PHYSICAL REVIEW VOLUME 77, NUMBER 5 MARCH 1, 1950

A Study of Penetrating Showers at 3260 Meters

WILLIAM D. WALKER*
Cornell University, Ithaca, New York

(Received November 7, 1949)

A series of experiments on local penetrating showers is described. Neon bulbs electronically connected to Geiger counters were lighted and photographed when those counters were struck in a simple coincidence. One row of counters recorded delayed coincidences. Most of the experiments described were performed at Echo Lake, Colorado, elevation 3250 meters.

The experiments indicate that there are approximately equal numbers of charged and neutral primary particles. The measured mean free path is found to decrease with increasing energy. The charged primary particles are shown to have a very strong zenith angle dependence.

Properties of the secondary particles of the showers were also studied. A large fraction of the penetrating particles locally produced are shown to be mesons. Of all the mesons that stop and decay in the apparatus, apparently about 16 percent are locally produced in penetrating showers. There are many short range particles produced that are not mesons. The angular distribution of the penetrating secondaries about the shower axis shows a strong concentration of the particles in the forward direction, such that they could not be emitted symmetrically in the center of gravity system.

I. INTRODUCTION

A LOCAL penetrating shower is usually defined experimentally as the local production of several charged particles, heavier than electrons and each capable of traversing several inches of lead.

The rate of occurrence of these showers increases very rapidly with altitude.[1] This indicates that few, if any, of the showers are produced by μ-mesons. The absorption of the shower primaries has been shown to be greater in carbon than in lead,[2] and therefore the primaries are not photons or electrons. The primaries of the penetrating showers have been called by the collective name "N component,"[3] which is thought to include nucleons and π-mesons (or possibly only nucleons). The present work is intended to be a study of showers produced by the N component and not those produced by μ-mesons or the cascade particles. In some phases of the work it was possible to detect showers whose secondaries were not at all penetrating. In spite of this apparent contradiction, the term "penetrating shower" used in this paper is intended to mean a shower produced by the N component.

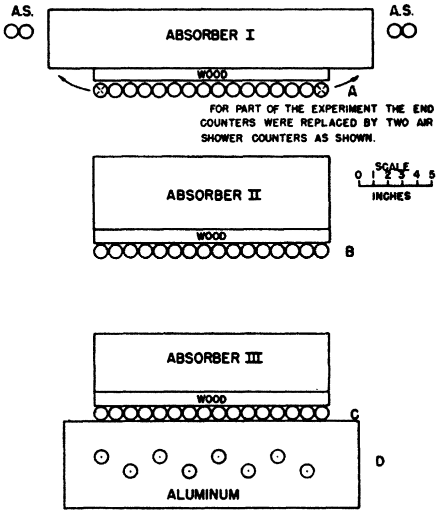

FIG. 1. Counter arrangement.

In investigating penetrating showers there are two general ways of selecting the events to be studied:

(a) Selecting so as to guarantee with high probability that only penetrating showers will be recorded, although certain classes of penetrating showers may be missed entirely.

(b) Selecting so that, as nearly as possible, every penetrating shower will be recorded, although other types of showers may also be recorded.

In this experiment a method of selection intermediate between (a) and (b) was used, in that the simplest coincidence which triggered the apparatus did not require that the secondaries of the shower be penetrating. As a result, a part of this paper is devoted to estimating the rate of showers produced by μ-mesons. Most of the arguments used in evaluating the correction depend upon the fact that the rate of penetrating showers increases much more rapidly with altitude than does the rate of showers produced by μ-mesons.

II. DESCRIPTION OF APPARATUS

The apparatus consisted of an array of 16-inch by one-inch Geiger-Mueller counters pictured in Fig. 1. Each counter was attached to a circuit which would light a neon bulb when the counter pulse was in coincidence with a master pulse. For the major part of the experiment the master pulse was triggered by the simple coincidence $A^{>0}B^{>0}C^{>2}$ (at least one counter struck in row A, at least one in B, and at least three in row C). The use of blocking oscillators in the mixing produced a resolving time of 1.2 μsec. for the production of a master pulse. The length of the master pulse was about 25 μsec.

The counters in tray D were employed in the detection of counts delayed in time between one and four μsec. from the coincidence $A^{>0}B^{>0}C^{>2}$. Pulses were

---

* Now at Rice Institute, Houston, Texas.

[1] J. Tinlot, Phys. Rev. 74, 1197 (1948).

[2] G. Cocconi, Phys. Rev. 75, 1974 (1949).

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

TABLE I. Corresponding coincidence rates at Echo Lake and Ithaca.

Absorber $I=0$, $II=0$, $III=8$-in. Pb					
Coincidence	$A^1B^1C^3$	$A^1B^1C^{4,5}$	$A^1B^1C^{>5}$	$A^1B^1C^{>7}$	$A^1B^{>0}C^{>2}$
Echo Lake rate (min.$^{-1}$)	1.63 ±0.025*	0.614±0.018	0.233 ±0.006	0.0735±0.003	0.41 ±0.015
Ithaca rate (min.$^{-1}$)	0.415±0.01	0.140±0.004	0.0339±0.002	0.006 ±0.0008	0.055±0.004
Ratio	3.95	4.4	6.9	12.5	7.5

* Errors indicated are the standard or r.m.s. errors.

channelled as to delay times 1–2 μsec., 2–3 μsec.,† etc., and as a check the lifetime of the meson was continuously measured.

Because of the very short resolving time, the probability of a chance coincidence triggering the apparatus was completely negligible (less than 0.05 percent of the observed rate). The most probable chance coincidence was the lighting of one extra neon bulb. The calculated probability for this is ½ percent per photograph.

III. CORRECTIONS

A. Soft Component

It is necessary to investigate the possibility that electrons and photons, as well as μ-mesons, can produce background showers.

In order for a single electron or photon to trip the apparatus the cascade would have to traverse, in all cases, at least 180 g/cm^2 of lead. This requires that it be of energy greater than about $10''$ ev. An electron or photon of this energy will only be found within a few centimeters of the core of an air shower. In the core of an air shower having electrons of this energy the density is so high that it is extremely improbable to have only one particle incident, and therefore only the case of many particles incident need be considered.

The following precautions were taken to avoid recording particles accompanied by air showers:

(1) There were always at least four unshielded counters in anti-coincidence (415 cm^2 total area) within one foot of row A.

(2) The absorber was always placed so that, in order to have counters struck in all three rows, several inches of lead had to be traversed, unless the particles were incident horizontally.

Because of the small total area of the air shower counters it was feared that some air showers might escape detection. With no lead above A such events would produce coincidences of the type $A^{>1}B^{>0}C^{>2}$ −A.S.,‡ and the rate of these would decrease markedly with increasing thickness of absorber. The following data show no strong decrease, and it is concluded that the rate of such events is not more than 0.04 min.$^{-1}$.

$A^{>1}B^{>0}C^{>2}$−A.S. with $I=0$, $III=8$-in. Pb

Absorber II	0	4-in. Pb	8-in. Pb
Rate (min.$^{-1}$)	0.10±0.005	0.072±0.005	0.060±0.004.

The rate of coincidences $A^1B^{>0}C^{>2}$, which is used frequently in analysis in most of the experiments, is always between 1.7 and 2.91 min.$^{-1}$. We see that the estimated upper limit of the background rate, 0.04 min.$^{-1}$, is forty to seventy times smaller. It is therefore concluded that the soft component need not be considered as contributing to the background.

B. Meson Background

μ-mesons can produce showers of electrons and photons either by knock-on or radiation processes. An attempt will now be made to estimate the rate of such showers recorded at Echo Lake. This will be done by comparing the rates of identical coincidences at Echo Lake and at Ithaca (see Table I), using the fact, shown below, that the increase in vertical intensity of mesons of energy greater than 1 Bev between Ithaca and Echo Lake is a factor of 1.5, while the N component increase is between 8 and 15.[3]

Let

$E.L.$ = counting rate of a given coincidence at Echo Lake (elevation 3250 m).

I = counting rate of the same coincidence at Ithaca (elevation 260 m).

x = the number of such coincidences produced by mesons at Echo Lake.

y = the number produced by the N component at Echo Lake.

N = ratio of the rate of nucleon-produced showers at Echo Lake to that at Ithaca.

Δ = ratio of rates of meson produced showers.

Then

$$E.L.=x+y$$
$$I=x/\Delta+y/N.$$

TABLE II. Rates with two different absorber thicknesses (Ithaca)

Coincidences $A^1B^1C^{>2}$ Absorber (Pb)	Rate
$I=0$, $II=0$, $III=8$ in.	0.61 ±0.02 min.$^{-1}$
$I=4$ in., $II=8$ in., $III=8$ in.	0.565±0.03 min.$^{-1}$

TABLE III. Ratio of vertical intensity of μ-mesons, Echo Lake to Ithaca.

Minimum range	Δ = ratio of vertical intensity	P(ev/c) (momentum)
196 g/cm^2/Pb +200 g/cm^2 Fe	1.55	$\geqslant 6\times10^8$
196 g/cm^2 Pb +342 g/cm^2 Fe	1.50	$\geqslant 9\times10^8$
196 g/cm Pb +485 g/cm^2 Fe	1.50	$\geqslant 11\times10^8$

---

† The delay time was not indicated on each separate photograph.

‡ "−A.S." means no air shower counters were struck.

Solving these equations for y, the corrected rate, or the rate produced by the N component, of any given coincidence is found.

$$y=\frac{E.L.-\Delta I}{1-(\Delta/N)}. \tag{1}$$

Notice that the calculated value of y is not strongly dependent on the assumed value of N, which is taken as 12.

$$\frac{1}{y}\frac{\partial y}{\partial N}=\frac{1}{N}\frac{\Delta}{N-\Delta}\approx\frac{1}{85}\quad\begin{cases}N=12\\ \Delta=\ 1.5.\end{cases}$$

Δ is estimated from the following evidence. According to the cloud-chamber data of J. G. Wilson,[4] nearly all of the μ-mesons which produce knock-on electrons have an energy of greater than 3×10^9 ev, and therefore we should expect that only high energy mesons produce coincidences. This is substantiated by data taken in Ithaca, shown in Table II, since the counting rate is changed very little by increasing the absorber on the apparatus.

If we suppose that only mesons of residual range greater than R are capable of producing a recorded shower, then after we add δR absorber, only mesons of initial range greater than $R+\delta R$ can be recorded. By examining the integral range spectrum at sea level given by Rossi,[3] we see that a decrease of 10 percent (roughly the change shown in Table II) by an increase of 350 g/cm^2 Pb (the change in absorber in this case) corresponds to a minimum energy of greater than 10^9 ev.

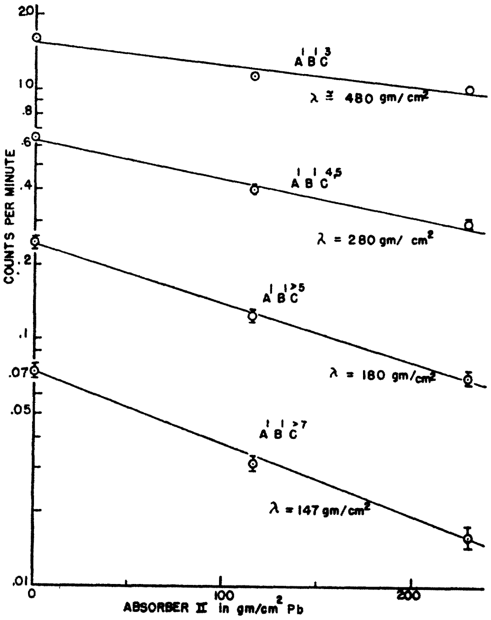

Fig. 2. Uncorrected rate $A^1B^1C^N$ *vs.* thickness of absorber *II*.

A direct measurement of the difference in intensity of mesons of energy $>10^9$ ev between these two altitudes has never been made. However, Rossi, *et al.*,[5] have measured the integral range spectrum at Echo Lake. Also the curve for the integral range spectrum at sea level has been given by Rossi,[3] as well as the decrease in mesons of range greater than 167 g/cm^2 Pb between altitudes corresponding to Echo Lake and Ithaca. Using this information an estimate of the decrease of mesons of $E>10^9$ ev has been made, and the results are given in Table III.

The ratio Δ is observed to change very slowly with the minimum energy selected. Since the probability of creating a knock-on shower goes rapidly to zero for energies less than 10^9 ev, and the number of mesons decreases rapidly with energy above 10^{10} ev, we consider that most of the knock-on showers are generated by mesons in the energy interval 10^9–10^{10} ev, and we have used $\Delta=1.50$ in making the corrections for μ-meson-produced showers. The uncertainty in the factor is considered to be less than 0.1, which makes very little difference in the calculated correction.

In the following sections, whenever a correction for μ-mesons seems necessary for interpretation of the data, it will be made in the way indicated above, by using Eq. (1) and the measured rates at the two different elevations.

IV. PROPERTIES OF THE PRIMARY PARTICLES

A. Mean Free Path *Versus* Energy

This experiment was performed in an attempt to learn whether the mean free path for absorption or

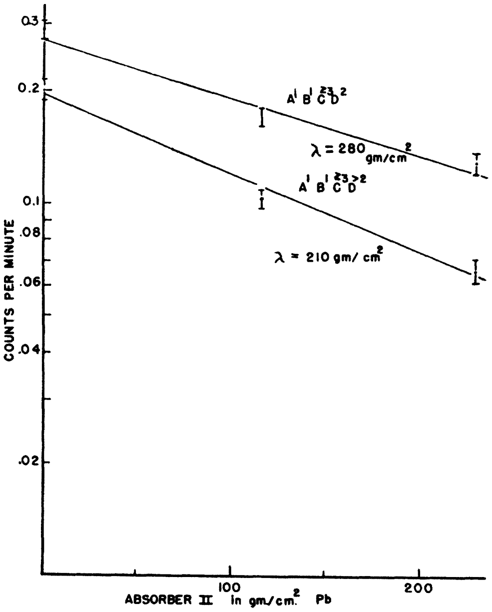

Fig. 3. Uncorrected rate $A^1B^1C^{>2}D^N$ *vs.* thickness of absorber *II*.

---

[4] J. G. Wilson, Nature **142**, 72 (1938).

[5] Rossi, Greisen, Stearns, Froman, and Koontz, Phys. Rev. **61**, 675 (1942).

shower production¶ varied with the energy of the primary particle.

Eight inches of lead was kept fixed in position *III*. The lead in position *II* was varied between zero and eight inches. The coincidences of interest were $A^1B^1C^{>2}$. These were thought to be caused by primary charged particles interacting in absorber *III* after traversing *II* with no interaction. We study the rate of these coincidences as a function of the thickness of absorber *II*. A decrease in this rate with increased absorber could be from the following causes:

1. Production of penetrating showers in absorber *II*. (Note that because of the 8-in. lead in *III* these showers may not be recorded at all.)
2. Loss of primary energy by collision processes in *II*.

The energies of the primaries were not measured directly, but it was assumed that the showers of many penetrating particles were made by primaries of very high energy, while the showers of fewer particles were made by primaries of lower energy. The data were therefore subdivided according to the number of counters struck into the following classifications:

(1) $A^1B^1C^3$
(2) $A^1B^1C^{4,5}$
(3) $A^1B^1C^{>5}$
(4) $A^1B^1C^{>7}$
(5) $A^1B^1C^{>2}D^2$
(6) $A^1B^1C^{>2}D^{>2}$

The uncorrected rates *vs.* absorber thickness *II* are shown in Fig. 2 for types 1, 2, 3, 4 and in Fig. 3 for types 5 and 6.

As discussed in Section I, because of the simplicity of the triggering coincidence, a sizeable percentage of background showers due to μ-mesons is expected. The curves in Fig. 4 have been corrected for this background by the method described in Section IIIB. Note that the coincidence rate $A^1B^1C^{>7}$ requires no correction, and that the mean free path from this curve is very close to that calculated from the geometric cross section.

It is found in Section VA that a large percentage of the showers observed have mostly short range secondaries. The following experiment was performed in order to find a separate mean free path for the primaries of these showers. Absorbers *II* and *III* were made 6 in. and $1\frac{1}{2}$ cm of lead respectively, while absorber *I* was varied from 0 to 8-in. lead. The coincidences $A^1B^1C^{>2}$ should be largely due to showers with secondaries of range less than $1\frac{1}{2}$-cm Pb, and $A^1B^{>1}C^{>2}$ should be caused by showers with 3 or more secondaries of range greater than $1\frac{1}{2}$-cm Pb. The results of this experiment, after correction for showers caused by μ-mesons, may be seen in Fig. 5.

It seems that the primary particles of the showers with mostly short range secondaries show a very long mean free path, 360 g/cm² of lead. This is in approximate agreement with measurements of absorption of star-producing radiation in lead ($\lambda=300$ g/cm², see Bernardini *et al.*[6]) which supports our belief that the penetrating showers with short range secondaries are essentially the same as high energy stars.

In conclusion, there seems to be little doubt that the measured mean free path of the primary particles increases with decreasing energy of the primary. However the presence of many showers with mostly short range secondaries means that there is the possibility of having the primary interact in the absorbing layer without the interaction being detected. Therefore, particularly for the smaller showers, we may no longer be measuring the mean free path for shower production, but rather the mean free path for absorption of the primary. The same is probably true of the experiments of Tinlot and Gregory,[7] and Cocconi,[2] particularly for thick absorbers.

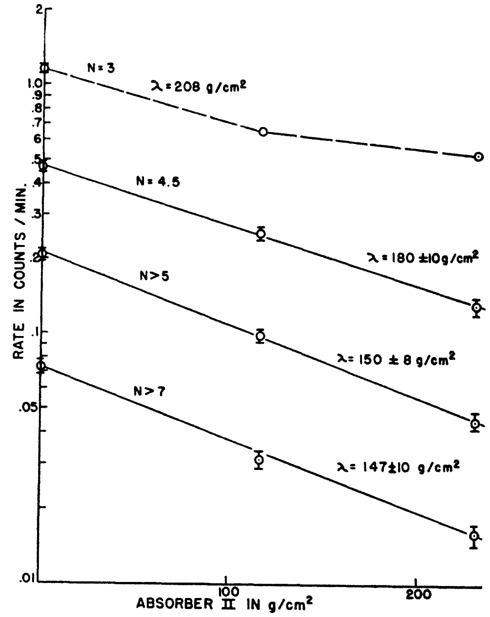

FIG. 4. Rate $A^1B^1C^N$ *vs.* thickness of absorber *II*. Corrected using $\Delta=1.50$.

B. Ratio of Charged to Neutral Primaries

The purpose to this experiment was to establish the relative number of charged and neutral particles producing penetrating showers. The experimental procedure was as follows.

Keeping eight inches of lead in position *III* fixed, two inches of lead were moved from position *II*, just below the counter tray *A*, to position *I*. We shall denote this lead by *M*. The counting rate of the coincidence $A^{>0}B^{>1}C^{>2}-$A.S. was taken for the two positions of *M*, and the rates were corrected for showers produced by μ-mesons.

¶ We are primarily interested in that for shower production, but the two effects are not separable with this experiment.

[6] Bernardini, Cortini, and Manfredini, Phys. Rev. 74, 845 (1948).

[7] J. Tinlot and B. Gregory, Phys. Rev. 75, 519 (1949).

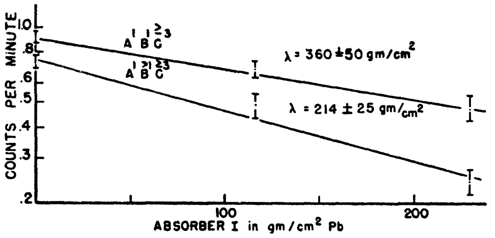

FIG. 5. Corrected absorption curves (I variable, $II=6$ in. $III=1.5$-cm Pb). Corrected using $\Delta=1.50$.

When M is in position II, showers originated in it by neutral particles will not be recorded unless the neutral particle is accompanied by one or more charged particles which strike row A, or unless a back projected charged particle produced in M strikes row A. With M in position I, charged primaries may produce showers that will be recorded as before, but also showers produced in M by neutral particles will be recorded.

There are three sources of error in this method. First, there was a slight change in geometry for the showers produced by charged particles when M was moved. The layer, M, was moved only four inches in order to keep this effect small. Second, because of the fact that the two measurements were, of course, taken at different times, barometric changes might influence the results. For this reason, several runs were made with the lead in each position. Third, it was noticed that with no lead in I and II some showers appeared to originate above row B. These were thought to be from the following causes:

(1) Particles producing, in addition to a shower starting in absorber III, one or more knock-on electrons striking counters in row B.

(2) Single primary particles striking two or more counters in row B because of large angle of incidence.

(3) Particles starting a shower in the counter walls or wood above B.

(4) Showers starting in III with back projected particles striking row B.

Since we are interested only in showers actually beginning in II a correction must be made for these four types of events.

As the absorber II is increased, the number of showers starting in III is decreased, and likewise it was estimated that the number of background events is decreased in the same proportion. Then

$$F=\frac{\text{rate } A^1B^{>1}C^{>2}}{\text{rate } A^1B^1C^{>2}} \quad (I=0,\ II=0,\ III=8\text{-in. Pb})$$

gives the fraction which the rate $A^1B^{>1}C^{>2}$ caused by background events (1), (2), (3), and (4) is of the rate $A^1B^1C^{>2}$ for any amount of lead in II. To show that this fraction is essentially constant for any amount of lead in II, we consider how the various events listed above are affected by increasing absorber II.‖

The fraction, rate (1)/rate ($A^1B^1C^{>2}$) may increase because of the additional material in which knock-ons can be generated, but the increase must be slight because saturation for the production of knock-ons is known to occur at very small thicknesses, and the material above row B was never less than the counter walls of row A (1 g/cm²) plus two wooden shelves (2 g/cm²), almost enough for saturation.

The zenith angle dependence of the primaries has been measured (see Zenith Angle Dependence) and found to be very steep, so that background due to events of type (2), and particularly the variation of this type of background, is negligible.

The background effects of types (3) and (4) would be expected to decrease in the same proportion as $A^1B^1C^{>2}$. (We assume that the addition of a small amount of lead** in II will not produce much change in the shape of the energy spectrum of the primaries.) We expect (4) to be a large effect because Cocconi and Tongiorgi[8] have found that there is an increase of 30 percent in their counting rate of penetrating showers when a ½-inch lead absorber is placed beneath their detecting apparatus.

To summarize, because Cocconi and Tongiorgi have shown that a large effect due to back projected particles does exist, and because (2) is negligible and the change

TABLE IV. Absorption of primary particles.

Absorber: $I=0$, II variable, $III=8$-in. Pb			
Uncorrected Echo Lake data			
Absorber II		Coincidence rate (min.$^{-1}$)	
	$A^1B^1C^3$	$A^1B^1C^{4,5}$	$A^1B^1C^{>5}$
0	1.63±0.025	0.614±0.018	0.233±0.008
4-in. Pb	1.13±0.02	0.404±0.012	0.123±0.004
8-in. Pb	1.01±0.02	0.287±0.008	0.070±0.003
Corrected Echo Lake data			
Absorber II	$A^1B^1C^3$	$A^1B^1C^{4,5}$	$A^1B^1C^{>5}$
0	1.15±0.025	0.462±0.018	0.208±0.008
4-in. Pb	0.65±0.02	0.252±0.012	0.098±0.008
8-in. Pb	0.53±0.02	0.135±0.008	0.045±0.003
Absorber: I variable, $II=6$-in. Pb, $III=1\frac{1}{2}$-cm Pb			
$I=0$	$A^1B^1C^{>2}$ (min.$^{-1}$)	$A^1B^{>1}C^{>2}$ (min.$^{-1}$)	
Echo Lake	1.76±0.05	1.17 ±0.04	
Ithaca	0.64±0.02	0.347±0.02	
Ratio, EL/I	2.76	3.35	
Uncorrected Echo Lake data			
Absorber I	$A^1B^1C^{>2}$	$A^1B^{>1}C^{>2}$	
0	1.76±0.05	1.17 ±0.04	
4-in. Pb	1.53±0.05	0.925±0.05	
8-in. Pb	1.32±0.06	0.67 ±0.03	
Corrected Echo Lake data			
Absorber I	$A^1B^1C^{>2}$	$A^1B^{>1}C^{>2}$	
0	0.91±0.05	0.73 ±0.04	
4-in. Pb	0.68±0.05	0.49 ±0.05	
8-in. Pb	0.47±0.06	0.24 ±0.03	

‖ As noted above, the correction for knock-ons due to μ-mesons has already been made.

** Absorber II was never more than 2-in. Pb when this correction was used.

[8] G. Cocconi and V. C. Tongiorgi (private communication).

in (1) is probably small, we shall use the correction, as outlined above, treating it as a constant fraction, F, of the showers starting below row B. We now calculate F from the data given in Table I.

$$F=\left[\frac{\text{rate } A^1B^{>1}C^{>2}}{\text{rate } A^1B^1C^{>2}}\right]^{\dagger\dagger}=\frac{0.38}{1.82}=0.21.$$

$$I=0$$

$$II=0$$

$$III=8\text{-in. Pb.}$$

The results of the experiment, after correction, are given in Table V.

In interpreting these data we must first consider the possibility that showers produced by neutral particles may occasionally be recorded when M is in position I by (a) being accompanied from the air by a charged particle that strikes row A; (b) producing a back-projected particle that strikes row A.

The column +A.S. in Table V indicates that probably less than 10 percent of the penetrating showers were accompanied by air showers. Previous investigators (Cocconi and Greisen,[9] Treat and Greisen,[10] Tinlot,[1] and Tinlot and Gregory[7]) have also found that only a few percent (less than 5 percent) of the penetrating showers are associated with air showers.

We estimate the effect of (b) by noting that such events would also produce a decrease in the rate $A^1B^1C^{>2}$, when absorber M is moved from position I to position II. The only other effect which might change the rate, the production in M of a single charged primary by a neutral primary, would also make the rate decrease when M was moved from I to II. Therefore the difference between the two rates, which from Table V is 0.02±0.04 min.$^{-1}$, is an upper limit on the rate of these coincidences produced by events of type (b).

TABLE V. Charged *vs.* neutral primaries.

Uncorrected Echo Lake data

Absorber (Pb)			Coincidence rate (min.$^{-1}$)		
I	II	III	$A^1B^1C^{>2}$	$A^{>0}B^{>1}C^{>2}-$A.S.	+A.S.
0	2 in.	8 in.	1.95±0.03	0.55±0.02	0.16±0.02
2 in.	0	8 in.	1.97±0.05	0.76±0.04	0.18±0.02
0	8 in.	8 in.	1.32±0.04	0.38±0.02	0.08±0.01
2 in.	6 in.	8 in.	1.38±0.03	0.54±0.02	0.11±0.01

Echo Lake data corrected for μ-meson background

I	II	III	$A^1B^1C^{>2}$	$A^{>0}B^{>1}C^{>2}-$A.S.	Difference
0	2 in.	8 in.	1.30±0.03	0.52±0.02	
2 in.	0	8 in.	1.32±0.03	0.73±0.04	0.21±0.05
0	8 in.	8 in.	0.67±0.04	0.35±0.02	
2 in.	6 in.	8 in.	0.73±0.03	0.51±0.02	0.16±0.04

$$(1)\quad F\times 1.31=0.21\times 1.31=0.275\text{ min.}^{-1*}$$

$$(2)\quad \frac{N+C}{C}=\frac{0.73-0.275}{0.52-0.275}=1.87\pm 0.2$$

* Background number of showers that appear to originate between tray A and tray B even when the material M is absent.

Since these two effects are small, it is assumed that

$$R=\left[\frac{\text{rate }(A^{>0}B^{>1}C^{>2}),\ M\text{ in }I,\ II=0,\ III=8\text{-in. Pb}}{\text{rate }(A^{>0}B^{>1}C^{>2}),\ I=0,\ M\text{ in }II,\ III=8\text{-in. Pb}}\right]_{\text{corrected}}=\frac{N+C}{C},$$

where N = number of showers produced in M by neutral particles, and C = number of showers produced in M by charged particles. From Table V,

$$(N+C)/C=R=1.87\pm 0.2;\quad\text{and}\quad N/C=0.87\pm 0.2.$$

If the neutral and charged particles have the same cross section for interaction, then the ratio N/C represents the ratio of the number of neutral and charged primaries of the penetrating showers. The results indicate that the numbers of charged and neutral primaries are about equal.

It was mentioned above that two effects, back projected charged particles from neutral primaries, and production in M of single charged primaries, would cause a decrease in the rate of $A^1B^1C^{>2}$ when M was moved from I to II. The small change in this rate is also interesting because it sets an upper limit on the second effect. Actually the small difference might be explained in terms of showers too small or too narrow to be detected by the top rows of counters, so it is concluded that the transition $N\rightarrow P$ without penetrating shower production probably does not occur for neutrons of sufficient energy to produce a penetrating shower.

The fact that there are such large numbers of neutral particles capable of producing penetrating showers seems to indicate some sort of heavy particle cascade phenomenon occurring in air. This experiment shows that it may be difficult to interpret absorption experiments (particularly in air) directly in terms of interaction cross sections.

C. Zenith Angle Dependence

Using the apparatus as an array of counter telescopes, the primary particle zenith angle, projected on a vertical plane, was measured. Greisen[11] has shown that if the zenith angle distribution is of the form $\cos^n\theta$, then the projected zenith angle distribution is of the form $\cos^n\theta_{\text{proj}}$. We expect this type of distribution if the charged particles producing showers have come undeviated through the atmosphere from outer space, or if, in case they are the progeny of a cascade phenomenon

---

†† Corrected for showers produced by μ-mesons.

[9] G. Cocconi and K. I. Greisen, Phys. Rev. 74, 62 (1948).

[10] J. E. Treat and K. I. Greisen, Phys. Rev. 74, 414 (1948).

[11] K. I. Greisen, Phys. Rev. 61, 212 (1942).

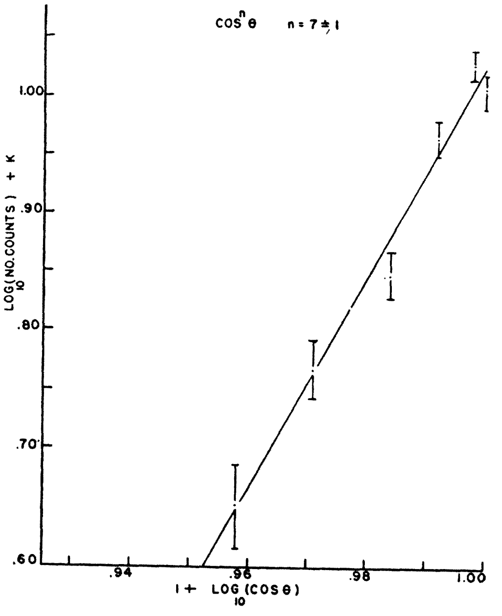

FIG. 6. Zenith angle dependence of primaries producing coincidences $A^1B^1C^{>3}D^{>1}$ (at Echo Lake).

(see Ratio of Charged to Neutral Primaries), they maintain the initial direction. The zenith angle distribution would then be of the form $\exp[-l/\lambda\cos\theta]$, l being the depth of the atmosphere, and λ the mean free path for disappearance. It will be noticed that $\exp[-n/\cos\theta]\approx e^{-n}\cos^n\theta$ for $n\leq 8$, $\theta\leq 30°$.

$A^1B^1C^{>3}D^{>1}$[‡‡] was selected as the coincidence to be studied for two reasons. First, A^1B^1 was necessary in order that the direction be determined. Second, a complex event was chosen to insure smaller background due to showers produced by μ-mesons. The corresponding rate was not measured in Ithaca, and no correction for meson-produced showers was made.

The number of primaries from each direction was multiplied by a weighting factor determined by the following geometrical considerations:

(1) The number of telescopes available decreases with angle. (Telescopes whose inclination and position were such that the secondaries might miss the bottom row were not counted.)

(2) Counters forming large angle telescopes are farther apart.

(3) Inclined particles may go through two counters in a given row, and will sometimes not be counted in this measurement. This decreases the area of the telescope by a factor of $(2\cos\theta-1)\approx\cos^2\theta$. This correction was reduced slightly because the sensitive areas of the counters were not immediately adjacent.

The weighted results of this tabulation are shown in Fig. 6. The zenith angle dependence is seen to be $\cos^7\theta$, and since $l=700$ g/cm² at Echo Lake, this gives $l/\lambda=7$; $\lambda=100$ g/cm² as the mean free path for absorption of the primaries in air.

In Figs. 7, 8, and 9 are plotted the zenith angle distributions of the primaries for the simplest type of coincidence (uncorrected), i.e., $A^1B^1C^3$, for $I=II=0$, $III=8$-in. Pb at Echo Lake (Fig. 8), for $I=0$, $II=8$-in. Pb, $III=8$-in. Pb at Echo Lake (Fig. 7), and for $I=II=0$, $III=8$-in. Pb at Ithaca (Fig. 9). From Greisen's measurement[11] we expect the zenith angle distribution for μ-mesons to be approximately $\cos^2\theta$, or likely even less steep because only mesons of energy above 10^9 ev produce such showers with much probability. We see that the zenith angle distributions for this simple event are not as sharp as for the more complex one shown in Fig. 6, and also that the curve becomes less steep with more absorber, either air or lead, above the apparatus. This is what we expect if part of these coincidences are the result of meson-produced showers, although a real variation of the mean free path of the N component with energy may be a contributing factor. However, these results do show that even the simplest coincidence at Ithaca, or with the maximum amount of lead on the apparatus at Echo Lake, was not entirely background caused by knock-ons of μ-mesons. The fraction, α, of the coincidences $A^1B^1C^3$, $I=II=0$, $III=8$-in. Pb, caused by μ-mesons is known approximately, so one may attempt to correct the zenith angle curves for this background by subtracting $\alpha\cos^2\theta$ from the curve. The results of this subtraction give a curve (see Fig. 10) which is of the form $\cos^{7.3}\theta$. This is in agreement with the zenith angle dependence for the more complex showers that were not corrected for showers produced by μ-mesons. As mentioned above, a zenith angle dependence of $\cos^{7\pm1.2}\theta$ implies a mean free path in air of 100±17 g/cm². This value of λ is somewhat smaller than that obtained by Tinlot[1] (118±2 g/cm²) but the difference

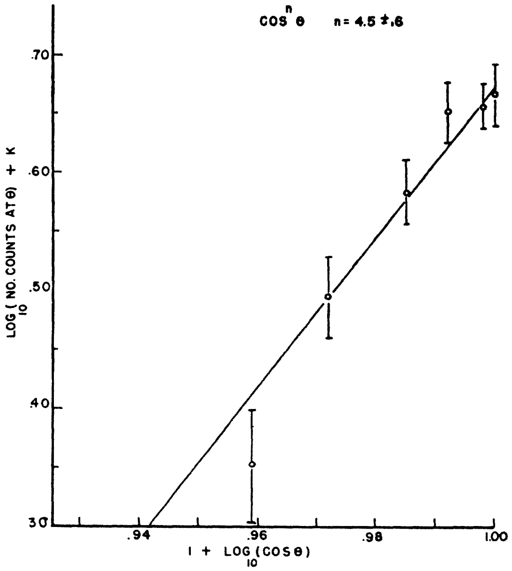

FIG. 7. Zenith angle dependence for primaries producing coincidences $A^1B^1C^3$ ($I=0$, $II=8$ in., $III=8$-in. Pb, at Echo Lake).

[‡‡] Also coincidences were accepted in which 3 counters were struck in row C, but with at least one counter separated from the other two by one counter space.

is within the statistical errors of the present measurements.

V. PROPERTIES OF THE SECONDARY PARTICLES

A. Range and Identity

In order to study the absorption of the secondary particles, one would like to observe the variation in the number of secondaries penetrating a lead absorber of variable thickness, these particles having been produced in a thin generator above the absorber. Actually we measured the rate of coincidence $A^1B^{>1}C^{>2}$, corrected for showers produced by μ-mesons, with $I=0$, $II=6$ in., and III variable. We assume that in this arrangement II is the generator and III is the variable absorber.

It is necessary to point out that there is an uncertainty of 6-in. Pb in the absorber thickness because of the thickness of the generator. However the *increase* in absorber thickness upon addition of absorber in position III is known accurately. If the absorption were exponential the effect of a given increase in the absorber thickness would be to produce the same fractional decrease in counting rate, regardless of the initial thickness. Therefore the use of a thick generator does not change the shape of an exponential absorption curve, but merely changes the position of the zero point. Also, as mentioned in Neutral *vs.* Charged Primaries, back projected secondaries can produce coincidences of this type. Cocconi and Tongiorgi¶¶ have found that such particles have a very short mean range (½ in.–¼-in. Pb), so that this effect should be constant after the addition of the first ½-inch of absorber in position III. In the first ½ inch of absorber III some shower production will make the apparent absorption a little too small.

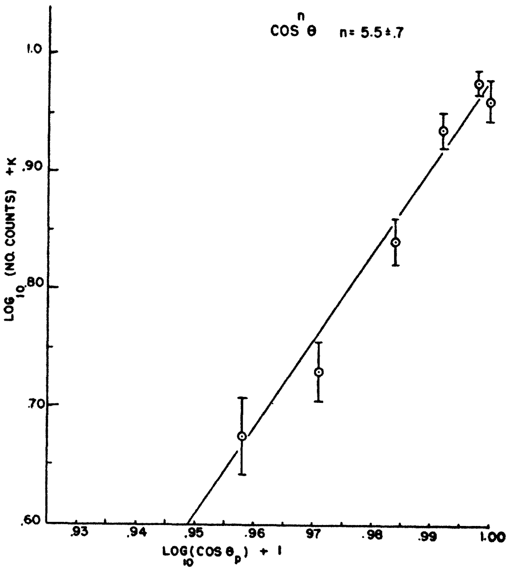

FIG. 8. Zenith angle dependence for primaries producing simple coincidences $A^1B^1C^3$ ($I=0$, $II=0$, $III=8$-in. Pb at *E.L.*).

The curves, both uncorrected and corrected for background showers produced by mesons, are given in Fig. 11.|| || The corrected curve has several interesting features. The first of these is the presence of many short range particles. The second feature is that the curve seems to have two distinct types of secondaries, one type having short range and another having long range.

The identity of the short-range secondaries is a point of interest. There are several possibilities:

a. Slow mesons
b. Electrons
c. Nuclear fragments (protons, α's, etc.)

We now consider the first possibility. From the range curve given in Fig. 11 it is seen that most of the short range component is absorbed out in 2–3 inches of lead. If $III=8$-in. Pb, only showers producing coincidences $A^1B^1C^{>2}$ (i.e., showers starting in III), can have short range secondaries capable of reaching row D. On the other hand, showers with long range secondaries could produce coincidences $A^1B^1C^{>2}$ or $A^{>0}B^{>1}C^{>2}$. The probability of stopping in the aluminum about D, having reached row C, is greater for a short range secondary than for a long range one. If the short range component and the long range component are each composed of about the same fraction of mesons, we would expect the coincidences $A^1B^1C^{>2}$ to be accompanied very much more often by delayed counts than coincidences $A^{>0}B^{>1}C^{>2}$. In Table VI is a comparison of rates with and without delayed counts.

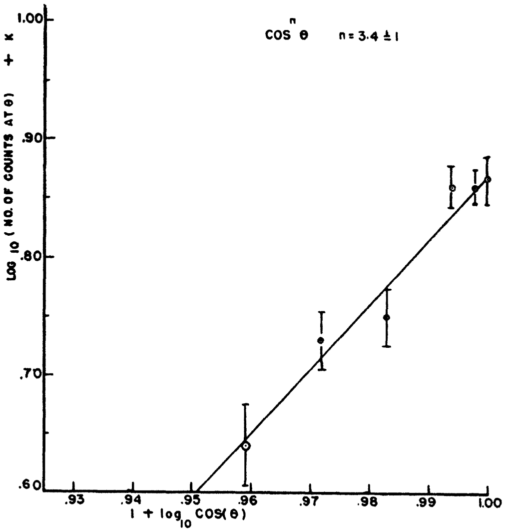

FIG. 9. Zenith angle dependence of primaries producing coincidences $A^1B^1C^{>2}$ ($I=II=0$, $III=8$-in. Pb at Ithaca).

¶¶ The author wishes to thank Drs. G. and V. T. Cocconi for communicating their results to him.

|| || As noted on the curve, the point $III=0$ was obtained from another coincidence, $A^1B^1C^{>2}$, with a different disposition of lead ($I=II=0$, $III=8$ in.). Consequently, this point gives only the order of magnitude.

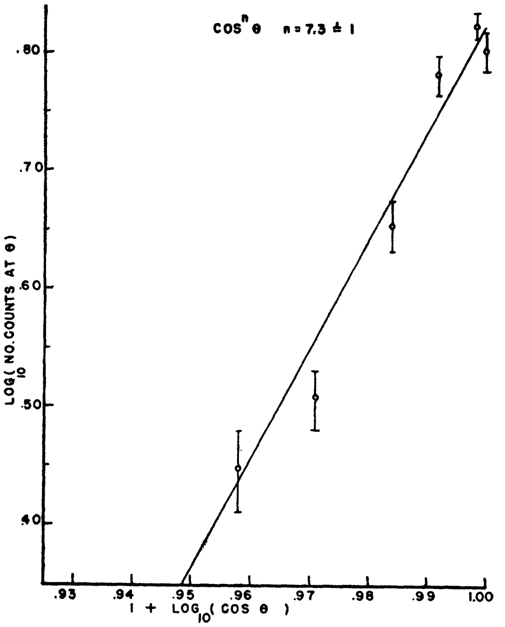

FIG. 10. Corrected zenith angle dependence for primaries producing coincidences $A^1B^1C^3$ ($I=II=0$, $III=8$-in. Pb at Echo Lake).

We see that mesons comprise a much larger fraction of the penetrating secondaries than of the non-penetrating, and that the fraction of the non-penetrating particles which are the mesons is extremely small.

According to Bridge and Hazen,[12] electrons in penetrating showers occur mostly in those of high energy which are much less numerous than showers of lower energy. According to the same authors, the lower energy showers occasionally have mesons but are usually composed of nuclear fragments. Therefore it is thought that the strong initial absorption is the absorption of nuclear fragments from such showers.

Next we shall attempt to interpret the less steep portion of the curve. In the following analysis we make the assumption that for each counter struck in row C there is only one particle.* In a shower of three particles only one must be absorbed in order that the shower not be recorded. Showers of four particles may lose one and still be recorded, etc. To carry such an analysis further we must know the relative number of coincidences $A^1B^{>1}C^3$, C^4, etc., for each value of absorber III. Plotting the frequency of $A^1B^{>1}C^N$ *versus* N ($N\geqslant 3$) for a given thickness of III, we obtain a curve of the form $N^{-\gamma}$ with $\gamma=2.67$. The slopes of all such curves seemed to be independent of the amount of absorber III from $III=2$-in. Pb to $III=8$-in. Pb. An example of such a curve is Fig. 12. (When II was changed to 6-in. C, the value of γ was unchanged.)

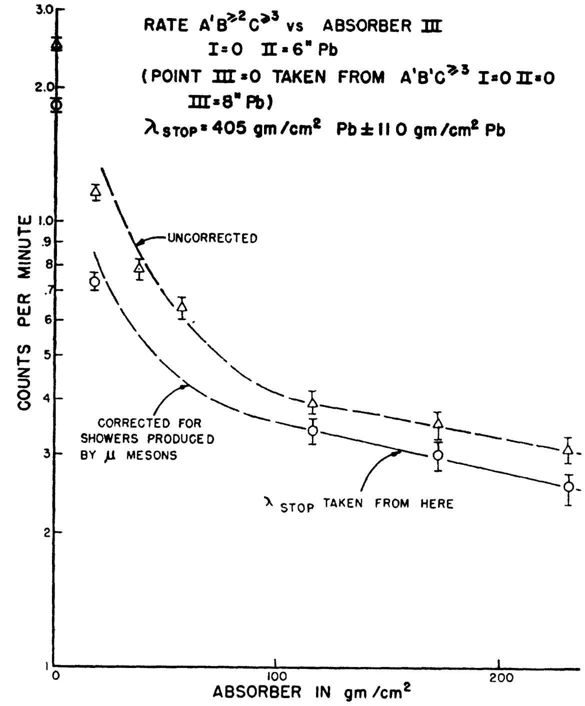

FIG. 11. Absorption of secondary particles produced in penetrating showers.

If λ_s is the mean free path for stopping of a secondary particle, then the probability that 3 particles traverse x without stopping is $\exp[-3x/\lambda_s]$. The probability of a particle stopping in x is $(1-\exp[-x/\lambda_s])$.

Let $N(K, x)=$ counting rate of $A^1B^{>1}C^K$ for $III=x$. Then

$$\begin{aligned}
N(3, x) &= N(3, 0)\exp[-3x/\lambda_s]+N(4, 0)\exp[-3x/\lambda_s] \\
&\quad\times[1-\exp[-x/\lambda_s]]4!/3!1! \\
&\quad+N(5, 0)\exp[-3x/\lambda_s] \\
&\quad\times[1-\exp[-x/\lambda_s]]^2 5!/3!2!+\cdots \\
&= N(3, 0)\exp[-3x/\lambda_s] \\
&\quad\times[1+[N(4, 0)/N(3, 0)]4[1-\exp[x/\lambda_s]] \\
&\quad+\cdots \\
&\approx N(3, 0)\exp[-3x/\lambda_s][1+4(3/4)^\gamma x/\lambda_s+\cdots] \\
&\approx N(3, 0)\exp[-3x/\lambda_s][1+2x/\lambda_s+\cdots] \\
&\approx N(3, 0)\exp[-x/\lambda_s].
\end{aligned}$$

Consequently λ_s for a secondary particle is obtained directly from the slope of the graph in Fig. 12 and is approximately 405 g/cm^2. This sets an upper limit on the true value of λ_s because one counter discharge may correspond to more than one particle striking the counter.

Of the coincidences $A^1B^{>1}C^{>2}$, about one in 150 showed a delayed count (see Table VI). From the absorption curve one expects about one particle in seven to stop in the aluminum surrounding the counters of tray D. Calculating the efficiency of the detecting

---

[12] H. Bridge and W. Hazen, Phys. Rev. 74, 579 (1948).

* The validity of this obviously depends on the geometry of the showers. By limiting our analysis to the smallest showers we hope that this condition will be more nearly fulfilled.

TABLE VI. Comparison of total coincidence rate with that accompanied by delayed counts.

	$I=0$, $II=2$-in. Pb, $III=8$-in. Pb	
Coincidence	$(A^{>0}B^{>1}C^{>2})$ corr.	$(A^1B^1C^{>2})$ corr. (for μ-mesons)
Total rate	0.52 ± 0.02 min.$^{-1}$	1.31 ± 0.03 min.$^{-1}$
$+D$ delay	0.0035 ± 0.0008 min.$^{-1}$	0.0049 ± 0.001 min.$^{-1}$
Mesons per coincidence	1/150	1/270

system for decay electrons (taking into account capture, geometrical loss, time loss) we get 1/43. However, some of the counters of tray D will be struck by the shower particles, making them insensitive to delayed electrons. This decrease in efficiency for recording delayed counts has been estimated to be a factor of 2.†

Consequently,

$$1/150=\bar{N}_\pi/(2\times 43\times 7)$$
$$\bar{N}_\pi=4.$$

$\bar{N}_\pi$ = average number of mesons incident on tray D in a shower producing a coincidence of the form $A^1B^{>1}C^{>2}$.

Piccioni[13] has shown that all, or nearly all, of the mesons produced in penetrating showers are π-mesons. In the calculation of the efficiency of the detecting system it was assumed that there are equal numbers of $\pm\pi$-mesons. The average energy of the decay electron was assumed to be about 40 Mev. As a result of possible errors in these assumptions and in other approximations made in this calculation the results could be wrong by a factor of at most 2.

In coincidences of the type selected above, on the average, four counters were struck in row C. As these coincidences are thought to be caused by showers of four particles penetrating 8 inches or so of lead, the above analysis would indicate that a large fraction of the particles stopping are π-mesons.

Since most of the long range secondaries are π-mesons, the flat portion of the range curve is approximately the integral range spectrum of π-mesons at production. Sands[14] has fitted the altitude variation of slow mesons by assuming the integral range spectrum at the point of production to be of the form $(R+\beta)^{-\alpha}$. The flat portion of the absorption curve in Fig. 11 may be fitted by this expression with the following values of β and α.

$$\alpha=1.6,\quad \beta=310 \text{ g/cm}^2 \text{ Pb}$$
$$\alpha=1.7,\quad \beta=460 \text{ g/cm}^2 \text{ Pb}.$$

Sands' values were as follows:

$$\alpha=1.9,\quad \beta=350 \text{ g/cm}^2 \text{ Pb } (200 \text{ g/cm}^2 \text{ air}).$$

The agreement with the production spectrum of the mesons in the atmosphere indicates that the penetrating showers (and the subsequent π-μ-decays) are probably the mechanism of origin of the μ-mesons. Moreover, the small absorption indicates that π-mesons of moderate or low energy are not stopped by nuclear interactions, in agreement with the conclusion of Piccioni (reported at New York meeting of Physical Society in 1948 and at Echo Lake Conference in June, 1949). π-mesons may, however, have nuclear interactions in which they are not stopped.

C. Angular Spread

In studying the angular distribution of the secondary particles, the direction of reference is naturally the direction of the primary particle. To define an angle precisely we must also know the starting point of the shower. Therefore, it is difficult to obtain precise information because this apparatus has only three full rows of counters.

In this investigation we have chosen to use the coincidences $A^1B^{>2}C^{3,4,5}$ with absorbers $I=0$, $II=4$ in.

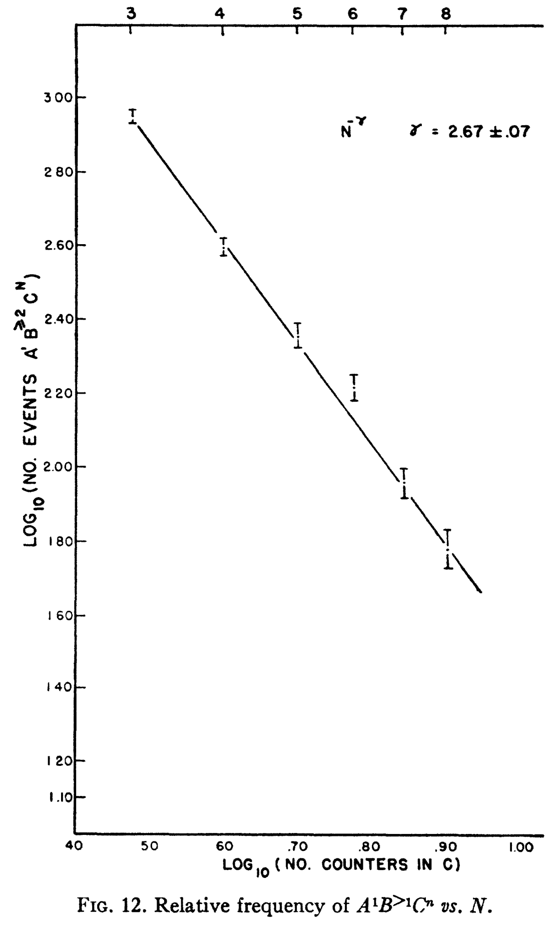

FIG. 12. Relative frequency of $A^1B^{>1}C^n$ vs. N.

---

† Because decay electrons have a short range (a 40-Mev electron has an average range of about 2 in. in Al), the electron from a meson is most apt to be detected near the point of stopping. In an average shower one or two counters will be struck in row D. If a meson of the shower stops, it will probably stop close (within 3 or 4 inches) to the counter struck. The decay electron can at most reach 4 counters in this region, and if two of the counters are dead then the probability of a delayed count being recorded is reduced by one-half.

[13] O. Piccioni, Bull. Am. Phys. Soc. 75, 1281 (1949).

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

TABLE VII. Range of secondaries.

Type of coincidence	Absorber (Pb) I	II	III	Rate Echo Lake (min.$^{-1}$)	Rate (min.$^{-1}$) Ithaca	Rate Echo Lake / Rate Ithaca	Fraction due to μ-mesons	Corrected rate (Echo Lake) (min.$^{-1}$)
$A^1B^1C^{>2}$	0	0	8 in.	2.52±0.03	0.61 ±0.02	4.13	0.272	1.83±0.03
$A^1B^{>1}C^{>2}$	0	6 in.	1.5 cm	1.17±0.04	0.35 ±0.02	3.35	0.378	0.73±0.04
$A^1B^{>1}C^{>2}$	0	6 in.	8 in.	0.31±0.02	0.058±0.007	5.35	0.176	0.26±0.02
$A^1B^{>1}C^{>2}$	0	6 in.	6 in.	0.35±0.02	0.058±0.007	6.04	0.142	0.30±0.02
$A^1B^{>1}C^{>2}$	0	6 in.	4 in.	0.39±0.015	0.058±0.007	6.7	0.115	0.34±0.02
$A^1B^{>1}C^{>2}$	0	6 in.	2 in.	0.64±0.03	No exp.			
$A^1B^{>1}C^{>2}$	0	6 in.	$1\frac{1}{4}$ in.	0.78±0.05	No exp.			

and III = 8-in. Pb. The origins of the showers were thereby located in absorber II, 13 in.±2 in. above row C. The angular separations of the penetrating secondaries were indicated by the counters struck in row C, while the reference direction or shower axis was determined by the line joining the counter struck in row A with the center of the group of counters struck in B.

Several features of this measurement should be noted. First, the angular distribution is obtained only for those secondaries capable of penetrating at least the 8-in. Pb in absorber III. Second, the results are limited to small showers (3 to 5 counters struck in row C), so that there should not be too much likelihood of several particles crossing a single counter, although some such effect undoubtedly occurs and tends to make the observed average angular spread too large. Third, it is possible that the angular distribution in the larger showers, which in general must have higher primary energy, is different from the angular distribution observed in these showers of few particles. Fourth, the angular interval defined by a counter in row C is pretty well known (0.08±0.013 radian), so that the projected angular spread between two secondaries does not have great uncertainty; but the direction of the shower axis is not very certain because more than one counter in row B is struck. This error, like that due to several particles crossing a single counter, tends to make the observed average deviation too large.

The results of this tabulation of data are given in Fig. 13. The number of times counters were struck when separated by n counters (i.e., $n-\frac{1}{2}$ to $n+\frac{1}{2}$) from the axis of the shower is plotted against the displacement, n. The curve indicates that the penetrating secondaries (those which traverse at least 8-in. Pb) show a strong tendency to be in the forward direction, although some do go off at large angles from the direction of the primary.

These data, as explained above, set an upper bound on the average angular spread on the secondaries. The average displacement, measured from the curve, is approximately 2 counters or 0.17 radian. Because only projected displacements were measured, this value should be multiplied by $\sqrt{2}$, so that we may say from this data that $\bar{\theta}<0.25$ radian. Considering the errors discussed above, $\bar{\theta}$ could be as small as 0.15 radian.

Assuming that the penetrating secondaries are mesons, in order to traverse eight inches of lead they must have momentum, p, greater than $3\mu c$ (where μ is the meson mass), and $\mu c/p$ must be less than 0.33. If the average angular divergence were of the order of $\mu c/p$,[‡] then $\bar{\theta}<0.33$ radians. If, on the other hand, the angles of the secondaries were distributed uniformly in the center of mass system, velocities being greater than that of the center of mass, then $\bar{\theta}\approx(2M/E_0)^{\frac{1}{2}}$.[¶] ($M$ and E_0 are the mass and energy of the primary.) Assuming the primaries to be protons, and setting 10^{10} ev as an upper limit on their average energy, we obtain $\theta\geqslant(2\times1/10)^{\frac{1}{2}}=0.45$ radians. We see that the second assumption is not consistent with these data, but that the data are consistent with smaller angular spreads, of the order of $\mu c/p$.

B. Mesons Produced Locally

The purpose of this part of the experiment was to estimate the number of low energy mesons locally

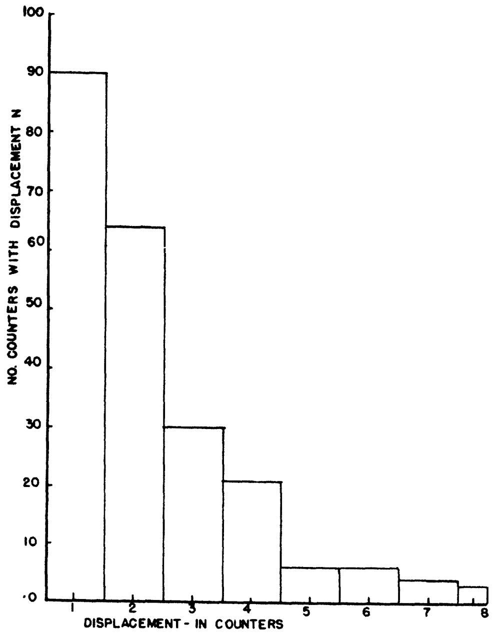

FIG. 13. Histogram. No. counters struck with displacement N vs. N, displacement from center of shower.

[‡] According to the scalar theory of mesons. See Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[¶] According to the symmetric pseudoscalar theory (Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948)).

produced, relative to the number of μ-mesons arriving from the air and stopping. The apparatus was triggered on the coincidence $A^{>0}B^{>0}C^{>0}+D_{\mathrm{delayed}}$ (between 1 and 4 μ-seconds). Using a delay discriminator, the lifetime of the meson was continuously checked (see Fig. 14).

Any simple coincidence, $A^1B^1C^1+D$ delayed, with the counters A, B, and C approximately in line, was attributed to a μ-meson arriving from the air. (Only in $\frac{1}{2}$ percent of the cases was there scattering which could not be accounted for by multiple scattering.) The next simplest coincidence, with two adjacent counters struck in any one row, could be the result of either local shower production, or a μ-meson plus a knock-on, or an inclined μ-meson. Mesons which stop in the apparatus have a very small probability of producing an energetic knock-on.[4] (See IIIB.) A calculation of the probability that any two adjacent counters will be struck by a single meson gives about 0.03 per row. This is seen, from Table VIII to be about the frequency of such a coincidence for rows B and C.

Any coincidence more complex than those mentioned above, i.e., two counters separated by one counter or three counters struck, etc., were thought to be caused by local shower production. A meson that stops in the aluminum could hardly be the primary of such an energetic shower; hence the meson must be a secondary particle produced in the shower.

The data from this experiment are given in Table VIII.

A coincidence in which several counters were struck in the top row could have been caused by a meson associated with an air shower. With regard to this possibility, it should be pointed out that, although the above data were taken with many different configurations of lead on the apparatus, there was always at least 230 g/cm² distributed between I, II, and III, and for about 85 percent of the experiment this included 57 g/cm² in I. In all, there were some 50 coincidences in which at least two non-adjacent counters were struck in row A. Certainly a large fraction can be accounted for by penetrating showers produced in $I=57$ g/cm² or in the roof above the apparatus, and by back projected particles from II. Therefore, we shall assume that most of these coincidences were caused by local shower production.

In order to find the fraction of the mesons that are produced locally, it is necessary to estimate the relative efficiency for detecting them. The efficiency for detecting mesons in showers is smaller than that for detecting single mesons for several different reasons. We estimate the various components of the efficiency as follows, the relative efficiency being the product of all of them.

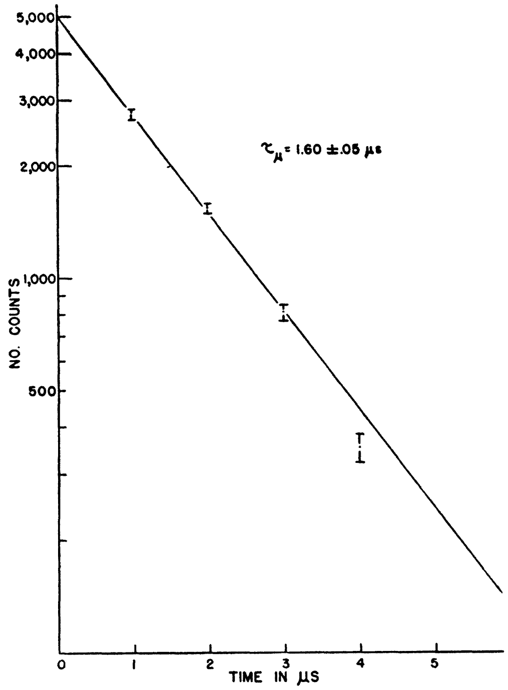

FIG. 14. Integral lifetime curve of mesons in aluminum.

TABLE VIII. Mesons produced locally *versus* mesons arriving from outside.

	Single mesons $A^1B^1C^1+D$ del.	Penetrating showers	$A^1B^1C^2$ tog. $+D$ del.	A^1B^2 tog. C_1 $+D$ del.
No. of cases	3490	212	134	88
Percent of total cases	86.3	6.2	3.9	2.6

(1) With 57 g/cm² Pb in I the efficiency for detection of the mesons that are produced by neutrons is about $\frac{1}{3}$ that for those produced by charged particles. The ratio of local showers produced by neutral particles to those produced by charged particles is approximately 0.9 from the section above. Therefore the efficiency factor is $1.3/1.9=0.7$.

(2) Since the locally produced mesons are π's, only the positive ones will be detected by π-μ-e-decay, whereas, of the μ-mesons arriving from the air, about $\frac{1}{3}$ of the negative mesons, as well as the positive ones will undergo decay. The factor, taking into account the shorter lifetime of the negative μ-mesons is 0.8.

(3) Because in a penetrating shower, on the average, $1\frac{1}{2}$ counters will be struck in row D, the efficiency for detecting the delay electron is smaller than that for a single meson, which will strike a counter in D with a probability of $\frac{1}{2}$. Since the decay electron can reach only about 4 counters in the region the efficiency factor is about 0.7.

As a result of these three factors, the efficiency for detecting mesons locally produced is $0.7\times 0.8\times 0.7=0.4$ of the efficiency for detecting mesons arriving singly from the air.

Since the fraction of mesons locally produced, detected by the apparatus, was 0.07, we have

$$\frac{0.07/0.4}{0.93+0.07/0.4}=0.16=\text{the fraction of mesons stopping}$$

that are produced locally.

The lifetime curve for mesons arriving from the air is shown in Fig. 14. The lifetime of the mesons produced locally was measured by measuring the delay times

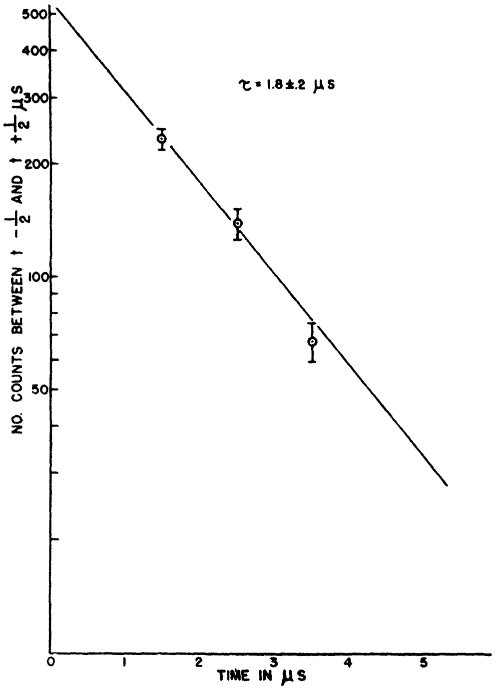

FIG. 15. Differential lifetime curve of mesons in penetrating showers.

associated with $A^{>0}B^{>0}C^{>2}+D$ delay. The differential lifetime curve obtained is given in Fig. 15. We expect a lifetime of about 2.15 μsec. (only π-mesons). The lifetime obtained from this curve is nearer 1.8 (±0.2 μsec. standard error). Repeated checks were made on the circuits, but nothing wrong could be found. The widths of the delay channels were measured and found to be equal to each other to within 5 percent. The reason for this discrepancy is not known at the present time, but the probability of a fluctuation of this magnitude is not very small. Also note that both curves, Fig. 14 and Fig. 15, err in the same direction by roughly the same amount, and that background effects such as that due to chance coincidences would make errors in the opposite direction.

CONCLUSIONS

From the data presented, the following conclusions have been drawn:

1. The mean free path for absorption or shower production of the charged primary particles decreases with increasing primary energy.
2. There are approximately equal numbers of charged and neutral particles producing penetrating showers, and the primary neutrons seldom change to protons without the production of a penetrating shower.
3. The charged primary particles have a very strong zenith angle dependence, indicating a mean free path in air of 100±17 g/cm^2.
4. There are large numbers of short range secondaries produced in penetrating showers; most of these particles are not mesons and are probably electrons or nuclear fragments (protons, α-particles, etc.).
5. The penetrating secondaries of a penetrating shower are projected mostly in the direction of the primary particle. The angles of divergence could be of the order of $\mu c/p$ if the secondary particles are mesons, μ and p being the mass and momentum of the secondary. A large fraction of these particles, probably almost all, are π-mesons.
6. At Echo Lake an appreciable fraction of the mesons which stop in our lowest absorber are locally produced in the absorbers above it. Considering the production by neutral as well as charged particles and the difference in efficiency of the apparatus for π- and μ-mesons and for single mesons as compared with those occurring in showers, we estimate the fraction of the slow mesons that are locally produced to be about 0.16.

ACKNOWLEDGMENT

The author wishes to thank Professor K. I. Greisen, at whose suggestion this work was undertaken, for his very generous aid, both in planning the experiment and in the analysis and presentation of the data. He also wishes to thank his wife for her help throughout the experiment.

The author is much indebted to Drs. Cohn and Iona of Denver University for their help and for making available the facilities of the Inter-University High Altitude Laboratory. He is grateful to the Research Corporation for a grant which made possible the stay at Echo Lake.

The expense of constructing the equipment was covered by an ONR contract.