Ionization losses of relativistic particles in thin glass layers

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The energy dependence of probable ionizations produced by protons, pions, and positrons is investigated. The particle Lorentz factors varied from 2 to 5200. Proportional counters filled with Ar (or Xe) and 5% CH_4 were used. The gas pressure in the counters was 750 mm Hg. The ionization was measured for particle paths of 5 and 17 cm. The relativistic ionization increase is found to be lower than that predicted by the Bethe-Bloch theory with corrections for the density effect calculated by the Sternheimer formulae. The ionization loss fluctuations are measured as functions of the gas-layer thickness. In this case the counter gas pressure was varied between 2.5 and 0.1 atm. abs.

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1. INTRODUCTION

In connection with the problem of particle identification by means of the relativistic increase of ionization losses, interest in the dependence of the ionization losses on the energy has greatly increased of late.[1–6] Furthermore, indications have appeared[2,5,6] that the increase of the probable ionization with increasing Lorentz factor of the particle $\gamma(\gamma = 1/\sqrt{1-\beta^2}$, $\beta = v/c$, where v is the particle velocity and c is the speed of light in vacuum) proceeds more slowly than predicted by the ionization-loss theory developed in Sternheimer's papers.[7]

It should also be noted that the question of fluctuations of the ionization losses of charged particles and of the ionization effect produced by these particles has not yet been sufficiently well studied. Although there are many experimental data, the results of different authors differ quite strongly from one another. At the same time, the calculation of the fluctuations of the ionization effect is a very complicated problem, not yet solved in general form, in spite of the large number of theoretical papers devoted to it (e.g., [8–13]). It is therefore of considerable interest to obtain new data on the magnitude of the fluctuations of the ionization effect, especially at very small thicknesses of the material ($\lesssim 10^{-3}$ g/cm^2).

We have investigated in the present study the energy dependence of the probable ionizations produced by positrons, pions, and protons, and also the dependence of the fluctuations of the ionization effect on the thickness of the gas layer in which the measurements were carried out. The investigations were carried out with the Serpukhov accelerator of the Institute of High Energy Physics, with the aid of proportional counters filled with argon (or xenon) to which 5% methane has been added. Measurements were made at a particle path length in the counter equal to 5 and 17 cm at a gas pressure in the counter from 0.1 to 2.5 atm.

The dependence of the obtained probable ionizations ε_{exp} on the Lorentz factor was compared with the probable ionization losses ε_{theor} calculated by Sternheimer's formulas,[7] and the dependence of the width of the distribution of the ionizations on the gas-layer thickness was compared with the predictions of[9,11,12].

2. EXPERIMENTAL CONDITIONS

The experimental setup is shown in Fig. 1. The particle source was the internal aluminum target T of the accelerator. The particles travel to the recording system through an analyzing magnet M, a first iron collimator K_1 of 5.4 m length and 120 mm diameter, and a second iron collimator K_2, inserted in the first, of length 1 m and diameter 30 mm. The scintillation counters S_1, S_2, S_3 were connected for coincidences, while A_1 and A_2 (with center holes of 30 mm diameter) were connected for anticoincidence and served to separate particles in a given solid angle and to cut off the particles with accompaniment. The guarding scintillation counters A_1 and A_2 were not used in the investigation of the fluctuations of the ionization effect.

The air-filled threshold Cerenkov counter $\check{C}_1$ registered only positrons, while counter $\check{C}_2$ was filled with freon and registered positrons and pions. By interconnecting these counters into coincidence and anticoincidence channels it was possible to separate definite particles.

By varying the current in the analyzing magnet, we selected the momentum of the registered particles. When working with protons, we registered effectively the $\beta\gamma$ region ($\beta\gamma = p/m_0c$, where p is the momentum and m_0 is the mass of the particle) in the range from 2.2 to 6.0; the corresponding ranges with pions and positrons were from 15 to 39 and from 780 to 5200, respectively.

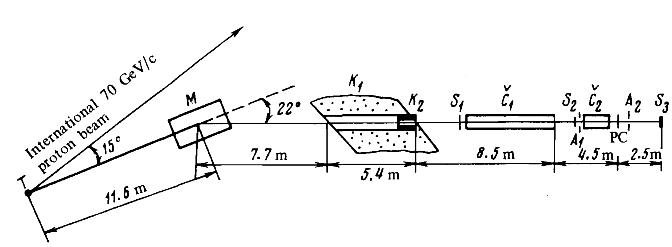

FIG. 1. Experimental setup. T—internal aluminum target of accelerator; M—analyzing magnet; K_1 and K_2—iron collimators; S_1, S_2, S_3—scintillation counters; A_1, A_2—guarding scintillation counters; PC—proportional counter; $\check{C}_1$, $\check{C}_2$—Cerenkov counters.

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In the investigation of the dependence of the probable ionization ε_{exp} on $\beta\gamma$, we passed through the entire discrete series of $\beta\gamma$ at our disposal in each experimental run by measuring in succession the ionizations due to protons, pions, and positrons. The measurements were performed under conditions when the number of coincidences of the type ($S_1S_2S_3$) did not exceed 3–5 per millisecond.

The ionization spectra from the proportional counter were registered by a standard AI-128 pulse-height analyzer and consisted of 3000 to 20,000 measurements.

The random-coincidence background was measured by delaying the control signal by 20 μsec. We chose the initial operating conditions such that the random-coincidence background could be disregarded.

3. MEASUREMENT ERRORS

The relative error in the determination of the particle momentum was ±10%. This estimate agrees well with the data of Belousov, Blik, and Kut'in.[14] The nonlinearity of the spectrometer channel did not exceed the errors of the voltage on the control generator (1–2%) and was therefore disregarded. The operating instability of the spectrometer setup over several days was ±1–2%. The errors due to the instability were decreased by carrying out short-duration (approximately one hour) cycles of measurements with protons, pions, and positrons with a new value of particle momentum in each set of measurements. Thus, each measurement cycle had its own normalization point relative to the protons. The total background of random coincidences for all the measurements was less than 1% of the sum of all the registered events in a given measurement.

The accuracy with which the probable value of the ionization ε_{exp} was determined by computer reduction of the spectra by the maximum likelihood method (with allowance for the methodological errors of the calculation program) was not worse than ±1–2%, and in the case of visual reduction of the ionization spectra it could reach ±4–5%. The effective counter length was estimated at $l = 17 \pm 1$ cm, when the particles move along the filament, and at $l = 5.0 \pm 3$ cm when the particles move across the filament. When comparing the experimental results with the theory, the errors of ε_{exp} included the errors (±1–3%) in the determination of the probable ionization of the normalization points, and the error (±1%) in the theoretical values of the probable ionization losses ε_{theor}, calculated with Sternheimer's formulas.[7] It was assumed here, naturally, that $\varepsilon_{exp} \equiv \varepsilon_{theor}$ at the normalization points. Hence, the total error in the determination of the probable value of the ionizations ε_{exp} for the remaining points amounts to ±2–4%.

In addition, when comparing the theory with experiment it is necessary to take into account one more source of errors due to the fact that in the experiment one measures not the energy lost by the particle, but the ionization produced by the particle. The difference between these two quantities consists, first, in that not all the energy lost by the particle goes to ionization—part of it goes to excitation of the atoms; second, the energy transferred to the high-energy δ electrons leads to a redistribution of the ionization among the layers of matter. The part of the energy transferred to the δ electrons in the interior of the counter is carried out of the counter. On the other hand, δ electrons generated by the particle in the walls of the counter enter into the volume of the counter together with the particle.

The fact that part of the energy lost by the particle is consumed in excitation of atoms leads only to a change in the coefficient of proportionality between the lost energy and the number of produced ion pairs. The energy carried away from the volume of the counter influences only the average value of the ionization, and for the most probable value this effect is inessential. Indeed, the only δ electrons that can leave the counter are those with energy exceeding the probable losses by tens of times. This cuts off the tail of the excitation, and nothing else. The most essential cause of the difference between the theory of ionization losses and the experimental investigations of the ionization effect may be the δ electrons that fall into the interior of the counter from its walls. The number of these δ electrons, however, can be relatively easily estimated.

In our experiment, when the beam of particles crossed the working region of the counter perpendicular to the filament, the thickness of the stainless-steel walls was 1 g/cm^2, and when the particles moved parallel to the filament their path went through a porcelain insulator 5 g/cm^2 thick in the form of a ring covering 6% of the beam area, and through a wall 2 g/cm^2 thick. Calculations show that in this case a δ electron should accompany the particle in approximately 10% of the cases. Some 90% of these δ electrons have an energy that exceeds 500 keV, i.e., they produce the same ionization in the counter as the particle itself. Therefore their influence reduces to the appearance of an additional "hump" in the distribution near double the value of the ionizations. By starting from the form of the distribution of the ionizations we can estimate that these electrons shift the maximum of the distribution by not more than 0.1%, so that the error introduced by them in the measurement of the most probable value of the ionization is much less than all the other experimental errors.

4. RESULTS OF MEASUREMENTS OF THE IONIZING ABILITY

The ionization spectra obtained at different values of $\beta\gamma$ and in different measurement runs were reduced by the maximum-likelihood method and the most probable ionization was determined for each spectrum. The reduction was by means of a special program with the BÉSM-4M computer.

Figures 2 and 3 show plots of ε_{exp} against $\beta\gamma$ as measured with a proportional counter. Results were obtained for two different gas mixtures filling identical counters. Figures 2 and 3 show only the results of an experiment with a counter filled with 95% Ar + 5% CH_4. The solid curves are the result of the calculation of ε_{theor}. The theory and experiment were normalized to the values of the ionization losses at the minimum.

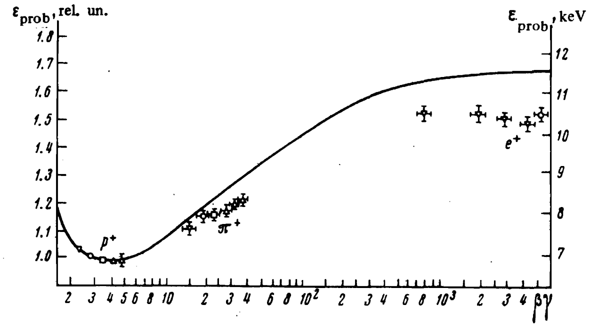

FIG. 2. Dependence of the probable ionization ε_{prob} in a proportional counter on the value of $\beta\gamma$ of the particle. Solid curve—calculation by Sternheimer's formulas.[7] Points with like symbols denote the values obtained during a single run (1–2 hours). The points for which the errors are not indicated are normalization points. The path length of the particle in the counter is 5 cm. The counter is filled with a mixture of 95% Ar + 5% CH_4.

From a comparison of the experimental results with those calculated by the Sternheimer formulas[7] (with allowance for the density effect) it can be seen that the relativistic growth of the ionization is lower in the experiment, and the difference between the theory and experiment is larger for thicker layers (5 cm).

The results of measurements with another gas mixture (95% Xe + 5% CH_4) are analogous to those given above, the only difference being that the discrepancy between theory and experiment is still larger here (for Ar the theoretical value of the relativistic growth $R = \varepsilon_{plateau}/\varepsilon_{min} = 1.69$ for $l = 5$ cm and 1.61 for $l = 17$ cm, while the experimental values are respectively 1.54 and 1.47; for Xe, R_{theor} is equal to 1.82 and 1.71, and R_{exp} is equal to 1.5 and 1.6, respectively).

One of the possible explanations of the observed effect is proposed by Garibyan and Ispiryan.[15] They suggest that the possible cause of the slowing down of the increase of the ionization may be transition effects (on the boundary between the metallic wall and the counter gas) connected with distortion of the electromagnetic field of the particle. The field of a particle entering the gas of the counter returns after a certain time to the value corresponding to the given gas, and the ionization of the particle in the gas should ultimately approach the calculated ionization energy losses.

Another explanation was proposed by Merzon and coworkers.[16] They state that correct allowance of the connection between the atomic electrons leads to a decrease of the relativistic growth of the ionization in thin layers of matter. The relativistic growth of the ionization calculated by them on the basis of this hypothesis agrees well with our experimental data.

5. FLUCTUATIONS OF THE IONIZATION EFFECT

The statistical character of the ionization losses was noted already by Bohr.[8] He has shown that distribution of the ionization losses in thick absorbers, in which many collision acts as well as different energy transfers to the atomic electrons average out, is Gaussian, and he calculated the variance of the distribution of the ionization losses.

In experiment, however, this is a very rare case for relativistic electrons. Usually one deals only with thin absorbers. For these, Landau[9] derived in 1944 the ionization-loss distribution function and obtained an expression for the most probable losses. These results were obtained, however, under certain simplifying assumptions, namely, that the observed energy losses in a layer x of matter should be sufficiently large in comparison with the average binding energy of the atomic electrons, and sufficiently small in comparison with the maximum possible energy transfer to the electron.

An experimental verification of the Landau distribution, carried out in a large number of studies, has shown that the theory does not always agree satisfactorily with experiment. It turns out that the experimental half-widths greatly exceed the half-width given by the Landau theory (the term "half-width" is used here to denote the width of the distribution at half height). In subsequent theoretical studies, attempts were made to improve the agreement between the theory and experiment. Thus, Blunck and Leisegang[11,12] refined the Landau solution by taking into account the next term of the expansion in the calculation of the distribution function. They obtained a broader distribution, which, in accordance with their recommendation, should be used if the parameter

$$b^2 = \frac{0.02\,(\mathrm{keV}) \cdot \bar{\Delta}(\mathrm{keV}) \cdot Z^{4/3}}{\xi^2 (\mathrm{keV})^2}$$

introduced by them has a value $b^2 \gtrsim 3$, where $\bar{\Delta}$ is the average energy loss in a layer of thickness x(g/cm^2)

$$\xi\,(\mathrm{keV}) = \frac{154 \sum_i Z_i}{\beta^2 \sum_i A_i} x.$$

The parameter b^2 is inversely proportional to the absorber thickness and is equal to zero for large thicknesses. In this case the Landau distribution can be used.

It should be noted, however, that the difference between the ionization losses and the ionization effect noted above can lead to a larger disparity between

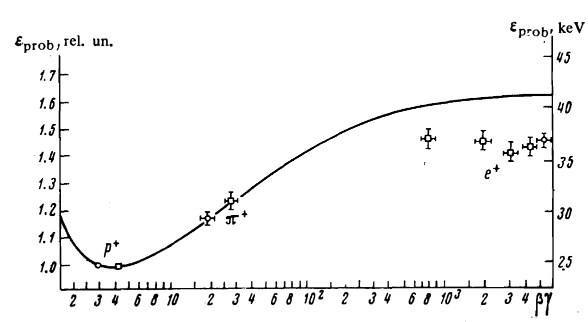

FIG. 3. The same as in Fig. 2, but the particle path length in the counter is 17 cm.

theory and experiment when it comes to determining the distribution width than when it comes to determining the most probable ionization. An essential role may be assumed here, for example, by the redistribution of the losses among the ionization and excitation of the atoms of the medium. This question has not yet been sufficiently resolved theoretically, so that the experiments usually compare the results of an investigation of the fluctuations of the ionization effect when the theories developed for fluctuations of the ionization losses by Landau,[9] Vavilov,[10] and Blunck and Leisegang.[11,12] It is obvious that observation of good agreement of these theories with experiment would make it possible to state that the difference between the ionization effect and the ionization losses is immaterial in this case.

We have investigated the fluctuations of the ionization in thin layers of gas. To this end, we used proportional counters filled with argon or xenon with 5% methane added. The pressure in the counters ranged from 2.5 to 0.1 atm.

Figure 4 shows a typical ionization spectrum obtained in our experiment. The statistics of the counts were sufficiently large (the number of measurements in one spectrum fluctuated from 3000 to 10,000). Figures 5–7 show the dependences of the half-widths of the distributions on the quantity Pl (atm-cm), where P is the gas pressure in the counter and l is the effective length of the particle path in the counter gas. The same figures show, parallel to the Pl axis also an axis representing one of the parameters, ξ(keV), of the Landau theory.[9] Landau believed that his theory should agree with experiment in those cases when ξ is much less than the average binding energy of the atomic electrons. The solid lines in the figures give the corresponding Landau curves (marked L) and the curve of Blunck and Leisegang (curve B).

Figures 5, 6, and 7, respectively, show the results of an experimental study of the fluctuations of ionization from protons, pions, and positrons with momenta 2.65

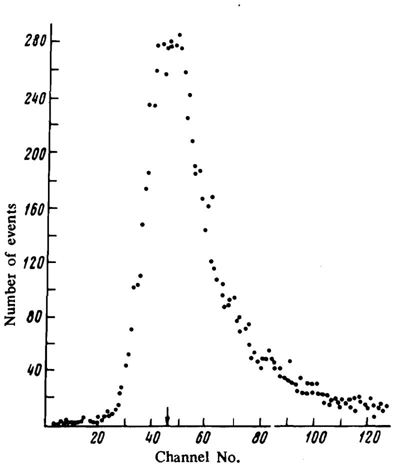

FIG. 4. Typical ionization spectrum obtained by bombarding a proportional counter with 2.65-GeV/c protons. The particle path encounter was 17 cm, the gas pressure was 1.5 atm. abs., and the gas composition 95% Ar + 5% CH_4.

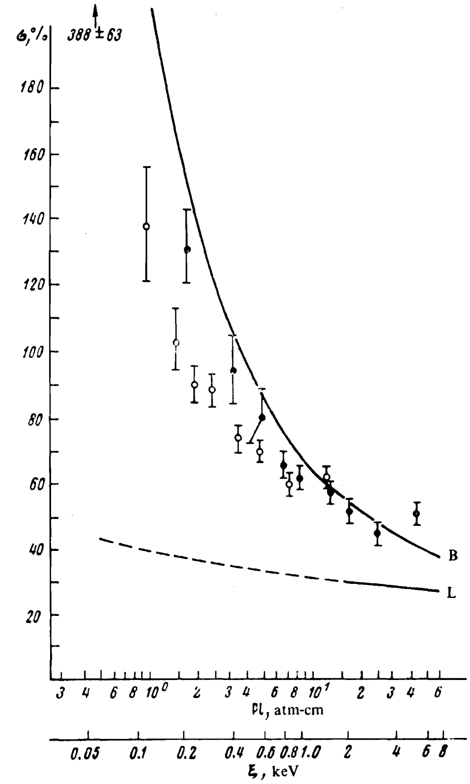

FIG. 5. Half-width σ of the ionization spectra of protons with momenta 2.65 GeV/sec vs. the thickness Pl of the gas layer. Smooth curves—calculation in accordance with Landau (curve L) and in accordance with Blunck and Leisegang (curve B). The counter is filled with a mixture 95% Ar + 5% CH_4. ○—l = 5 cm, ●—l = 17 cm.

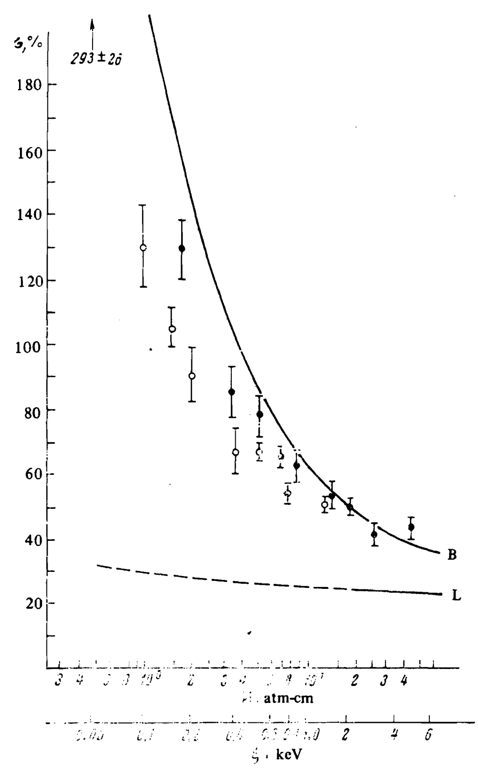

FIG. 6. The same as in Fig. 5, but for pions with momentum 2.65 GeV/sec.

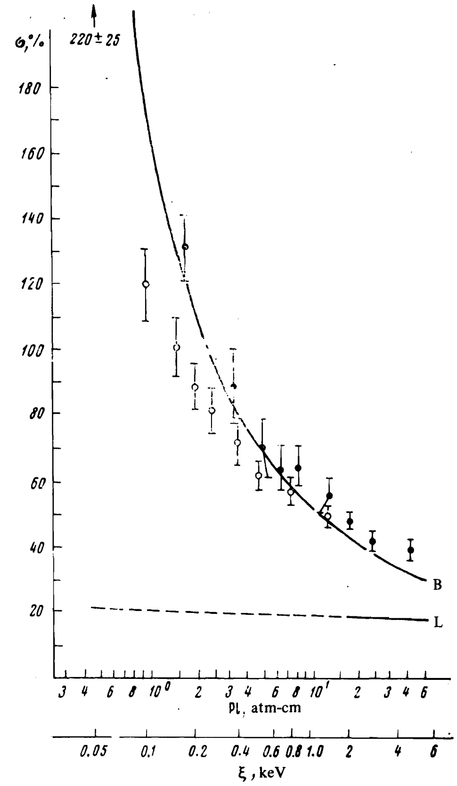

FIG. 7. The same as in Fig. 5, but for positrons with momentum 2.65 GeV/sec.

GeV/sec, in a proportional counter filled with 95% Ar + 5% CH_4, at a temperature 20 °C and effective particle path lengths in the counter 5 and 17 cm. We note that in argon the average binding energy of the atomic electrons is $\varepsilon_0 \approx 200$ eV. The results for a counter filled with 95% Xe + 5% CH_4 are analogous.

The degree of agreement between the half widths of the experimental distributions of the ionization from protons, pions, and positrons with the calculated corresponding half-widths of the distribution of the ion losses after Landau and after Blunck and Leisegang can be seen from the figures. We note that the conditions under which the experiment was performed go beyond the region of applicability of the Landau theory (the L curve is drawn dashed in this case).

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[1]G. L. Bashindzagyan, V. P. Vasiliev, V. S. Murzin, L. I. Sarycheva, and N. B. Sinev, Acta Phys. Hung. **29**, sup. 4, 487 (1970).
[2]P. V. Ramana Murthy, Nucl. Instrum. Methods **63**, 77 (1968).
[3]Z. Dimchivski, J. Favier, T. Charpak, and G. Amato, Nucl. Instrum. Methods **94**, 151 (1971).
[4]V. S. Puchkov, Dissertatsiya, Fiz. Inst. Akad. Nauk, 1973.
[5]D. Jeanne, P. Lazeyras, I. Lehraus, R. Mathewson, W. Tejessy, and M. Aderholz, Nucl. Instrum. Methods **111**, 287 (1973).
[6]M. Aderholz, P. Lazeyras, I. Lahraus, R. Mathewson, and W. Tejessy, Nucl. Instrum. Methods **123**, 237 (1975).
[7]R. M. Sternheimer and R. F. Peierls, Phys. Rev. **3B**, 368 (1971).
[8]N. Bohr, Philos. Mag. **30**, 581 (1915).
[9]L. D. Landau, Sobranie trudov (Collected Works), Nauka **1**, 482 (1969).
[10]P. V. Vavilov, Zh. Eksp. Teor. Fiz. **32**, 920 (1957) [Sov. Phys.-JETP **5**, 749 (1957)].
[11]O. Blunck and S. Leisegang, Z. Phys. **128**, 500 (1950).
[12]O. Blunck and K. Westphal, Z. Phys. **130**, 641 (1951).
[13]M. I. Podgoretskiĭ, Tr. Fiz. Inst. Akad. Nauk SSSR **6**, 3 (1955).
[14]V. I. Belousov, A. M. Blik, and V. M. Kut'in, Preprint IFVE-73, **42**, Serpukhov, 1973.
[15]G. M. Garibyan and K. A. Ispiryan, Pis'ma Zh. Eksp. Teor. Fiz. **16**, 585 (1972) [JETP Lett. **16**, 413 (1972)].
[16]A. V. Alakoz, V. A. Chechin, L. P. Kotenko, G. I. Merzon, and V. S. Ermilova, Nucl. Instrum. Methods **124**, 41 (1975).

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