SCATTERING OF MUONS WITH MOMENTA NEAR 100 Mev/c BY COPPER AND IRON

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A study was made of the scattering of μ mesons by copper plates (for momenta from 85 to 144 Mev/c) and by iron plates (for momenta from 81.2 to 135 Mev/c). The μ-meson angular distribution based on 2,350 scattering events agrees satisfactorily with the distribution for a point nucleus.

1. INTRODUCTION

IT has been reported in a number of papers on the scattering of μ mesons by nuclei that fewer scattering events occurred than had been expected for a Coulomb interaction between the μ mesons and the nuclei. The most complete review of data on μ-meson scattering has been written by Fowler and Wolfendale.[1] In the opinion of these authors there is no anomalous scattering in the low-energy region (below 600 Mev), and the excess reported in individual publications is due to experimental error. This opinion is supported by the results of three recent investigations conducted with slow μ mesons.

Kirillov-Ugryumov and Moskvichev[2] studied the scattering of μ mesons with momenta of 130 ± 16 Mev/c in beryllium plates 1 cm thick, located inside a Wilson chamber. For 2,250 events of μ-meson scattering not a single case was recorded where the scattering was into an angle greater than 6°. The experimental distributions were in good agreement with those computed according to the Moliere theory.

Using a magnetic mass spectrometer, Alikhanyan and Arutyunyan[3] measured μ-meson scattering in lead plates (t = 7 mm). The total μ-meson range was 19 m. Their experimental results were in agreement with the theory of the finite-size nucleus. Further, a negative result in regard to the existence of anomalous scattering was obtained by Chidley et al.,[4] who studied the scattering of 23-Mev μ mesons in a lead plate 0.56 mm thick located inside a propane bubble chamber.

Fukui, Kitamura, and Vataze (private communication) have not discovered any anomalous scattering of μ mesons in the high-energy region (about 1 Bev), even though this result is in conflict with other experimental data and with the theory developed by Fowler and Wolfendale.[1] Essentially these authors are in agreement with the Coulomb interaction theory only when the μ-meson trajectories are selected by recording μ-e decay.

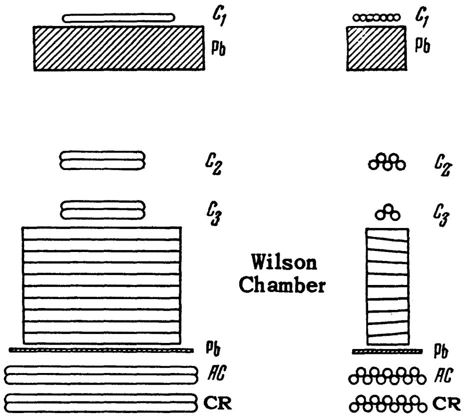

FIG. 1. Diagram of the setup.

In view of the importance of settling once and for all the question of the absence or presence of anomalous scattering, we measured the scattering of μ mesons with momenta from 81.2 to 144 Mev/c by copper and iron plates four millimeters thick. Although the nuclei of these elements contain comparatively large numbers of nucleons it is possible, if the energy and angular interval is properly selected for comparison with the experimental results, to apply the exact Moliere formula without resorting to approximate data on charge distribution in the nuclei.

2. DESCRIPTION OF THE EXPERIMENTAL SETUP

Measurements were made with the setup shown in Fig. 1. The large rectangular Wilson chamber,[5] 55 × 40 × 14 cm working volume, was triggered by a counter telescope, three rows of which (C_1, C_2, and C_3) were in coincidence while the last row, AC, was in anti-coincidence. In order to reduce the number of miscounts by the anti-coincidence row, a control row CR was connected to a duplicate anti-coincidence circuit. Use of this row reduced the miscounts in the circuit to 0.5%.

The complete unit was operated at sea level. A lead filter 15 cm thick was installed on top of the Wilson chamber to absorb the electronic component of cosmic rays. The μ mesons were scattered in nine plates 4 mm thick placed inside the Wilson chamber. These plates were of copper for one series of measurements and of iron for another. So that decay electrons from μ mesons stopped by the plates would not reach the anti-coincidence row, a lead filter 0.8 cm thick was placed under the chamber. Special precautions were taken to reduce track distortion in the Wilson chamber (temperature stabilization, use of high-speed spark valves). The chamber pictures were obtained by a stereoscopic camera with a 13.5 cm base from a distance of 115 cm. Optical distortion of the angular projections was thus kept to an undetectable minimum.

From the known quantity of material above the Wilson chamber, including the combined thickness of the overhead horizontal partitions of the building housing the apparatus, the rate of operation of the Wilson chamber was computed and this computed rate agreed well with the one observed during the experiment.

3. PARTICLE IDENTIFICATION AND MEASUREMENT OF μ-MESON MOMENTA AND SCATTERING ANGLES

The particles were visually identified by their ionization density and multiple scattering in the plates in the chamber.

The scattering and the ionization density gradient of the μ mesons tracks stopped by the plates in the chamber were appreciably different from those of electron and proton tracks. A calculation of the predicted number of stopped protons indicated that they should amount to less than 2% of the total number of recorded particles. The observed number of particles identified as protons was (1.5 ± 0.5)%. These particles were excluded from subsequent processing of the scattering data.

The number of stopped μ mesons and the associated decay electrons was in good agreement with the computed number, which took into account the ratio of positive to negative μ mesons, as well as the geometric configuration.

The method of identification used was not suitable for differentiating π from μ mesons. However, calculations applying to our experimental conditions indicated that the admixture of π mesons would amount to less than 1% of the μ mesons stopped.

It can be shown that such an admixture of π mesons introduces practically no change in the expected theoretical angular distribution of the scattered μ mesons. The mass of the particles which were identified as μ mesons was computed from their scattering and range and amounts to $(209 \pm 10)\ m_e$.

Because theoretical angular distributions for μ mesons differ substantially even for neighboring momentum values, accuracy in the measurement of momenta and angles is of great importance in scattering experiments. For this reason we used comparatively thin plates.

The residual range of the μ meson was used to measure its momentum. It was assumed that mesons are scattered and stopped in the middle of a plate. In computing the residual range, we took into account the deviation of the direction, at which the μ mesons entered the plate, from the vertical. For this purpose experimental distributions were plotted for the incident angle θ (from the vertical), the resultant rms values are as follows:

No. of plates from place of stoppage	1	2	3	4	5	6	7	8	9
$(\overline{\theta^2_{\exp}})^{1/2}$ in degrees	14.5	12.2	10.5	9	8.5	8	7.5	7	6

It can easily be shown that for non-vertical penetration the effective thickness of a plate exceeds its true thickness by $\sec(\overline{\theta^2_{\exp}})^{1/2}$.

Momentum errors caused by inaccuracy in the residual range due to the finite thickness of the plate, as well as by momentum variation within the plate itself, was computed and taken into account when the scattering curves were being constructed. Scattering was studied in the plates, starting with the second plate from the one where the meson was stopped rather than the first, since there would have been too great an error in the momentum measured in the first plate.

Scattering angles were measured in a projection on a plane parallel to the front galss of the chamber. This plane is not the same, in general, as the plane passing through the original direction taken by the particle for which the theoretical distribution of scattering angles is derived. However, thanks to the fact that the chamber was narrow (effective depth 9.5 cm) and high (40 cm), the original direction of a particle cannot be inclined more than 4° — 5° from the vertical. Hence, the difference between the projections of the angles on the two planes lies within the range of accuracy with which the angles were measured.

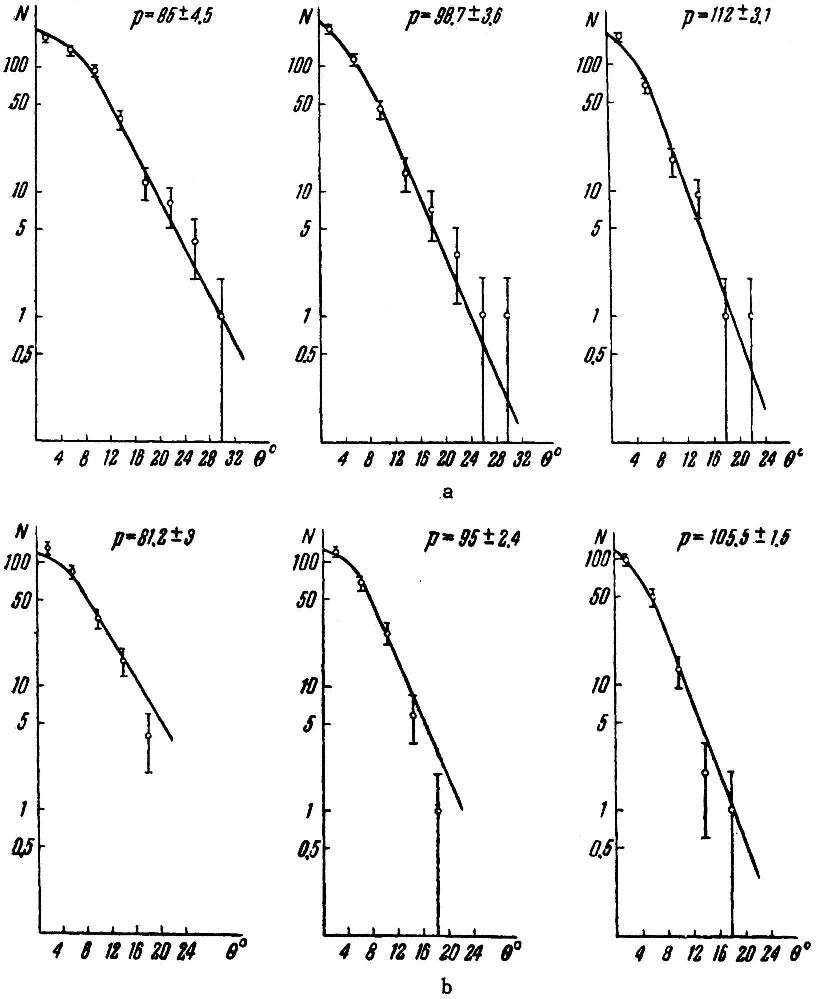

FIG. 2. Differential angular distribution for three momentum intervals: a – copper, b – iron; p is in Mev/c.

The scattering angles were measured repeatedly by several observers. The mean-square error did not exceed 30′.

The geometric dimensions of the detecting apparatus are essential in the measurement of the experimental angular distribution. As Cousins et al.[6] have shown, geometric corrections based on different probabilities for detecting the various angles can lead to incorrect deductions from the experimental data. In this investigation cognizance was taken of the geometric corrections, and they were incorporated in the experimental curves for the angular distribution. Computation of the geometric corrections (cf. Appendix) shows, however, that they have little effect on the form of the curves. This is due to the fact that the chamber is wide enough (55 cm) in relation to the rather narrow solid angle within which μ mesons enter the chamber. Then, too, the shallow depth of the chamber has no effect, since scattering in a plane perpendicular to the plane of photography necessitates no correction in the experimental angular distribution (this holds true for those cases where the angular distribution of scattering can be described as normal).

4. MEASUREMENT RESULTS AND THEIR INTERPRETATION

Two separate series of measurements were made, one with copper and one with iron plates. During the 3,600 hours of operation of the apparatus with copper plates, 475 records were obtained of μ mesons stopped inside the Wilson chamber, and these correspond to 1,460 scattering events with momenta greater than 75 Mev/c. When the iron plates were used, 890 scattering events were recorded.

Differential angular distributions were plotted individually for each group of μ mesons having the same momentum. These experimental data were compared with the theoretical curves computed by the Moliere formulae for a point nucleus. The Moliere theory is applicable to μ meson scattering by copper or iron plates 4 mm thick because the finite dimension of the nucleus begins to be effective only for angles greater than $\lambda\!\!\!^{-}/R$ ($\lambda\!\!\!^{-}$ is the μ meson wavelength and R is the radius of the nucleus). For our momenta this means angles $\sim 25° - 35°$. Comparison of the theoretical predictions of the point nucleus with the experimental

Observed and predicted total scattering events in copper for angles greater than the given angle

$\theta° >$	0	4	8	12	16	20	24	28
Experiment	1460	678	279	107	42	20	7	2
Theory	1460	705	275	97.6	37.6	15 65	7.55	2.95

data indicates a satisfactory agreement in every angular interval (see Fig. 2).

In addition, a total differential distribution was plotted as a function of dimensionless parameter

$$\varphi_0 = \theta_i / B^{1/2}\xi. \quad (1)$$

Here θ_i is the angle of scattering in radians, B is a slowly varying function of the thickness of the plate and the particle momentum and is equal to

$$B = 2G = 2\left[5.66 + 1.24 \lg \frac{Z^{4/3}A^{-1}t}{1.13\beta^2 + 3.76(z/137)^2}\right], \quad (2)$$

where β is the average velocity of the μ mesons in the momentum interval of interest (in our case $\beta = 0.6$, $G = 6.56$, and $B = 13.12$), and ξ is given by

$$\xi = 4\pi N e^4 t Z (Z+1) z^2 / (pV)^2; \quad (3)$$

where N is the number of atoms per cm^3, t the thickness of the plate in g/cm^2, Z the charge of the scattering nucleus, z the charge of the particle, p the momentum of the particle, and V its velocity.

Figure 3 shows the total angular distribution for copper and iron versus the dimensionless parameter φ_0. This distribution characterizes scattering over the entire momentum interval from 81.2 to 144 Mev/c.

Application of the χ^2 criterion showed that the experimental values were in good agreement with the theoretical distribution ($p_{\chi^2} = 0.4$). To compare the experimental and theoretical total distributions, values for the entire momentum interval from 85 to 144 Mev/c (in the case of scattering by copper) are listed in the table.

Thus, the analysis of the results of our work indicates satisfactory agreement between experimental and theoretical data in which only the Coulomb interaction between μ mesons and the nucleus is considered.

Earlier measurements of slow μ-meson scattering in copper were made by Alikhanyan and Kirillov-Ugryumov[7] with a magnetic mass spectrometer. It was found that the experimental and predicted distributions were in good agreement in the region of small angles, but for angles greater than 15 there was a small excess of recorded events (23 observed, 15.67 predicted). This discrepancy appears to have been due to the fact that the angle through which the μ mesons entered the Wilson chamber of the mass spectrometer was relatively large, and hence the application of the geometric correction may very well eliminate the discrepancy. For π mesons, the angle of incidence will vary less from the vertical than for μ mesons, and the geometric correction will be correspondingly less. Actually the theoretical and experimental data were found to be in better agreement for π mesons than for μ mesons.

Thus, as in other investigations,[2-4,7] the present investigation has not confirmed the existence of anomalous μ-meson scattering in the low-energy regions.

We take this opportunity to thank Prof. A. I. Alikhanyan for his unfailing interest and valuable comments, B. I. Luchkov for his great help with the investigation, and also to thank F. R. Arutyunyan and M. I. Ter-Mikaelyan, who participated in the analysis.

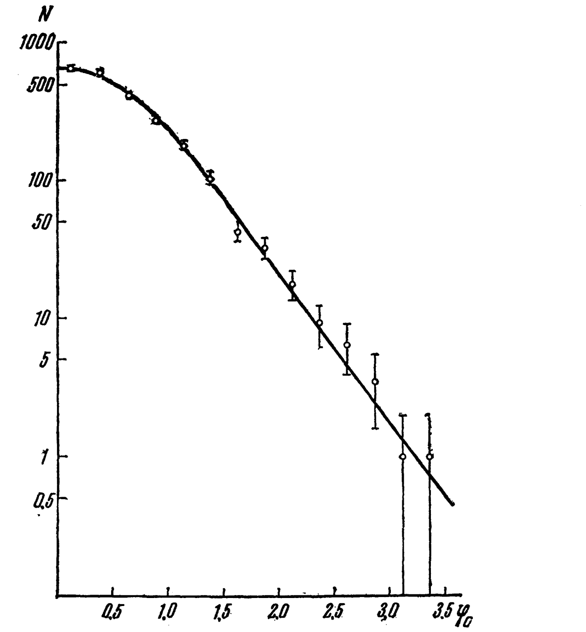

FIG. 3. The total differential distribution for copper and iron vs. the dimensionless parameter φ_0.

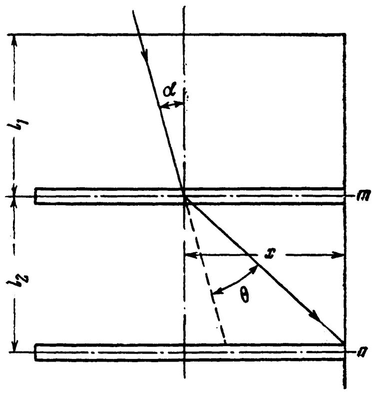

FIG. 4

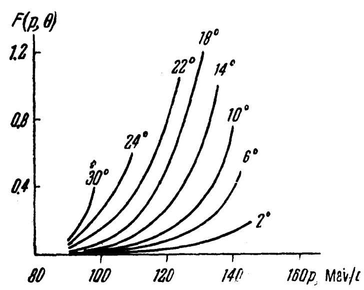

FIG. 6. The geometric correction curve for various angles θ as a function of the momentum of a μ meson at the scattering point.

APPENDIX

COMPUTING GEOMETRIC CORRECTIONS IN THE MEASUREMENT OF ANGLES

Let us consider a point x in plate m, where a μ meson is scattered and is subsequently stopped in plate n (see Fig. 4). Because of the finite dimensions of the telescope, mesons arrive at point x within a given angle of incidence α. If one neglects scattering in the plates in front of plate m, then the angular interval, α, is characterized by the diagram shown in Fig. 5. Since the apparatus is symmetrical, only half of the chamber is considered, i.e., 25.5 cm $\geq x \geq 0$.

Since the range of incidence angles for any x is sufficiently small ($\sim 10°$), the angular distribution of μ mesons within this interval can be considered isotropic. Then the area S in the diagram is proportional to the probability that a μ meson strikes the plate m.

If scattering occurs in plates in front of plate m, then the diagram should be "expanded" along both the x and θ axes. It can be shown with sufficient accuracy that scattering causes an expansion along

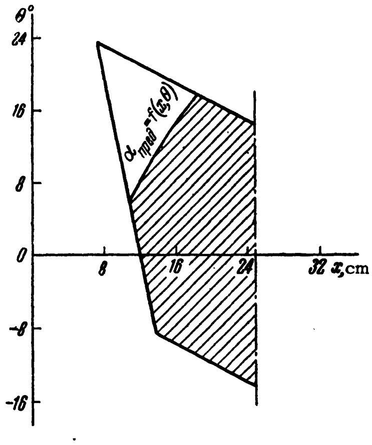

FIG. 5. Angular diagram.

the θ axis of an amount $\sigma_1 = 0.35\,\sigma$ and along the x axis of $l_1 \tan \sigma_1$, where σ is the mean-square angle for scattering a μ meson with a momentum equal to that of the μ meson stopped in plate n in a thickness t equal to the sum of all the plates before m, while l_1 is the distance from the top of the chamber to plate m.

A meson entering point x in plate m and having the right momentum to be stopped in plate n could be scattered out of the chamber either immediately in plate m or in plates between m and n. To allow for the μ mesons scattered out of the chamber because of both of these possibilities, we assume (in any case we shall overestimate the geometric correction) that scattering into the angle θ at point x in plate m is equivalent to scattering by n-m plates into an angle $\theta_1 = \theta\sqrt{n-m}$. Then the probability that a particle will remain in the chamber will depend on the maximum incidence angle, which is given by

$$x = l_2 \tan(\theta\sqrt{n-m} + \alpha_{max}).$$

The curve $\alpha_{max} = f(x, \theta)$ cuts off a section of the diagram proportional to the number of mesons scattered out of the chamber. Hence the probability for detecting a meson that has the right momentum to be stopped in plate n and is scattered by plate m into an angle θ will be equal to the ratio of the shaded area of the diagram to whole area S.

If the proportion of scattering events in plates m = 1, 2, ... 7 is known from the experimental angular distributions for a given momentum (i.e., for n − m = const), then F(p, θ) can be found, i.e., the correction can be made for the angle θ (see Fig. 6). Consequently, when plotting experimental angular distributions, one should use quantity

$$N = N_{exp}(p, \theta)\, F(p, \theta),$$

where $N_{exp}(p, \theta)$ is the measured number of scattering events for μ mesons with momentum p into the angle θ.

[1] G. N. Fowler and A. W. Wolfendale, Progress in Elementary Particle and Cosmic Ray Physics, Amsterdam (1958), pp. 123-153.

[2] V. G. Kirillov-Ugryumov and A. M. Moskvichev, J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 322 (1958), Soviet Phys. JETP **7**, 224 (1958).

[3] A. I. Alikhanyan and F. R. Arutyunyan, J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 32 (1959), Soviet Phys. **9**, 23 (1959).

[4] Chidley, Hinmann, Goldstein, Summers, and Adler, Can. J. Phys. **36**, 801 (1958).

[5] Kirillov-Ugryumov, Deryagin and Merzon, Приборы и техника эксперимента (Instruments and Meas. Engg.) **3**, 15 (1957).

[6] Cousins, Nash, and Pointon, Nuovo cimento **6**, 1113 (1957).

[7] A. I. Alikhanyan and V. G. Kirillov-Ugryumov, Izv. Akad. Nauk SSSR, ser. fiz. **19**, 737 (1955), Columbia Techn. Transl. p. 667.

Translated by A. Skumanich
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ERRATA TO VOLUME 9

Page	Reads	Should read
115, Col. 2, line 18 from top	R. Gatto and M. A. Ruderman, [Nuovo cimento 8, 775, (1958)]	T. Goto, Nuovo cimento 8, 625 (1958)
294, Col. 2, line 4 from bottom	$N = N_{exp}(p, \theta)\, F(p, \theta)$	$N = N_{exp}(p, \theta)\, 1 + F(p, \theta)$
462, Col. 1, line 8 from top	which are approximately 13Z ev	and approximately equal to 13Z ev
646, Col. 1, line 3 from top	$\langle j_1' t_1' \alpha \vert R^{J_2} \vert j_1 t_1 \alpha_1 \rangle$	$\langle j_1' t_1' \alpha \vert R^{J_1} \vert j_1 t_1 \alpha_1 \rangle$
661, Col 1, line 6 from top	$\lambda\!\!\!^{-} = 2.14 \times 10^{-13}$	$\lambda\!\!\!^{-} = 1.04 \times 10^{-13}$