Mean Free Path of High-Energy Nucleons in the Atmosphere*

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An altitude-variation experiment to determine the absorption mean free path in the atmosphere of high-energy nucleons of the cosmic radiation has been performed using a large ionization chamber and associated counter trays. It is estimated that the nucleons studied in this experiment range in energy from 200 to 2000 Bev, which is a higher energy region than has been investigated previously in similar experiments. The absorption mean free path for protons is found to be 125±9 g/cm² and for neutrons 105±8 g/cm², and the charged-to-neutral ratio is 1.54±0.15. These values are in good agreement with previous altitude variation experiments. There seems to be no change in the mean free path with energy.

These results are compared with the calculations of Olbert and Stora, who consider the Fermi model for nuclear interactions with the assumption of no nucleon-antinucleon pair production and partial elasticity for the collision. It is seen that the experimental values fit fairly well into this picture.

Evidence is presented for the presence of high-energy nucleons near the cores of air showers, in agreement with previous work. If a power law is fitted to the density spectrum of air showers associated with nucleons, a crude value of 0.64 may be found for the exponent. Considering the scarcity of the data on which the evaluation of this particular quantity is based, the result may be considered to be in reasonably good agreement with the only previous determination which is equal to 0.5.

INTRODUCTION

PREVIOUS measurements of the mean free path of high-energy nucleons in the atmosphere have, with the exception of the results of two experiments, yielded values of approximately 130 g/cm².[1–8] This value, however, was subject to question because the two experiments mentioned both gave results close to the geometric value of 65 g/cm² for the mean free path[9,10] (assuming the nuclear radius to be $1.38\times10^{-13}A^{\frac{1}{3}}$ cm). The present experiment was planned to obtain a value of this quantity which would have a smaller statistical error, less experimental uncertainty, and a better defined measure of the nucleon energy than had been possible in earlier work.

The range of nucleon energies is estimated to lie between 200 and 2000 Bev in this experiment. This is a considerably higher range than that of previous measurements with hard-shower detectors and ionization chambers, which were estimated to deal with values from 14 Bev to a maximum of 260 Bev, with average around 60 Bev.[3,5,6,9,10] Higher energies, $\gtrsim$100 Bev, were specially selected in another experiment with emulsion cloud chambers, but relatively few events were obtained.[8]

Absorption in the atmosphere is more easily interpreted than absorption in dense materials,[11] and can be measured in several ways. The method used in the present experiment is the altitude-variation technique. The detector was placed at three different altitudes separated by approximately one absorption mean free path in vertical distance. The attenuation in counting rates as altitude decreased was used, after suitable corrections, to obtain the absorption mean free path desired.

DESCRIPTION OF APPARATUS

The detector used in this experiment consists of a pulse ionization chamber and associated equipment for measuring the energy released in the gas of the chamber. The theory of the pulse ionization chamber has been discussed in detail elsewhere.[12–14]

The internal structure of the double ionization chamber used in this experiment is shown in detail in Fig. 1. The square steel box contains two electrically independent collecting grids separated by a $\frac{1}{4}$-in. lead plate. This plate, and the 1-in. lead plates above and below the top and bottom collecting grids, respectively, act as high voltage electrodes. The collecting grids themselves consist of 10-mil tungsten wires stretched between frames, which are supported as shown by a series of insulators and studs arranged on either side of the lead plates. When in operation, the chamber is filled with argon to a (gauge) pressure of 120±2.5 psi.

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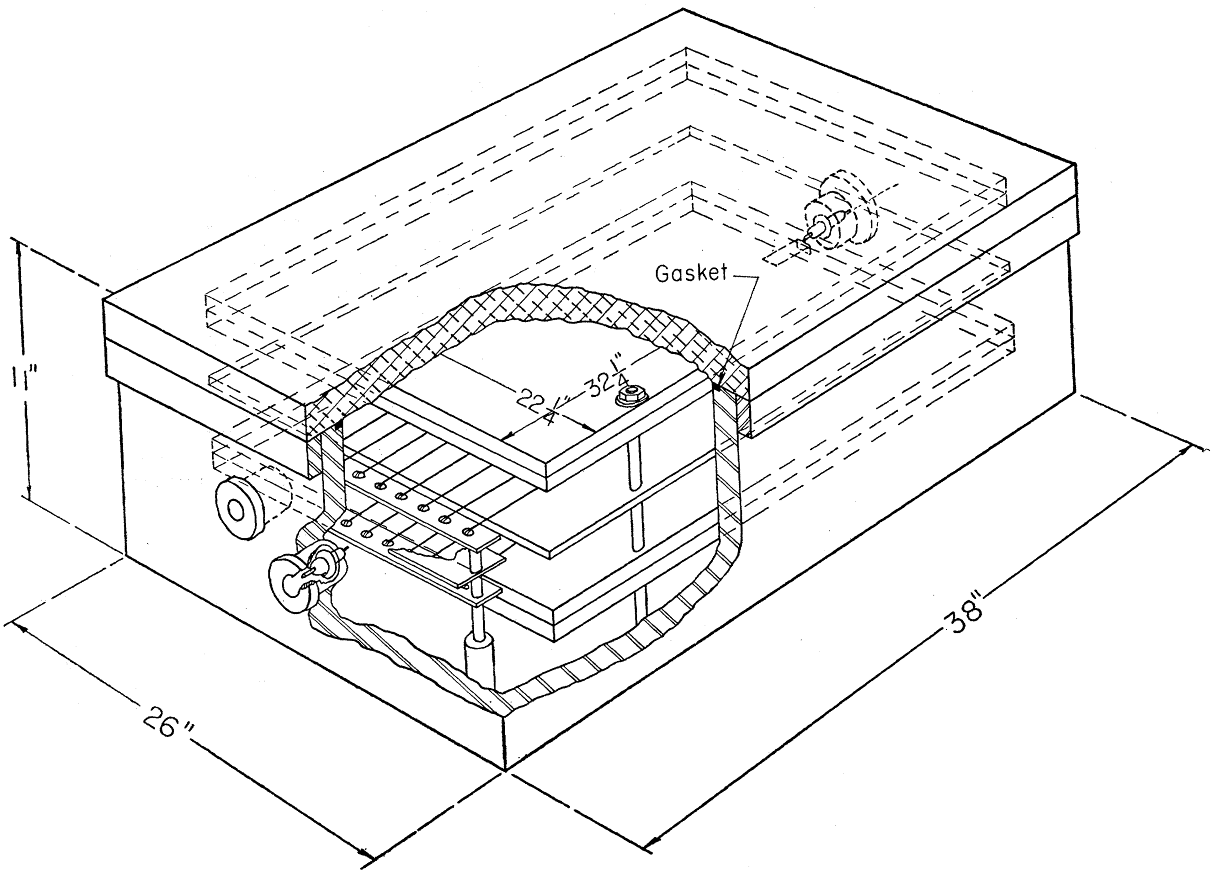

FIG. 1. Cutaway drawing of the double ionization chamber.

Figure 2 shows the large double ionization chamber and its associated equipment in the complete experimental set-up. The 17 in. of carbon of density 1.65 g/cc above the chamber represents 1.60 radiation lengths. When the neutrons, protons, and $\pi^{\pm}$ mesons of the N-component traverse the carbon, nuclear interactions may occur with the resulting production of π^0 mesons, which in turn develop into electron showers by means of the familiar cascade process in the lead plates of the double ionization chamber. Use of low-Z material both for the producing layer and for the cover of the chamber leads to production of a shower whose size is essentially independent of the point of occurrence of the nuclear interaction, since nearly all of the shower development takes place inside the lead plates. The top area of the carbon block is covered completely with a large tray of 45 Geiger tubes, each tube being 4 feet long. This tray is shielded with $\frac{1}{2}$ in. of lead. Below the double ionization chamber there is an 8-in. layer of lead; below the lead layer there is a bottom tray of 24 Geiger tubes. Because of this heavy lead shielding, only penetrating particles will be able to discharge tubes in the bottom tray. These tubes are separated from one another by $\frac{1}{4}$-in. lead spacers to prevent discharge by knock-ons from μ mesons.

Each collecting grid of the ion chamber is connected to the input of a Model 100 preamplifier. The output signal from each preamplifier is shaped into a square pulse by means of delay line clipping and is fed to a series of Model 100 amplifiers. This arrangement may be seen as a part of Fig. 3, which is a block diagram of all the circuitry used in this experiment.

The chamber is calibrated wlth the aid of prepared sources of polonium α particles. The discriminators following the six Model 100 amplifiers shown in Fig. 3 are set for pulse heights which are multiples of the pulse caused by a polonium α disintegration, namely, 9α, 15α, 27α, 81α, and 243α.

Coincidence between the two electrically independent collecting grids is required in order to discriminate against spurious events which are caused by the heavily ionizing prongs of low-energy stars produced near the surface inside a lead plate. To obviate such background, the two discriminators set at 9α for each of the two collecting grids of the main ionization chamber are connected to the inputs of a two-fold coincidence circuit, whose input generates what will be referred to as the master coincidence (see Fig. 3). This master coincidence must be generated in order for any other information to

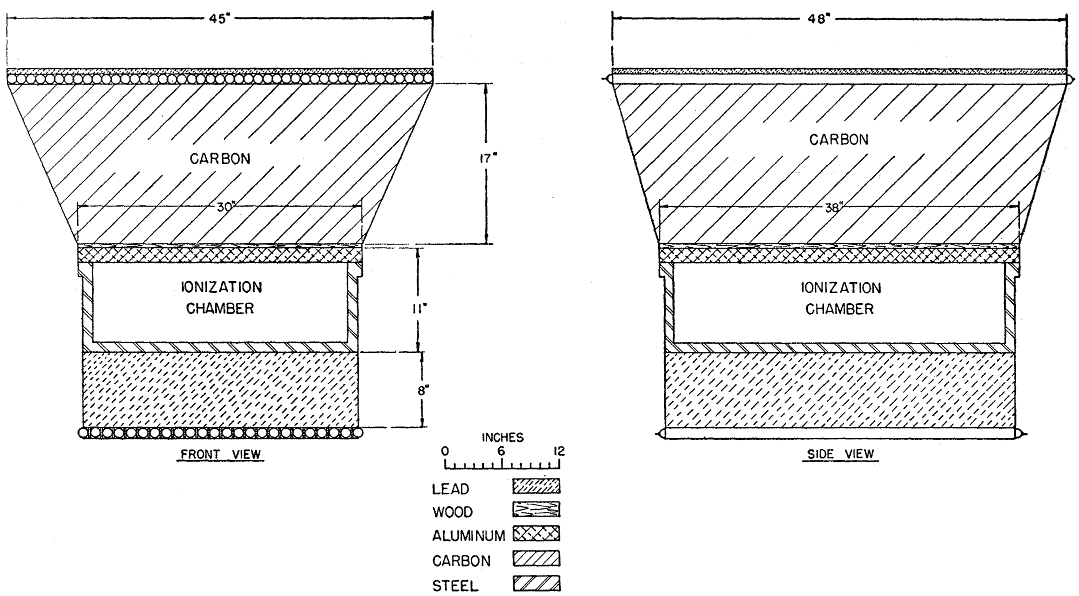

FIG. 2. Double ionization chamber and associated equipment in the experimental setup.

be recorded; it gates the discriminators corresponding to larger pulse heights.

The purpose of the top tray shown in Fig. 2 is to determine whether a charged or an uncharged nucleon initiated the event recorded. The outputs of the Geiger tube pulse-shaping circuits are fed to the input of an adding circuit, whose output in turn is connected to the inputs of two discriminators. The first of these discriminators is set to trip on the pulse from one or more shaped Geiger-tube pulses, the second on the sum of two or more such pulses occurring simultaneously. The outputs of these two discriminators are gated by the master coincidence. Ideally, then, if the initiating nucleon is a neutron, neither of these discriminators will be tripped. If it is a proton or a charged pion, then just the discriminator set at the lower level will record. If, however, a large air shower strikes the apparatus, such that a large number of electrons of this shower passes through the double ionization chamber and gives rise to a pulse, then many tubes of the top tray will be struck and both discriminators will record. The $\frac{1}{2}$ in. of lead shielding above the tray is there to allow development of any high-energy electrons into a shower so that more than one tube of the top tray will be struck. This may avoid the possibility of mistaking a neutron accompanied by an electron for a proton.

The tubes of the bottom tray are arranged in five independent groups. No adding circuits or discriminators are used, so that it is not known how many tubes in a group have been struck when the appropriate group discriminator records.

Not shown in Fig. 2 are two cylindrical ionization chambers of the type described in a previous paper.[13] These were placed away from the main body of the equipment on either side of it at a distance of about 1 meter. Each of these chambers is also equipped with a Model 100 amplifier, whose output is connected as shown in Fig. 3. These chambers can be triggered only by air showers or by stars produced in their thin brass walls. However, because of the coincidence requirements, it is unlikely that pulses caused by stars will be recorded. This is borne out by the data. These ionization chambers are also calibrated with an α-particle source and a pulse from the chambers measured in terms of the α-particle end point can be used to find the density of particles of the electron shower passing through the gas of the chambers.[15]

The actual method of recording the data is unique in that IBM punched cards are used. An IBM Type 517 punch is used to punch the data directly onto the cards, with one card being used for each event. The machine is controlled externally by the register drive circuits shown in Fig. 3, which are triggered when the corresponding coincidence circuits are triggered. With such a system, the analysis is speedy and accurate, since the cards may be fed into other IBM machines which sort out the different types of events as desired.

The apparatus was operated at three different altitudes: at Idaho Springs (7500 ft, mean barometric pressure 58 cm Hg), Echo Lake (10 600 ft, mean pressure 51.7 cm Hg), and on the top of Mount Evans (14 260 ft, mean pressure 46 cm Hg). Barometric pressure records were obtained by a recording barograph calibrated by means of a mercury barometer equipped with a vernier.

ESTIMATE OF THE PRIMARY ENERGY

At the completion of the experiment, 4065 events had been recorded at Mount Evans in a running time of

[15] R. W. Williams, Phys. Rev. 74, 1489 (1948).

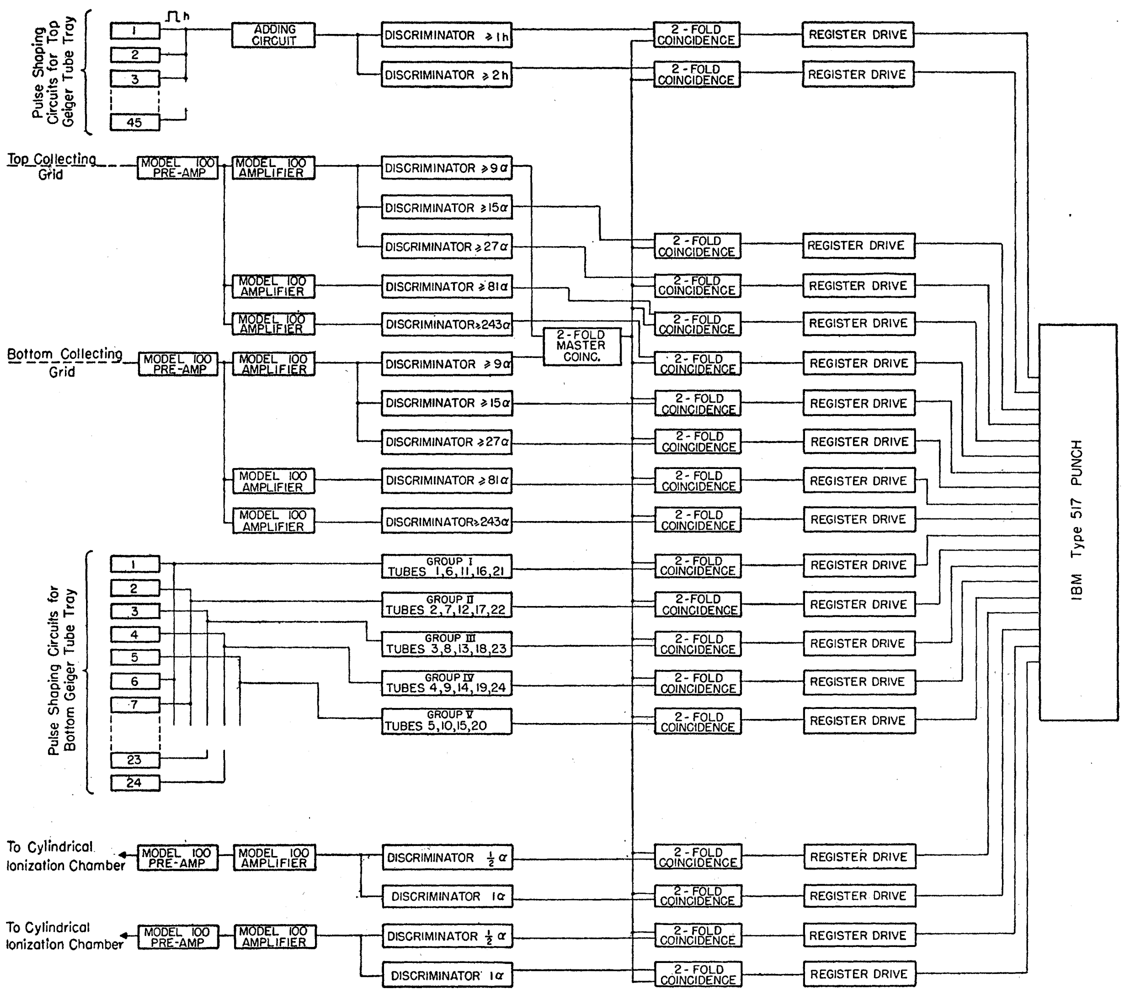

FIG. 3. Block diagram of the circuitry.

155.2 hours, 6127 events at Echo Lake in a running time of 604.5 hours, and 2724 events at Idaho Springs in 573.7 hours.

In performing the analysis of this information, the events are classified according to two criteria, one dealing with the number of tubes struck in the top tray, i.e. none, one, or two or more, and the other dealing with the pulse height recorded in the large double ionization chamber, i.e. $\geq 9\alpha$, $\geq 15\alpha$, $\geq 27\alpha$, $\geq 81\alpha$, $\geq 243\alpha$. More specifically, $\geq 9\alpha$ includes all events from 9α to ∞, $\geq 15\alpha$ includes all events from 15α to ∞, etc. For each pulse-height category above ($\geq 9\alpha$), there are two sets of numbers, one for each half of the chamber. These numbers differ slightly because it is sometimes possible in a single event for the pulse height coming from the top chamber to be in a lower category than that coming from the bottom chamber, or vice versa. This does not happen very often; usually both halves register pulse heights in the same category. Within the statistics, no significance is attached to the difference, and so a simple average is taken of the two numbers in each category. These are then converted to counting rates, which are listed in Table I.

It is possible to obtain from these pulse heights an estimate of energy in the electron shower. Using methods similar to Bridge and Rediker,[11] and the results of Blocker *et al.*,[16] one can find the "local" number of electrons. Shower theory affords a relationship between the number of electrons in a shower at a given thickness of material and the energy of the initiating electron or photon. Because the trajectories of the shower particles are at many angles to the vertical, it was decided somewhat arbitrarily to choose the optimum thickness, i.e., the depth at which a shower initiated by a particle of a particular energy has developed the greatest number of electrons. This may be justified by observing that for initiating particles of high energy the shower curves are flat at the maximum.[17] If this optimum thickness is used, then the number of electrons as a function of the

[16] Blocker, Kenney, and Panofsky, Phys. Rev. **79**, 419 (1950).
[17] Bruno Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 259.

energy E_0 of the initiating particle is given by standard shower theory.[18] The various values of E_0 are listed in Table II.

According to the cloud chamber work of Salvini and Kim[19] and the photoplate observations of Kaplon and Ritson[20] and Kaplon, Walker, and Koshiba,[21] on the average about one third of the energy lost by a high-energy nucleon undergoing an interaction goes into the production of π^0 mesons. If such collisions are assumed to be completely inelastic, then the energy of the initial nucleon is obtained by multiplying the computed photon energy by three, as listed in the last column of Table II. If elasticity is present, then these estimates will have to be raised accordingly. In any case, the error in these estimates is $\pm 50\%$.

CALCULATION OF THE μ-MESON BACKGROUND

In the experimental setup considered here, background pulses may be produced by μ mesons. High-energy photons and electrons may be generated by the familiar processes of bremsstrahlung, knock-ons, and direct pair production undergone by μ mesons passing through the carbon, the aluminum cover of the chamber, or the top lead plate. The evaluation of this background was done theoretically, using a μ-meson spectrum obtained from measurements underground,[22] and taking account of the geometry of the system.

Table I. Total counting rates averaged over both halves of the large ionization chamber. All rates are in hr^{-1}.

Number of counters discharged in top tray	Alt. cm Hg	Ionization chamber pulse height $\geq 9\alpha$	$\geq 15\alpha$	$\geq 27\alpha$	$\geq 81\alpha$
≥ 2	46	14.25±0.25	8.90±0.17	3.70±0.09	0.65±0.04
	51.7	7.87±0.11	4.73±0.07	2.08±0.04	0.38±0.02
	58	3.63±0.08	2.37±0.07	0.90±0.03	0.19±0.02
1	46	1.95±0.09	0.88±0.06	0.28±0.03	
	51.7	1.21±0.04	0.55±0.02	0.16±0.02	
	58	0.58±0.03	0.28±0.02	0.06±0.01	
0	46	1.80±0.09	0.76±0.05	0.22±0.02	
	51.7	1.05±0.04	0.48±0.02	0.13±0.01	
	58	0.54±0.03	0.27±0.02	0.07±0.01	
All events	46	18.00±0.28	10.54±0.19	4.30±0.10	0.68±0.04
	51.7	10.13±0.13	5.76±0.07	2.37±0.04	0.39±0.02
	58	4.75±0.09	2.92±0.08	1.03±0.03	0.20±0.02

At the high energies considered in this experiment, the differential intensity in $\text{sterad}^{-1}\ \text{cm}^{-2}\ \text{sec}^{-1}\ \text{ev}^{-1}$ of μ mesons may be represented as a power law with exponent 3.6. This is multiplied by the sum of the theoretical integral probabilities for the three processes of interest and also by the area-solid angle product for the particular geometry at hand. The resulting expression must be integrated numerically over suitable limits. The final results are listed in Table III. Note that the background for events in the $\geq 27\alpha$ category and above is completely negligible.

[18] Reference 17, p. 260.
[19] G. Salvini and Y. B. Kim, Phys. Rev. **88**, 40 (1952).
[20] M. F. Kaplon and D. M. Ritson, Phys. Rev. **88**, 386 (1952).
[21] Kaplon, Walker, and Koshiba, Phys. Rev. **93**, 1424 (1954).
[22] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).

Table II. Energy calibration of the large pulse ionization chamber. In evaluating the primary nucleon energy, no elasticity is assumed. All energy values in Bev.

Pulse height	Number of electrons	Corrected number of electrons	E_0 Bev	Primary nucleon energy Bev
9α	598	848	60.8	182
15α	998	1416	106	318
27α	1795	2550	198	594
81α	5385	7640	620	1860
243α	16 155	22 900	1960	5880

CALCULATION OF THE MEAN FREE PATH AND CHARGED-TO-NEUTRAL RATIO

It is now possible to find the absolute number of events caused by protons and neutrons arriving upon the apparatus unassociated with air showers within the dimensions of the apparatus. If the background of events caused by μ mesons passing through the top tray is subtracted from the total number of events with just one tube in the top tray discharged, then the resulting counting rate can be ascribed solely to singly charged particles interacting either in the carbon, the aluminum cover, or the top lead plate of the chamber. However, if the same thing is done for events with no tubes discharged in the top tray, the resulting counting rate includes not only interacting neutrons, but also interacting protons or pions which come from the side and do not pass through the top tray. There is enough available information, however, to calculate the number of charged particles falling into this category.

At a given energy and altitude, high-energy nucleons may be considered to have a zenith angle dependence of $\cos^6\theta$.[3] By using experimental determinations of the interaction mean free paths of high-energy nucleons in carbon, aluminum, and lead,[23] and taking account of the zenith-angle dependence and the geometry of the sys-

Table III. μ-meson background from the top lead plate of the chamber, the aluminum cover of the chamber, and the carbon producing layer. Distinction is made between those μ mesons with trajectories passing through the top tray and those arriving from the side. All numbers refer to counting rates in units of hr^{-1}.

		$\geq 9\alpha$ Top	$\geq 9\alpha$ Side	$\geq 15\alpha$ Top	$\geq 15\alpha$ Side
Lead	radiation	0.05	0.26	0.02	0.07
	knock-ons	0.00	0.01	0.00	0.00
Aluminum	radiation	0.02	0.01	0.00	0.00
	knock-ons	0.00	0.00	0.00	0.00
Carbon	radiation	0.10	0.00	0.00	0.00
	knock-ons	0.02	0.01	0.00	0.00
Total		0.20	0.28	0.02	0.07

[23] R. W. Williams, Phys. Rev. **98**, 1393 (1955).

TABLE IV. Counting rates in hr^{-1} corrected for μ-meson background and geometry.

	Alt. cm Hg	Atmospheric depth g/cm²	Ionization chamber pulse height $\geq 9\alpha$	$\geq 15\alpha$	$\geq 27\alpha$	$\geq 81\alpha$
2 or more counters discharged in top tray	46	626	14.25±0.25	8.90±0.17	3.70±0.09	0.65±0.04
	51.7	703	7.87±0.11	4.73±0.07	2.08±0.04	0.38±0.02
	58	790	3.63±0.08	2.73±0.07	0.90±0.03	0.19±0.02
Unassociated charged particles	46	626	1.87±0.09	0.92±0.05	0.30±0.03	
	51.7	703	1.08±0.04	0.57±0.02	0.17±0.02	
	58	790	0.41±0.03	0.30±0.02	0.06±0.01	
Unassociated neutral particles	46	626	1.39±0.09	0.63±0.05	0.20±0.02	
	51.7	703	0.70±0.04	0.37±0.02	0.12±0.01	
	58	790	0.23±0.03	0.18±0.02	0.07±0.01	
All events	46	626	17.53±0.28	10.54±0.19	4.29±0.10	0.68±0.04
	51.7	703	9.66±0.13	5.75±0.07	2.36±0.04	0.39±0.02
	58	790	4.27±0.09	2.92±0.08	1.03±0.03	0.20±0.02

tem, it is possible to determine what fraction of the charged particles passing through the top tray interacted in the carbon, aluminum, and lead, respectively. It is further possible to calculate in a similar manner the numbers of those nucleons which interact in the carbon, aluminum, or lead but do not pass through the top tray, and the resulting numbers may be used to find the ratio of those interacting nucleons which do not pass through the top tray to those interacting nucleons which do. Applying these ratios to the experimentally determined numbers of charged particles passing through the top tray yields the rates for charged particles which do not pass through the top tray but do interact. In order to find the true number of neutron-initiated events, it is simply necessary to subtract from the counting rate for events with no tubes discharged in the top tray both the background rate for μ mesons not passing through the top tray, and the rate calculated above for charged particles not passing through the top tray. Once the corrected charged-particle and neutron events are found, the computation of the charged-to-neutral ratio is obvious. The results, listed in Table IV, are derived from rates in Table I by applying corrections as just described.

By using Table IV, it is possible to calculate the mean free path of neutrons and charged particles in the atmosphere in each of the energy categories. In doing this, it is assumed that the counting rates for a particular energy group lie on an exponential curve:

$$y=Ae^{-x/\Lambda}, \qquad (1)$$

where x is the atmospheric depth in g/cm² and Λ is the absorption mean free path in g/cm². The atmospheric depths listed in Table IV were determined from barographic records by taking a simple mean over the running time at each altitude. With these values of x, the optimum values of Λ and the errors may be found by using Eq. (1) and a method of least squares. The final results, after the application of the Gross transformation,[24] are listed in Table V. These include the mean free paths not only of single neutrons and charged particles, but also of those events with more than two tubes discharged in the top tray, and of all events. It is clear that, within the experimental error, there is no variation with energy.

[24] Reference 17, p. 439.

From the counting rates for neutrons and charged particles listed in Table V, it is a simple matter to obtain the charged-to-neutral ratio. This has been done at all three altitudes for nucleons with energy greater than the minimum, as listed in Table VI.

NUCLEON CASCADE

The results for the absorption mean free path and the charged-to-neutral ratio presented here are in substantial agreement with those obtained in other altitude variation experiments, and in disagreement with the two previously mentioned determinations which are close to the geometric value of 65 g/cm². Therefore it is of interest to compare the present results with a model for the nucleon cascade in the atmosphere.

In attempting to deal with the nucleon cascade, Olbert and Stora[25] of this laboratory have used the Fermi theory[26] of high-energy meson production while at the same time taking account of the fact that the atmosphere is composed of air nuclei and not just of single nucleons. The air nucleus is considered to be a spherical volume containing A nucleons moving at random, and the probability that the incident nucleon collides successively with i nucleons according to Fermi's model can then be computed by using the Poisson dis-

TABLE V. Absorption mean free paths in g/cm².

	$\geq 9\alpha$	$\geq 15\alpha$	$\geq 27\alpha$	$\geq 81\alpha$
≥2	135±4	139±6	130±7	148±20
Charged	124±9	141±20	120±21	
Neutral	105±8	150±28	180±48	
All events	137±3	142±6	130±6	148±20

[25] S. Olbert and R. F. Stora (to be published).
[26] E. Fermi, Progr. Theoret. Phys. Japan 5, 570 (1950).

tribution. Production of nucleon-antinucleon pairs is neglected, since photoplate evidence does not indicate any marked increase of multiplicity with energy. Some elasticity is assumed: otherwise the absorption mean free path which is calculated is too short. Lastly, it is assumed, for the exact expressions to be quoted below, that the $\pi^{\pm}$ mesons produced do not interact again and contribute to the production of nucleons.

The expressions for the charged-to-neutral ratio R and the absorption mean free path Λ are given by

$$R=\left\{\exp\left[\left(1-\frac{\lambda}{\Lambda}\right)\frac{x}{\lambda}\right]+1\right\}\Big/\left\{\exp\left[\left(1-\frac{\lambda}{\Lambda}\right)\frac{x}{\lambda}\right]-1\right\}, \quad (2)$$

$$\Lambda=\frac{\lambda}{1-\zeta^{(\epsilon-1)}}\text{g/cm}^2. \quad (3)$$

The elasticity parameter ζ represents the fraction of the original nucleon energy which the nucleon retains after collision; ϵ is the exponent of the primary differential nucleon spectrum and is taken as 2.5; λ is the collision mean free path of nucleons in air. At an atmospheric depth of 703 g/cm², $\Lambda=125$ g/cm² for charged nucleons of energy greater than 182 Bev (see Table V). If λ is taken to be 100 g/cm², then R is found to be 1.65, which is in good agreement with the experimental value. However, the R in Eq. (2) is the ratio only of protons to neutrons and neglects completely the pion contribution. Thus the closeness of the agreement must be considered fortuitous, unless the pion contribution is small in this energy region.

The elasticity parameter is calculated to be 34%; hence the energy estimates for the primary nucleons must be raised accordingly.

ASSOCIATION OF AIR SHOWERS AND NUCLEONS

The production of π^0 mesons in a nuclear interaction, their subsequent decay into photons, and the development of a cascade shower can take place in the atmosphere as well as in a detector, and the result is known as an air shower. It is known that the core of such an air shower may contain not only a soft component consisting of high-energy electrons and photons, but also a hard component of nucleons capable of causing penetrating showers. Although this experiment was not intended primarily to explore the association of nucleons with air showers, it is possible to obtain some information on this point from the data.

TABLE VI. Charged-to-neutral ratio for all events at each atmospheric depth.

Atmospheric depth g/cm²	$R=C/N$
626	1.35±0.15
703	1.54±0.15
790	1.78±0.36

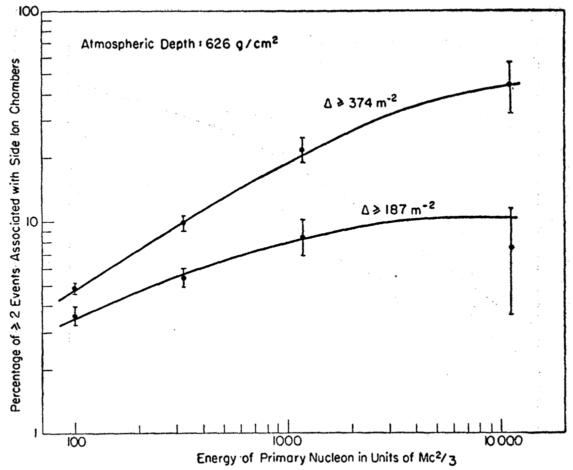

FIG. 4. The percentage of ≥ 2 events in the main chamber accompanied by pulses from the side chamber as a function of one-third the primary nucleon energy, at an atmospheric depth of 626 g/cm².

The events with just one or no tubes of the top counter tray discharged have been interpreted as being due to neutrons, protons or charged π mesons unassociated with air showers. Those events with more than one tube discharged in the top tray may be due only to air showers of sufficient size to trigger the equipment, or they may be due mainly to nuclear interactions accompanied by some air-shower particles.

It is impossible to determine the relative importance of the two types of contributions directly. However, data from the unshielded side ionization chambers mentioned briefly above yield some quantitative information on this question. The calibration of these cylindrical chambers is described in a previous paper[27]; it turns out that the $\frac{1}{2}\alpha$ setting is equivalent to a shower density of 187 particles/m², and the 1α setting to 374 particles/m². It is found that in no case is there a pulse from either of the side ion chambers in coincidence with an event in the main chamber accompanied by just one or no tubes discharged in the top counter tray. Therefore only those events in the main chamber accompanied by a multiple discharge in the top tray will be considered in the following discussion.

Since the side ion chambers are only one meter away from the main chamber, it will be assumed that the density of the air shower striking both side and main chambers is usually the same. Therefore there is reason to believe that for the ≥ 2 events most of the ionization in the main chamber comes as the result of a nuclear interaction, since an air shower with a density of at least 1200 particles/m² would be necessary to trigger the main chamber even if it were completely unshielded. In

[27] Hazen, Williams, and Randall, Phys. Rev. 93, 578 (1954).

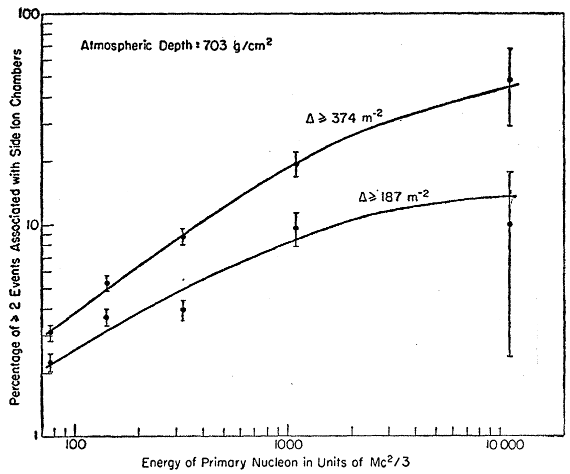

FIG. 5. The percentage of ≥ 2 events in the main chamber accompanied by pulses from the side chamber as a function of one-third the primary nucleon energy, at an atmospheric depth of 703 g/cm^2.

the graphs of Figs. 4 and 5, the percentage of ≥ 2 events in the main chamber accompanied by pulses from the side chamber has been plotted *vs* E_0 (which is one-third the energy of the primary nucleon, assuming no elasticity) in units of Mc^2, the rest energy of a nucleon. This is done for both particle densities at each of two altitudes. As can be seen, for those showers with density Δ greater than 187 particles/m^2, the percentage begins to level off or even to drop at the highest energy recorded in the main chamber, whereas for the curve for showers with density greater than 374 particles/m^2, this percentage is still rising towards 100%, although it is beginning to level off in the highest energy region recorded. The drop in the lower density curve occurs because at higher energies most showers fall in the higher density category.

These results seem to indicate that there is a concentration of the higher energy nucleons near the core of the shower. As can be seen from Table I, there are almost no unassociated nucleons at the highest energies at any altitude, whereas the greater E_0, the greater the percentage of events associated with air showers of the higher of the two densities recorded. This is evidence that the apparatus has been struck closer to the shower core for events initiated by the higher energy nucleons, which is in accord with previous and more detailed work on this subject.[28]

Upon fitting the two values of air shower density to a power law, it is possible to obtain a crude value for the exponent of this power law, without any attempt being made to estimate the error. The results for all energies in the main chamber give a value of 0.62 at an atmospheric depth of 626 g/cm^2, and 0.65 at 703 g/cm^2. Considering the large errors and the lack of more than two points, this is in good agreement with the value 0.5, which is the only other determination of this quantity which has been made.[29]

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