The Differential Range Spectrum of Cosmic-Ray Mesons*

LAWRENCE GERMAIN†
Department of Physics, University of California Berkeley, California
(Received May 18, 1950)

A counter-controlled cloud chamber has been used to investigate the differential range spectrum of mesons at sea level. The chamber contains eight lead plates each $7\frac{1}{2}$ in. wide and one-half in. thick. A lead absorber of variable thickness, up to 27 in., may be placed above the chamber. The number of mesons observed the stop in the chamber per unit time has been found for various thicknesses of absorber above the chamber. A plot of the counting rate of particles which stop *versus* the thickness of absorber above the chamber reveals a broad low peak which has its maximum at a 6-in. thickness of absorber. The counting rate at the peak is 2.20×10^{-6} count/sec./sterad/g, about 10 percent higher than the counting rate with no absorber. Correction has been made for particles lost through scattering in the absorber. The corrected results show a more marked peak whose maximum occurs with a 9-in. thickness of absorber. The counting rate at the maximum of the corrected curve is 3.73×10^{-6} count/sec./sterad/g.

I. INTRODUCTION

It is well known that mesons found in cosmic rays have a large spread in energy and therefore a large spread in range. The number of mesons having a range greater than R, when given as a function of R, is called the integral range spectrum of the mesons, while the number of mesons having a range between R and $R+dR$ as a function of R is called the differential range spectrum. Rossi[1] has given both differential and integral range spectrum curves drawing upon the results of several workers.

The differential range spectrum can be measured either directly or indirectly. Indirect measurements can be obtained by differentiating integral spectrum data or by measuring the differential momentum spectrum and converting the momentum values to ranges by the use of range-momentum curves. The integral spectrum has been investigated by several authors.[2–9] The momentum spectrum has been found by Wilson,[10] Jones,[11] and Blackett and Brode.[12]

There are two methods for measuring the differential range spectrum directly. Both involve a counter telescope to define the incoming particles with absorber of variable thickness in or above the counter telescope and an absorber below the telescope in which the mesons are to be stopped. In the delayed coincidence method the number of delayed coincidences between counters placed around the lower absorber with the counters in the counter telescope is measured. The number of mesons which stopped can be found from the number of decay electrons thus observed. If an element of large Z is used as the absorber this method will detect only positive mesons. The anticoincidence method consists of a measurement of the number of anticoincidences between the counter telescope and counters placed below the lower absorber. This tells the number of particles which enter the lower absorber but which fail to penetrate it. Delayed coincidence measurements have been made by Sands[9] and Shamos and Levy.[13] Some data have been obtained by Koenig[14] using the anticoincidence method. Later and more extensive data have been obtained by Rogozinski and Lesage,[15] Kellerman and Westerman,[16] Kraushaar,[17] and Sands.[9]

Each of these two methods has disadvantages. The The energy spectrum of the decay electrons is not well known, and it is difficult to correct for the number of decay electrons which do not reach the delay coincidence counters. Thus it is difficult to obtain absolute values for the values of the differential range spectrum with this method, but relative values can be found easily. While the anticoincidence method tells the number of particles which do not penetrate the lower absorber, it says nothing about their natures and there is no way to tell the mesons from the electrons or protons with small absorber thicknesses.

The present experiment was a measurement of the differential range spectrum at sea level using the anticoincidence method. The nature of the particle was determined with the aid of a cloud chamber. The absorber in which the particles were to stop took the form of several lead plates in a cloud chamber. The nature of the track of the stopped particle determined whether it was an electron, proton, or meson. Thus the difficulty cited above has been circumvented.

* Assisted by the joint program of the ONR and AEC.
† Now at Reed College, Portland, Oregon.
[1] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).
[2] A. Emhart, Zeits. f. Physik **106**, 751 (1937).
[3] V. C. Wilson, Phys. Rev. **53**, 337 (1938).
[4] Nielsen, Reyerson, Nordheim, and Morgan, Phys. Rev. **59**, 547 (1941).
[5] Rossi, Hillsberry, and Hoag, Phys. Rev. **57**, 461 (1940).
[6] Bernardini, Cocciapuoti, Ferretti, Piccioni, and Wick, Phys. Rev. **58**, 1017 (1940).
[7] D. B. Hall, Phys. Rev. **66**, 321 (1944).
[8] Carr, Schein, and Barbour, Phys. Rev. **73**, 1419 (1948).
[9] Matthew Sands. Phys. Rev. **77**, 180 (1950).
[10] J. G. Wilson, Nature **158**, 415 (1946).
[11] H. Jones, Rev. Mod. Phys. **11**, 235 (1939).
[12] P. M. S. Blackett and R. B. Brode, Proc. Roy. Soc. **A154**, 573 (1936).
[13] M. H. Shamos and M. G. Levy, Phys. Rev. **73**, 1396 (1948).
[14] H. P. Koenig, Phys. Rev. **69**, 590 (1946).
[15] A. Rogozinski and M. Lesage, Comptes Rendus **227**, 1027 (1948).
[16] E. W. Kellerman and K. Westerman, Proc. Phys. Soc., Lond. **A62**, 356 (1949).
[17] W. L. Kraushaar, Phys. Rev. **76**, 1045 (1949).

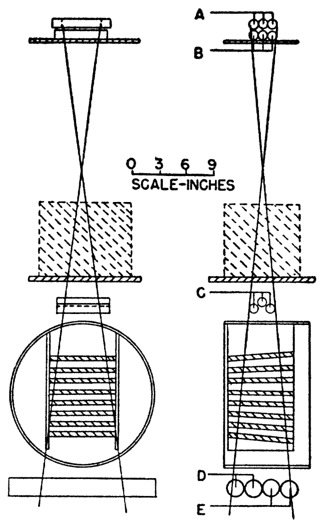

FIG. 1. Apparatus for observation of meson range spectrum.

This work was undertaken with two results in mind. In the first place, there are no extensive direct measurements of the differential range spectrum over a large spread of ranges. In the second place, it is desirable to perform experiments dealing with slow mesons or mesons that stop in such a manner that the total range of the mesons in the apparatus corresponds to a maximum value of the differential range spectrum, for in this case the rate of gathering data will be a maximum. Thus it is of interest to see whether a considerable peak is to be found in the differential range spectrum, as would be expected from an examination of the momentum spectrum.

II. APPARATUS

The apparatus is shown schematically in Fig. 1. The cloud chamber was 41.5 cm in diameter and had an illuminated region 12.7 cm deep. The eight lead plates were each 19 cm wide and 1.32 cm thick. The cloud chamber was tripped by every (A, B, C—D, E) event. Stereoscopic pictures of each expansion were taken.

It was found that it was not possible to identify the particles which stopped in the top plate in the chamber. Furthermore, identification of the particles stopping in the second plate was not reliable. Therefore only six of the plates in the chamber were used for the observation of stopped particles. Since this amounted to about three inches of lead, lead was added above the chamber in three inch intervals from zero up to 27 inches. However, no measurements were made with 18 or 24 inches of lead above the chamber. There were certain other absorbers which were in the solid angle at all times: roof, cloud chamber walls, Geiger counter walls, and stands supporting the absorber and counters. These absorbers were equivalent to 17.3 g/cm² of lead. No correction need be made for the fact that particles travelling at an angle to the vertical penetrate more absorber than vertical particles because the counter dimensions are small compared with their separation.

III. RESULTS

The results are given in Table I and are shown in the form of a histogram in Fig. 2. The errors given are probable errors based on the number of counts. The conversion from g/cm² of lead to g/cm² of air was made with the aid of range-momentum curves given by Rossi and Greisen.[18]

A glance at the histogram shows that the measured peak in the differential range spectrum is very low. The counting rate at the peak is only about 10 percent greater than the counting rate with no lead above the chamber. This in itself shows that placing lead above a chamber will not greatly increase the number of mesons stopping in the chamber. This means that experiments which deal with slow mesons cannot be speeded up by placing an absorber above the apparatus.

IV. CORRECTIONS

While the experimental results give the number of mesons stopping in the chamber, they do not accurately represent the true differential range spectrum of the mesons in the solid angle defined by the apparatus, since some particles which should be counted are lost from the apparatus because of scattering. Mesons that are going to stop in the chamber must have a relatively low energy when passing through the absorber above the chamber. Particles of low energy are severely scattered in the absorber. There are two ways in which this scattering may cause particles to be lost to the apparatus. In the first place, many of the particles emerging from counter C will no longer be going to the right direction to hit the plates in the cloud chamber. In the second place, some particles which have passed through counter B and are travelling in such a direction that they should hit counter C will be scattered away from counter C. This effect is largely compensated by particles which are scattered in such a direction that they hit counter C when they would not have done so if there were no scattering. However, the net effect is a loss of particles. Calculations of both of these corrections have been made. The first of these two corrections is by far the larger, and will be considered first.

TABLE I. Experimental results.

Thickness of lead absorber above chamber (inches)	Stopped particles	Minutes	Counts/min. ($\times 10^{-3}$)	Counts/sec./cm²/sterad/g/cm² of air ($\times 10^{-6}$)
0	64	11,589	5.52±0.47	2.02±0.20
3	64	11,360	5.63±0.48	2.06±0.20
6	72	11,995	6.00±0.48	2.20±0.21
9	70	12,185	5.74±0.46	2.10±0.20
12	70	13,391	5.23±0.42	1.91±0.18
15	53	12,214	4.34±0.40	1.59±0.17
21	50	14,285	3.50±0.33	1.28±0.14
27	51	25,919	1.97±0.18	0.72±0.08

[18] B. Rossi and K. Greisen, Rev. Mod. Phys. 13, 240 (1941).

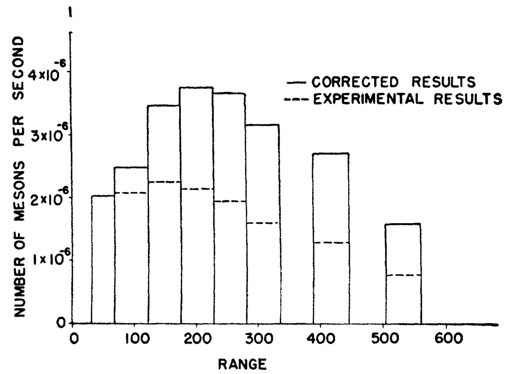

FIG. 2. Corrected and uncorrected observations of the differential range spectrum of mesons at sea level. The range is measured in grams per square centimeter of air.

Rossi and Greisen[18] have derived a formula for the mean square scattering angle, considering energy losses in the absorber. Assuming that the scattering angles are distributed according to a Gaussian distribution with the mean square given by the Rossi and Greisen formula, one can calculate the fraction of the particles with such an energy that they should stop in a given plate and which would be travelling at such an angle that they get to the plate. These values were calculated for each plate in the chamber and then averaged to give the fraction of the mesons received with various thickness of absorber. The results are as follows:

t (inches)	3	6	9	12	15	21	27
f (percent)	83.9	63.9	56.8	53.3	51.5	49.7	49.0

The corrections are seen to be large. About one-half of the desired mesons are lost to the apparatus when large thicknesses of absorber are used.

The second correction has been worked out in a two-dimensional case assuming a uniform distribution of the scattered particles from the vertical to the maximum allowable angle, rather than a Gaussian one. Since the correction is a small one, these assumptions have little effect when both corrections are considered. The percent loss of mesons depends on the fractional loss of momentum, λ. The loss is proportional to

$$\{\lambda+(1-\lambda)[\lambda+2\ln(1-\lambda)]\}\cdot 1/\lambda^3.$$

This relation between the percentage loss and the fraction of momentum lost was derived by Foldy[19] and put in the form used here by Wouthuysen.[20] The calculation of the percentage lost involves also the distance between the counters of the telescope and the mean square displacement due to scattering in the absorber. The results of this correction, averaged over all of the plates in the chamber and given as the percentage of the particles scattered away from the lower counter, are given below for each thickness of absorber used. The top line gives the various absorber thicknesses, while the bottom line gives the percentage of particles lost.

3	6	9	12	15	21	27 (inches)
0.08	0.36	0.82	1.44	2.12	3.62	5.85

The corrected results are shown in Table II and Fig. 2. The results of this experiment give somewhat lower rates but a more marked peak than the curve given by Rossi.[1] For a range of between 100 and 200 g/cm² of air, Rossi gives a meson flux of about 5.5×10^{-6} mesons/sec./sterad/cm²/g/cm² of air. The present experiment yields a value of about 3.5×10^{-6}. It is of interest to compare these values with other recent results on mesons in this same range interval. Sands[9] has obtained 5.5×10^{-6} using the coincidence method. However, using the anticoincidence and delayed coincidence methods, he found a value of 3.1×10^{-6}. Koenig[14] found a meson flux of 3.7×10^{-6} by the anticoincidence method, and Steinberger[21] obtained 4.36×10^{-6} using the delayed coincidence method. The anticoincidence experiments of Kellerman and Westerman[11] when reduced to the above units yield a result of the order of 2×10^{-6}. Kraushaar[17] has found the meson flux to be 5.5×10^{-6}. While Kraushaar used the anticoincidence method, he did not find the meson flux directly from the anticoincidence counting rates but found the fraction of the particles which stop in an absorber. The absolute number of particles stopping can then be found from the value of the integral spectrum at that range. Thus it appears that meson flux measurements made employing the coincidence method yield larger results than measurements using the other methods. It is true that the coincidence method is by far the simplest, and therefore one would place more faith in results obtained by that method. However, the possibility exists that the coincidence method detects some particles which are not mesons and therefore gives a value which is somewhat high. Merkle[22] has found about equal numbers of protons and mesons in the energy region below 300 Mev. If, as this result indicates, the proton flux at sea level is greater than had

TABLE II. Corrected results

Thickness of lead absorber above chamber (inches)	Total range of particles stopped in the chamber (g/cm² of air)	Counting rate counts/sec./cm²/sterad/g/cm² of air
0	27 to 80	2.02×10^{-6}
3	69 to 125	2.46×10^{-6}
6	123 to 179	3.45×10^{-6}
9	171 to 232	3.73×10^{-6}
12	230 to 286	3.64×10^{-6}
15	284 to 340	3.15×10^{-6}
21	394 to 450	2.67×10^{-6}
27	504 to 560	1.56×10^{-6}

[19] L. L. Foldy, Phys. Rev. **75**, 311 (1949).
[20] S. Wouthuysen, private communication.
[21] J. Steinberger, Phys. Rev. **75**, 1137 (1949).
[22] T. C. Merkle, private communication.

been thought, the results of the coincidence method would be expected to be too large. However, very few protons were identified in the photographs obtained in the present experiment.

The author is indebted to William B. Fretter who suggested and directed this research and to Professor Robert B. Brode whose interest and helpfulness greatly facilitated the work.

PHYSICAL REVIEW VOLUME 80, NUMBER 4 NOVEMBER 15, 1950

Latitude and Altitude Dependence of the Local Hard Showers of Cosmic Rays*

T. G. WALSH† AND O. PICCIONI
Brookhaven National Laboratory, Upton, Long Island, New York

(Received July 17, 1950)

The latitude effect of the local hard showers penetrating at least 350 g/cm^2 of lead has been measured at two airplane altitudes, and found to be (12±2) percent between Rome, New York, and Canal Zone.

The two separate latitude effects, obtained respectively at 30,500 ft. (300 g/cm^2) and at 25,000 ft. (383 g/cm^2) coincide within the experimental errors. This slow dependence on altitude of the latitude effect seems to allow an estimate of the energy of the hard shower producing particles as they arrive at the apparatus. An average energy of 20 to 30 Bev is obtained from the present data and the current ideas on the absorption of the nucleonic component. This large value is discussed in connection with other experiments and in view of the fact that at sea level or at mountain altitudes pi-mesons of that energy have a large probability of undergoing a nuclear collision before decaying into mu-mesons.

The measured altitude dependence of hard showers gives for the absorption mean free path of the producing radiation in air, the value of 112±2 g/cm^2, if interpreted in terms of a simple exponential. However, because of the geometry of the apparatus, the value 140 g/cm^2, as obtained from the data according to the Gross transform, seems to be more acceptable when referred to strictly vertical particles.

The latitude effect of the normal penetrating component was 1.33 at 30,500 ft., 1.24 at 25,000 ft., and 1.08 at sea level.

I. INTRODUCTION

LOCAL hard showers (*HS*) have been the object of several investigations[1] and their connection with the nucleonic component of the cosmic rays is now fairly well established. The present research leads to an estimate of the energy of the hard shower producing particles which are mainly protons and neutrons, at least when the observations are performed at airplane altitudes. We have obtained such an energy estimate by measuring the latitude dependence of the rate of occurrence of *HS* at two altitudes, 30,500 ft. (300 g/cm^2) and 25 000 ft. (383 g/cm^2).

Previous information on this subject was available before we performed our experiment. Appapillai and Mailvaganam[2] reproduced the apparatus of Broadbent and Jánossy[1] at the latitude 4°S and did not find large latitude effect at sea level. However, in general, the energies of the secondary nucleons which actually produce a *HS* are smaller than the energies of their primaries. Therefore, any estimate of the energy of the secondary particles based on latitude effect is the more reliable the smaller the depth of the atmosphere at which the experiment is performed. For this reason the present measurements were taken aboard a B-29 aircraft. Also, the apparatus (Fig. 1) was designed so that it would detect particles of lower energy than that of Appapillai and Mailvaganam. In order to obtain a measurable effect we used a relatively small thickness of absorbing material and disposed the counters in such a geometry that even a *HS* of two particles could give a registered count. Both of these features help to make the rate of registered *HS* large enough to obtain good statistical accuracy. Yet, in spite of the simple geometry, the fraction of *HS* produced by mu-mesons was, as we shall show later, as small as two percent at airplane altitudes. Like other experimenters, we believe that these spurious *HS* are produced by mu-mesons by means of knock-on electrons or by electromagnetic radiation, and that their contribution to the *HS* intensity is the greater the less severe we make the requirements for *HS* detection.

II. THE APPARATUS

As may be seen from Fig. 1, our disposition of counters is somewhat similar to that used by Tinlot,[1] but our geometry is not expected to favor vertical particles as was the case with Tinlot's geometry. Therefore, the *HS* dependence on altitude obtained by

* The present research has been carried out under the auspices of the AEC.

† Work performed in partial fulfillment of the requirements of Fordham University for the Degree of Doctor of Philosophy.

[1] We quote only a few papers in which references are made that will allow the collection of a complete bibliography: Wataghin, de Souza Santos, and Pompeia, Phys. Rev. **57**, 61 (1940). L. Jánossy and P. Ingleby, Nature **145**, 511 (1940). D. Broadbent and L. Jánossy, Proc. Roy. Soc. **A190**, 497 (1947). W. B. Fretter, Phys. Rev. **73**, 41 (1948). Rochester, Butler, Mitza, and Rosser, Rev. Mod. Phys. **21**, 20 (1949). J. Tinlot, Phys. Rev. **74**, 1197 (1948). O. Piccioni, Phys. Rev. **77**, 1 (1950).

[2] V. Appapillai and A. W. Mailvaganam, Nature **162**, 887 (1948).