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The Scattering of Mesotrons in Tungsten

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Measurements of the scattering of mesotrons have been made with a 30-cm counter-controlled cloud chamber in a 12,900-oersted magnetic field. The scattering block consisted of 3.8 cm of tungsten, and the lowest Geiger-Mueller counter was mounted directly over the center of the tungsten. Scattering angle and curvature measurements were made on 359 tracks. In addition, there were 92 high energy tracks with a deflection too small to be measurable. The scattering angles varied from 0 to 18.7°, and the mean energies $\bar{E}$ were nearly all less than 2×10^9 ev. The values of the product $\bar{E}\theta$ varied from zero to a maximum of 13.7×10^9 ev degrees. These results confirm Williams' prediction of a Gaussian distribution of multiple scattering. A number of cases of anomalous large-angle scattering were obtained, as contrasted with the single case of large-angle scattering observed by Wilson, establishing a departure at these angles from the Gaussian law. This further substantiates Williams' theory with reference to large-angle scattering caused by nuclear forces. The mean value of the multiple electrical scattering calculated from Wilson's equation is 2.2×10^9 ev degrees for this experimental arrangement, which compares with the experimental value of 2.14×10^9. This very satisfactory agreement supports Williams' assumption that the main force responsible for the Gaussian part of the scattering is that arising from the electric charges of the mesotron and of the nucleus.

Introduction

The scattering of cosmic-ray particles was first investigated by Anderson[1] in 1933. More extensive scattering measurements were later made by Blackett and Wilson,[2] who found their results to be in approximate agreement with the simple theory then available. The theory of scattering for very energetic particles was developed in 1939 by Williams,[3] who differentiated between the scattering caused by the Coulomb field of the nucleus and that arising from the short range interaction with the individual protons and neutrons of which the nucleus is composed. According to this theory, when the impact parameter is greater than r_0 (approximately the nuclear radius), the scattering occurs in the Coulomb field of the nucleus. Most of the scattering observed arises from this, and Williams assigned two limits for the extreme collision distances. An upper limit is determined by the shielding of the orbital electrons, and a lower limit r_0 by the modification of the electrostatic field within the nuclear radius.

Williams concluded that these Coulomb collisions result mainly in multiple scattering, and predicted that the distribution of the observed scattering angles should be Gaussian. These Coulomb collisions would normally also lead to a "tail" of large-angle single scattering, corresponding to close collisions which generally do not occur more than once per particle in the scattering plate. However, Williams showed that the effect of the lower limit of the impact parameter is to suppress this "tail" completely.

When the impact parameter is less than r_0, the incoming particle approaches closer to the center of the nucleus than the nuclear radius. Any scattering in this region is caused by the short range interaction between the incoming particle and the individual neutrons and protons in the nucleus. Williams showed that, for these short range collisions, the scattering in the Coulomb field of separate nuclear protons is negligible. Many more large-angle deflections are likely to be produced by the short range forces than arise from the multiple Coulomb scattering. In a further development of the theory, Wilson[4] has shown that a fairly sharp separation in angular range is to be expected between these two types of scattering, and has pointed out that the predicted absence of a single-scattering "tail" to the Gaussian curve for the multiple Coulomb scattering is particularly favorable to the detection of scattering caused by close collisions with nuclear particles.

The following experimental data are of interest

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[1] C. D. Anderson, Phys. Rev. **43**, 381 (1933).

[2] P. M. S. Blackett and J. G. Wilson, Proc. Roy. Soc. **A165**, 209 (1938).

[3] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

[4] J. G. Wilson, Proc. Roy. Soc. **A174**, 73 (1940).

in this connection. Vargus,[5] in 1939, using some of Anderson and Neddermeyer's photographs, investigated the angular distribution of cosmic-ray particles scattered in one centimeter of platinum. With 55 tracks of energies less than 5×10^8 ev, he obtained an approximate Gaussian distribution for the values of the product $\bar{E}\theta$, in which the energy in 10^9 ev is multiplied by the scattering angle in degrees. In Vargus' calculations β was assumed to be unity for cosmic-ray particles.

Wilson[4] summarized his previous results on particles traversing lead, copper and gold, along with new data on 2 cm of gold. From 185 carefully selected pictures of cosmic-ray tracks, he confirmed Williams' conclusion that the angular distribution caused by multiple scattering in the Coulomb field is Gaussian. He took an upper limit of energy at 2×10^9 ev, in order that the region for which earlier measurements indicated a possible anomaly might be excluded. For tracks passing through 2 cm of gold he showed that the exclusion of electrons is complete. For results with lead and copper plates he discarded tracks with energies less than 2×10^8 ev. Hence he concluded that the number of electrons remaining is negligible. Protons, however, are not excluded; but he says that the effect of a proton component of this magnitude (probably about 5 percent or less) is shown to be negligible for the number of tracks observed.

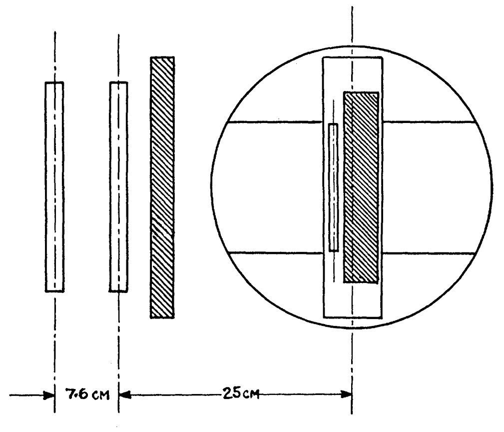

FIG. 1. Arrangement of counter-controlled cloud chamber showing the two large G-M counters and 1-inch lead bar above the chamber, and the small G-M counter and scattering block of $1\frac{1}{2}$-inch tungsten mounted in the horizontal box across the center of the chamber.

Regarding anomalous scattering, Wilson found only one particle out of the 185 measured tracks falling appreciably outside the Gaussian distribution for multiple scattering. This particle had an electron energy of 1.5×10^9 ev and a scattering angle of 4°. He considers this track to be a case of large-angle scattering.

EXPERIMENTAL ARRANGEMENT

In the present experiment the scattering block was 3.8 cm of tungsten. Because of its high density (19.06) and large thickness (equivalent in mass to 6.3 cm of lead) this block gives much larger scattering angles than the maximum (approximately 5°) previously recorded. Also the arrangement with the lowest Geiger-Mueller counter mounted directly above the tungsten in the center of the magnetic field removes any bias against recording emergent rays of low energy or with large scattering angle. Wilson pointed out[4] that the geometry of the counters and scattering block determines the efficiency with which large deflections are observed. The above conditions are favorable for detecting cases of anomalous large-angle scattering.

The apparatus used for this experiment consists mainly of the large electromagnet with oil-cooled windings and other accessory equipment as described by Jones and Hughes.[6] The magnet is similar in design to that used by Blackett.[7] The cloud chamber, which was 30 cm in diameter, was mounted with its back plate fixed to one polepiece of the magnet.

A new front plate was made of nonmagnetic stainless steel and to this was attached a brass box extending horizontally across the center of the chamber as shown in Fig. 1. This box was 6.35 cm high and 4.45 cm deep, and was open at the front so that the tungsten scattering block and small Geiger-Mueller counter could be inserted without dismantling the chamber. The six tungsten bars, each $8\times 1.25\times 0.25$ inches, were placed one above the other in the bottom of the box. Windows of $\frac{1}{2}$-inch plate glass were inserted in the front plate above and below the box, and through these the cosmic-ray tracks

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[5] J. A. Vargus, Jr., Phys. Rev. **56**, 480 (1939).

[6] Haydn Jones and Donald Hughes, Rev. Sci. Inst. **11**, 79 (1940).

[7] P. M. S. Blackett, Proc. Roy. Soc. **A154**, 564 (1936).

were photographed. To favor the production of showers, a 1-inch bar of lead was mounted just above the chamber.

The Geiger-Mueller counters were filled with petroleum ether. Two large counters, each electrically shielded in a copper box, were mounted vertically above the chamber. The third counter was shorter and of smaller diameter and was clipped in place inside the box directly over the center of the tungsten. The magnetic field strength was 12,900 oersteds, requiring a magnetizing current of 800 amp. at about 80 v. The small counter operated in the center of this magnetic field.

The curvature measurements were taken over a track length of 8 cm in nearly all cases. The same micrometer device was used for measuring the curvatures as described by Jones and Hughes.[6] The scattering angles were measured to 0.1°. Particular care was taken in the measurements for the cases where the scattering angle was unusually large.

The tracks were photographed on 35-mm ultra-speed panchromatic film with an *f*:2.8 lens of 5 cm focal length. The illumination was supplied by a water-cooled high pressure capillary mercury arc which ran continuously. A shutter admitted light to the chamber only at the time of expansion. The chamber was filled with argon and ethyl alcohol vapor to a pressure of 88 cm Hg.

Experimental Results

The results obtained from the scattering angle and curvature on 359 tracks are plotted in Fig. 2. In addition to these, there were 92 high energy tracks which had a curvature too small to be measurable with our apparatus. There were also many pictures in which the ray went out at the side, giving too short a track in the bottom to be measurable.

For each track the measurements of scattering angle and of curvature were recorded and averaged. The angle measured was the projection of the true scattering angle on the plane of the chamber. While the radius of curvature really measures momentum rather than energy, still it is convenient to express the momentum in terms of the energy an electron would have if its track curvature were the same as that of the particle.[8] This electron energy $E_e = 300\, H\rho$ was calculated for each track. The geometric mean value $\bar{E}$ of the energies measured in top and bottom of the chamber was then obtained, and the product $\bar{E}\theta$ calculated. Williams[3] shows that the product $\beta E_e \theta$ is a measure of the multiple scattering. In calculating the results β was assumed to be very nearly unity for cosmic-ray particles at these energies.

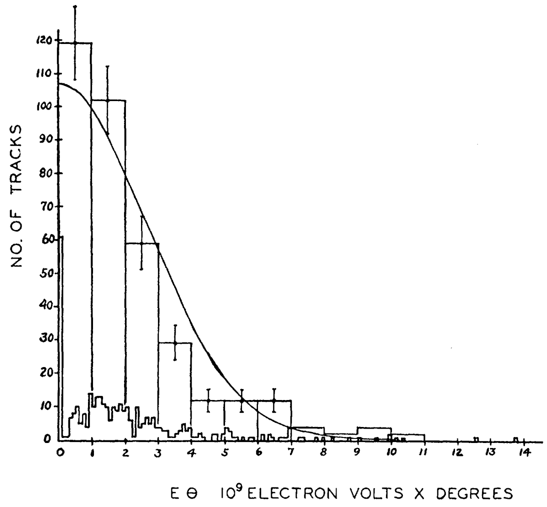

FIG. 2. The distribution of scattering for mesotrons showing expected theoretical Gaussian distribution for multiple scattering. The block diagram was drawn at intervals of 10^8 ev degrees with the number of tracks as ordinate for each group. Then the total number in each 10^9 interval was plotted vertically. The standard statistical errors are indicated.

The values of $\bar{E}\theta$ obtained from the data on these 359 tracks varied from zero to 13.7×10^9 ev degrees. Figure 2 shows a block diagram of the distribution of these values. They were plotted as abscissae at intervals of 10^8 ev degrees, with the number of tracks as the ordinate for each group.

The theoretical mean value of $\bar{E}\theta$ was calculated from the equation given by Wilson:[4]

$$\bar{\theta}_{\mathrm{th}} = (19.5 - 3.1 \log_{10} Z)^{\frac{1}{2}} 600 Z e (Nt)^{\frac{1}{2}} / \beta E,$$

where Z is the atomic number of the scattering material; t the thickness; and N is the number of atoms per cm³.

For 1 cm of lead Wilson obtains the numerical value of $(\theta_{\mathrm{th}} E_e \beta)_{\mathrm{Av}}$ as 0.90×10^9 ev degrees. In this experiment with 1.5 inches of tungsten, this

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[8] Cf. the system of units recently proposed by B. Rossi, Phys. Rev. 57, 660 (1940).

equation gives 2.2×10^9 as the mean value of the multiple electrical scattering. From the average of the values of $\bar{E}\theta$ obtained from the 359 measurable tracks, the experimental mean value of $\bar{E}\theta$ came out as 2.14×10^9. The very satisfactory agreement of this value with that predicted by Wilson's calculation supports the assumption that the main force responsible for the scattering is that arising from the electric charges of the mesotron and of the nucleus.

A theoretical Gaussian distribution having the same area as the statistical diagram was plotted for this mean value of $\bar{E}\theta$. The experimental values of $\bar{E}\theta$ less than 7×10^9 group themselves satisfactorily about this curve. The presence of a "tail" in the experimental curve, greater than the scattering calculated for large angles from the Gaussian curve, is caused by cases of anomalous large-angle scattering. The experimental results show 10 tracks having a value of $\bar{E}\theta$ greater than 8×10^9, whereas from the Gaussian law only 1.5 were to be expected.

The scattering angles were distributed over a range from zero to maximum of 18.7°. In Table I is given a list of tracks selected to include those with the largest scattering angles. The six tracks with the greatest scattering angles have relatively low energies, but five tracks with angles of 10° or over have energies too high to be measurable with our equipment. The track giving the largest value of $\bar{E}\theta$ (13.73×10^9) had an initial energy of 1.41×10^9 ev, and an emergent energy of 1.03×10^9 ev. The direction of its curvature indicated that this track was caused by a positively charged particle.

TABLE I. *A list of tracks selected to include those with large scattering angles.*

SCATTERING ANGLE (DEGREES)	CHARGE ON PARTICLE	MEAN $\bar{E}$ ENERGY ($\times10^9$ EV)	PRODUCT $\bar{E}\theta$ ($\times10^9$ EV DEGREES)
18.7	+	0.364	6.80
15.8	−	0.439	6.94
15.7	+	0.606	9.53
15.0	+	0.313	4.70
14.8	−	0.392	5.80
14.2	+	0.475	6.75
13.9	(curvature not measurable)		
13.1	−	0.755	9.90
12.9	+	0.972	12.55
12.8	−	0.565	7.23
12.1	+	1.21	13.73
12.1	+	0.836	10.11
11.5	−	0.55	6.34
11.35	+	0.774	8.79
11.2	(curvature not measurable)		
11.1	(curvature not measurable)		
11.0	−	0.472	5.20
10.8	+	0.48	5.16
10.8	−	0.377	4.07
10.7	+	0.394	4.22
10.4	−	0.33	3.42
10.4	(curvature not measurable)		
10.0	(curvature not measurable)		
9.6	+	0.83	7.97
9.2	+	1.12	10.30

Electrons can be taken as practically excluded from these measurements. They would have to penetrate the 1.5 inches of tungsten used as a scattering block without any evident shower production, and, in addition, the 1 inch bar of lead above the chamber, giving a total equivalent thickness of 9.5 cm of lead. Protons are not excluded, and Wilson suggests a probable proton component of about 5 percent or less. He points out that in this energy range protons would give rise to a component of scattering of appreciably larger mean angle than that of mesotrons. That protons do not form a large part of the particles here studied is, however, shown by the normal ratio of the number of negative to those of positive particles. Our results may be, therefore, taken as representing the scattering by mesotrons.

CONCLUSION

The results of these scattering measurements further confirm the prediction of Williams that the multiple scattering in the Coulomb field of the nucleus should have a Gaussian distribution. Thus these data confirm both the results obtained by Vargus, and also the more detailed analysis by Wilson.

Furthermore, these data present a sufficient number of additional cases of anomalous large-angle scattering to establish a departure from the Gaussian distribution. This further confirms the theory developed by Williams with reference to large-angle single scattering, for which Wilson's results supply only a single example.

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