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The Absorption Mean Free Path of Large Hard Showers in Air*

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In this report an experiment is described in which altitude curves of hard showers of various sizes produced in a lead block were obtained. The sizes were determined by means of a hodoscope; for the largest hard shower group a minimum energy of 260 Bev was estimated by extrapolation to the top of the atmosphere. All altitude curves show an exponential absorption in the atmosphere with a mean free path of $\sim$125 g cm^{-2}. It appears that these large attenuation lengths are difficult to reconcile with a geometric collision mean free path for a nucleon-nucleus collision.

I. INTRODUCTION

IN the spring and summer of 1950 an experiment was carried out in which the altitude dependence of the rate of penetrating showers of various sizes produced in a lead block was measured. At the time it was hoped that such altitude curves might yield some information about the dependence, if any, of the collision mean free path of primaries on their energy. Unfortunately the importance of secondaries even in this high energy region was not sufficiently appreciated and as a consequence the experimental results were not unambiguous with respect to a clear differentiation between the collision and the absorption mean free paths.

In the last two years new theories[1] concerning high energy nucleon-nucleon collisions have been published and the existence of some new particles established[2-4] and it will be necessary to perform calculations to see to what extent these new factors involving the primary act succeed in explaining the grosser features of the cosmic radiation. The data obtained in this experiment might be useful as a parameter in such calculations and they are presented in this spirit.

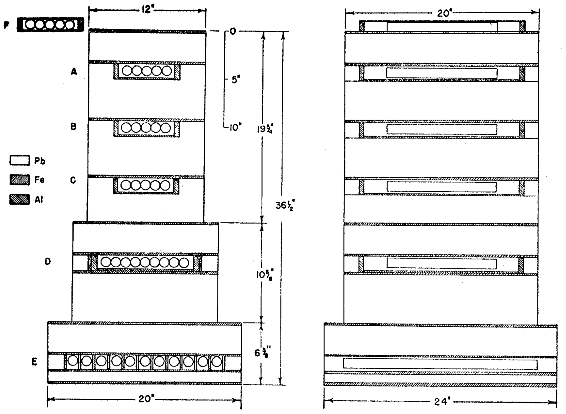

FIG. 1. Cross-sectional view of the counter tube and absorber assembly.

II. APPARATUS

Cross-sectional views of the absorber and counter tube assembly are shown in Fig. 1. Each of the counter trays A, B, C, and F had a sensitive area of 340 cm^2, trays D and E had sensitive areas of 610 cm^2 and 1420 cm^2, respectively. The absorbers, from top to bottom, were 3 in. (86 g cm^{-2}), 4 in. (115 g cm^{-2}), 4 in., 6 in. (172 g cm^{-2}), 8 in. (230 g cm^{-2}), and 1 in. (29 g cm^{-2}) of lead. Steel plates, $\frac{1}{4}$-in. thick, were inserted at various levels indicated in the diagram to give the shield mechanical rigidity. The counters were housed in thin-walled aluminum boxes; those of tray E were separated by $\frac{1}{4}$-in. steel spacers to reduce the chance of multiple firing in that tray due to knock-ons and electron cascades starting in the lead above it. The absorbers were left unchanged throughout the course of the experiment.

The circuit, associated with the counter assembly, consisted of two major parts: (a) a coincidence circuit which generated a master pulse P whenever at least one counter in tray A, at least two counters in tray B, and at least two counters in tray C were discharged simultaneously, and (b) a hodoscope which displayed by means of neon bulbs all those counters in trays D and E which were discharged in coincidence with the master pulse P. The resolving times in the two circuits were shorter than 2 microseconds; as a result all chance coincidences were negligible. P events were caused mainly by hard showers generated in the lead above tray B; the hodoscope permitted classification with respect to their size. Separate neon bulbs also indicated whether a given P event resulted from the firing of one or at least two of the counters in tray A, $P(A_1)$ or $P(A_2)$, and whether or not the P pulse was in coincidence with a pulse from one (or more) of the counters in tray F, $P(F)$ or $P(-F)$; i.e., whether it was an "extensive" or a "local" hard shower. The F tray was used only during the White Mountain part of the experiment. The P pulse also actuated a mechanical register and operated the shutter of a camera which

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* The flight time was made available by the ONR and the Air Forces.

[1] E. Fermi, Prog. Theoret. Phys. **5**, 570 (1950); Phys. Rev. **81**, 683 (1951).

[2] G. D. Rochester and C. C. Butler, Nature **160**, 855 (1947); also Seriff, Leighton, Hsiao, Cowan, and Anderson, Phys. Rev. **78**, 290 (1950).

[3] C. O'Ceallaigh, Phil. Mag. **42**, 1032 (1951).

[4] Fowler, Menon, Powell, and Rochat, Phil. Mag. **42**, 1040 (1951).

photographed the panel on which the mechanical register and the hodoscope neon bulbs were displayed.

The equipment was flown in a heated plywood box in the bomb bay of a B-29 at 37,000, 30,000, and 23,000 feet. Subsequently, the equipment was operated at White Mountain Laboratory at an altitude of 10,000 feet. At each altitude, except 23,000 feet, about 10,000 *P* counts were obtained. The 23,000 foot altitude was abandoned when it became apparent that the counting rate of *P* pulses was too low to make B-29 flights at that altitude practical. After the flights the B-29 pressure altimeter was recalibrated in the laboratory and the four altitudes were found to correspond to 222, 305, 418, and 720 g cm^{-2} of air. The apparatus was checked hourly during the B-29 flights and daily at White Mountain; subsidiary counting rates obtained during these checks, and the rate of *P* events in separate time intervals at a given altitude always agreed within statistical error.

Except for one flight at 30,000 feet to a geomagnetic latitude of 52°N, all the data were gathered at 42°N. As no latitude effect was observed, the 30,000 foot data from both latitudes were combined.

TABLE I. Counting rates of *P* events at four altitudes.

1 Altitude (g cm^{-2})	2 Time (h)	3 Total *P* count	4 *P* rate (h^{-1})	5 ($A_1B_1C_1$) (min^{-1})	6 *P* rate corr.* (h^{-1})
222	12.5	9597	770 ±8	238 ±2	763 ±8
305	28.3	10,648	376 ±4	187 ±1	372 ±4
418	6.0	847	141 ±4.5	131 ±2	138 ±4.5
720	877.3	11,408	13.0±0.1	54.8±0.5	11.7±0.1

* Corrected for *P* events produced by μ-mesons causing knock-on discharges in both trays *B* and *C*.

During the run at White Mountain, the daily record of the apparatus was compared with solar flare data. No correlation was observed.

III. THE ABSORPTION MEAN FREE PATH

The counting rates of *P* events at the four altitudes are listed in Table I. It has been shown[5] that approximately 0.04 percent of the single μ-mesons passing through a lead absorber produce knock-ons in two successive counter trays imbedded in the lead; such double knock-ons constitute the most serious cause of spurious *P* events. In the last column of Table I the *P* events resulting from this cause have been subtracted using the single meson rate given in column 5. The four corrected points fall on a straight line on a semilogarithmic plot and yield an absorption mean free path of 118.5 ±0.4 g cm^{-2} of air, in excellent agreement with the results of Tinlot[6] and other investigators.[5,7]

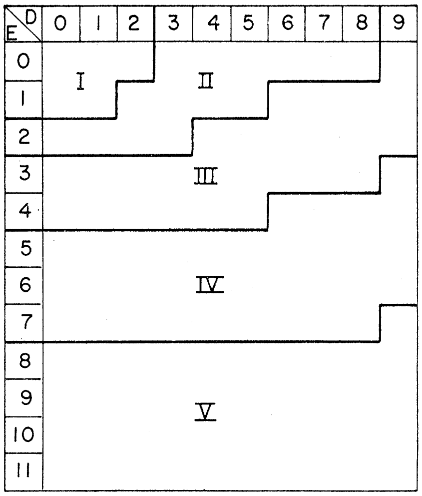

FIG. 2. Boundaries of the hard shower size groups of the array $P(m, n)$.

The hard shower data gathered at each altitude were next classified by means of the hodoscope according to the number of counters discharged in trays *D* and *E*, and arranged into a rectangular array $P(m, n)$; $P(m, n)$ is the number of events *P* with *m* counters discharged in tray *D*, and *n* counters discharged in tray *E*. Each array was then divided into five categories of increasing hard shower size as shown in Fig. 2. The boundaries in the array $P(m, n)$ were chosen as follows: assuming that the particles which discharged the counters in trays *D* and *E* were the only particles produced in the hard shower, the energy corresponding to each element of the array $P(m, n)$ was calculated from range-energy relations and the production spectra of Camerini.[8] The boundaries were then drawn through equienergetic regions and the data of each region were combined.

Figure 3 shows the counting rates of the five hard shower size categories at the four altitudes; it appears that for all hard shower sizes the altitude points may be fitted by straight lines. For each hard shower size the corresponding absorption mean free path resulting from a least squares analysis is also listed. When the array $P(m, n)$ was subdivided into five regions with substantially different boundaries, essentially the same results as above were obtained.

In order to obtain the actual absorption mean free paths from the measured values, a Gross correction due to the finite acceptance solid angle of the instrument must be applied. An approximate calculation based on geometric reasoning indicates that the actual absorption mean free paths are about 10 percent larger than the observed values.

Next, an attempt was made to correlate the hard shower size as exhibited on the hodoscope with the energy of the particle which produced the shower.

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[5] E. P. George and A. C. Jason, Proc. Phys. Soc. (London) **A63**, 1081 (1950). See also J. Tinlot, unpublished, Massachusetts Institute of Technology, Technical Report (ONR) No. 18, p. 17.

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

[7] J. J. Lord, Phys. Rev. **81**, 901 (1951).

[8] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

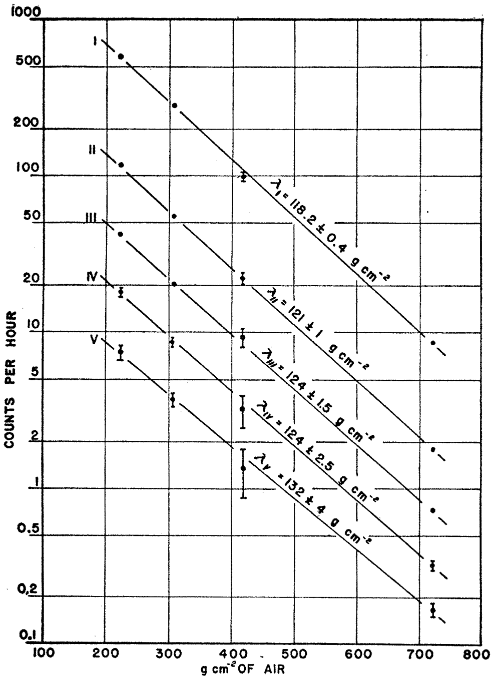

FIG. 3. Absorption curves of hard showers of the five size categories in the atmosphere. The listed values of the mean free path have not been corrected by the Gross transformation.

The energy scale which results from considerations indicated before in connection with the choice of hard shower size boundaries is very likely to be a severe underestimate of the energy of the incident particles for the following reasons: (a) Hard showers are not well collimated and hence some fraction of the particles produced in the original hard shower will miss trays D and E. (b) Particles with insufficient energy to reach tray D, neutral particles, and many electronic cascades resulting from the decay of neutral π-mesons of the original hard shower will not be recorded. (c) In the case of large hard showers several particles may pass through a given E counter. (d) The penetrating particles resulting from the original hard shower are capable of producing hard showers and may disappear by such nuclear encounters. The last point merits closer examination. The collision mean free path of high energy nucleons in lead is geometric, $\lambda_{\mathrm{Pb}}=160$ g cm^{-2},[9] and photographic evidence favors a geometric cross section for π-mesons also.[8] The lead between trays A and D, and A and E was equivalent to 2.5 and 4 mean free paths, respectively. As a result it appears very likely that most of the particles which cross trays D and E are the descendants, after several generations,[10, 11] of the particles which were produced in the original hard shower which produced the P event. It is therefore reasonable to consider the number of D and E counters discharged as *a measure of the penetration of a hard cascade into the lead block.* Electronic cascades may also be formed in the lead but their effect cannot be disproportionately large, especially in the case of the mutually shielded E counters, since according to Greisen[12] the chance of recording a 1-Bev photon, for example, under 160 g cm^{-2} of lead is less than 2 percent. On the other hand, there is the possibility that occasionally a hard shower may appear more energetic because one of the hard shower particles produces a secondary event in the immediate vicinity of one of the counter trays. An investigation of the hodoscope record, as to the relative number of events when the number of E counters discharged was considerably larger than the number of D counters discharged, revealed that such events comprise about 10 percent of the total in each size category; this will not affect the conclusions of this experiment.

TABLE II. Extrapolation of the flux at 37,000 ft to the top of the atmosphere and comparison with the spectrum of the primaries.

Shower size	Differential shower size distribution at 37,000 ft	Vertical flux of shower generators[a] at 37,000 ft (cm^2 sec sterad)$^{-1}$	Extrapolated flux at the top of the atmosphere[b] (cm^2 sec sterad)$^{-1}$	Estimated[c] energy band Bev
I	7231	3.3×10^{-3}	1.8×10^{-2}	14–43
II	1449	6.6×10^{-4}	3.5×10^{-3}	43–75
III	520	2.4×10^{-4}	1.2×10^{-3}	75–125
IV	228	1.1×10^{-4}	5.4×10^{-4}	125–260
V	93	4.3×10^{-5}	2.0×10^{-4}	260–∞

[a] $t=12.48\times3600$ sec; solid angle × area $=65.5$ cm^2 sterad; detection efficiency $=[1-\exp(-\bar{x}/\lambda_{\mathrm{Pb}})]=0.74$.
[b] Extrapolation factor $=\exp(222/\lambda_{\mathrm{air}})$.
[c] Using the primary spectrum of Winkler (see reference 13).

In view of the important role which secondary production plays in an apparatus of this sort, the energy scale computation mentioned before was considered merely as a guide in arranging the hard showers as to their size, under the assumption that in the majority of the hard showers the "apparent" energy obtained from this energy scale is related to the true energy in a monotone fashion.

A better estimate of the energy of the particles which generate the hard showers may be obtained by extrapolating the 37,000 foot data to the top of the atmosphere using the altitude curves. The differential hard shower size distribution of the second column of Table II was first converted to an incident vertical particle flux per cm^2 sec sterad. In this calculation the expression $[1-\exp(-\bar{x}/\lambda_{\mathrm{Pb}})]=0.74$ was used for the detection efficiency of shower generating particles, where $\bar{x}$ is the average thickness of lead above tray B; 65.5 cm^2 was used for the area-solid angle product of the apparatus (computed for a $\cos^2\theta$ distribution which presumably exists at 37,000 feet). The energy limits for the five hard shower size groups were then obtained by com-

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[9] K. Sitte, Phys. Rev. **78**, 714 (1950); W. D. Walker, Phys. Rev. **77**, 686 (1950).

[10] Cocconi, Cocconi-Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).

[11] M. B. Gottlieb, Phys. Rev. **82**, 349 (1951).

[12] K. Greisen, Phys. Rev. **75**, 1071 (1949).

TABLE III. Ratio of P events in which more than one counter in tray A is discharged to P events which are due to a single discharge in tray A.

Shower size	Altitude 222 g cm^{-2} ϕ	 305 g cm^{-2} ϕ	 720 g cm^{-2} ϕ
I	0.95±0.02*	0.96±0.02*	0.86±0.02*
II	1.31±0.07	1.20±0.06	1.25±0.06
III	1.74±0.14	1.49±0.12	1.57±0.13
IV	2.04±0.27	2.21±0.29	2.33±0.31
V	4.5 ±1.1	6.0 ±1.4	6.3 ±1.5

* Corrected for double knock-on phenomena of μ-mesons.

parison of the extrapolated flux with the primary spectrum published by Winkler and collaborators.[13]

According to this computation 14 Bev is the smallest energy a particle must have to be able to produce a recordable hard shower. This is in accord with the absence of a detectable latitude effect during the flight to 52°N geomagnetic latitude and is also substantially in agreement with the measurements of Walsh and Piccioni[14] who concluded from the latitude effect which they observed that for their apparatus the minimum energy was approximately 10 Bev. This reasonable result suggests that the extrapolation procedure is satisfactory *per se* in the low energy region where the primary particle spectrum is known with some precision and questions of ordering the showers into sizes do not arise. At the high energy end the results are rendered much less certain both by the difficulties of reliable size classification and also by the scant knowledge of the primary spectrum. Winkler *et al.* have assumed that in the energy region beyond that accessible to geomagnetic measurements, the primary spectrum goes over into Hillberry's $E^{-1.75}$ power law. Recent experiments[15,16] suggest that the spectrum of primaries is considerably flatter in the high energy region; in that case the energy values given in Table II are underestimated. On the whole, in view of these uncertainties the energy limits of the large hard shower sizes can be considered no better than estimates correct within a factor of 2.5.

To a first approximation the $P(A_1)$ events are mainly hard showers generated between trays A and B and produced predominantly by charged particles; the $P(A_2)$ events, originating in the lead above tray A, can be caused by both charged and neutral particles. If one neglects the hard showers originating above the apparatus and hard showers generated below tray A which contain particles projected backward which cross tray A, then roughly

$$P(A_2)=(N_c+N_n)\{1-\exp(-x_1/\lambda_{\text{Pb}})\}P_1, \tag{1}$$

$$P(A_1)=N_c\exp(-x_1/\lambda_{\text{Pb}})\{1-\exp(-x_2/\lambda_{\text{Pb}})\}P_2, \tag{2}$$

and

$$\phi=P(A_2)/P(A_1)\sim 1.4(P_1/P_2)(1+N_n/N_c), \tag{3}$$

where x_1 and P_1 are the thickness of lead above tray A and the probability of observing a hard shower originating there, respectively, and x_2 and P_2 are the corresponding quantities for the lead between trays A and B. The effect of the back-projected particles is difficult to assess; if one assumes, for example, that each hard shower has a back-projected particle whose range in lead is 1.25 cm,[11] then

$$\phi\sim 1.9(P_1/P_2)(1+0.7N_n/N_c). \tag{4}$$

The ratio P_1/P_2 must be smaller than one both because trays D and E subtend a larger solid angle when viewed from below tray A than when seen from above A; also generally larger energies are required to produce showers of a given size (as registered on the hodoscope) when they originate above tray A.

The ratios ϕ corresponding to different altitudes and shower sizes are shown in Table III. Since it is hard to see how the ratio N_n/N_c could become appreciably larger than one in this energy region where ionization losses are negligible, it appears that some other phenomenon is contributing to increase ϕ for the largest shower size at all altitudes. Showers originating above the apparatus or a greatly increased number of high energy back-projected particles, or both, could explain this result. To decide between these possibilities tray F was added during the operation of the apparatus at White Mountain. Such an "extension" tray should be very sensitive to electronic showers which are known to accompany hard showers in air.

IV. THE WHITE MOUNTAIN DATA

The detailed results obtained at White Mountain are presented in Table IV. The first four columns list the

TABLE IV. Breakdown of data gathered at 10,000 ft with respect to discharges in the extension tray F and multiple discharges in tray A.

Shower size	(1) $P(A_2, -F)$	(2) $P(A_1, -F)$	(3) $P(A_2, F)$	(4) $P(A_1, F)$	(5) $\phi(-F)$	(6) $P(F)/P$	(7) $\phi(F)$	(8) $\phi(F)_{\text{corr}}$[b]
I	3248[a]	3947[a]	207	90	0.82±0.02[a]	0.040±0.002[a]	2.3±0.3	1.54±0.23
II	793	690	102	24	1.15±0.06	0.078±0.007	4.3±1.0	3.1 ±0.8
III	323	234	70	17	1.38±0.12	0.135±0.016	4.1±1.1	2.9 ±0.85
IV	115	71	82	14	1.62±0.25	0.34 ±0.04	5.9±1.7	4.3 ±1.3
V	32	15	94	5	2.13±0.65	0.68 ±0.09	19.0±8.0	14.0 ±6.0

[a] Corrected for double knock-on phenomena of μ-mesons.
[b] Corrected for cascade shower particles penetrating to counter tray A according to $\phi(F)_{\text{corr}}=0.77\phi(F)-0.23$.

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[13] Winkler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[14] T. G. Walsh and O. Piccioni, Phys. Rev. **80**, 619 (1950).

[15] Unpublished report ESN **6**, 1 (1952). Report on work by D. H. Perkins, R. Daniel, J. Davies, and J. Mulvey.

[16] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

number of P events subdivided according to whether they were due to a discharge of a single counter in tray A or several, and whether or not they were accompanied by discharge(s) in tray F. Column (5) presents the ratios $\phi(-F)$ of $P(A_2)$ and $P(A_1)$ counts not accompanied by discharges in tray F; $\varphi(-F)$ remains compatible with Eqs. (3) and (4) for all shower sizes. It seems reasonable, therefore, to interpret the large values of ϕ obtained previously (Table III) as due to atmospheric events, rather than caused by back-projected particles (for which a very artificial angular distribution would have to be assumed).

Column (6) lists the ratios $P(F)/P$ of P events accompanied by discharges in tray F to all P events in each size group. This ratio for the data of all size groups together is 7 percent in fair agreement with the results of Tinlot,[6] but the contribution of atmospheric events increases with increasing shower size and becomes predominant for size V showers.

In view of this close association between P events and air showers it becomes important to investigate to what extent the electronic component in the atmospheric events could have been instrumental in discharging counters in the lead block. That electronic cascades could not penetrate the lead block to the extent of causing P events may be seen at once: the contribution of atmospheric events to the P rate for the small shower sizes is quite small; furthermore, Cocconi *et al.*[17] have shown that 40 radiation units of lead effectively stop the electronic component of air showers. However, the effect of the electronic component can take another form; an atmospheric shower may arrive at the apparatus inclined, the N-component in this shower produces the P event but some of the counters in trays D and E are discharged by electrons scattered through the rather inadequate shielding on the sides and ends. Spurious results of this sort certainly cannot be ruled out on the basis of the present data, but it can be shown that they cannot constitute an important contribution to the counting rate of large P events. In the first place it is well known that for altitudes larger than 350 g cm^{-2} of air the intensity of air showers decreases with increasing altitude;[18,19] the altitude curves recorded here show no change in slope near 350 g cm^{-2} of air. At 10,000 ft, where the information supplied by tray F was available, the following analysis was carried out. Tray E was actually exposed at its ends much more than tray D. Therefore, in the presence of an air shower ($P(F)$ event) there should be more P events with a large number of E counters but few D counters discharged than in the absence of an air shower. An analysis of the data of size V showers showed that about 10 percent of the $P(F)$ events could be explained as due to electronic cascades. If it is assumed that this contribution due to air showers existed only at 10,000 ft then the measured value of the absorption mean free path should be reduced by about 1.5 percent.

The increase of the ratio $P(F)/P$ with hard shower size has been previously observed.[20] It has been interpreted qualitatively as follows: most of the particles creating penetrating showers at mountain altitudes are secondaries of interactions occurring farther up in the atmosphere. The higher the energy of particle generating the penetrating shower in the lead block the higher is the energy of the interaction in which this particle was created, and the higher, on the average, the energy of the other particles produced in the same event and the greater their collimation. Both of the last-mentioned effects would tend to increase the probability of observing other secondaries in addition to the P event generator. The ratio $P(F)/P$ is a measure of this probability.

The ratios $\phi(F)$ of $P(A_2)$ and $P(A_1)$ events which are accompanied by discharges in tray F are listed in column (7) of Table IV. The ratios obtained in this case are considerably larger than the corresponding ratios $\phi(-F)$. This must be due, at least in part, to the fact that the 3 in. of lead above tray A were inadequate to stop the electronic component. It has been shown[6,20] that the electronic cascades accompanying the N-component are relatively dense, of the order of 200 particles per m^2. Thus it is reasonable to suppose that, had tray A been completely unshielded, it would have been discharged in every $P(F)$ event by the electronic component also. If this premise is accepted then it is possible to calculate how many of the $P(A_1, F)$ events appeared as $P(A_2, F)$ events because of the penetration of the electron cascades to tray A. It has been found that 3 in. of lead over *one* counter tray of a set, detecting extensive air showers, reduces the rate of coincidences to 23 percent,[21,22] hence 23 percent of the $P(A_1, F)$ events will be recorded as $P(A_2, F)$ events. When a correction based on this argument is applied to $\phi(F)$, according to $\phi(F)_{\text{corr}} = 0.77\phi(F) - 0.23$, the last column of Table IV results. The ratios $\phi(F)_{\text{corr}}$ are still larger than the ratios $\phi(-F)$ and the discrepancy appears to increase with hard shower size.

V. CONCLUSIONS

The experiment suggests that the absorption mean free path, or perhaps more accurately the attenuation length, of hard showers of all sizes investigated here remains in the vicinity of 125 g cm^{-2} (before Gross correction). By extrapolation to the top of the atmosphere an energy larger than 260 Bev was assigned to the largest hard shower category. The attenuation length observed is approximately twice that which would result from a geometric cross section (67 g cm^{-2} of air). This is in agreement with the results of many

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[17] Cocconi, Cocconi-Tongiorgi, and Greisen, Phys Rev. **75**, 1063 (1949).

[18] Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949).

[19] H. L. Kraybill, Phys. Rev. **76**, 1092 (1949).

[20] Greisen, Walker, and Walker, Phys. Rev. **80**, 535 (1950).

[21] Auger, Daudin, Freon, and Maze, Compt. rend. **228**, 178 (1949).

[22] G. T. Reynolds and W. D. Hardin, Phys. Rev. **74**, 1549 (1948).

investigations at lower energies and also with the results of Christy *et al.*[23] in essentially the same energy region and altitude range. For heavy materials the results of investigations by diverse techniques all indicate that the collision cross section is geometric; for light materials the results are not so clear-cut; some experimenters[24,25] have obtained an approximately geometric collision mean free path in carbon, while others[26,27] have observed some transparency.

Since the attenuation length observed in air is longer than the geometric mean free path it would be important to decide to what extent this lengthening is due to the contribution of secondaries originating farther up in the atmosphere and producing hard showers in the apparatus. That secondaries do contribute cannot be doubted in view of the existence of $P(F)$ events. This is also in accord with the finding of several investigators[11,20] that at mountain altitudes neutrons and protons of a few Bev are equally abundant.

If one assumes that the collision mean free path of the nuclear particles in air is geometric, then a question arises as to the nature of the secondary particles which lengthen the absorption mean free path. These may be of three types: nucleons, π-mesons, and heavier mesons of the V, κ, and τ varieties whose existence has recently been established.

The longest mean life that has been quoted for any of these heavy mesons is 10^{-9} sec[4] for the κ-meson whose mass is reported to be about 1200 m_e. A meson with these properties and an energy of 260 Bev should have a mean range before decay of only about 130 m and can therefore not contribute to the hard showers measured in this experiment. Mesons of comparable mass which decay into π-mesons with even shorter mean lives may, for the purposes of this discussion, be considered as π-mesons.

Many investigators have considered the formation of a cascade of nucleons in the atmosphere. In a most recent paper, Caldirola *et al.*[28] have shown that the fact that the attenuation length is about twice the geometric mean free path may be satisfactorily accounted for if one assumes that the nucleon-nucleon collision cross section is near geometric and that the two nucleons which come out of the interaction share on the average 75 percent of the energy of the incident nucleon, while 25 percent is dissipated in π-meson production. It seems unlikely that such a high degree of elasticity should prevail up to the energies involved here; according to this model 260-Bev nucleons should arise from primaries with 700 Bev, or a total energy of 37 Bev in the C-system. According to Fermi,[1] 8 π-mesons should be created in such an interaction; recent work[15] with photographic emulsions suggests that particles with energies larger than 50 Bev lose about 90 percent of their energy to meson production in nuclear collisions. If 10 percent is adopted as the fraction of the energy of the primary nucleons which is retained by the two nucleons issuing from the collision, then, using the relation in reference 28, secondary nucleons will increase the attenuation length beyond the collision mean free path by about 1 percent for a primary power law exponent of -1.8; even if the fraction of energy retained by secondary nucleons is as high as 40 percent, and the power law exponent[16] is -1.35 the lengthening is only 33 percent.

π-mesons with energies above 260 Bev have mean ranges before decay of 14.3 km and therefore can penetrate most of the lower part of the atmosphere. Assuming that π-mesons and nucleons of equal energy create hard showers of comparable size in the lead absorber, the observed altitude curve of hard showers of a given size should be due partly to π-mesons and partly to nucleons in the specified energy interval. The altitude curve of the π-mesons alone then is of the form

$$N_\pi(x)=k\{\exp(-x/\lambda)-\exp(-x/\lambda_n)\}, \qquad (5)$$

with λ the observed attenuation length, λ_n the attenuation length of nucleons alone and k the extrapolated flux for the given size shower at the top of the atmosphere (Table II). From such a π-meson altitude curve, the number of μ-mesons in a corresponding energy range can be estimated from the well-known constants of the $\pi-\mu$ decay, and this number can be compared with the underground μ-meson spectrum given by George.[29] Such a comparison may be used to adjust the parameter λ_n and yields $\lambda_n=0.92\lambda$ for size V events. It is perhaps worth noting that this procedure is relatively insensitive with respect to the energy extrapolation (Table II) since with an increase of the estimated energy both the number of high energy μ-mesons and also the decay probability of the π-mesons decrease.

In conclusion it would therefore appear that in the energy region investigated here the experimental results cannot be explained without assuming an appreciable nuclear transparency effect. Unfortunately its exact value cannot be assessed until the contribution of secondaries is more closely studied. Such experiments are contemplated.

VI. ACKNOWLEDGMENTS

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[23] Christy, Biehl, Inonu, and Neher, Phys. Rev. **81**, 647 (1951).
[24] R. R. Brown, Phys. Rev. **85**, 773 (1952).
[25] L. Mezzetti and R. Querzoli, Phys. Rev. **79**, 168 (1950).
[26] Walker, Walker, and Greisen, Phys. Rev. **80**, 546 (1950).
[27] H. W. Boehmer and H. S. Bridge, Phys. Rev. **85**, 863 (1952).
[28] Caldirola, Fieschi, and Gulmanelli, Nuovo cimento **IX**, 5 (1952).
[29] E. P. George, *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1951), pp. 403–413.