THE IONIZATION-MOMENTUM RELATION FOR VARIOUS PARTICLES IN THE RELATIVISTIC REGION

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New data have been obtained on the momentum dependence of the blob density along the tracks of electrons in the 50 MeV/c — 5 BeV/c momentum range (Ilford G-5 and NIKFI-R emulsions) and of protons and π mesons in the 1.4—1.9 BeV/c and 0.3—6 BeV/c momentum range, respectively (Ilford G-5 emulsion). The results confirm the conclusion, previously arrived at by the authors,[1-3] that for $p\beta c > 200\ mc^2$ a drop, which is in agreement with the calculations which take radiative corrections into account,[2] is observed in the ionization-momentum curve instead of the plateau predicted by earlier theory.[4]

We reported already that a decrease in the blob density is observed for electrons in the momentum range 0.1—2 BeV/c in the NIKFI-R emulsion for increasing momentum,[1] rather than the generally accepted plateau of the theoretical curve. A theoretical interpretation was then given of the above effect[2,3] and additional data for electrons have been presented for the Ilford G-5 and NIKFI-R emulsions.

In the following, we present new, more detailed data on the momentum dependence of the blob density for electrons, and for π mesons and protons.

For the measurements we used pellicles of Ilford G-5 emulsion (9 layers 12 cm × 19.5 cm, 600 μ thick) and NIKFI-R (one layer 10 cm × 20 cm, 400 μ thick), irradiated by 19.6 BeV/c protons. The π-meson and proton tracks were selected from stars produced by primary protons on the emulsion nuclei, while the tracks of electrons were selected from electron-positron pairs produced by the photons from the decay of π^0 mesons produced in the same interactions. The measurements were carried out along tracks which were as a rule longer than 1 cm. The angle of dip of the π-meson and proton tracks was less than 1°, and of the electron tracks less than 2°. The particle momentum was determined from the mean multiple-scattering angle. The events in which the momentum changed by more than a standard deviation along the electron tracks (because of bremsstrahlung) were either excluded from further analysis, or the corresponding parts of the track were considered as different tracks. The relative ionization was determined by measuring the blob density along the tracks of the investigated particle and of primary protons passing nearby at about the same depth.

The multiple-scattering measurements were carried out using the KSM-1 microscope, and the blob density measurements using the MBI-3 and MBI-9 microscopes with 60 × 15 × 1.5 or 90 × 15 magnification.

The characteristic dependence of the blob density on depth along the primary proton tracks is shown in Fig. 1. It can be seen that for the NIKFI-R emulsion at depths of 15—120 μ from the surface the corresponding variation in the blob density amounts to ~ 3%, and we have therefore chosen the depth range 20—120 μ from the surface (in developed emulsion) as the working region.

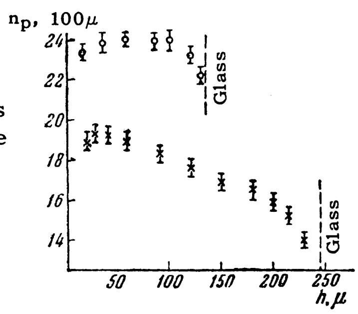

FIG. 1. Dependence of the blob density along tracks of 19.6 BeV/c protons on the depth of the track in the developed emulsion: o – for the NIKFI-R emulsion, × – for the Ilford G-5 emulsion.

For the Ilford G-5 emulsion, we observed a very small change of blob density at 20—60 μ, and in the range 60—200 μ a marked (~ 15%) linear decrease in the density with the depth. We have therefore chosen as the working region for the relative ionization measurements the range 20—200 μ from the surface. The blob density along the tracks of primary protons remained constant in different places of a given layer at the same

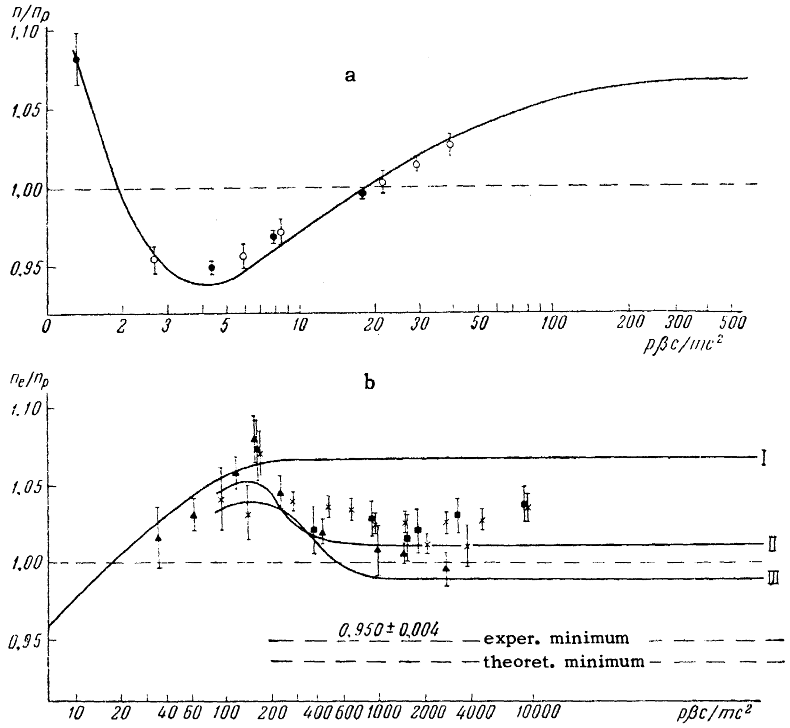

FIG. 3. Momentum dependence of the specific ionization for heavy particles (a) and electrons (b): o, ●, × – data for π mesons, protons, and electrons respectively (Ilford G-5 emulsion), ▲ – old data[1] and ■ – new data for electrons (emulsion NIKFI-R). Curves in (b) correspond to: I – theory without radiative corrections,[7] II, III – theory[2,3] taking the radiative corrections into account, for the parameter $1/\zeta$ equal to 100 and 200 respectively (for $p\beta c < 1000$ mc^2 the curves are only approximate). The levels $n/n_p = 1$ and $n_e/n_p = 1$ correspond to the track density of 19.6 BeV/c protons.

depth, within the limits of statistical errors. The mean scatter of the blob density along the tracks of primary protons and of electrons amounted to $0.88/\sqrt{N}$ and $0.82/\sqrt{N}$ for the Ilford G-5 and NIKFI-R emulsions, respectively, where N is the mean number of blobs per given length. Repeated measurements of the blob density along the same segment of a track by the same observer differed by less than 1%.

Both the number of blobs and the number of grains were counted on a number of tracks. On the primary proton tracks the relation between the grain density and blob density amounted to 1.15 ± 0.01 for Ilford G-5 and to 1.12 ± 0.01 for NIKFI-R emulsion. On electron tracks (total length of 15 cm for Ilford G-5 and 8 cm for NIKFI-R emulsion) the mean value of the relative ionization from the grain count was found to be greater than from the blob count: by 2–2.5% for Ilford G-5 and by 1–1.5% for NIKFI-R.

The variation of the total noise with cell length in multiple scattering measurements is given in Fig. 2 for primary proton tracks. The error in the momentum determination for an individual particle was 10–15% in the momentum range 0.1–1 BeV/c, 15–25% in the range 1–2 BeV/c, and 20–30% for momenta greater than 2 BeV/c. The error in the determination of relative ionization from a single track amounted to 1.5–3%.

All the data obtained for electrons, π mesons, and protons, including the data for electrons published earlier,[1] are shown in Fig. 3. In addition to the generally accepted theoretical ionization-

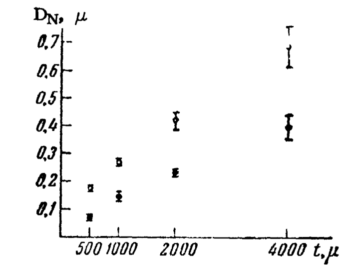

FIG. 2. Total noise in multiple-scattering measurements as a function of cell length for 19.6 BeV/c proton tracks: o – for the NIKFI-R emulsion, ● – for the Ilford G-5 emulsion. The y axis represents the second difference due to noise, D_N.

momentum curve (I), the theoretical curves of Tsytovich[2] calculated with allowance for the radiative corrections (II and III) are shown in the lower part of Fig. 3.

A comparison of the experimental data with the theoretical curves shows that in the momentum range $p\beta c \approx 3$–50 mc^2 an increase in the blob density is observed, in agreement with theoretical curve (I), while in the momentum range $p\beta c > 200$ mc^2 a decrease in the blob density is observed on electron tracks, in satisfactory agreement with curve (II). Moreover, there are indications that the effect of the blob density decrease is somewhat different in magnitude for emulsions of different type and sensitivity.

In order to assess the statistical significance of the results obtained by the χ^2 test (according to the experiment and the results of calculation[2,3]) we have assumed that the ionization remains constant in the energy range 0.4–3 BeV for electrons.[1)]

[1)]It is possible that at energies >3 BeV the ionization begins to increase again.

From the six points obtained by us for the Ilford G-5 emulsion and seven points for the NIKFI-R emulsion we found the values of χ^2 as a function of the quantity n_e/n_p, and at significance levels of 80, 95, and 99% as indicated in Fig. 4. It can be seen that at the 95% level it is still impossible to conclude about a difference between the response of the Ilford G-5 and NIKFI-R emulsions. Moreover, from a theoretical estimate of the parameter

$$\zeta = \frac{e^2}{\hbar c}\frac{\omega_0}{\langle\omega_s\rangle}\ln\frac{c}{\langle v\rangle}$$

the value $\frac{1}{100}$ fits the data much better than $\frac{1}{200}$. Any agreement between our data and the theory of Sternheimer,[4] which neglects the radiative corrections (arrow I in Fig. 4), is practically excluded.

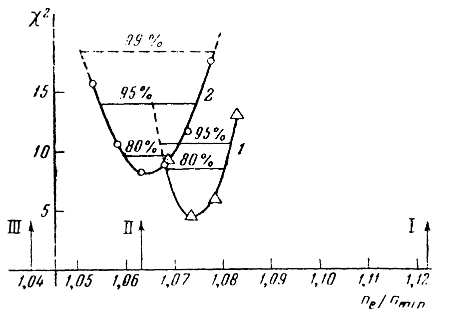

FIG. 4. Statistical correlation between the experimental data and the possible constant values of the relative ionization, in the electron energy range 0.4–3 BeV. Curve 1 – for Ilford G-5 emulsion, curve 2 – for NIKFI-R emulsion. The arrows I–III denote the positions of the corresponding curves shown in Fig. 3. n_{min} is the value of the blob density at the minimum of the experimental curve.

From the study of the blob-density momentum dependence for electrons with momentum below 100 MeV/c, it is very difficult to establish accurately the position of the maximum on the ionization curve and the form of the curve before the maximum. It is therefore very desirable to carry out an additional study in the momentum range $p\beta c \approx 50\ mc^2$ and higher for heavy particles and, in particular, π mesons.

There is a weak indication in [5] that a maximum occurs in the ionization curve for electrons around 100 MeV. Ionization measurements for momenta above 100 MeV/c were carried out, however, with a very low accuracy (~ 4% error). The data obtained in [6] also do not contradict our data, within the limits of experimental errors. However, in that case, too, the low accuracy of the experiment, does not permit us to conclude about a decrease in the ionization with increasing momentum for electrons with energy greater than 100 MeV.

The most accurate measurements to date (with statistics comparable to ours) of the ionization-momentum relations for electrons are those of Stiller[7] using various emulsions, among them NIKFI-R and Ilford G-5. The mean value of the relative ionization for electrons in the range 165—800 MeV for the Ilford G-5 emulsion is in a good agreement with the corresponding results of our measurements, and amounts to 1.07 of the ionization at minimum. For the emulsion NIKFI-R, the data of Stiller disagree sharply with our data and with the data of Stiller himself for the Ilford G-5 emulsion, attaining about 1.17—1.18 (of the ionization curve minimum) in the range 165—800 MeV. A serious drawback of the experiments of Stiller, however, is the separate irradiation of the pellicles by electrons and by the π-meson beam, used to obtain the calibration point. The temperature variation of the sensitivity could, in principle, cause a systematical error attaining, according to an estimate of Stiller himself, a value of the order of 10%, i.e., considerably greater than the statistical errors. For this reason we think that the experimental method used by Stiller needs additional refinement.

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[1] Alekseeva, Zhdanov, Zamchalova, Novak, Tret'yakova, and Shcherbakova, Trans. Intern. Nucl. Photography Colloquium, Moscow, 1961, p. 396 (in Russian).

[2] Zhdanov, Tret'yakova, Tsytovich, and Shcherbakova, JETP **43**, 342 (1962), Soviet Phys. JETP **16**, 245 (1963).

[3] Alekseeva, Zhdanov, Tret'yakova, Tsytovich, and Shcherbakova, Trans. IV Intern. Nucl. Photography Colloquium, Munich, 1962.

[4] R. M. Sternheimer, Phys. Rev. **91**, 256 (1959).

[5] J. W. Patrick and W. H. Barkas, Supplemento, Nuovo cimento **23**, 1 (1962).

[6] B. Jongejans, Nuovo cimento **16**, 625 (1960).

[7] B. Stiller, Trans. IV Intern. Nucl. Photography Colloquium, Munich, 1962.

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