = \frac{5}{r_0} \text{ for } 3r_0 < b \leqslant 5r_0, \ldots, \quad \Delta_0 = \frac{r_0 + b}{r_0^2} \text{ for } b \gg r_0. \tag{10}$$

We divide each element into "sub-elements" of size $r_1 \times r_1$ (Fig. 7) and arrange the sub-elements so that a line passing through the center of an element parallel to the particle track bisects the central sub-element. The number of sub-elements in an element will be

$$\Delta_1 = (r_0/r_1)^2. \tag{11}$$

However, for the value of b specified, all the sub-elements will not overlap the track in all elements. We will designate the number of sub-elements which overlap the track in the i-th element by Δ_{1i}, and let the average electron density in them be λ_i. Then the number of sub-elements in the i-th element occupied, if only by one electron, is equal to

$$j_i = \Delta_{1i}(1 - e^{-\lambda_i}). \tag{12}$$

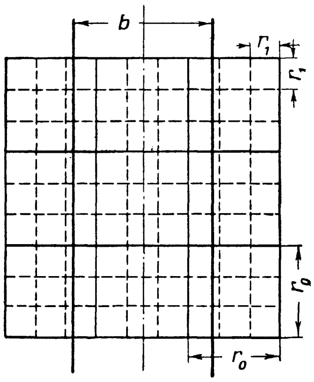

FIG. 7. Location of the sub-elements and elements relative to the particle trajectory. The dash-dot line is the direction of motion of the particle, the solid lines are the boundaries of the elements, and the dotted lines are the boundaries of the sub-elements.

These sub-elements are potential centers for the development of a streamer in the element. The average multiplicity of a potential center (the average number of electrons in occupied sub-elements) is equal to

$$k_i = \frac{\lambda_i \Delta_{1i}}{j_i} = \frac{\lambda_i}{1 - \exp(-\lambda_i)}. \tag{13}$$

As $r_1 \to 0$ or $b \to \infty$, the quantity $k_i \to 1$. This means that the potential centers approach a multiplicity of 1 and the showers develop from single electrons.

According to (9), (12), and (13), the average number of centers of luminescence per unit length of track is given by the expression

$$N = \sum_i \{1 - \exp[-\Delta_{1i}(1 - e^{-\lambda_i}) F_{k_i}(l/l_M)]\}. \tag{14}$$

Here the summation is carried out over all elements which overlap the track.

In carrying out numerical calculations it is necessary to choose the value of the parameters r_1 and r_0. As was indicated above, the parameter r_1 can be chosen equal to the mean diameter of the luminous centers, i.e., equal to 1.6 mm, and r_0 can be found from the fact that the maximum number of luminous centers for a small delay time ($\tau_d = 1.0\,\mu$sec) is 1.4. According to (14) we find that the size r_0 of an element is 6.7 mm.

4. COMPARISON OF THEORY AND EXPERIMENT

In comparison of the experimentally determined number of luminous centers with the calculated number, it is necessary to take into account that the brightness of the streamers increases in proportion to their development in the electric field. In our case (for the aperture and film sensitivity used) the streamer length should be approximately 5–6 mm if we are to obtain good photographs. For a streamer velocity $v_s = 10^8$ cm/sec, the time t_s necessary for the development of the streamer will be $(0.5-0.6) \times 10^{-8}$ sec.

The total time T required for formation of a visible track is composed of the time t_t, during which the transitions of the showers into streamers are completed, and the time of streamer development t_s:

$$T = t_t + t_s. \tag{15}$$

For a constant velocity of propagation v_{sh} of showers in the electric field,

$$t_t = \frac{l_t}{v_{sh}} = l_t \cdot 10^{-7} \text{ sec}, \tag{16}$$

where l_t is the distance in which the showers complete the transition to streamers.

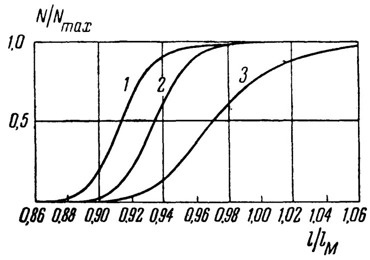

FIG. 8. Variation of the number of luminescent centers with the path length traversed by the showers in the electric field, for different values of τ_d: 1) $\tau_d = 1\ \mu$sec, $N_{max} = 1.4$; 2) $\tau_d = 11\ \mu$sec, $N_{max} = 1.5$; 3) $\tau_d = 200\ \mu$sec, $N_{max} = 1.48$. Curve 3 was computed taking into account the loss of electrons by attachment to air molecules.

Figure 8 shows the results of calculations made using formula (14). The abscissa is the distance traversed by the showers in the electric field in units of l_M (in our case $l_M = 3.34$ mm), and the ordinate is the number of showers which have transferred to streamers, relative to N_{max}. It follows from Fig. 8 that an increase in delay results in an increase in the time interval during which the transition of the showers into streamers occurs. If this time, for $\tau_d = 1\ \mu$sec, is 1.3×10^{-9} sec ($\Delta l = 0.04\ l_M$), then for delays of 10 μsec and 200 μsec it has the values 1.8×10^{-9} sec ($\Delta l = 0.05\ l_M$) and 3.6×10^{-9} sec ($\Delta l = 0.10\ l_M$), respectively. An increase in the time interval during which the showers transfer to streamers should result in increased fluctuations in the dimensions of the luminous centers, which is in qualitative agreement with experiment.

For a delay $\tau_d = 1\ \mu$sec, 90% of all the luminous centers appear within a time $t_t = 3.11 \times 10^{-8}$ sec ($l = 0.93\ l_M$), and the total length of the high voltage pulse which is necessary for obtaining good tracks should be 3.71×10^{-8} sec. An increase in delay with no change in high voltage pulse length, in agreement with experiment, should produce a decrease in brightness of the luminous centers. Actually, for a delay $\tau_d = 10\ \mu$sec, the appearance of 90% of all centers occurs at a time $t_t = 3.21 \times 10^{-8}$ sec, and for $\tau_d = 200\ \mu$sec, at a time $t_t = 3.44 \times 10^{-8}$ sec. Therefore, for development of "young" streamers there remains a time in the first case of 0.5×10^{-8} sec, and in the second case 0.27×10^{-8} sec. The length of these streamers will be 5 and 2.7 mm, respectively.

The number of luminous centers calculated according to formula (14) is in good agreement with the experimentally observed number. For small delays, $\tau_d \leq 11\ \mu$sec, the calculated number 1.4 agrees with the experimental value. For the same high voltage pulse length, and a delay time $\tau_d = 200\ \mu$sec, the calculated number of appreciably bright centers is small, in agreement with experiment. An increase in pulse length by 5% leads to an increase of the calculated number of centers to 2.75. The number of luminous centers observed experimentally for the same increase in high voltage pulse length is 2.8.

Within the framework of the model which we have developed, we have been successful also in explaining qualitatively the experimental data relating to track width. Because of diffusion, the primary electrons are distributed across the track according to a normal distribution with a root-mean-square deviation $\sigma_{diff} = \sqrt{2D\tau_d}$. Therefore the occupied sub-elements which are close to the center of the track will have a higher multiplicity, that is, they will contain more electrons, than the occupied sub-elements which are at the periphery. As a consequence of this, the shower-to-streamer transition will occur with a higher probability in the central sub-elements than in the peripheral ones. This will lead to a narrowing of the distribution of the luminous centers about the true trajectory in comparison with the distribution of the primary electrons. A second factor leading to the same effect results from the fact that the position of the center of a group of several electrons which initiate a single shower and produce a shower-to-streamer transition, as the result of statistical averaging, will fluctuate less than the position of the primary electrons. It is extremely difficult to carry out a quantitative calculation in the general case; however, for the two extreme cases—for very small and very large delay time—such evaluations can be made. For

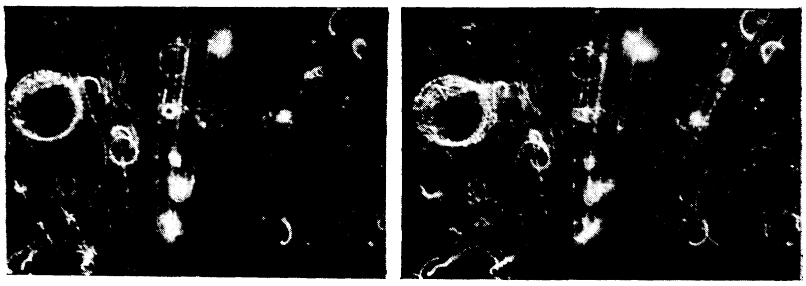

FIG. 9. Stereo photograph of a soft shower in a track spark chamber located in a magnetic field.

$\tau_d = 1\,\mu$sec, the track width b is less than the dimension of the sub-element. Therefore a narrowing of the track due to the first factor does not occur, and only the second factor is effective. In this case the root-mean-square deviation of the luminous centers from the trajectory will be $\sigma = \sigma_{diff}/\sqrt{m}$, where m is the multiplicity of electrons filling the sub-element (m = 3.89 for $\tau_d = 1\,\mu$sec).

The value of σ calculated in this way, which is in good agreement with the experimental value, is plotted in Fig. 5. For very large delays, $\tau_d \geq 150$ μsec, the diffusion width is so great that the multiplicity of filling of the occupied sub-elements is practically equal to unity, independent of the position of the sub-element; therefore both factors leading to narrowing of the track are absent and, in agreement with experiment, the distribution of the deviations of the luminous centers should agree with the distribution of the deviations of the primary electrons from the true trajectory of the particle.

Consequently the experimental facts relating to track spark chamber operation can be quantitatively explained on the basis of calculations of fluctuations in shower development, suppression by a streamer of nearby showers, and formation of combined showers from closely spaced primary electrons.

CONCLUSIONS

While the track spark chamber possesses all of the positive qualities of ordinary spark chambers, in particular good time resolution, short recovery time, and extreme simplicity of design and use, it has one further extremely important property. In contrast to ordinary spark chambers, this type of chamber is an apparatus with isotropic properties which permit equally well the reproduction in space of the tracks of particles going at all angles, individually or in large groups, and also of particles which have originated within the chamber.

The possibility of obtaining in a track chamber tracks of a meter or more in length, together with the complete absence of any thermal distortion or distortion resulting from mechanical motion of the working medium, permits the measurement in a magnetic field of charged particle momenta an order of magnitude greater than momenta measurable in a cloud chamber or a bubble chamber. For a track length of 1 meter and a magnetic field intensity of 10^4 Oe, the track spark chamber permits measurement of charged particle momenta up to 400 BeV/c.

The experimental possibilities of the track spark chamber lead us to believe that it will become a new powerful tool for the study of the nature and interactions of elementary particles.

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Supplement (December 26, 1963). The track spark chamber described above was placed in the electromagnet of the Bakuriani High Altitude Station with a magnetic field intensity of 7000 Oe. The strength of the electric field pulse applied to the mesh electrodes was 20 kV/cm. The length of the high voltage pulse was controlled by a shunting high pressure spark gap. The photography was carried out by a stereo camera through openings in the magnet pole and through a mesh electrode.

Figure 9 shows a typical stereo photograph of a soft shower generated by cosmic radiation in an absorber above the apparatus, which demonstrates the operation in a magnetic field of a track chamber with isotropic properties. As we should expect, on turning on the magnetic field no change is required in the regime of operation of the track spark chamber, and the root-mean-square deviation of the luminous centers from the particle trajectory remains the same (0.3 mm) as in the absence of a magnetic field.

The track images obtained in a spark chamber operated in the track regime [4,10] are of better quality than the photographs obtained in the regime described by Alikhanyan et al [11].

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