2000 meters elevation, going about as $\cos^8\theta$. Deutschmann[17] also observed about the same zenith-angle dependence as Daudin. Williams[18] observed a very steep distribution at 3050 meters. Only 2 showers out of a total of 100 had projected zenith angles greater than 30 degrees. In the showers we observed, 36 out of 166 had projected zenith angles greater than 30 degrees. Some of this disagreement may be attributed to the different methods of shower selection that were used in the two experiments.

V. Cocconi Tongiorgi[10] has concluded from counter studies of the moderate energy (3–15 Mev) neutrons associated with air showers that there should be a fast nucleonic component of air showers with an intensity of the order of magnitude of 2 to 3 percent of the intensity of the electronic component of the showers (i.e. about double the intensity of ionizing penetrating particles in the showers). We have fairly reliable direct evidence that a high energy neutron component can exist in air showers in numbers roughly 0.5 percent of the intensity of the electronic component when the cores are mostly from 4 to 24 meters from the place of observation. Both of these estimates assume a mean free path of 300 g/cm² for nuclear interaction of nucleons in lead. Our results indicate that there are more high energy neutral particles than energetic highly interacting ionizing particles associated with air showers.

The authors wish to thank Professors K. Greisen and G. Cocconi for suggesting this experiment and for their generous help both in solving experimental problems and in discussions of the results. They are grateful to the Research Corporation for a grant which covered the expense of performing this experiment. The cost of constructing the apparatus was provided through an ONR contract. The facilities of the Inter-University High Altitude Laboratories were of great help in performing the experiment.

[17] M. Deutschmann, Zeits. f. Naturforschung **2**, 61 (1947).
[18] R. W. Williams, Phys. Rev. **74**, 1689 (1948).

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Cosmic-Ray Mesons near Sea Level

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The differential and integral intensities of mesons have been studied using delayed coincidence, anti-coincidence, and coincidence methods. It is shown that the differential range spectrum of slow mesons is nearly flat out to 100 g cm^{-2} of air-equivalent at sea level and at Echo Lake (3240 meters). The zenith angle distribution of slow mesons has been measured, and can be expressed by $\cos^{3.3}\theta$ at Ithaca and $\cos^{3.1}\theta$ at Echo Lake. Three independent measurements of the differential intensity of mesons lead to a value of $(6.0\pm0.15)\times10^{-6}$ sterad^{-1} g^{-1} sec.$^{-1}$ at a range of 105 g cm^{-2} of air-equivalent at Ithaca, New York (260 meters). The sea level electron intensity is considered, and it is concluded that this intensity is consistent with the electron-2 neutrino decay scheme for the μ-meson provided there is a source in addition to mesons contributing electrons with a very steep zenith angle distribution.

I. INTRODUCTION

THE present measurements were undertaken originally as part of an attempt to evaluate accurately the sea level electron intensity. As is well known, meson decay and collision processes are responsible for a large fraction of the sea level electron component. Other sources of electrons (meson radiation, nuclear interactions, proton collision processes, etc.) contribute the remainder. The subject has been discussed frequently.[1–3] Reliable methods have been developed for calculating the intensity of electrons that should arise from the decay and collision processes of mesons. On the other hand, the experimental determination of the electron intensity is beset by troublesome complicating factors. Low energy electrons predominate and as a result the apparent electron intensity is a very sensitive function of the geometric details of the detecting apparatus.

One procedure has been to measure the total ionizing cosmic-ray intensity, and to subtract from this quantity the meson intensity. In this connection, the slow meson intensity and zenith angle distribution have been uncertain, and indirect methods have been used to evaluate that portion of the soft component due to these slow mesons.

Frequently, wide discrepancies have been reported between the observed and predicted intensities. At the time this investigation was started, it was believed that the decay products of a meson at rest were a neutrino and a 50-Mev electron. Under this assumption, it was

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[1] Bernardini, Cacciapuoti, and Querzoli, Phys. Rev. **73**, 328, 335 (1948).
[2] K. Greisen, Phys. Rev. **63**, 326 (1943).
[3] B. Rossi, Rev. Mod. Phys. **21**, 104 (1949).

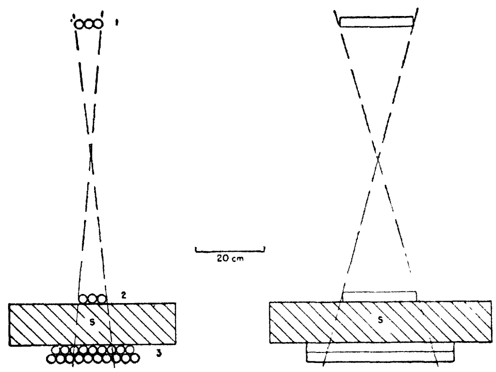

FIG. 1. Telescope geometry for experiment I: Absolute vertical intensity of mesons having a range greater than 80 g cm^{-2} of air equivalent.

difficult to understand the frequent result that there were *fewer* electrons than should arise from meson processes alone. Further, the zenith angle and altitude dependence of electrons near sea level is stronger than that of the mesons, implying that there are additional sources contributing significantly to the sea level electron intensity. It therefore seemed desirable to reexamine the problem. Mr. E. D. Palmatier of Cornell has made a careful measurement of the total cosmic-ray intensity using thin-wall aluminum Geiger counters. These results will be reported by him in a later paper. The present measurements bearing on this subject have been concerned largely with the slow meson intensity. The method of delayed coincidences has been used to study the shape of the low energy end of the meson spectrum, and the zenith angle distribution of these slow mesons. Because of the complicated geometry and uncertainty in the range of the decay electron, it was not possible to obtain accurate absolute intensities from this experiment alone. The measurements were therefore normalized to coincidence and anti-coincidence measurements of the differential intensity. Different experimenters have found widely varying values for the differential intensity of mesons, and it is believed that most of the difficulty has been due to scattering. Particular attention has been focused on this source of error, and the results of three independent measurements are shown to be in agreement.

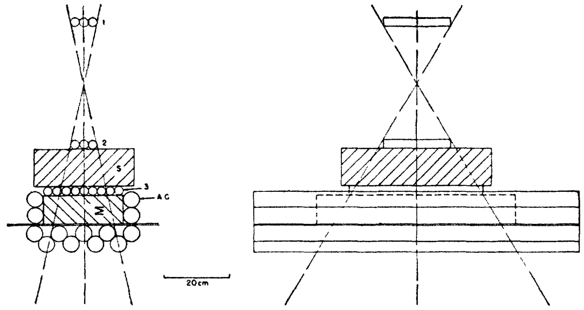

FIG. 2. Telescope geometry for experiment II: Anti-coincidence measurement of the number of mesons in a given range interval.

These experiments complete those intended to aid in evaluating the sea level electron component. Other experiments designed to study certain aspects of the meson component as such were performed at Echo Lake, Colorado. At this altitude (3240 meters) the differential range spectrum and zenith angle distribution of slow mesons have been measured. Some of our data have permitted a rough estimate of the slow proton intensity.

Finally, a short discussion has been devoted to a reevaluation of the sea level electron intensity, using the slow meson information as obtained from these experiments and the total cosmic-ray intensity as measured by Greisen.[2]

II. DESCRIPTION OF EXPERIMENTAL EQUIPMENT AND PRESENTATION OF RESULTS

Several different counter geometries were used in the course of the experiments to be described. Common to all was the use of all-metal Geiger counters of the self-quenching variety with brass walls 0.5 or 0.6 mm thick. The pertinent dimensions are evident from the figures.

The errors reported are standard statistical errors. Where experimental conditions have permitted, the data have been taken so that lack of internal consistency would be evident. In the measurement of the shape of the low energy end of the meson spectrum, and the zenith angle dependence of slow mesons, for instance, the measurements were interlapped, running under one condition for about two days at a time, where the total running time for a given condition was 10 or 12 days. The internal consistency was satisfactory in all cases except one, which will be pointed out.

The integrated intensities J that are reported refer to the number of particles crossing a sphere of unit cross-sectional area.

A. Experiment I. Absolute Vertical Intensity of Mesons Having a Range Greater Than 80 g cm^{-2} of Air-Equivalent

The telescope geometry in which threefold coincidences were recorded is shown in Fig. 1. It is to be noticed that the telescope differs from the usual cosmic ray telescope in that there is no absorbing material between the counters which define the solid angle. This has a twofold purpose. In the first place, the presence of a dense material near a counter has the effect of increasing the effective area of the counter, in that some 7 percent of the mesons emerging from thick layers of a dense material, such as lead, are accompanied by electrons of energy greater than 2 Mev. Hence an incident meson not in the solid angle defined by the telescope may cause a count to be recorded through the effect of its knock-on electrons, and the absolute rate tends to be over estimated. Secondly, in a material of high atomic number, the scattering even of reasonably fast mesons is a large effect. If lead is between the counters of a telescope, the effective solid angle is in general distorted in a complicated way. Some of the mesons originally in the solid angle are scattered out, while some originally out of the solid angle are scattered in. In the special case of a most simple telescope, one counter tray above and one below the lead, this effect can be shown to cancel in very good approximation. In more complicated geometries, involving three or more separated counters, this cancellation is destroyed.

The third coincidence tray was covered with lead in such a way that the recording of threefold coincidences due to incident electron showers should be very rare.

In an experiment such as this where there is a tray containing a large number of counters there is always an uncertainty about the efficiency of the tray. This is especially serious when the counters are connected in parallel since then the pulse heights are reduced by the extra capacity introduced by the other counters in the tray, and further, the voltage on the other counters is reduced when one or more counters are discharged. A clamp circuit was therefore devised that prevented coincidences from being recorded for a 400-microsecond interval following any detectable pulse from tray 3. In this way a larger inefficiency has been introduced, but it can be evaluated with an accuracy limited only by how well the length of the 400-microsecond interval and pulse rate from the tray in question can be measured.

The threefold coincidence rate, corrected only for the intentionally introduced inefficiency of tray 3 (0.74 percent), was 1.865 ± 0.010 min.$^{-1}$. The geometric factors for converting this rate to units of absolute intensity have been obtained from expressions deduced by Greisen,[4] and our result for the absolute vertical intensity is $I_v(R)=(0.880\pm0.005)\times10^{-2}$ cm^{-2} sterad^{-1} sec.$^{-1}$. Our result is very insensitive to the exact value of R, the minimum range set for mesons by the apparatus. As is shown in subsequent sections, about 0.04 percent of the meson component is stopped per g cm^{-2} of lead. It is clear that no large errors are involved in taking R as just the measured thickness of absorbing material, equivalent here to 138 g cm^{-2} of lead or 80 g cm^{-2} of air-equivalent.

It is possible that the 12 days during which this experiment was being run were non-typical, because of barometric fluctuations, etc. This question can be at least partially answered by considering some data obtained by E. D. Palmatier, who had a twofold coincidence wide-angle telescope operating continuously in Ithaca during the months of April and May, 1948. The average rate of this equipment during the 12-day period was 168.2 counts per minute, whereas for the two month period the average was 169.8 counts per minute. The correlation with barometric pressure was excellent. It therefore seems reasonable that the present value of I_v be increased in the ratio 169.8/168.2, giving $I_v(R)=(0.887\pm0.005)\times10^{-2}$ cm^{-2} sterad^{-1} sec.$^{-1}$. Since the

[4] K. Greisen, Phys. Rev. **61**, 212 (1942).

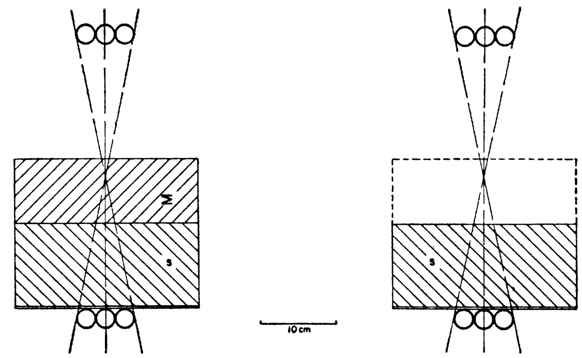

FIG. 3. Telescope geometry for experiment III: Coincidence measurement of the number of mesons in a given range interval.

observed zenith angle dependence of these mesons is $\cos^{2.09}\theta$ just multiplying by $2\pi/3.09$ gives $J(R)$, the number crossing a sphere of 1 cm^2 cross-sectional area per second. Hence $J(R)=(1.801\pm0.011)\times10^{-2}$ cm^{-2} sec.$^{-1}$.

It should be pointed out that only five of the six counters defining the solid angle were measured for effective length. The sixth one failed in the course of another experiment before the lengths of the counters were measured. The maximum variation among the effective lengths of the five counters was $\frac{1}{4}''$, and if the sixth one was not outside these limits, our results can not be affected by more than 0.5 percent by assuming its length to be the average of the others. We estimate that the telescope dimensions were measured to an accuracy such that the result could be in error by as much as 0.25 percent from this cause alone. Considering these two sources of error and the statistical uncertainty, we may state the result as $J(R)=(1.801\pm0.014)\times10^{-2}$ cm^{-2} sec.$^{-1}$ averaged over April and May, 1948, at Ithaca (elevation 260 m).

B. Experiment II. Anti-Coincidence Measurement of the Number of Mesons in a Given Range Interval

The number of mesons in a given range interval has frequently been measured by simple absorption curves

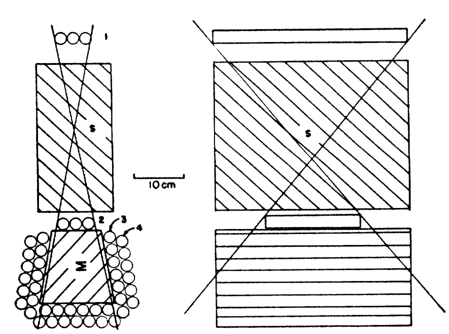

FIG. 4. Telescope geometry for experiments IV and VI: Shape of the low energy end of the meson spectrum and slow meson zenith angle dependence by delayed coincidences.

TABLE I. Delayed coincidence counting rates.

θ	S	Delayed coincidences Total	Rate, hr^{-1}	Accidental rate, hr^{-1}	Rate corrected for accidentals and geometry, hr^{-1}
0°	0	443	1.26±0.06	0.03	1.27±0.06
30°	0	140	0.75±0.06	0.02	0.74±0.06
60°	0	27	0.14±0.03	0.01	0.12±0.03
0°	25 g cm^{-2} C	479	1.52±0.07	0.02	1.54±0.07
0°	50 g cm^{-2} C	419	1.53±0.07	0.01	1.56±0.07
0°	82 g cm^{-2} Al	398	1.63±0.08	0.01	1.67±0.08

(provided enough absorber is used to eliminate electrons) and by anti-coincidence methods. The results by the two methods have usually not been in agreement.

The pitfalls in an anti-coincidence measurement are many and varied. The more striking ones will be taken up one at a time, together with their relative importance in the present geometry, shown in Fig. 2.

First there are "side showers" which we may define as two or more genetically related cosmic-ray particles that may give rise to spurious coincidences. It is customary to obtain a background anti-coincidence rate in experiments of this kind by removing the absorber between the last coincidence tray and the anti-coincidence tray, and to subtract the background from the measured rate with the absorber in place. It is likely, however, that the shower background does not stay the same, since the absorber above the anti-coincidence counters serves to protect them from soft particles. In the present experiment there were two features tending to reduce the number of spurious counts due to side showers. In the first place, coincidence tray 3 was well protected by lead so that only a very energetic electron or a particle traveling horizontally could get at it. Secondly, the anti-coincidence counters presented a large unshielded area, and this area was changed only slightly when the lead Σ was removed. Hence it is unlikely that a shower could cause a threefold coincidence, and even more unlikely that it could cause a threefold coincidence and not have

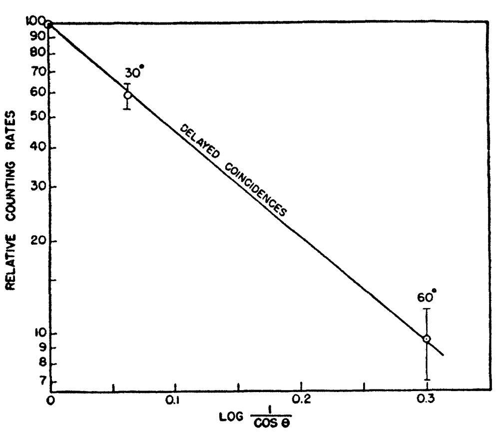

FIG. 5. Zenith angle dependence of slow mesons at Ithaca. The straight line represents $I(\theta)=I(0)\cos^n\theta$ with $n=3.3$.

any of its particles strike the large area presented by the anti-coincidence counters.

Here again, as in simple coincidence measurements, there are unfortunate consequences if one places an absorber between the coincidence counters that define the telescope solid angle. The effective area of the counter below the lead is increased, but not equally so for all mesons. Usually $\sim$100 g cm^{-2} of lead is used above the anti-coincidence counters, so that the maximum momentum that a meson destined to stop in the lead can have in passing through the last coincidence counter is $\sim 2.2\times 10^8$ ev/c. This sets an upper limit on the energy that its knock-on electron can have at 5 Mev, which is about the energy limit set by the counter walls for electrons. Hence the effective area of the counter is increased only for the fast mesons, and it is usually the ratio of number of anti-coincidences to number of coincidences that is of interest. This source of error has been largely eliminated in the present experiment by defining the solid angle with no absorber except the counter walls between the sensitive counter volumes.

A serious source of discrepancy has arisen in the past out of attempts to reduce the anti-coincidence background rate; i.e., the anti-coincidence rate with the lead Σ removed. This rate is usually subtracted directly from the observed anti-coincidence rate with Σ in, and so the natural inclination is to make it as small as possible.

Let us consider some of the sources of this background rate. If we assume that shower effects have been made small there remain: (1) dead time inefficiency of the anti-coincidence tray which may be $\sim$1 percent depending upon the size of the anti-coincidence counters, (2) particles stopping in the counter walls; i.e., real anti-coincidences, (3) large time delays in the anti-coincidence counters, (4) chance anti-coincidences, and (5) insufficient coverage of the meson beam emerging from the telescope array by the anti-coincidence counters. Direct subtraction of the background anti-coincidence rate due to causes (1) through (4) can lead to only small errors in the evaluation of the true number of mesons stopping in a given range interval. It is (5) which we wish to emphasize.

Some of the particles emerging from the last coincidence counters have been badly scattered in the layer of absorber S above them. In fact, as is seen from an expression given by Rossi and Greisen[5] for the mean square angle of emergence, even those mesons that can penetrate halfway down into absorber Σ emerge from S with $\langle\theta^2\rangle^{\frac{1}{2}}\approx 25$ degrees. If, as has usually been the case, the anti-coincidence counters cover little more than the solid angle defined by the telescope array, some of these particles will be recorded as anti-coincidences whether or not Σ is in place. If the resulting high background rate is subtracted from the anti-coincidence rate with Σ in place, the number of particles stopping

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

in Σ is underestimated, because the badly scattered particles referred to above have, in general, low energy and would be stopped in Σ.

Since the high background rate is not desirable, it has often been reduced by methods which in effect redefine a solid angle for the particles emerging from the first absorber. This can be done either by judicious placement of a second group of anti-coincidence counters, or by the use of what amounts to a second coincidence telescope. An example of this method of attack is to be found in experiment IV. In either method it is clear that the low energy particles are being discriminated against. It should be pointed out that these methods are perfectly satisfactory for most of the purposes for which the measurements were intended. For instance, meson lifetime measurements have sometimes been concerned with the ratio of two anti-coincidence measurements at different altitudes, or angles with the zenith. In these cases there is only a second-order error involved, due to a possible change in the shape of the incident meson spectrum. Discrepancies arise when experiments using methods such as these are compared in order to arrive at the absolute number of mesons in a given range interval.

The present experiment, it is believed, has avoided a large portion of the discrepancies due to scattering. This was accomplished by placing anti-coincidence counters in positions such that with the lead Σ removed they would be in the path of practically all of the badly scattered mesons emerging from the lead above coincidence tray 3, and at the same time not interfere with the stopping of these particles while Σ is in place.

The threefold coincidence rate was 440 ± 2 hr.$^{-1}$. The background anti-coincidence rate (with Σ removed), corrected only for the small artificial inefficiency, was 2.4 ± 0.2 hr.$^{-1}$, or 0.5 percent of the coincidence rate. (The artificial inefficiency was introduced by a clamp circuit, as in experiment I, which rendered the recording circuit inoperative for a period of 500 microseconds after any pulse from the anti-coincidence tray.) Of this background, about 40 percent is due to residual inefficiency of the anti-coincidence tray, and about 30 percent can be accounted for by mesons stopping in the counter walls. The remainder is probably due to a combination of side showers and scattering, and is too small to affect our results significantly.

The anti-coincidence rate with Σ in place was 20.8 ± 0.4 hr.$^{-1}$, or 4.7 ± 0.1 percent of the coincidence rate. Subtracting the background, and including a geometric factor of 1.02 arising because of the different zenith angle distributions of fast and slow mesons (investigated in experiments IV and V below), we find $(4.26\pm0.10)\times10^{-2}$ for the fraction of the particles in the vertical direction that can penetrate S but not $S+\Sigma$.

The absorber Σ had a vertical thickness of 93.4 g cm^{-2} of lead plus 5 g cm^{-2} of iron, and the total is equivalent to 99.3 g cm^{-2} of lead. The absorber S was equivalent to 131 g cm^{-2} of lead, which includes the 5 g cm^{-2} of iron and the counter walls.

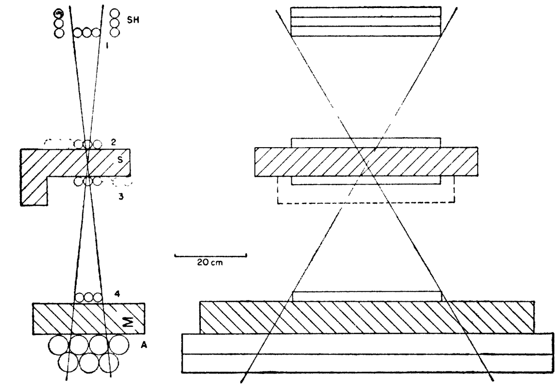

FIG. 6. Telescope geometry for experiment V: Anti-coincidence measurement of the number of mesons in a given range interval as a function of zenith angle.

It is often convenient to have the results in a slightly different form.[6] Of the mesons traveling vertically that can penetrate at least 180 g cm^{-2} of lead (0.044 ± 0.001) percent are stopped per g cm^{-2} of lead.

We prefer not to translate these quantities into other units such as g cm^{-2} of air-equivalent or momentum because there is some question about the effect of multiple scattering in the lead, and that discussion is taken up later.

C. Experiment III. Coincidence Measurement of the Number of Mesons in a Given Range Interval

The measurement of the number of mesons in a given range interval by the coincidence or absorption curve method suffers from one striking disadvantage; namely,

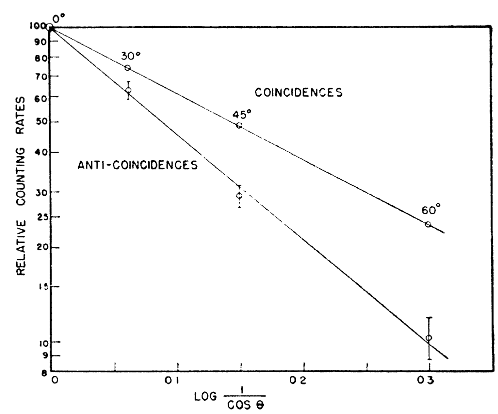

FIG. 7. Zenith angle dependence of mesons with ranges between 94 and 188 g cm^{-2} of lead at Ithaca. The straight lines follow $\cos^n\theta$ with $n=2.09$ and 3.3.

[6] Because the absorbers Σ are often rather thick, it is desirable to define an absorber $S'=S+\frac{1}{2}\Sigma$, and a coincidence rate $N'=N-\frac{1}{2}$ A.C. The fractional number of particles stopped is then A.C. rate$/N'\Sigma$ per g cm^{-2} at a range S'. The extension of this to coincidence measurements is obvious.

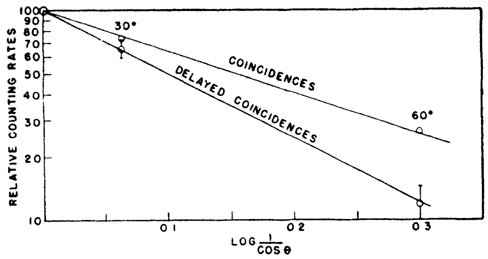

FIG. 8. Zenith angle dependence of mesons able to penetrate 170 g cm^{-2} of lead but not an additional 25 g cm^{-2} of carbon at Echo Lake. The straight lines follow $\cos^n\theta$ with $n=2.0$ and 3.1.

it is required to find the slope of the absorption curve, which inherently involves being concerned with a small difference between two or more relatively large counting rates measured independently. Small changes in the experimental conditions such as would result in 1 percent changes in counting rates introduce 25 percent errors or more in the quantity being measured. The rates for two different thicknesses of absorber cannot be measured at the same time on the same piece of equipment, so that fluctuations in the barometric pressure introduce errors, unless such effects are carefully taken into account. On the other hand, the method as we have used it has some rather striking advantages, in that most of the spurious effects with which we were concerned in the anti-coincidence method cancel, and so leave the measured result in a form not subject to much question.

Consider the effect of side showers. In a simple coincidence experiment such as that used and shown in Fig. 3, the vulnerability of the counters to side showers is virtually unchanged when an additional absorber is placed between the counters. Hence when the rates are subtracted the same number of spurious side showers is included in both rates, and the difference is unaffected.

The effect of the scattering of mesons in the lead absorbers can be shown to be small by the following considerations. If the mesons incident upon the apparatus are isotropic, the scattering into and out of the telescope solid angle cancel, so that the measured coincidence rate is in very good approximation equal to the number of mesons incident in the telescope solid angle, with a minimum range as determined by the absorber thickness. This cancelation is only slightly disturbed by a $\cos^3\theta$ zenith angle distribution. Further, however, the differential range spectrum of mesons is essentially flat (see Fig. 10) so that for different absorbers whatever scattering errors there may be are the same with both thicknesses, and so the errors cancel in the difference of the counting rates.

TABLE II. Portions of the data bearing on the meson range spectrum.

	$\Sigma=8.3$ g cm^{-2} of carbon		$\Sigma=57.5$ g cm^{-2} of lead	
S	D.E. Rate, hr^{-1}	A.C. Rate, min^{-1}	D.E. Rate, hr^{-1}	A.C. Rate, min^{-1}
0	7.1 ±0.4			
8″ Pb	6.1 ±0.4	1.31±0.04	1.96±0.15	5.34±0.05
20½″ Pb	4.2 ±0.4	0.64±0.09	1.44±0.22	2.99±0.05
Ratio 8″ Pb / 20½″ Pb	1.45±0.17	2.04±0.29	1.36±0.23	1.78±0.03

A certain fraction of the mesons emerging from an absorber is accompanied by electrons, and some of these electrons may pass through one of the bottom counters, while the meson does not. The resulting coincidence is of course indistinguishable from a meson passing through the telescope in the normal fashion. These knock-on electrons are in equilibrium with the meson beam, however, and once again the effect cancels in the subtraction of the rates.

In order to minimize the effect of barometric fluctuations, the experiment was run using two identical pieces of apparatus, operating side by side. The absorber was shifted from one telescope to the other every day for 22 days.

Corrected for chance coincidences, the fractional absorption in Σ was $(4.19\pm0.39)\times10^{-2}$ from the data of one telescope and $(3.55\pm0.40)\times10^{-2}$ from the other. Assuming the difference between the absorption as deduced from the two telescopes has arisen from noncanceling barometric fluctuations and statistical fluctuations, we may consider the two values to be of equal validity, and take the average. By doing this we get $(3.87\pm0.28)\times10^{-2}$ for the fractional absorption. The absorber Σ in this experiment was 93.4 g cm^{-2} of lead, and S was equivalent to 131 g cm^{-2} of lead. The solid angle as defined by this experiment was the same as that in experiment II, and the appropriate geometric factor for correction to the zenith direction is the same, 1.02. Our result then is that of the mesons traveling vertically that can penetrate at least 178 g cm^{-2} of lead, (0.042 ±0.003) percent are stopped per g cm^{-2} of lead.

D. Experiment IV. Shape of the Low Energy End of the Meson Spectrum and Slow Meson Zenith Angle Dependence by the Method of Delayed Coincidences

The preceding three experiments have been concerned with mesons with ranges greater than some 130 g cm^{-2} of lead. Smaller thicknesses of lead permit an increasing number of electrons to get through, but the method of delayed coincidences serves very effectively to separate the mesons from the electrons. The telescope geometry is shown in Fig. 4. The absorber Σ was composed of graphite.

The following type of event was recorded as a delayed coincidence: a coincidence 1, 2 at time $t=0$, accompanied by no count from trays 3 or 4 from $t=-15$ microseconds to $t=1$ microsecond, but followed by a coincidence between trays 3 and 4 in the interval $t=1$ to $t=7$ microseconds. This 6-microsecond interval was split into three channels, 1 to 3, 3 to 5, and 5 to 7 microseconds, and a comparison of the number of counts in the three channels served as a check on the operation of the equipment, since the mean life of the meson is known to be about 2.2 microseconds. The delay discriminator was similar to that of Sands.[7]

The pertinent results are given in Table I. The geometric correction was necessary because of the finite resolution of the telescope. Corrected for accidentals, the distribution of delayed events in the three channels 1–3, 3–5, and 5–7 microseconds was 1194, 516, and 196 respectively. For a 2.15-microsecond lifetime the ratio between adjacent channels should be 2.5 and is seen to be 2.3 ± 0.1 and 2.6 ± 0.2.

The geometry of the decay electron counter trays did not lend itself to an accurate determination of the absolute detection efficiency, hence these are relative measurements, and require normalization. The largest thickness of absorber used, 82 g cm^{-2} of aluminum, is in the range accessible to anti-coincidence measurements, and the normalization may be made at this point.

Figure 5 shows the observed zenith angle dependence of the lowest momentum group of mesons measured, those that could penetrate the counter walls of the telescope, but not the counter walls plus 25 g cm^{-2} of carbon plus one of the counter walls comprising tray 3. Of course, the exact distribution could hardly be expected to follow so simple a function as $\cos^{3.3}\theta$, but this function gives a good empirical fit within the accuracy of the data.

E. Experiment V. Anti-Coincidence Measurement of the Number of Mesons in a Given Range Interval as a Function of Zenith Angle

The geometry for experiment V is shown in Fig. 6. Anti-coincidences (1, 2, 3, 4)—SH and anti-coincidences (1, 2, 3, 4)—SH—A were recorded.

The lead above and to the side of coincidence tray 3 and the anti-coincidence counters near tray 1 served to keep the effects of side showers very small. The absorbers S and Σ each had a thickness of 93.4 g cm^{-2} of lead, plus the counter walls.

It will be noticed that counter trays 3 and 4 serve to redefine a solid angle for mesons emerging from S. This does not affect the detection of fast mesons, but definitely discriminates against the slower mesons which tend to be scattered in passing through S. The measurement is therefore unsatisfactory for determining the absolute intensity of mesons in a given range interval, but should be satisfactory for measuring the relative number of mesons in a given range interval as a function of zenith angle. In principle, scattering could influence even this relative measurement if the shape of the incident meson spectrum were very different at different angles with the zenith, but the present experiments have shown that the shape of the spectrum is not a sensitive function of the zenith angle.

[7] M. Sands, M.I.T. thesis (1948).

TABLE III.

Σ	Anti-coincidence rate, hr^{-1}	Decay electron rate, hr^{-1}
40.0 g cm^{-2} Fe	281 ± 4	3.45 ± 0.28
57.5 g cm^{-2} Pb	320 ± 3	1.96 ± 0.15
8.3 g cm^{-2} C	78 ± 2	6.15 ± 0.40

Because the extreme counters of the telescope were separated by a distance large compared to the width of the telescope trays, there are no geometric corrections large enough to apply here. In order to be certain that the influence of side showers was not large, trays 2 and 3 of the telescope were displaced as shown in Fig. 6. This, it was assumed, did not change the vulnerability of the equipment to side showers, and made it most improbable for a single particle to go through the necessary counters and be recorded. Under these conditions the anti-coincidence rates were in all cases less than the statistical errors in the results with the counters in line. Further, at least some of these events were subtracted with the background, obtained with Σ removed, and therefore no special correction for side showers has been made.

The present experiment provides a good example of the sort of scattering difficulties one may encounter in such an anti-coincidence measurement. Absorber Σ here was about the same as the corresponding absorbers in experiments II and III, and the number of anti-coincidences was only 2.35 percent of the number of coincidences, as compared to 4 percent in the other experiments.

Figure 7 shows the coincidence and anti-coincidence rates as a function of $1/\cos\theta$, plotted on a log-log scale. Both measurements are seen to be well expressed by $\cos^n\theta$, with $n=2.09$ for the integral or coincidence data, in general agreement with many other measurements, and $n=3.3$ for the anti-coincidences, the same exponent found in the measurement of the lowest momentum group of experiment IV.

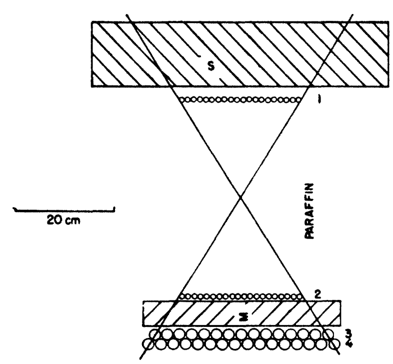

FIG. 9. Telescope geometry for experiments VII and VIII: Anti-coincidence and delayed coincidence measurements at Echo Lake and at Ithaca.

TABLE IV. Comparison of the data taken at Echo Lake and at Ithaca.

	$\Sigma=8.3$ g cm^{-2} carbon D.E., hr^{-1}	$\Sigma=8.3$ g cm^{-2} carbon A.C., min^{-1}	$\Sigma=40$ g cm^{-2} iron D.E., hr^{-1}	$\Sigma=40$ g cm^{-2} iron A.C., min^{-1}
Ithaca $S=158$ g cm^{-2} of Pb	2.4 ± 0.2	0.417 ± 0.015	1.38 ± 0.11	1.55 ± 0.02
Echo Lake $S=230$ g cm^{-2} (8″) of Pb	6.1 ± 0.4	1.31 ± 0.04	3.45 ± 0.28	4.68 ± 0.06
Ratio, Echo Lake/Ithaca	2.6 ± 0.2	3.14 ± 0.15	2.5 ± 0.3	3.02 ± 0.06

F. Experiment VI. Measurement of the Number of Mesons in a Given Range Interval as a Function of Zenith Angle at Echo Lake, by the Method of Delayed Coincidences

The experiment used the same telescope and detecting equipment as were used for experiment IV. The absorber S was 170 g cm^{-2} of lead, and the data were taken at Echo Lake, Colorado.

The distribution of delayed events in the three channels 1–3, 3–5, 5–7 microseconds was 267, 104, and 45, respectively, and if the expected numbers of accidentals are subtracted, we get 262, 99, and 40. The expected ratio between the number of counts in adjacent channels is about 2.5 for an assumed meson lifetime of 2.15 microseconds, and the above data are consistent with this.

The data normalized to 100 for $\theta=0$ have been plotted in Fig. 8. The zenith angle distributions of both the coincidence counting rate and delayed counting rate are seen to be practically the same as those of the corresponding quantities at Ithaca.

Since the telescope geometry was the same as that used in experiment IV at Ithaca, the relative rates of both coincidences and delayed coincidences can be compared at the two altitudes. Making a small correction for the difference in the absorbers S as used at the two places (118 g cm^{-2} of lead-equivalent at Ithaca, 170 g cm^{-2} at Echo Lake) we find for the integral intensity, I_v (170 g cm^{-2} Pb) at Echo Lake/I_v (170 g cm^{-2} Pb) at Ithaca$=1.71\pm0.02$. For the slow mesons, there is no appreciable correction due to the change in the absorbers, and we find for the differential intensity, i_v at Echo Lake/i_v at Ithaca$=2.0\pm0.2$.

TABLE V. Comparison of number of mesons in a given range as given by three different experiments.

Experiment	S' in g cm^{-2} of Pb	Σ	% stopped per g cm^{-2} of Σ	% stopped per g cm^{-2} of Pb corrected for multiple scattering
II, Anti-coincidence	180	Pb	0.044 ± 0.0010	0.040 ± 0.0010
III, Coincidence	180	Pb	0.042 ± 0.003	0.038 ± 0.003
VIII, Anti-coincidence	184	Fe	0.060 ± 0.003	0.041 ± 0.002

G. Experiment VII. Measurement of the Differential Range Spectrum of Mesons by the Method of Delayed Coincidences at Echo Lake

This was actually a part of another experiment (performed in collaboration with V. T. Cocconi) designed to investigate the neutrons associated with the stopping of mesons in various materials. Figure 9 shows the geometry of the experiment pertinent to this discussion.

The events recorded were coincidences 1, 2; anti-coincidences (1, 2)—(3 or 4); and delayed coincidences (1, 2), (3, 4). The detecting equipment was the same as used in experiments IV and VI, except for the addition of an anti-coincidence circuit similar to that used in experiment II.

It will be noticed from Fig. 9 that in this experiment the solid angle has been defined after the particles have passed through the first absorber, S. Scattering in S will not affect the detection of the fast mesons. For the slower mesons, the scattering should have the effect of making the angular distribution below the absorber more nearly isotropic than it was above it. An evaluation of the vertical intensity of mesons stopping in Σ requires a knowledge of their angular distribution incident upon the telescope, but the dependence of the result upon this angular distribution is slight. In treating the data we have assumed that the angular distribution of the slow mesons is one power of $\cos\theta$ greater than that of the fast mesons, as indicated approximately by the zenith angle experiments IV, V, and VI.

A possible source of error in this experiment is the effect of knock-on electrons. Imagine a fast meson incident upon the absorber S, passing through counter tray 1 but missing tray 2. It may be accompanied by a secondary electron that passes through tray 2 but stops in the absorber Σ and so causes an anti-coincidence, indistinguishable from one caused by a meson stopping in Σ. Because of the low mean energy of the secondary electrons, those that strike tray 2 must be produced mostly in the paraffin above tray 2 and can never emerge from the paraffin far from the trajectory of the meson. Therefore such an event occurs only for a small fraction of the mesons that traverse tray 1 and pass near tray 2 without striking it. From reported experimental determinations of the magnitude of similar effects[2,8] we estimate that our anti-coincidence rates in this experiment may be 5 or 10 percent too high. There are no errors arising from this effect in the delayed coincidence measurements, and only second-order errors in the comparison of anti-coincidence measurements at different altitudes or with different absorbers in positions S and Σ.

Experiments VII and VIII were run using the same apparatus. The portions of the data bearing on the meson range spectrum at Echo Lake are given in

[8] C. Milone and V. Tongiorgi, Phys. Rev. 72, 735 (1947).

Table II. Accidental coincidences and anti-coincidence background rates have been subtracted.

One point regarding the reliability of the data should be mentioned. In considering the distribution of delayed events in the three timing channels, 1–3, 3–5, and 5–7 microseconds, we find 625, 232, and 123 counts, respectively, corrected for accidentals. The ratio of the number of counts between adjacent channels should be 2.5, and is seen to be 2.69 ± 0.21 and 1.89 ± 0.21, the latter rather far outside the standard error. Similar data, not pertinent to the present discussion but taken under the same conditions, showed the same tendency with more statistical accuracy. This was of concern, and the apparatus was tested thoroughly many times in attempts to find some reason. Perhaps the most convincing checks were the following: random pulses from large trays of counters were fed into the circuits in such a way that there were a large number of accidental delayed counts, and no real ones. The distribution of accidental counts in the three channels was 527, 562, and 538 counts whereas the expected number for channels of 2 microseconds width was 536 per channel. As a further test, tray 2 was placed under trays 3 and 4, so that any particle passing through trays 1 and 2 must have passed through trays 3 and 4 also. In this condition no delayed counts were observed in 22 hours. It must be stated frankly that the reason for the distribution observed is not understood. In the other experiments IV, VI, and VIII, in which the same delay discriminator was used, the distribution of counts in the three channels was quite normal.

By comparing the ratios of the rates with 8 inches of lead to those with 20.5 inches of lead, it is seen that the two delayed coincidence measurements are in agreement with each other, as are the two anti-coincidence measurements. The delayed coincidence measurements are not in good agreement with the anti-coincidence measurements, however, and they should be, under the hypothesis that both represent only mesons. The reasons for the disagreement are not certain, but the effect is in a direction which would support the hypothesis that there are significant numbers of slow protons at Echo Lake, with rapidly increasing numbers under smaller thicknesses of absorber.

To a fairly good approximation, the mesons emerging from a slab of lead some 200 g cm^{-2} thick are distributed rather uniformly in range, at least for ranges up to an additional 60 g cm^{-2} of lead. This permits us to interpret the anti-coincidence data from experiments VII and VIII, in terms of the relative efficiency of lead and iron per g cm^{-2} for removing or absorbing mesons from the beam. While there are certainly some particles other than mesons capable of penetrating the 8 inches of lead used in this experiment, they are a small fraction of the total, and further the dependence of the ionization losses upon the atomic number is not at all a sensitive function of the mass of the particle in question.

The necessary data are included in Table III. All were taken under an absorber S consisting of 8 inches (230 g cm^{-2}) of lead.

TABLE VI.

A. At Ithaca
I_v (80 g cm^{-2} air) $=(0.887\pm0.005)\times10^{-2}$ cm^{-2} sterad^{-1} sec.$^{-1}$
J (80 g cm^{-2} air) $=(1.801\pm0.011)\times10^{-2}$ cm^{-2} sec.$^{-1}$
i_v (105 g cm^{-2} air) $=(6.0\pm0.15)\times10^{-6}$ sterad^{-1} g^{-1} sec.$^{-1}$
j (105 g cm^{-2} air) $=(8.7\pm0.2)\times10^{-6}$ g^{-1} sec.$^{-1}$
$I_\theta(R)=I_v(R)\cos^{2.09}\theta$ ($R=60$ g cm^{-2} air)
$i_\theta(R)=i_v(R)\cos^{3.3}\theta$ ($R=90$ g cm^{-2} air)
$i_\theta(R)=i_v(R)\cos^{3.3}\theta$ ($R=15$ g cm^{-2} air)
B. At Sea Level
I_v (80 g cm^{-2} air) $=0.845\times10^{-2}$ cm^{-2} sterad^{-1} sec.$^{-1}$
J (80 g cm^{-2} air) $=1.71\times10^{-2}$ cm^{-2} sec.$^{-1}$
i_v (105 g cm^{-2} air) $=5.5\times10^{-6}$ sterad^{-1} g^{-1} sec.$^{-1}$
j (105 g cm^{-2} air) $=8.0\times10^{-6}$ g^{-1} sec.$^{-1}$

Let us first note that for ionization losses alone, on the basis of the calculations of Wick,[9] 40 g cm^{-2} of iron are equivalent to 57.5 g cm^{-2} of lead, where g cm^{-2} means distance as measured along the path of the particle. Hence it might first be expected that the anti-coincidence rates should be equal, while in fact they are in the ratio $Pb/Fe=1.14\pm0.02$.

Now the decay electrons emitted by mesons stopping in the absorbers must certainly have an effect of the above ratio. The operation of the circuits was such that after a twofold coincidence, any pulse in either of trays 3 or 4 up to 8 microseconds later was recorded as a particle passing all the way through the absorber. For a decay electron to be recorded, it was required to pass through both trays 3 and 4, during a 6-microsecond interval starting at 1 microsecond. If the decay electron rates are increased so as to include those decay electrons emitted from 0 to 1 and from 7 to 8 microseconds, we get 5.7 hr^{-1} and 3.2 hr^{-1} for the iron and lead respectively (and 10.2 hr^{-1} for the carbon). The anti-coincidence rates must be increased by at least this much. But then the question arises as to how many decay electrons pass through either one of trays 3 or 4 but do not pass through both of these trays. In order to bring the anti-coincidence results into agreement it would be necessary to assume that 16 times as many decay electrons pass through either tray 3 or 4 as pass through trays 3 and 4. This is an improbably large factor, and indeed would have the effect of increasing the detection efficiency for the decay electrons in carbon to a value considerably above unity, even disregarding a factor ~2.5 due to the comparatively small solid angle covered by the decay electron trays.[10]

So far, the effect of multiple Coulomb scattering in the absorbers has been neglected. Koenig[11] has treated

[9] G. Wick, Nuovo Cimento **1**, 302 (1943).

[10] We have neglected here the possibility that the decay electrons emerging from the carbon have a higher average energy than those emerging from the iron and lead. This is undoubtedly the case since the vertical thickness of the carbon is less than the expected range of the decay electron. The basic argument is, however, unchanged.

[11] H. Koenig, Phys. Rev. **69**, 590 (1946).

TABLE VII.

Author	Anti-coincidence measurements S	Stopping material	Percent absorption per g cm^{-2} of air-equivalent at 100 g cm^{-2} of air-equivalent (sea level).
Koenig[11]	160 g cm^{-2} Pb	Pb	0.057±0.002
	160 g cm^{-2} Pb	Fe	0.051±0.002
	160 g cm^{-2} Pb	Al	0.049±0.004
	160 g cm^{-2} Pb	H_2O	0.047±0.002
Addario and Cocconi[12]	310 g cm^{-2} Pb	Pb	0.046±0.002
	113 g cm^{-2} Pb + 105 g cm^{-2} H_2O	Pb	0.052±0.002
Sands[7]	167 g cm^{-2} Pb	C	0.045
Exp. II	125 g cm^{-2} Pb	Pb	0.066±0.002
Exp. VIII	158 g cm^{-2} Pb	Fe	0.068±0.002
	Coincidence measurements		
Nielson, *et al*[13]		Pb	0.082±0.008
Rossi, *et al*[14]	187 g cm^{-2} Pb	C	0.058±0.008
	144 g cm^{-2} Pb	Pb	0.057±0.008
Sands[7]	167 g cm^{-2} Pb	Pb	0.063
Exp. III	125 g cm^{-2} Pb	Pb	0.064±0.004

this problem on the basis of the scattering theory of Williams, and finds that to a good approximation the vertical thickness of anti-coincidence absorbers should be increased by the following factors: lead 1/0.907, iron 1/0.975, aluminum 1/0.986. We have repeated Koenig's calculation for lead absorbers from 50 to 180 g cm^{-2} thick and find that the correction is, to a very good approximation, linear. If the iron and lead absorbers used here are increased in accordance with the above factors we find they are equivalent to 41 g cm^{-2} of iron and 63.5 g cm^{-2} of lead.

Turning again to Wick's range-momenta data we find that 41 g cm^{-2} of iron are equivalent to 58 g cm^{-2} of lead, so that we would expect the anti-coincidence rates to be in the ratio 58:63.5 or 1:1.095, assuming the effect of the decay electrons to have been evaluated accurately. Now to bring the observed data into agreement we find that the number of decay electrons passing through trays 3 or 4 must be 4±2 times the number passing through 3 and 4, a much more acceptable factor. This argument simply serves to show that Koenig's multiple scattering factors are reasonable, and we propose to use them further in the section below.

H. Experiment VIII. Second Anti-Coincidence Measurement of the Number of Mesons in a Given Range Interval at Ithaca

This experiment is the same as experiment VII, except that it was run at Ithaca, and the data are not as complete. It serves as an independent check on the number of mesons in a given range interval, and permits an evaluation of the increase in the number of mesons at Echo Lake over those at Ithaca.

In Table IV are listed the Ithaca data, together with the Echo Lake data suitable for comparison. Because the differential range curve is so mild a function of the range, there is very little error in comparing differential measurements under slightly different thicknesses of absorber at the two altitudes.

As seen from the table, the anti-coincidence measurements are in agreement in the sense that both the iron and carbon data increased by compatible factors in going from Ithaca to Echo Lake. The decay electron measurements are in similar internal agreement,[15] but the decay electron and anti-coincidence data differ from each other, the decay electron events increasing by a smaller factor than the anti-coincidences. This is in the same direction as the similar effect noted in comparing the Echo Lake data under different thicknesses of absorber—there seem to be too many anti-coincidences (or too few delayed coincidences) at Echo Lake under the 230 g cm^{-2} of lead absorber. It should be noted however, that these observations are not independent in the case of carbon, the same data (Echo Lake, 8.3 g cm^{-2} of carbon under 230 g cm^{-2} of lead) having entered both considerations. Some further discussion of this disagreement is to be found in Section III B where the Echo Lake measurements are considered in more detail.

This experiment permits another evaluation of the number of mesons in a given range interval at Ithaca. In the preceding section a comparison was made of the number of particles stopping in iron and lead at Echo Lake, the telescope geometry being the same as was used here. It was found that the results were in agreement with the known ionization losses in these materials provided multiple scattering and a reasonable assumption about the effect of the decay electrons were taken into account. We have taken these factors into account in treating the data obtained at Ithaca, and find the fractional absorption at 184 g cm^{-2} of lead to be $(0.041\pm0.002)\times10^{-2}$ per g cm^{-2} of lead.

I. Summary of Intensity Measurements

In this section a comparison will be made of the present experimental evaluations of some of the quantities measured in more than one way. Where possible a best value will be selected and used in the subsequent discussions.

[12] M. Addario and G. Cocconi, Nuovo Cimento 4, 1 (1947).
[13] Nielson, Ryerson, Nordheim, and Morgan, Phys. Rev. 59, 547 (1941).
[14] Rossi, Hilberry, and Hoag, Phys. Rev. 57, 461 (1940).

[15] Negative μ-mesons decay in carbon, but are captured in iron. Negative π-mesons are believed to be captured in both iron and carbon. Positive π- or μ-mesons decay in iron and carbon. Now positive π-mesons could conceivably contribute to our delayed coincidence counting rates by stopping in our absorbers and decaying into a μ-meson which promptly decays into an electron. However, our delayed coincidence rates increased for carbon and for iron absorbers by equal factors in going from Ithaca to Echo Lake. Either the relative number of π- and μ-mesons is the same at the two altitudes, (which is most unlikely) or the number of π-mesons at Echo Lake is such that our rates are not affected appreciably. We shall assume the latter.

Three measurements have been made of the number of mesons in a given range interval at Ithaca. They are given in Table V in a form suitable for comparison.

These are seen to be in satisfactory agreement. Two things about experiment VIII should be recalled. First, the agreement between absorption in iron and lead has essentially been forced, though on a reasonable basis, at Echo Lake. Hence the agreement of experiment VIII with the others at sea level should not be interpreted as an indication of the validity of the assumed relative ionization losses of mesons in iron and lead. Rather, it bears only on the evaluation of the number of mesons in a given range interval at Ithaca. Secondly, we have remarked that there may be some spurious effects attributable to knock-on electrons contributing to this anti-coincidence measurement. We have proceeded believing the effect to be small, but must regard this measurement with less confidence than the others.

The result of experiment II will be adopted as the "best result" for further use, because its statistical error is smaller than the others and the method is believed to be sound.

It remains to convert this result into suitable units of absolute intensity. Our absorber S' was 180 g cm^{-2} of lead, and this is equivalent to 105 g cm^{-2} of air. Under the conditions of our experiment, (dense) air is 1.73 times as effective as lead for stopping mesons. Hence of the mesons that can penetrate 105 g cm^{-2} of (dense) air, (0.069 ± 0.002) percent are stopped per g cm^{-2} of air. Now the result of experiment I may be corrected from 80 to 105 g cm^{-2} of air, $(25\times0.069=1.7$ percent correction), to give us the absolute vertical intensity at this range, and we find $I_v(105 \text{ g cm}^{-2} \text{ of air})=(0.872\pm0.005)\times10^{-2}$ cm^{-2} sterad^{-1} sec.$^{-1}$. The differential vertical intensity is then $(6.0\pm0.15)\times10^{-6}$ sterad^{-1} g^{-1} sec.$^{-1}$, at 105 g cm^{-2} of air-equivalent. (In all cases, absorber thicknesses are measured along the actual path of the particle.)

Some of the useful results are tabulated in Table VI, where the errors are the standard statistical errors, not including estimates of the systematic errors, which are believed to be smaller than the statistical uncertainties.

The intensity measurements may be corrected to sea level by an extrapolation of our data on the altitude variation, and some data recently compiled by Rossi.[16] For slow mesons, $i_v(R)$ at 1007 g cm$^{-2}/i_v(R)$ at 1035 g cm$^{-2}=1.09$. The corresponding factor for the hard component is 1.05.

III. COMPARISON WITH OTHER MEASUREMENTS AND CALCULATIONS

A. Measurements at Ithaca

So far as we know, the only other measurement of the absolute integrated intensity of the hard component suitable for comparison with the present result is that of Greisen.[2] Here the minimum range set by the apparatus was 71 g cm^{-2} air-equivalent (of lead). Our present result has been corrected to this range, using the differential intensity of mesons as found in experiment II.

Greisen: $J(71 \text{ g cm}^{-2} \text{ of air}) = (1.803\pm0.012)\times10^{-2}$ cm^{-2} sec.$^{-1}$.

Experiment I: $J(71 \text{ g cm}^{-2} \text{ of air}) = (1.806\pm0.014)\times10^{-2}$ cm^{-2} sec.$^{-1}$.

The agreement is seen to be excellent. Both measurements were made at Ithaca (1007 g cm^{-2}).

Ithaca is appreciably above sea level (260 meters) and the present experiments cannot fairly be compared with others without taking this into account. As stated previously, our results may be transformed to sea level intensities by decreasing the hard component by 1/1.05, and decreasing the slow meson intensity by 1/1.09.

First let us consider the experiments measuring the percentage of particles stopped per g cm^{-2} of absorber. Different experimenters have stopped the mesons in different materials, so it is convenient to refer the measurements to g cm^{-2} of air, taking the multiple scattering into account in each case. The zenith angle dependence of the stopped mesons has been taken as one power of $\cos\theta$ greater than that of the hard component. It has been assumed that 113 g cm^{-2} of lead (19 radiation lengths) reduces the number of electrons detected to a negligible amount.

The actual absorber S was in general different for each experiment listed in Table VII. The percentage of stopped particles has been corrected so that the different results can be compared at 100 g cm^{-2} of air-equivalent. In doing this, the differential range spectrum has been assumed to be flat, and only the hard component as measured by the apparatus has been adjusted.

It is seen that the coincidence measurements tend to give results higher than the anti-coincidence measurements (except in the case of the present measurements), in agreement with the hypothesis put forth previously,

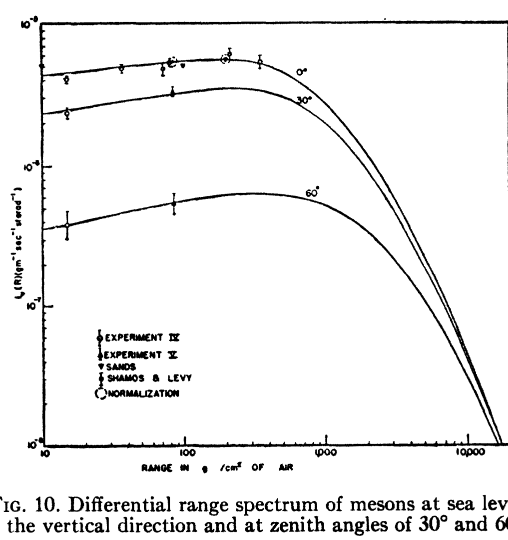

FIG. 10. Differential range spectrum of mesons at sea level in the vertical direction and at zenith angles of 30° and 60°.

[16] B. Rossi, Rev. Mod. Phys. 20, 537 (1948).

that most anti-coincidence measurements have in the past discriminated in one way or another against the slow mesons.

Simple counter experiments, such as the coincidence and anti-coincidence methods that have been described, have been interpreted at sea level in terms of mesons since the relative number of other penetrating particles is believed to be small. It should be pointed out that the direct evidence for the intensity of penetrating particles other than mesons at sea level is scanty. On the basis of cloud-chamber studies by a number of experimenters, the penetrating component at sea level is believed to be composed of ~ 1 percent fast protons, and ~ 0.2 percent slow protons such as might stop in an apparatus like ours (see Rossi[16] and Janossy[17]). No attempt will be made to correct our data for this; the estimates of proton intensity are entirely too tentative.

The other measurements that were made at sea level were concerned with relative meson intensities and are best presented in the form of curves. The zenith angle distributions of two slow meson groups have already been presented in Figs. 5 and 7 and as far as we know there are no measurements with which they may be compared. The zenith angle distribution of the fast mesons has been measured by many experimenters, with essentially the same result as ours, $I_\theta = I_v \cos^n\theta$, with $n=2$ or 2.1.

Rossi has recently published a curve showing the differential range spectrum in the vertical direction of mesons at sea level, as deduced from the results of many different experimenters.[16] The solid curve of Fig. 10 marked "0°" is essentially a reproduction of Rossi's curve. The results of our present experiments (II, III, and VIII) on the absolute differential vertical intensity of mesons are in perfect agreement with this curve at range 105 g cm^{-2}, and are not shown on the graph. We have plotted the results of our delayed coincidence measurements, the results of the anti-coincidence zenith angle experiment, and the delayed coincidence measurements of two other experimenters on the graph.[7,18] Since none of these were measurements of absolute intensities, it has been necessary to normalize them. The procedure was as follows: we had three delayed coincidence measurements of the relative differential vertical intensity at three different ranges. The largest range among these corresponded to 86 g cm^{-2} of air, whereas our absolute (anti-coincidence) measurement of the differential vertical intensity was at 105 g cm^{-2} of air. Because our measurements and the data of Sands[7] both indicate that the differential vertical intensity is a very insensitive function of the range, it was considered legitimate to extrapolate over this 19 g cm^{-2} of air so as to fit the delayed coincidence measurements to the anti-coincidence measurements on an absolute scale. Sands' data, on the other hand, have been normalized to the curve at 200 g cm^{-2} of air, while those of Shamos and Levy have been adjusted to show that they are not inconsistent with the shape of the curve. The anti-coincidence zenith angle measurement, experiment V, has been normalized at the vertical intensity, and the standard errors indicated on the 30 and 60 degree measurements are those of the ratio i_θ/i_v.

It is clear that the 0° curve is consistent with the available slow meson data at sea level. We have not included any of the meson intensity measurements made underground or with cloud chambers in Fig. 10. Rossi has shown that these data are in agreement with the curve.

The other curves in Fig. 10 labeled 30° and 60° were deduced as follows. For the small ranges, our zenith angle measurements have been used. For the larger ranges (>1000 g cm^{-2}) we know of no differential measurements, and have calculated the curves. Sands[7] has found a meson production spectrum which predicts accurately many features of the meson component. This production spectrum is $N(x,R)=(R+210)^{-2.9} \times\exp(-x/125)$ where $N(x,R)dxdR$ is proportional to the number of mesons created at atmospheric depth x in dx g cm^{-2} of air with residual range R in dR g cm^{-2} of air. By taking proper account of the meson decay, and integrating over the atmosphere, vertical meson intensities may be predicted. The 0° curve is in fact a curve calculated in this way.

We have extended this production spectrum to include other zenith angles by assuming it to be of the form $(R+210)^{-2.9}\exp(-x/125\cos\theta)/\cos\theta$, keeping the same normalization as used for 0°. The spectra so calculated have been used in the 30° and 60° curves for ranges greater than 1000 g cm^{-2}. The calculated spectra for smaller ranges do not agree with our observations, the observations indicating higher intensities than those calculated. This is not surprising since we have assumed that mesons when produced follow the direction of the producing component, whose intensity we have assumed in turn to fall off as $\exp(-x/125\cos\theta)$. Further, we have neglected atmospheric Coulomb scattering. These assumptions are clearly correct only in the limit of high energies.

It should be pointed out that an integration of the curves of Fig. 10 results in a zenith angle dependence for the *integrated* meson intensity which is in excellent agreement with observations. Figure 10 then, we regard as representing reasonably well the sea level meson intensity for 0, 30, and 60 degrees.

B. Measurements at Echo Lake

Some of the results of the Echo Lake experiments have been discussed briefly in earlier sections. It will be noticed that the vertical intensity of slow mesons at Echo Lake, as deduced from the delayed coincidence experiments IV and VI, is not in good agreement with the similar determinations from experiments VII and VIII. From experiments IV and VI we have 2.0 ± 0.2 for

[17] L. Janossy, *Cosmic Rays* (Oxford University Press, London, 1948).

[18] M. H. Shamos and M. G. Levy, Phys. Rev. **73**, 1396 (1948).

ratio Echo Lake/Ithaca, where as from experiments VII and VIII we have 2.6±0.2 and 2.5±0.3. The probability for a deviation this large is about 5 percent. The weighted mean of the three ratios, assuming the deviations to be purely statistical, is 2.37±0.12. Sands[7] and Rossi, Sands, and Sard[19] have measured the variation of the number of slow mesons with altitude by using a delayed coincidence apparatus in an airplane. The points nearest to ours were taken at 600 and 1030 g cm^{-2} of air. If these results are interpolated to 707 and 1007 g cm^{-2} for Echo Lake and Ithaca respectively, the corresponding ratio is 3.3. It is not possible to say whether this large difference in supposedly comparable measurements represents a real effect, an unfortunate statistical fluctuation, or instrumental difficulties.

Calculations similar to those made for the sea level meson spectrum were carried out for the altitude of Echo Lake (707 g cm^{-2}). Contrary to what might first be supposed, the predicted zenith angle dependence for slow mesons is stronger than that predicted for sea level. This comes about because even at sea level, there is predicted appreciable local production of slow mesons near the zenith, and almost none at large angles. As the atmospheric depth decreases, this local production near the zenith increases very rapidly, but because of the exponential nature of the absorption of the producing radiation, there is still only an insignificant number of slow mesons locally produced by primaries traveling at large zenith angles. Now our *measured* zenith angle dependence of slow mesons was the same at Echo Lake as it was at Ithaca. It is likely that there are particles capable of producing low energy mesons that have not traversed the amount of atmosphere implied by the zenith angle of the produced meson. This could result either from large angular spread in the producing event, or from angular spreads in a series of nuclear interacactions from which the producing particle descended. It is of interest to note that the maximum transverse momentum that a μ-meson may receive from the decay of a π-meson is about 30 Mev/c, so that practically speaking, the μ-mesons with which we are concerned have taken on the direction of their parent π.

It has been pointed out that the ratio of anti-coincidences to delayed coincidences did not remain constant in going from Ithaca to Echo Lake. Similarly, at Echo Lake this ratio was not constant under different absorbers. Both of these observations are consistent with the assumption that non-decaying particles were contributing appreciably to our anti-coincidence measurement under the 8-inch lead absorber at Echo Lake. Let us assume that none of these particles contributes to the anti-coincidence rates at Ithaca, or at Echo Lake under 20.5 in. of lead. Then our anti-coincidence and delayed coincidence data are compatible if the intensity of these non-decaying particles under 8 in. of lead at Echo Lake is about 4×10^{-6} g^{-1} $sterad^{-1}$ $sec.^{-1}$, or some 20 percent of the differential slow meson intensity. We believe the most likely particles to be identified with this intensity are slow protons either incident upon the apparatus or produced in our absorbers. Rossi[13] has estimated from some data of Leprince-Ringuet[20] that the differential vertical intensity of protons having a range of 100 g cm^{-2} of air should be 4×10^{-7} g^{-1} $sterad^{-1}$ $sec.^{-1}$ at an altitude of 1000 meters. Assuming that the number of protons varies with atmospheric depth, x, as $\exp(-x/125)$, the intensity at Echo Lake should be $\sim2.5\times10^{-6}$ g^{-1} $sterad^{-1}$ $sec.^{-1}$, in reasonable agreement with the estimate given above.

IV. THE SEA LEVEL ELECTRON COMPONENT

We have used the total integrated intensity measurements of Greisen[2] and our meson intensity measurements to deduce electron intensities. An attempt has been made to include the effect of scattering on the energy limits set for electrons by Greisen's apparatus, and we find for the integrated intensity of electrons with energy greater than 10 Mev, 0.60×10^{-2} cm^{-2} $sec.^{-1}$.

The intensity of the meson-produced electrons can be calculated (given the decay products), since their origin and behavior may be described by well-founded general principles. Thus Rossi and Greisen[21] have described a method of calculating the electrons arising from the decay of fast mesons ($p/\mu>2.5$) using the conservation laws in a manner which avoids sensitive dependence on the meson spectrum or detailed cascade shower theory. Rossi and Klapman[22] have calculated accurately the track length for shower electrons above 10 Mev as a function of the primary electron energy, and have applied these results to a calculation of the electron intensity arising from the collision processes of mesons. Greisen,[2] making use of conservation laws, has calculated the electrons arising from the decay of slow mesons ($p/\mu<2.5$). We have applied these methods to a calculation of the intensity of electrons of energy greater than 10 Mev, and under two likely hypotheses of the meson decay scheme, find:

Source	Intensity, cm^{-2} $sec.^{-1}$ Average Energy of Decay Electron	
	$\frac{1}{3}\mu c^2$	$\frac{1}{2}\mu c^2$
Decay of fast mesons	0.303×10^{-2}	0.455×10^{-2}
Decay of slow mesons	0.010	0.015
Collision processes	0.114	0.114
Decay of mesons at rest	0.003	0.005
Total (from mesons)	0.430	0.589

The measured electron intensity of 0.60×10^{-2} cm^{-2} $sec.^{-1}$ is in good agreement with the calculated total electron intensity obtained by assuming that half of the meson rest energy is given to the electron.[23] However,

[19] Rossi, Sands, and Sard, Phys. Rev. **72**, 120 (1947).

[20] L. Leprince-Ringuet, Comptes Rendus **221**, 406 (1945).

[21] B. Rossi and K. Greisen, Phys. Rev. **61**, 121 (1942).

[22] B. Rossi and S. Klapman, Phys. Rev. **61**, 414 (1942).

[23] We have used 2.15×10^{-6} sec. for themean life and 109 Mev/c^2 for the mass of the meson. Bernardini *et al.*[1] have used 2.3×10^{-6} sec. and 90 Mev/c^2, respectively. Their calculated electron intensities agree with ours if this is taken into account.

it has been pointed out repeatedly that the zenith angle and altitude dependence of the electron component near sea level are such that a source of electrons other than mesons is indicated. The zenith angle dependence of the total meson component is $\cos^2\theta$, and the electrons from this source should have a zenith angle dependence no stronger than this, while the observed electron zenith angle dependence is more nearly $\cos^3\theta$. Similarly, the electron component appears to increase with altitude faster than can be explained by meson processes alone. It therefore seems likely that on the average, only $\frac{1}{3}$ of the meson rest energy is given to the electron, and that there is an additional intensity of about 0.17×10^{-2} cm^{-2} sec.$^{-1}$ probably arising from nuclear interactions. Such an additional source would be expected to have a very steep zenith angle and altitude dependence because of the exponential character of the absorption of high energy nucleons in the atmosphere, and would therefore account for the observed zenith angle and altitude dependence of the total electron component. This is likewise in agreement with the recent cloud-chamber experiments of Anderson, Leighton, and Seriff,[24] which suggest that the decay products of the μ-meson are an electron and two neutrinos.

V. SUMMARY

The present investigation has been concerned mostly with the meson component. We have made a careful measurement of the absolute intensity of the number of mesons in a given range interval, and believe that these measurements have succeeded in eliminating most of the errors associated with the serious discrepancies among similar measurements reported in the literature. The differential intensity as a function of zenith angle has been measured for mesons having two different residual ranges, and it has been found that the zenith angle dependence is considerably stronger than that for the integral intensity, but approximately the same for the two low energy groups. Using the method of delayed coincidences, we have investigated the shape of the low energy end of the meson spectrum in the vertical direction, and found that the differential range spectrum is essentially flat in this low energy region. Since it is flat in the vertical direction, and the zenith angle dependence is independent of range up to $\sim$100 g cm^{-2}, the differential range spectrum is also rather flat for ranges up to $\sim$100 g cm^{-2} at large zenith angles.

Measurements similar to those made at Ithaca have been made at Echo Lake, Colorado (altitude 3240 m), and it has been found that the differential range spectrum is still moderately flat up to ranges corresponding to $\sim$100 g cm^{-2} of air. The differential intensity as a function of zenith angle was found to be similar to that at Ithaca, as is the zenith angle dependence of the integrated intensity. By comparing anti-coincidence and delayed coincidence data under 230 g cm^{-2} of lead, we have suggested that the differential intensity of protons under this thickness of lead may be $\sim4\times10^{-6}$ g^{-1} sec.$^{-1}$, or $\sim$20 percent of the differential slow meson intensity. The slow meson intensity was found to increase by a factor 2.4 ± 0.1 between Ithaca and Echo Lake, while the integrated intensity of all penetrating particles increased by 1.74.

We have applied our meson intensity measurements to a re-evaluation of the sea-level electron intensity using the total cosmic-ray intensity as measured by Greisen. These considerations are consistent with the electron-2 neutrino decay scheme for the μ-meson, provided there are some electrons at sea level not descended from mesons.

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[24] Anderson, Leighton, and Seriff, Phys. Rev. **75**, 1466A (1949).