SCATTERING OF 1–5 Bev/c MUONS IN LEAD

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The scattering of 1 — 5 Bev/c muons in 2-cm thick lead plates was studied in a cloud chamber. The experimental results are in good agreement with the multiple scattering theory of Cooper and Rainwater, in which the finite size of the nucleus is taken into account.

1. INTRODUCTION

DURING the last eight to ten years many studies of high-energy muon scattering have been published. Interest was aroused by the fact that the great majority of these investigations indicated the existence of so-called anomalous scattering. Large-angle muon scattering exceeded the predictions of electromagnetic theory. The results of many papers on interactions between muons and various substances have been collected in reference 1. All data for high-energy ($p \geq 1$ Bev/c) muon scattering, with the exception of the new data,[1] point to the existence of anomalies.

In the present work we studied the scattering of muons with momenta ranging from 1 to 5 Bev/c in five 2-cm lead plates inside of a cloud chamber. The experimental angular distribution was compared with theoretical integral curves of multiple scattering by a point-charge nucleus (Molière's theory)[2] as well as with the theory of Cooper and Rainwater[3] for an extended nucleus. The experimental results are found to be in good agreement with the latter theory after plural and single scattering are excluded and the so-called noise effect (errors in angle measurements and track distortions) is taken into account.

2. EXPERIMENTAL TECHNIQUE

The principal units of our apparatus (Fig. 1) were a large SP-29 electromagnet, a GK-7 hodoscope system, and a cloud chamber.

Three sets of coordinated counters (1, 2, and 3), each consisting of two trays, were placed parallel to the field in the $100 \times 30 \times 14$ cm pole gap of the electromagnet. The counter diameter was 0.46 cm; the working region was 12 cm long. The counter cathodes were aluminum tubes with $\sim 150\,\mu$ walls. Each set comprised 83 coordinated counters.

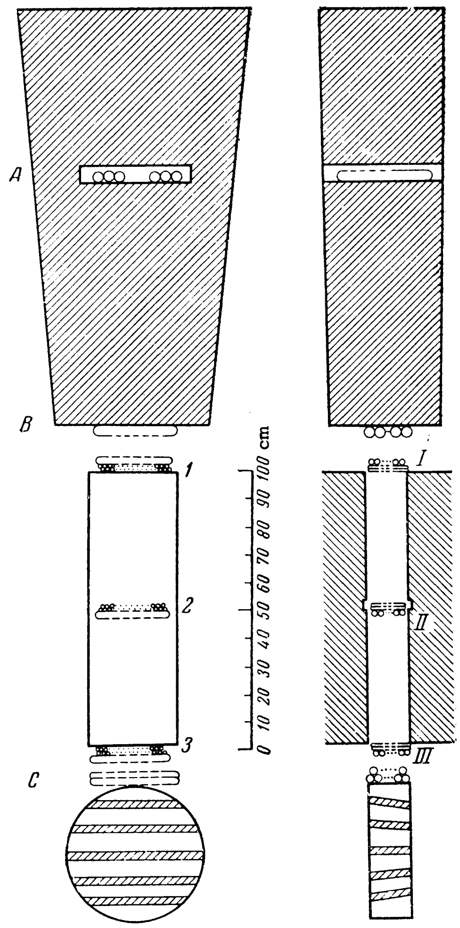

FIG. 1. Arrangement of apparatus (two views).

Aluminum counters with the dimensions 0.8×30 cm (trays I, II, and III containing 13 counters each) were placed directly above or below the coordinated counters and perpendicular to the latter. These counters, with $\sim 200\,\mu$ wall thickness, served to trace particle trajectories in a plane perpendicular to the field, as was required for the selection of the individual tracks whose momenta were to be determined.

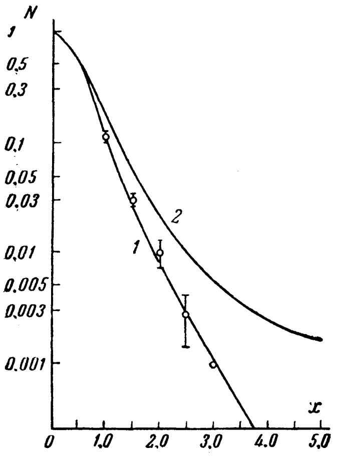

FIG. 2. Integral distribution in the dimensionless variable x. Ordinates represent the number of instances in which x is greater than the indicated value. Theoretical curves: 1 – representing theory of Cooper and Rainwater; 2 – representing theory of Molière.

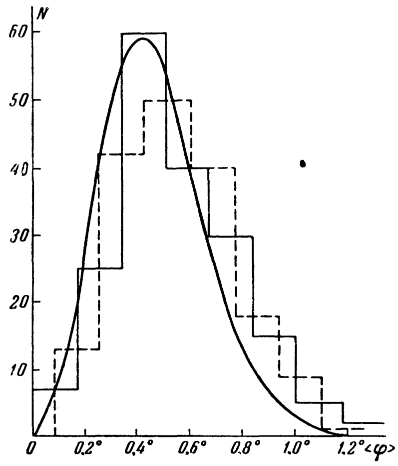

FIG. 3. Distribution of rms scattering angles on 200 tracks. The dashed and solid histograms were plotted for two groups of tracks selected at random. The theoretical curve was plotted for n = 3 and $\sigma_1 = 0.5°$.

Pulses produced by triple coincidences in counters A, B, and C were fed simultaneously to the hodoscope and to the cloud chamber control. The cloud chamber containing the five plates each 2 cm thick, was placed under the electromagnet gap. The chamber was side-illuminated by two pulsed lamps, and a mirror forming an angle of 45° with the bottom of the chamber was used in photographing. A 1700 g/cm^2 lead layer above the magnet gap excluded electrons, protons, and pions, thus permitting the registration of muons alone.

Momenta were determined from the conventional formula $pc = 300 H\rho$, where H is the magnetic field strength (10 000 oe in our experiment), and ρ is the track radius of curvature. Errors in measuring momenta of 1, 3, and 5 Bev/c were 2.5, 5, and 11%, respectively.

The photographed angles of scattering in the lead plates were measured with a UIM-21 microscope; the errors did not exceed 40′.

3. EXPERIMENTAL RESULTS AND DISCUSSION

We investigated 1134 muon scattering events in lead, with momenta in the range 1 — 5 Bev/c. Our results were compared with the integral curves for multiple Coulomb scattering by both point[2] and extended[3] nuclei. The data were compared with the theory of Cooper and Rainwater,[3] but not with Olbert's theory,[4] because the latter overestimates greatly the effect of an extended nucleus, whereas Cooper and Rainwater use a nuclear form factor based upon Hofstadter's well-known experiments[5] on fast electron scattering by nuclei.

The theory employs the variable

$$x = \varphi / \sqrt{B}\chi_c,$$

which is proportional to the product of the scattering angle by pv; $\sqrt{B}\,\chi_c$ is the characteristic angle in the theory of multiple Coulomb scattering. For a complete comparison of theory with experiment it is therefore desirable to determine experimentally the momentum of each scattered particle. In the great majority of experiments on muon scattering the momentum of each particle was not measured and multiple scattering curves were plotted for the momentum spectrum. Our data afford an advantage in this respect.

Our results are shown in Fig. 2. The experimental points represent 1134 muon traversals of a 2-cm lead plate. The theoretical curves represent integrals of the form $2\int_x^\infty f(\alpha)\,d\alpha$. The advantage of plotting scattering curves in the variable x lies in the fact that scattering data can be combined for different energies, different plate thicknesses, and even for different substances. Integral curves for particles with a momentum spectrum S(p) are customarily plotted according to the formula

$$\int_\varphi^\infty f(\varphi, p)\,d\varphi \int_{p_1}^{p_2} S(p)\,dp = (p_2 - p_1)\sqrt{B}\chi_c(p_0)\,S(p_0) \int_{x(p_0)}^\infty f(x)\,dx,$$

where p_2 and p_1 are the boundary values of the momenta, with $p_1 \le p_0 \le p_2$, where p_0 is the "average" momentum. Arushanov[6] has obtained different expressions in the form of series for the integral when f(x) is given by Molière's theory.

In treating the experimental results it is necessary to keep in mind the so-called noise effect, which has various causes. One particular cause can be distortion (such as that resulting from track diffusion or turbulent eddies associated with the operation of the cloud chamber), which leads to uncertainty of the scattering angle measurements. It is especially difficult to measure the projections of scattering angles in the first and last plates of the chamber, and we have not included the data obtained from these plates.

We have followed the procedure of McDiarmid[7] for the purpose of excluding plural and single scattering, which cause large scattering angles. We also followed McDiarmid in taking account of the noise effect. Figure 3 shows histograms of the rms scattering angle distribution for 200 tracks selected at random. Increased dispersion of the distribution as a result of the noise effect is associated with a diminishing true value of x:

$$x \to x\sqrt{1 + 2\sigma_1^2/B\chi_c^2},$$

where σ_1^2 is the variance of spurious scattering (noise), and n is the number of plates.

Figure 2 shows that our results are in good agreement, within the limits of experimental accuracy, with Cooper and Rainwater's theory, but that the experimental values lie below the Molière curve.

It should be noted that experiments with δ rays ejected by muons,[8] underground detection of muon pairs,[9] experiments with μ-mesic atoms,[10] and muon pair production by γ rays[11] all confirm the purely electromagnetic character of the muon-nucleon interaction.

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