IDENTIFICATION OF PARTICLES BY THE PHOTOGRAPHIC EMULSION TECHNIQUE

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It is proposed to identify particles with 1.5 BeV $\leq p\beta c \leq$ 2.5 BeV, whose nature cannot be determined by scattering or ionization measurements, by means of the δ electrons which these particles produce. It is shown that in this energy range the particles produced in 9-BeV proton-neutron interactions are mainly π mesons. The possibility is investigated that in the range 1 to 17.5 BeV the particle energies obtained from multiple Coulomb scattering measurements may be overestimated. It is found that for long cells the Coulomb-scattering second difference and the ratio ρ of the third difference to the second differ appreciably from the theoretical values. It is recommended that $p\beta c$ be measured using cells for which ρ lies between 1.2 and 1.5, which corresponds to a minimum total error in $p\beta c$.

INTRODUCTION

In numerous experiments (e.g. [1-6]) on the interaction of particles with emulsion nuclei, the secondary particles were identified by measuring the multiple scattering ($p\beta c$) and the specific ionization (or, strictly speaking, the blob density along the track). In the range $p\beta c < 1.5$ BeV, particle identification does not present serious difficulties. A correct identification of a particle in that range depends essentially on the measurement of $p\beta c$. In the range $p\beta c > 2.5$ BeV, the identification depends on a correct determination of the ionization. In the range 1.5 BeV $\leq p\beta c \leq$ 2.5 BeV in which the same ionization corresponds to a single value of $p\beta c$ for various particles, the nature of particles remains unknown, and can only be inferred in an indirect way. It is possible that a positive identification of the nature of all secondary particles in the $p\beta c$ range under consideration would help greatly to disclose the elementary particle interaction mechanism. It seems therefore important to develop another method, which can serve as a good complement to the existing methods of particle identification, viz. the identification of particles with $p\beta c$ = 1.5—2.5 BeV by counting the δ electrons.

Moreover, special attention should be paid to the accuracy of the measurement of $p\beta c$ in the range $\geq$ 1 BeV, in order to check on important conclusions made by various authors.[4-6] Thus, e.g., a possible overestimate of the energy could lead to incorrect results, and it is therefore desirable to assess the accuracy of the energy determination by the multiple scattering method.

1. IDENTIFICATION OF PARTICLES BY MEANS OF δ ELECTRONS

The possibility of particle identification by means of high-energy δ electrons emitted in a spatial angle of less than 35° has already been discussed earlier.[7] From the energy and momentum conservation laws for the colliding particles we can determine, using these δ electrons, the value of β of the unknown particle, or the quantity $\gamma = 1/\sqrt{1-\beta^2}$. If γ = 10—18 corresponds to a particle with $p\beta c$ = 1.5—2.8 BeV, then we can claim, with good accuracy, that this particle is a π meson. For protons with the same $p\beta c$ the range of γ is only 2—3. In order to determine γ of an unknown particle from at least one or two high-energy δ electrons, a track length of the order of 10 cm is required on the average.[7]

In the present article we discuss the identification of particles by counting the δ electrons. The number of δ electrons in an energy range from T_1 to T_2, produced per unit path by a fast singly-charged particle, can be calculated using a modified Rutherford formula

$$N_\delta = 2\pi N \frac{e^4}{mc^2\beta^2}\left(\frac{1}{T_1} - \frac{1}{T_2}\right), \quad (1)$$

where N is the number of electrons per cm^3 of the emulsion, and m is the electron mass. The value of N_δ calculated by Mott's formula differs little from that given by Eq. (1). In determining N_δ we count δ electrons with energy $T_1 \approx 15$ keV and more, which usually produce tracks consisting of four and more grains (including the grain on the primary particle track). The value of T_2 corresponds to the maximum possible energy T_{max}

Table I

Emulsion	Year and place of irradiation	Nature of primary particles	Energy of primary particles, BeV	N_δ per 1 cm	N_c per 1 cm
NIKFI-R	1959, Dubna	protons	9	8.9±0.3	2.50±0.16
	1961, »	»	9	7.5±0.3	1.49±0.39
	1961, »	»	4	9.4±0.7	3.00±0.39
	1961, »	»	2	10.9±0.3	2.2±0.16
Ilford G-5	1961, Geneva	π-mesons	17.5	6.2±0.03	1.60±0.13

$= [2\beta^2/(1-\beta^2)]\,mc^2$ transferred to the electrons. In practice we can assume that T_2 always equals T_{max}. In deducing Eq. (1) it has been assumed that the electrons in atoms are free, and the spin of the interacting particles has been neglected.

In the following we give the results of the measurements of N_δ for δ electrons produced by protons of 2, 4, and 9 BeV in NIKFI-R emulsion and by π mesons of 17.5 BeV in Ilford G-5 emulsion. In NIKFI-R emulsion, the δ electrons were counted on a total track length of more than five meters, and in Ilford G-5 emulsion on over 1 m.

The average values of N_δ, corresponding to clearly established δ electrons, and the numbers N_d, corresponding to doubtful events, are given in Table I. The given errors of N_δ and N_d are statistical. N_d includes those δ electrons for which it was doubtful whether the track was due to a δ electron or to a background electron, or represented a random cluster of grains. For inexperienced observers the values N_d differ greatly from one person to another, and can attain a large magnitude. For an observer having a certain experience, however, the values of N_d fluctuate, in the emulsions used, about a mean value of 2—3 per 1 cm.

The values of N_δ for different pellicles from a single NIKFI-R emulsion stack exposed in 1959 are given in Table II. (This stack contains nucleon-nucleon interactions which have been analyzed earlier.[3,4]) It can be seen that N_δ does not vary from plate to plate in the same stack. The measurements show also that N_δ is independent of the depth of the track in the emulsion, which is very important from the methodological point of view.

Table II

No. of plate	N_δ per 1 cm
18	7.8±1.0
28	9.0±0.8
99	9.1±0.5
133	9.5±1.2
176	8.9±0.8
199	8.8±0.7

The 1961 NIKFI-R stacks were irradiated twice, almost simultaneously: one by 9-BeV protons, and by 2 BeV protons perpendicular to them in the emulsion plane and the other in a similar way by 9-BeV and 4-BeV protons. According to Table I, N_δ seems to depend on β. From Eq. (1) the ratio of $N_{\delta_2}/N_{\delta_9}$ for 2 and 9 BeV equals 1.12. The corresponding experimental value is 1.45 ± 0.07. For 4 and 9 BeV the ratios are 1.04 and 1.26 ± 0.11 respectively. The ratios almost do not change when background δ electrons are taken into account. The observed differences between the experiment and the calculation are evidently due to the assumptions made in deducing Eq. (1).

The N_δ distributions of 9-BeV ($\gamma = 10.5$) and 2-BeV ($\gamma = 3.1$) proton tracks in the same emulsion stack are compared in Fig. 1. The same distributions are shown in Fig. 2, but $\overline{N}_\delta$ corresponds to the average number of δ electrons per cm, and has been measured on separate tracks each 3—5 cm long. From the distributions it follows that for sufficiently long tracks we can differentiate between particles with $\gamma = 10.5$ and par-

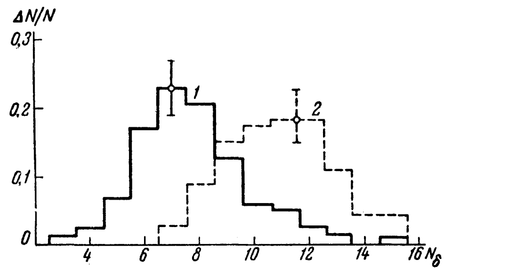

FIG. 1. Distribution of the number of δ electrons (per cm); solid line – on tracks of 9 BeV proton (50 tracks), dashed line – 2 BeV protons (60 tracks).

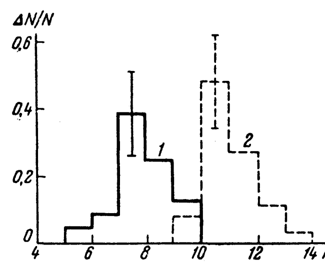

FIG. 2. Distribution of of the average number of δ electrons (per cm) on separate proton tracks 3-5 cm long. Solid and dashed lines denote the same as in Fig. 1.

ticles with $\gamma = 3.1$. On the basis of Fig. 2 we can hope to establish the nature of particles which cannot be identified by $p\beta c$ and ionization.

In the range of interest, $p\beta c = 1.5$—2.5 BeV, we have to differentiate between particles with $\gamma = 10$—18 (mesons) and $\gamma = 2$—3 (protons). We can calculate δ-electron statistics needed for this purpose. Experimenters usually consider that the error should equal two standard deviations. Assuming that the distribution of the δ-electron number is given by the Poisson law, we can write

$$N_{\delta p} - N_{\delta\pi} = 2\Delta N_{\delta\pi} = 2\sqrt{N_{\delta\pi}}. \qquad (2)$$

Using this condition and Eq. (1), we find easily

$$N_{\delta\pi} = 4\,[\beta_p^2/(\beta_\pi^2 - \beta_p^2)].$$

Thus, the number of δ electrons necessary for the identification of a particle is ~40 for $p\beta c = 1.5$ BeV and ~260 for 2.5 BeV. For the identification of particles with $p\beta c = 1.5$ BeV with δ electrons a track length of the order of 4 to 5 cm is necessary. For $p\beta c = 2.5$ BeV, the identification of separate particles will be less satisfactory for such a track length. It is, however, meaningful to find at least a statistical distribution of N_δ for particles with $p\beta c = 1.5$—2.5 BeV in order to have some idea about their nature.

The distributions of N_δ, analogous to Figs. 1 and 2, for particles with tracks longer than 2 cm and $p\beta c = 1.5$—2.5 BeV, produced in proton-neutron interactions at 9 BeV [3,4], are shown in Fig. 3. For a comparison are shown the distributions of N_δ found along the tracks of the primary protons. From the comparison it follows that the bulk of secondary particles with $p\beta c = 1.5$—2.5 BeV have $\gamma \geq 10$, i.e., they are π mesons.

The N_δ distribution corresponding to secondary particles with $p\beta c = 0.8$—1.5 BeV, identified by ionization as π mesons ($\gamma = 6$—10) and protons

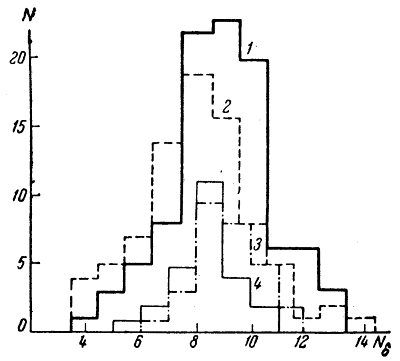

FIG. 3. Distribution of the number of δ electrons (per cm) found on particle tracks of: 1, 3 – 9 BeV protons; 2, 4 – secondary particles of $1.5 \leq p\beta c \leq 2.5$ BeV; 1, 2 – as in Fig. 1; 3, 4 – as in Fig. 2.

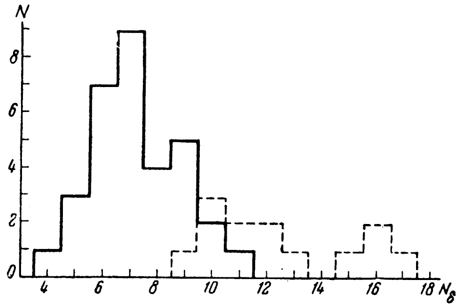

FIG. 4. Distribution of the mean values of $\overline{N_\delta}$ (per cm) on tracks of particles with $0.8\text{ BeV} \leq p\beta c \leq 1.5$ BeV; solid line – π mesons; dashed line – protons.

($\gamma = 1.5$—2), is shown in Fig. 4. This is the fraction of the protons which give a substantial contribution to the asymmetry [3,4] of the angular distribution of the protons in the c.m.s., an asymmetry opposite to that obtained in [5]. As can be seen from Fig. 4, the identification of the particles by ionization is apparently correct for $p\beta c \sim 0.8$—1.5 BeV since the large value of N_δ corresponds to the protons.

From the above it follows that the identification of particles with energy ≤ 9 BeV made in [3,4,6] is correct, and the statement that particles with $p\beta c = 1.5$—2.5 BeV are π mesons [4] is corroborated.

2. ERRORS IN THE DETERMINATION OF PARTICLE ENERGY

In determining the energy of fast particles from measurements of the multiple Coulomb scattering we meet with a definite difficulty due to spurious scattering.[8-15]

It is usually attempted to make the measurements on cells where the total error of the energy measurement, due to spurious scattering and statistics, is minimal. The selection of such a cell length is difficult for separate particle tracks, since neither the Coulomb ($\overline{D}_C$) nor spurious ($\overline{D}_S$) scattering is known beforehand. Experimenters try therefore to measure the scattering with the longest acceptable cells, in order to be able to neglect spurious scattering. In reality, as it is shown below, scattering measurements on very long cells lead to an overestimate of the energy.

The variation of the directly measured second difference $\overline{D}$ with the cell length t, for 25 and 33 particle tracks with $p\beta c$ equal to 1.04 and 260 BeV/c respectively, is shown in Fig. 5. The emulsions were irradiated by protons at the Joint Institute for Nuclear Research. The variation of $\overline{D}_C$ with t, calculated for the same energies according to the formula

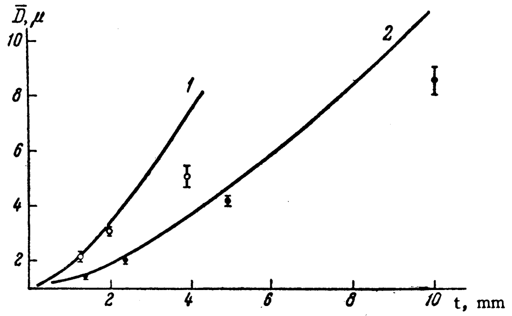

FIG. 5. Variation of the second difference with cell length: 1 and 2 – theoretical curves for $p\beta c$ equal to 1.04 and 2.6 BeV, respectively. The points correspond to experiments at these energies.

$$\bar{D}_C = 100\,Kt^{3/2}/57.3\,p\beta c$$

is also shown in the figure. The emulsion constant K has been taken from [10], taking into account the fact that the values $D_i \geq 4\bar{D}$ are excluded. In Fig. 5 we see that for long cells the experimental points fall below the theoretical curve. Moreover, for long cells the values $D_i \geq 4\bar{D}$ were not excluded, since such big deviations did not occur. This means that the measurement of the scattering on long cells leads to an overestimate of the energy. For particles with $p\beta c = 1$ BeV the error is of the order of 50% if the scattering is measured on a cell $t \sim 4$ mm. For particles with $p\beta c \sim 16$—25 BeV, an overestimate will result if the scattering is measured on cells longer than 1 cm.[11,12] Thus, we can see that the maximum acceptable cell must be chosen very carefully.

The optimum cell, as has been mentioned earlier,[8] can be found by using the quantity ρ, the ratio of the third and second differences. It is known that for Coulomb scattering the value of ρ_C found theoretically[13] is 1.22. For spurious scattering ρ_S has been found experimentally to vary between 1.61 and 1.81 for different cells and emulsions.[12,14,15]

The dependence of the measured value of ρ on the cell length t for protons with $p\beta c = 1.04$, 2.60, and 10 BeV and for π mesons with $p\beta c = 17.5$ BeV (72 tracks) is shown in Fig. 6. Ilford G-5 emulsion was irradiated by the mesons at CERN. It follows from Fig. 6 that for long cells we observe a considerable deviation of ρ from the theoretical value ρ_C. For short cells the deviation can be explained by a large contribution of spurious scattering, and for long cells it must evidently be considered as a result of the approximate nature of the theoretical treatment of Coulomb scattering. The most acceptable range of cell length is that in which ρ decreases with increasing cell length from $\rho \leq 1.50$ ($\bar{D}_C \gtrsim \bar{D}_S$) to ρ_C.

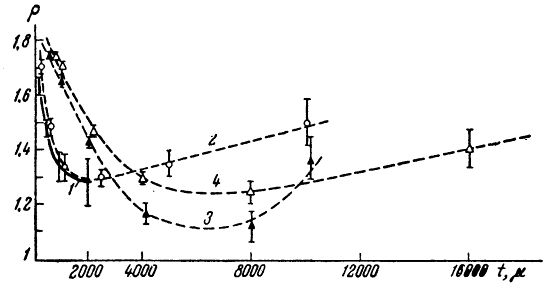

FIG. 6. Variation of ρ with cell length for different values of $p\beta c$; curve 1 – for 1.04 BeV; 2 – for 2.6 BeV; 3 – for 10 BeV (43 tracks); 4 – for 17.5 BeV (π mesons).

Where it is possible to attain $\rho \sim \rho_C$ the error due to false scattering is negligible. In the case where $\bar{D}_C \approx \bar{D}_S$, which is very often met in practice, it is very difficult to find the particle energy.

The directly measured second difference $\bar{D}$ is composed of $\bar{D}_C$ and $\bar{D}_S$ as follows

$$\bar{D}^2 = \bar{D}_C^2 + \bar{D}_S^2. \tag{3}$$

Having determined $\bar{D}_S$ from particle tracks with a known energy in a given emulsion layer or its part, we can find $\bar{D}_C$ from this relation. However, in the case where $\bar{D}_C \approx \bar{D}_S$, the inaccuracy of such an approach is considerable, since $\bar{D}_S$ depends on the geometrical position of the track in the emulsion, and on other factors which are not completely clear. The quantity $\bar{D}_S$ depends very strongly on the cell length and the type of emulsion.

If the contribution of spurious scattering is large, it is better to determine the Coulomb scattering from the equation[14]

$$\bar{D}_C = \bar{D}\,[(\rho_S^2 - \rho^2)/(\rho_S^2 - \rho_C^2)]^{1/2}, \tag{4}$$

where the unknown is ρ_S, which is almost constant (it depends very little on the cell length and the emulsion type[12,14,15]). ρ_S can be found experimentally using Eq. (4), by measuring $\bar{D}_C$ and ρ on the tracks of particles with known energy.

In the cases where $\bar{D}_C$ is unknown, ρ_S can be found from the equation

$$\rho_C^2 = [(t_2/t_1)^3\,\overline{D_1^{III2}} - \overline{D_2^{III2}}]/[(t_2/t_1)^3\,\bar{D}_1^2 - \bar{D}_2^2],$$

where $\bar{D}_1$ and $\overline{D_1^{III}}$ and $\bar{D}_2$, $\overline{D_2^{III}}$ are second and third differences on cells t_1 and t_2.

The choice between Eqs. (3) and (4) can be made after comparing the results for the same experimental material. For this purpose we used the data from earlier scattering measurements on 43 proton tracks with energy 9 BeV, in one layer of the emulsion.[8,9] From these data ρ_S was found to equal 1.75 ± 0.03 on a cell of $t = 1$ mm and 1.80 ± 0.03 on a cell of 2 mm. We determined the Coulomb scattering for these cells according to Eqs. (3) and (4).

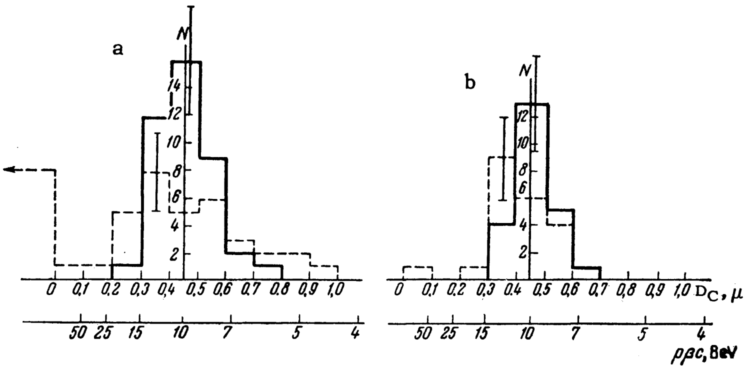

FIG. 7. Distribution of the values of $\overline{D}_C$ found from Eq. (3) (dashed line) and Eq. (4) (solid line) for a--1.52 $\leq \rho \leq$ 1.67 and b--1.35 $\leq \rho \leq$ 1.52.

The distributions of D_C found from Eqs. (3) and (4) are shown in Figs. 7a for the case $0.5 \leq \overline{D}_C/\overline{D}_S \leq 1$, which corresponds to $1.52 \leq \rho \leq 1.67$. It follows from Fig. 7 that the distribution of $\overline{D}_C$ (or $p\beta c$) obtained from Eq. (4) is much narrower (solid line) than from Eq. (3). The analogous distributions of $\overline{D}_C$ for $1 \leq \overline{D}_C/\overline{D}_S \leq 2$ ($1.35 \leq \rho \leq 1.52$) are given in Fig. 7b. In this figure, as well as in Fig. 7a, the values of $\overline{D}_C$ refer to a cell length t = 2 mm. In the second case the distributions $\overline{D}_C$ found by different methods do not differ much, although the distribution corresponding to Eq. (4) is more symmetrical.[1)]

To find the total error in $\overline{D}_C$ (or $p\beta c$) from Eq. (4) it is necessary to know the errors of the measurement of $\overline{D}_i$ and ρ_i, and also the coefficient of correlation between them. The relative statistical errors $\Delta\overline{D}_i/\overline{D}_i$ and $\Delta\rho_i/\rho_i$ are usually found according to the formula $C/\sqrt{N}$. The experimental values of these errors are [13]

$$\Delta\overline{D}_i/\overline{D}_i = 0.81/\sqrt{N}, \qquad \Delta\rho_i/\rho_i = 0.50/\sqrt{N},$$

where N is the number of second differences per track and $\Delta\overline{D}$ (like $\Delta\rho$) was found from the relation

$$\Delta\overline{D} = \Big[\sum_{i}^{n} |\overline{D}_i - \overline{D}|^2/(n-1)\Big]^{1/2},$$

where n is the number of tracks, $\overline{D}_i$ is the arithmetic mean of the second differences on the i-th track, and $\overline{D}$ is the average value for all tracks.

The variation of the correlation coefficient r with ρ (and, consequently, $\overline{D}_C/\overline{D}_S$) is shown in Fig. 8. The correlation coefficient r was found from the equation

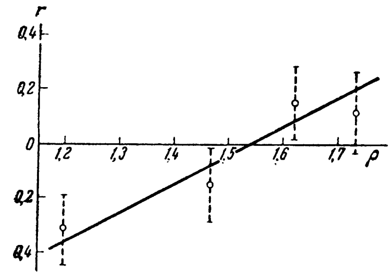

FIG. 8. Variation of the correlation coefficient r with ρ.

$$r = \frac{\Big[\sum_{i=1}^{n} (D_i - \overline{D})(\rho_i - \overline{\rho})\Big]}{\Big[\sum_{i=1}^{n} (D_i - \overline{D})^2\Big]^{1/2}\Big[\sum_{i=1}^{n} (\rho_i - \overline{\rho})^2\Big]^{1/2}}.$$

It can be seen that the correlation is small. In the case where the spurious scattering predominates the correlation is positive, becoming negative for predominant Coulomb scattering. The arithmetic mean deviation of r was found from the formula $\sigma_r = (1 - r^2)/\sqrt{n}$, where n is the number of tracks.

We can now obtain the formula for the total error of $\overline{D}_C$ in the usual way (for finding the errors of a function of random quantities):

$$\frac{\Delta\overline{D}_C}{\overline{D}_C} = \frac{C}{\sqrt{N}},$$

$$C = 0.81\left[1 - 2r\left(\frac{0.50}{0.81}\right)\frac{\rho^2}{\rho_л^2 - \rho^2} + \left(\frac{0.50}{0.81}\right)^2 \frac{\rho^4}{(\rho_л^2 - \rho^2)^2}\right]^{1/2}.$$

The variation of C with ρ (or $\overline{D}_C/\overline{D}_S$) is shown

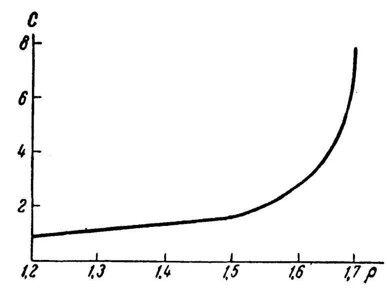

FIG. 9. Variation of the coefficient C with ρ.

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1)Analogous results were obtained by us for 72 17.5-BeV π-meson tracks in Ilford G-5 emulsion. It was also shown that the method of multiple cells[8,12] gives less accurate results than Eq. (4) which was used for all tracks on cells where $\rho_C \leq \rho \leq 1.50$, and the total error of $\overline{D}_C$ was minimal.

in Fig. 9. For $\rho \geq 1.50$ the $\geq$ quantity C, and, correspondingly, the total error of D_C, are large and depend strongly on ρ. It is therefore recommended to determine in practice D_C on a cell where $\rho_C \leq \rho \leq 1.50$. For a limited track length, the optimum cell will be that one for which the error $(\Delta\bar{D}_C/\bar{D}_C)$ is smallest.

In conclusion, the authors express their gratitude to Prof. V. I. Veksler for cooperation in irradiating the emulsion at the Joint Institute for Nuclear Research and to Prof. W. Lock for supplying the emulsion irradiated at CERN, and also to members of our laboratory V. A. Botvin, E. G. Boos, and others for taking part in the discussion, and to M. Izbasarov for help in measurements and calculations.

[1] Belyakov, Wang, Glagolev, Dalkhazhav, Lebedev, Mel'nikova, Nikitin, Petrzilka, Sviridov, Suk, and Tolstov, JETP **39**, 937 (1960), Soviet Phys. JETP **12**, 650 (1961).

[2] Wang, Visky, Gramenitskiĭ, Grishin, Dalkhazhav, Lebedev, Nomofilov, Podgoretskiĭ, and Strel'tsov, JETP **39**, 957 (1960), Soviet Phys. JETP **12**, 663 (1961).

[3] Takibaev, Botvin, and Chasnikov, DAN SSSR **135**, 571 (1960), Soviet Phys. Doklady **5**, 1249 (1961).

[4] Botvin, Takibaev, Chasnikov, Pavlova, and Boos, JETP **41**, 993 (1961), Soviet Phys. JETP **14**, 689 (1962).

[5] Visky, Gramenitskiĭ, Korbel, Nomofilov, Podgoretskiĭ, Rob, Strel'tsov, Tuvdendorzh, and Khvastunov, JETP **41**, 1069 (1962), Soviet Phys. JETP **14**, 740 (1963).

[6] Botvin, Takibaev, and Usik, DAN SSSR **146**, 785 (1962), Soviet Phys. Doklady **7**, 887 (1963).

[7] I. Ya. Chasnikov, Vestnik AN KazSSR **8**, 96 (1962).

[8] I. Ya. Chasnikov, Vestnik AN KazSSR **3**, 64 (1960).

[9] Chasnikov, Takibaev, Tursunov, and Sharapov, PTÉ **5**, 15 (1960).

[10] L. Voyvodic and E. Pickup, Phys. Rev. **85**, 91 (1952).

[11] Hossain, Votruba, and Wataghin, Nuovo cimento **22**, 308 (1961).

[12] Y. Pal and A. K. Ray, Nuovo cimento **27**, 960 (1963).

[13] Biswas, Georg, Peters, and Swamy, Nuovo cimento Suppl. **12**, 361 (1954).

[14] Tursunov, Chasnikov, and Sharapov, Yadernaya fotografiya (Nuclear Photography), AN SSSR, 1962, p. 231.

[15] S. P. Lagnaux and P. Renard, Bulletin, Université de Bruxelles, 3, 1962.

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