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Penetrating Showers*

W. B. FRETTER
Department of Physics, University of California, Berkeley, California

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Penetrating showers produced in lead have been observed in a large cloud chamber at sea level and 3027 meters. Observations made on the showers include frequency of occurrence, multiplicity, angular distribution, and production of high energy electrons. An attempt is made to compare the numerical data obtained with predictions of various meson theories, assuming that the events are produced by high energy nucleons.

I. INTRODUCTION

THE penetrating showers produced in lead by high energy particles can be observed in cloud chambers. Several experimenters[1] have been able to photograph these rather rare events and draw from them conclusions about the nuclear interactions which they probably represent. Recently[2,3] multi-plate cloud chambers have been used to make detailed analyses of the various types of events which can occur. The present paper will report measurements on penetrating showers observed in a large cloud chamber at sea level and at 3027 meters elevation at Tioga Pass in Yosemite National Park.

The penetrating showers observed have been divided into two main categories, those produced by isolated particles to be called *local* showers, and those produced by particles which are *accompanied* by extensive showers. The types of data obtained from analysis of these showers include: frequencies of occurrence, multiplicity of penetrating particles produced, identification of particles, angular distribution of penetrating particles produced, and simultaneous production of electronic radiation.

II. THE APPARATUS

The cloud chamber, shown schematically in Fig. 1, contained 16 lead plates each $\frac{1}{2}$ inch thick, separated at the center of the illuminated region by approximately 0.8 inch. Photography was with a stereoscopic camera using flash tubes FT-422 (G. E.) with parabolic reflectors for right-angle illumination.

The chamber was counter-controlled, the coincidence arrangement requiring at least one particle through the upper counters and two below the cloud chamber, a fourfold coincidence (Fig. 1) being required. The result of this loose selection of events was that at sea level 75 percent of the pictures showed single tracks, presumably mesons which made knock-on electrons near the lower counters. The remaining pictures were mostly air showers or not identifiable. At 3027 meters, however, the air showers made up 57 percent of the pictures, the single penetrating particles only 28 percent. The frequencies of these and other events will be discussed in the next section.

In addition to the counters used to trigger the cloud chamber, auxiliary counter trays and circuits were used which provided information on whether or not the event observed in the cloud chamber occurred simultaneously with an air shower. An unshielded tray of area of about 1200 cm^2 was located at a distance of about 6 meters from the cloud chamber. If a pulse from this tray occurred coincidentally with a fourfold coincidence of the counters controlling the chamber, a neon light on the side of the chamber flashed and was photographed. Four other counter trays being used in an experiment performed by John Ise, Jr., were similarly connected to neon lights. During the course of the summer, these four other trays were covered with various amounts of lead

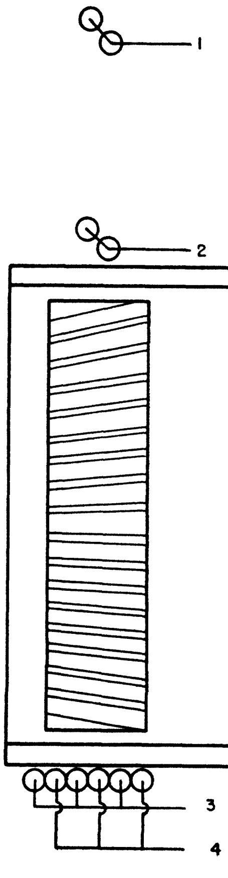

FIG. 1. Experimental arrangement.

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[*] Assisted by the Joint Program of the ONR and the AEC.

[1] W. B. Fretter, Phys. Rev. **73**, 41 (1948) (bibliography).

[2] W. B. Fretter, Am. J. Phys. **17**, 148 (1949).

[3] C. Y. Chao, Phys. Rev. **75**, 581 (1949).

TABLE I. Frequencies of events (all rates per hour).*

Event	Single penetrating particles	Electron showers	Local penetrating showers	Accompanied penetrating showers
Sea level	2.33±0.035	0.503±0.016	0.016±0.003	0.018±0.003
3027 m	2.56±0.05	5.15 ±0.07	0.192±0.013	0.130±0.011

* The probable errors are from statistics only.

and some information was obtained about coincidence of penetrating showers in the cloud chamber with extensive penetrating showers. A separate paper will be devoted to this study and to the study of the air showers observed in the cloud chamber.

The cloud chamber was housed in a thermally insulated trailer with a thin sheet steel roof under which were $\frac{1}{4}$ inch of plywood and 2 inches of glass wool insulation.

III. ANALYSIS OF DATA

A. Frequencies of Occurrence

The total number of penetrating showers observed was: 133 local showers and 93 accompanied showers. In many cases the events were successive, so the total number of penetrating events observed was much larger. In a few cases the accompanied showers did not register a count in one of the extensive shower trays, but the presence of electronic radiation or other penetrating particles simultaneously present in the chamber permitted their classification as "accompanied."

The frequencies of various types of events at sea level and at 3027 meters are given in Table I.

The small increase in the number of penetrating particles is probably not to be taken too seriously. The photographs at high altitudes were not as good quality as those at sea level and there was a higher proportion of pictures in which identification of the event was difficult. Each of the penetrating particles observed must have penetrated more than 20 cm of Pb and made a knock-on in order to be observed, so that only very high energy penetrating particles are observed, and these do not increase very fast with altitude. There is an additional effect of hardening of the energy spectrum as the mesons proceed through the atmosphere; the relatively higher energy mesons at sea level will produce a greater proportion of knock-on electrons than those at 3027 meters. Another important effect is the simultaneous occurrence in a picture of electrons and penetrating particles; these were classed as electron showers and are not included in the rate of penetrating particles.

The electron showers increase by a factor of 10 between the two altitudes, in agreement with other observers.

The penetrating showers accompanied by electron showers increase by a factor of 7.2±1.3. Since the accompanying electron showers are usually responsible for tripping the counters, the factor of increase for these accompanied penetrating showers should be very nearly the same as that for electron showers, and it is believed that the difference is not significant.

The local penetrating showers increase by a factor of 12±2.4. If the particles producing them have an exponential absorption between 3027 meters and sea level, the mean free path for absorption is 123±10 g/cm^2. This is in agreement with the results of Tinlot[4] and indicates we are probably observing the same phenomena.

Tinlot and Gregory[5] concluded from auxiliary counter measurements, however, that a negligible proportion of penetrating showers are accompanied by air showers, whereas we observed almost as many accompanied showers (93) as local showers (133). The number of accompanied showers observed when actual frequencies were being taken was 84, compared to a total number of electron showers identified under the same conditions as 3229. Thus, for our particular detection equipment, one electron shower in 38 showed a penetrating shower produced in our apparatus. The uncertainties of solid angle and density of electrons make it impossible to

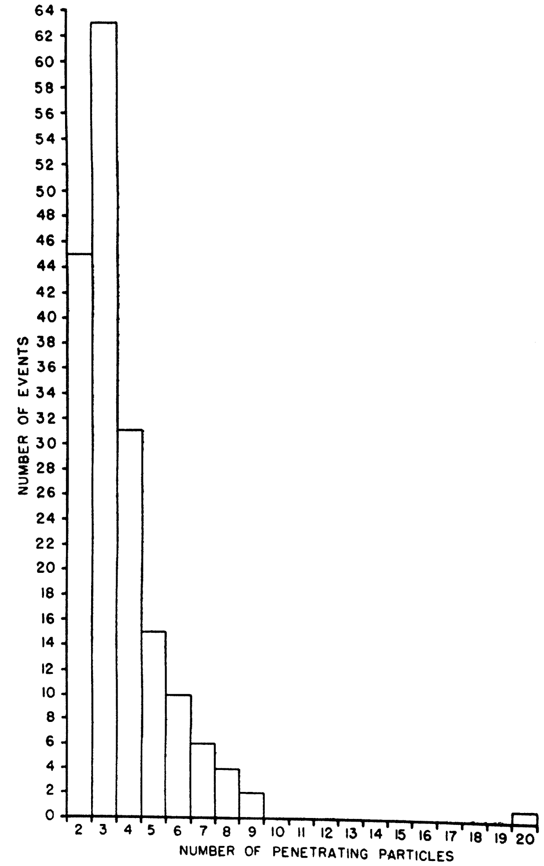

FIG. 2. Multiplicity of penetrating particles in local penetrating showers.

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[4] J. Tinlot, Phys. Rev. **73**, 1476 (1948).

[5] J. Tinlot and B. Gregory, Phys. Rev. **75**, 520 (1949).

calculate from this a density of penetrating shower producing particles in an air shower, but the presence of particles capable of producing penetrating showers in air showers is clearly demonstrated. In addition, it might be remarked that the areas of extended counters used by Tinlot and Gregory[5] were such as to record only high density showers whereas some of the penetrating showers detected in the cloud chamber were accompanied by relatively few particles.

B. Multiplicity

The multiplicity of production of charged penetrating particles is shown for local showers in Fig. 2, and for accompanied showers in Fig. 3. These were obtained simply by counting the number of penetrating particles produced to each event. To be classified as penetrating, a particle had to go through one $\frac{1}{2}$-inch lead plate without producing secondaries; thus protons and mesons are included. These are minimum values, undoubtedly some particles were missed because of poor illumination or unfortunate location in the chamber. The peak at three particles in the local shower curve is probably instrumental; with the counter arrangement used it is, of course, more probable to detect highly multiple events than those containing only two particles. This is borne out by the curve for accompanied showers which shows no such peak since in most cases the counters were tripped by particles in the air shower.

The multiplicities are, however, mostly fairly low, averaging about four particles per event. Twelve showers are omitted from these graphs because their electronic density was so high that no count of penetrating particles could be made.

Using the criteria of ionization and scattering developed by Powell,[6] it was possible to identify 35 mesons and 21 protons which stopped in the chamber after traversing one or more lead plates. Further classification of the mesons (into π- or μ-types) was not possible. Some cases of anomalously large scattering of the produced particles will be discussed later.

Slow protons and mesons were produced abundantly in these showers. These were evidenced by heavy tracks found at the beginning and throughout the shower. About half the initial events showed production of slow protons or mesons (not distinguishable in these pictures), the average number being two per event when they were observed at all. It seems likely that slow mesons or protons are produced in nearly every penetrating shower and that whether or not they are observed depends on the position of the event in the lead plate.

In addition to the heavy tracks produced in the initial event, heavy tracks are frequently observed scattered at random through the shower. On the average, 1.5 heavy tracks are observed per shower which are not associated with the original event. In one case fifteen such tracks were observed and in another, where there was a twelve-particle star, twenty heavy tracks were found. These are probably produced by the neutrons which Cocconi, Tongiorgi, and Greisen[7] have found to be produced in penetrating showers in large numbers.

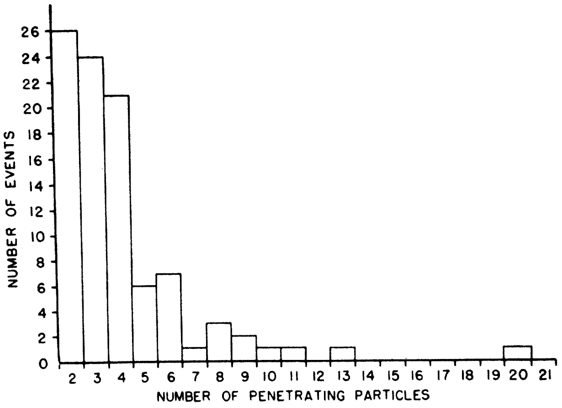

FIG. 3. Multiplicity of penetrating particles in accompanied penetrating showers.

C. Angular Distribution

The projected angle between the initiating particle and the charged penetrating particles produced has been measured for local and accompanied penetrating showers and the results plotted in Figs. 4 and 5. Again the counter selectivity must be considered; showers with very wide angular dispersion will not be detected. The local and accompanied showers show very little difference in angular distribution, however, so the counter selection could not have been too rigorous. The similarity in angular distribution lends support to the idea that the two types of penetrating showers are probably similar in their mechanisms.

With the information on multiplicity and angular distribution at hand, we can compare the experimental results with theoretical calculations. Lewis, Oppenheimer, and Wouthuysen[8] have made calculations of multiplicities and angular distributions of mesons according to various theories. In the energy range where most of the showers observed in the present investigation lie the asymptotic solution for very high energies does not apply. Professor Lewis[9] has very kindly made calculations to cover the lower energy range.

It should be noted that any conclusions about multiplicity and angular distributions from this experiment are uncertain because of lack of identification of particles and lack of knowledge of energies.

The *average projected* angle for the charged penetrating particles in this experiment is 18.6°. The average

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[6] W. M. Powell, Phys. Rev. **69**, 385 (1946).

[7] Cocconi, Cocconi-Tongiorgi, and Greisen, Phys. Rev. **74**, 1867 (1948).

[8] Lewis, Oppenheimer, and Wouthuysen, Phys. Rev. **73**, 127 (1948).

[9] H. W. Lewis, Phys. Rev. **76**, 566 (1949).

angle is related to the root-mean-square angle (assuming a Gaussian distribution which may not be correct) by $\langle\theta^2\rangle_{\text{Av}}^{\frac{1}{2}}=(\pi/2)^{\frac{1}{2}}\langle\theta\rangle_{\text{Av}}$ and the true angle related to the projected angle by $\sqrt{2}$ so that the true r.m.s. angle is about 33°, or about $\frac{1}{2}$ radian. According to Lewis, $\langle\theta^2\rangle_{\text{Av}}^{\frac{1}{2}}=[2/(1+\gamma_0)]^{\frac{1}{2}}$, thus the average γ_0 for these primaries is about 7.

If we now compare the average γ_0 with the curves for multiplicity, we see that for an average multiplicity of about 4 and a γ_0 of 7 the factor α must be of the order of magnitude 1.5, and this seems quite reasonable. It can also be noted that energies of the order of 7-Bev are very common in the primary cosmic rays. Thus, although the agreement between the theory and this experiment may in this case be completely coincidental, it is seen that at least the order of magnitude given must be correct.

D. Production and Penetration of Electronic Radiation

It is now well established by ionization-chamber[10] and cloud-chamber[1] work that high energy electronic radiation is often produced simultaneously with the penetrating particles. The rapid interaction of high energy γ-rays and electrons with lead makes it impossible to say whether the radiation which initiates the observed electron showers has the character of γ-rays or electrons. Some information can be obtained, however, from a study of the electron showers produced.

The production and penetration of these electron showers is plotted in Fig. 6. Since no difference in production of electrons was noticed in local and accompanied showers, the electron production for all showers is given. The value given for zero plates penetrated does not mean that *no* electrons or γ-rays were produced; it simply means that such radiation was not energetic enough to create an electron shower capable of penetrating $\frac{1}{2}$ inch of lead. It must also be remarked that the production and penetration of electrons is not always a clear-cut visible phenomenon, especially for small penetrations, and some judgment had to be used in classifying these events. The peak in the region of three plate penetration is instrumental; if showers occurred near the bottom of the chamber the *minimum* penetration was observed and plotted on the graph. The actual penetration, or energy, in many cases was higher.

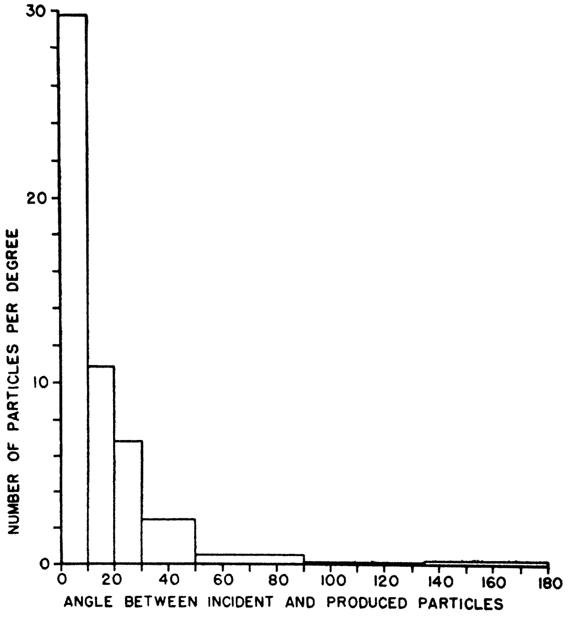

FIG. 4. Projected angle between the initiating particle and the charged penetrating particles produced in local penetrating showers.

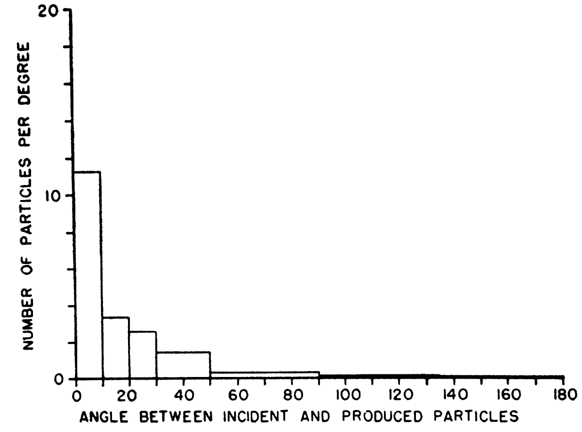

FIG. 5. Projected angle between the initiating particle and the charged penetrating particle produced in accompanied penetrating showers.

The most satisfactory way of estimating the energy of an electron shower is to count the number of particles at its maximum.[11] In most of the present cases this procedure was impossible because of the large number of particles present. Thus, only a rough idea can be had of the energy of the shower by observing its penetration in lead. The thickness of each plate corresponds to 1.27 cm or 2.44 shower units (one shower unit = 0.52 cm). Four plates correspond very nearly to ten shower units and a shower that has died out while penetrating four plates should have had roughly about 200 Mev, while one capable of penetrating eight plates, or twenty shower units, may have had an energy of the order of 1000 Mev. The most energetic electron shower observed penetrated twelve plates, or thirty shower units and must have had an energy of the order of 5×10^{10} Mev.

In considering the origin of these electron showers it is of interest to observe whether single or multiple cores or cores at angles occur. Table II gives the angle from the incident particle and penetration in the case where

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[10] Bridge, Hazen, Rossi, and Williams, Phys. Rev. 74, 1083 (1948).

[11] S. Nassar and W. E. Hazen, Phys. Rev. 69, 298 (1946).

the angle was large or the shower simple enough to make the effect noticeable.

From these pictures and those of Chao[3] it is clear that for low energy events the electrons sometimes come off at appreciable angles from the initiating particle. The energies are relatively low in most cases; in the case of the two cores which penetrated 7 plates each, the angle between them was small. With more data, a study of the angular distribution of the electron showers and their energy might reveal details of the production process.

Another observation which may be of interest is the correlation of multiplicities of penetrating particles with production of electrons. Table III gives data for all showers which could be analyzed.

If we assume that the relative probability of obtaining charged penetrating particles is twice as great as obtaining uncharged particles (neutral mesons) or γ-rays we can write:

$(\frac{2}{3})^N$ = probability of getting N charged particles only.

$(\frac{1}{3})^N$ = probability of getting N uncharged particles only.

For $N=9$, for example, $(\frac{2}{3})^9=1/38.4$, or one shower in 38.4, with total multiplicity 9 should show only charged particles. At first glance, the probability of observing a nine-particle shower with no electrons seems very small, since only four showers were observed with multiplicity 9. However, it must be remembered that some of the other showers with lower multiplicity of charged particles might actually have had a total multiplicity of 9. If we take the factor $1/(\frac{2}{3})^N$, and multiply it by the actual number of showers of corresponding multiplicity from $N=2$ to 9 in which no electrons were observed, and sum all these numbers, we find that a total of 144 showers should have been recorded in order to record the numbers seen without electrons. A total of 255 showers were actually counted in this survey. This rough calculation leaves out all energy dependence considerations, and was made only to determine whether, under the assumptions made, it was at all reasonable to find as many showers without electrons as we did. Since electron showers of less than 100 Mev may easily have been missed, it seems reasonable to conclude that an assumption of 2:1 probability for production of charged and neutral particles will explain the results.

TABLE II. Angles from the incident and penetration.

Picture No.	Angle θ_1	Penetration (1)	Angle θ_2	Penetration (2)
3490	$-3°$	7 plates	$+6°$	7 plates
10640	28°	3 plates	no other core	
11977	46°	2 plates	no other core	
12292	0°	2 plates	$+24°$	2 plates
12759	$-16°$	4 plates	$+16°$	3 plates
13325	$-4°$	5 plates	$+22°$	4 plates
13980	$+10°$	4 plates	$+22°$	3 plates

TABLE III. Correlation of multiplicities with the production of electrons.

Multiplicity N	2	3	4	5	6	7	8	9	>9
Number of showers with no high energy electrons	20	37	15	4	3	1	2	1	0
Total number observed with this multiplicity	71	87	42	21	17	7	7	3	4

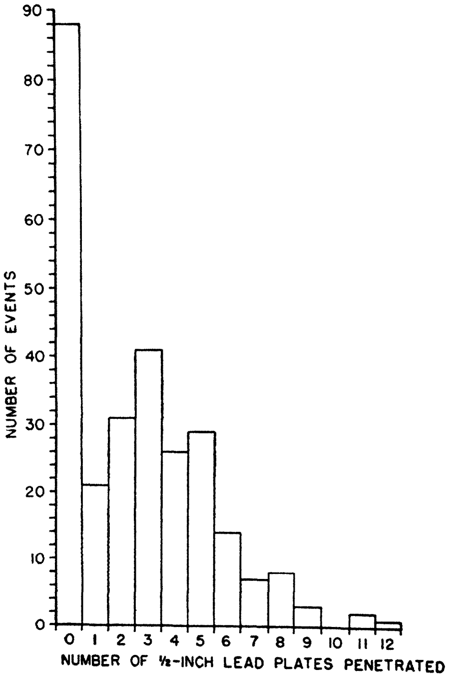

FIG. 6. Production and penetration of electrons in penetrating showers.

E. Free Path and Flux of Primaries

The distribution of single events through the cloud chamber is shown in Fig. 7. In consideration of these data two factors must be taken into account: the free path of the primaries in lead and the selection bias of the counters. If we assume that the primaries are absorbed exponentially we can write that the number which have not made a penetrating shower after traveling a distance x through the lead is $n=n_0e^{-x/L}$ where L is the mean free path for shower production. The number which collide between x and $x+dx$ is $dn=-(n_0/L)e^{-x/L}dx$. The probability of detecting the event will depend on the position of the event in the cloud chamber, the multiplicity N, and the counter arrangement. We can write the probability of detection $P(r,\ N)=k(N)A/r^2$, where $k(N)$ depends on the multiplicity and the counter arrangement; A/r^2 represents the solid angle of the counters subtended at a distance r from the event.

Thus, the number observed in dx will be proportional to

$$(n_0/L)e^{-x/L}(k(N)A/r^2)dx,$$

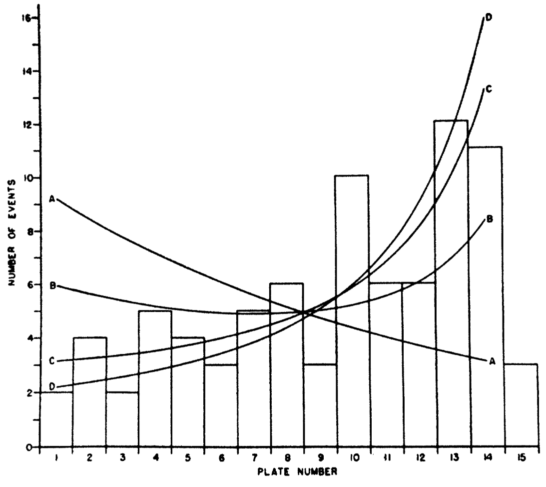

FIG. 7. Distribution of single local showers in the cloud chamber, and calculated distribution for $L=170$ g cm^{-2} with no counter bias (curve A). The calculated distributions including counter bias are given by $L=86$ g/cm^{-2} (curve B), $L=170$ g/cm^2 (curve C) and $L=350$ g/cm^{-2} (curve D).

r and x are related by the geometry of the counters and cloud chamber, A is constant, and $K(N)$ can be considered to have a constant value for some average multiplicity. Thus a fraction proportional to $f=e^{-x/L}/r^2$ can be calculated which gives the fraction of observed events occurring in each plate. This is calculated for various assumed values of L and the results normalized to the total number of events occurring in plate 1 to 14. Plate 15 is omitted because of difficulty of identification of showers.

Curves are drawn for $L=86$ g/cm^2 (curve B), 170 g/cm^2 (curve C), and 350 g/cm^2, (curve D), Fig. 7.

It is seen that the data are reasonably well fitted by $L\sim 170$ g/cm^2 but that a longer mean free path would not be excluded. A free path as short as 86 g/cm^2 in lead, however, seems too small. Thus the recent values of 160–300 g/cm^2 obtained by various observers are in agreement with the present results.

The total flux of primaries at 10,600 feet has been estimated by Hazen, Randall, and Tiffany[12] to be $1.1\pm 0.3\times 10^{-4}$ cm^{-2} sec.$^{-1}$ steradian^{-1}. In the present experiment, the solid angle was 0.145 steradian, the active area of counters 103 cm^2, so the expected rate of primary particles is about 0.59/hr. The observed rate of local penetrating showers was 0.192/hr. at 3027 meters. If the mean free path, as used by Hazen, is 180 g/cm^2 of Pb, and we assume that 7 in. or 202 g/cm^2 Pb are useful in this case to produce observable showers, $(1-e^{-202/180})=0.67$, so 67 percent of the particles should have made showers in the chamber. This would give a rate of 0.4/hr. The lower observed rate of 0.192/hr. means that some showers were lost due to the geometry, spreading, and low multiplicity, but taking these into account, the present experiment agrees in order of magnitude with the value given by Hazen. The expected distribution of events in the chamber with no counter bias (curve A, Fig. 7) shows that a great number of events which occurred near the top of the chamber were not observed because of the arrangement of the lower counters.

SUCCESSIVE EVENTS

Free Path of Secondaries

In fifty-eight photographs of penetrating showers, successive production of penetrating particles was observed, sometimes as many as three successive events. Most of these events occured more or less in line with the original particle, but in several cases, particles which were definitely secondaries produced additional penetrating showers. It is of interest to analyze these events to see if a free path for successive events can be calculated.

A minimum free path can be calculated by measuring the distance between two events and taking the weighted average distance. The weight must be taken according to (1) the inverse of the distance between events (it is more probable to observe short distances than long ones simply because of the limited size of the cloud chamber), and (2) the position of the second event in the cloud chamber. If the second event occurs near the lower counters it is more likely to be recorded than if it is near the top of the chamber. The second weight was calculated according to solid angle considerations similar to those used in consideration of position of single events in the cloud chamber. The minimum free path thus calculated comes out about 80 g/cm^2. The actual free path must be larger than this, because many secondaries made no successive events.

The total track length of penetrating particles emerging at minimum ionization from the showers would give some information on the free path. A count has been made of the total number of traversals of charged secondary particles through the $\frac{1}{2}$-inch lead plates. 4675 traversals were observed. These include not only the secondary particles produced, but also the primary particle if it was not absorbed catastrophically. The secondaries may have been either mesons or protons. In this number of traversals, 78 additional penetrating events and stars were observed to be produced by the charged secondaries, and twelve cases of large single scattering ($>15°$) were observed. Assuming that the single scattering is also due to nuclear interaction, the mean free path for total nuclear interaction of the secondaries comes out to be 750 g/cm^2 of lead. This represents a maximum free path, since other stars and possibly penetrating showers occurred in the cores of large events where identification was difficult and energies of particles concerned may have been too low to produce nuclear events. The corresponding cross section is 5.3×10^{-25} cm^2 per lead nucleus. If we consider the anomalous scattering only, the cross section

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[12] Hazen, Randall, and Tiffany, Phys. Rev. **75**, 694 (1949).

for scattering through an angle greater than 15° is $\sim 3\times 10^{-28}$ cm^2 per *nucleon.*

It is not very meaningful to compare the observed scattering cross section with the cross sections calculated from various meson theories, since the energies of the particles are not known and the calculated values are quite energy dependent. It seems, however, that most meson theories, coupled with reasonable estimates of the energies, give scattering cross sections which are an order of magnitude or more greater than the observed cross section.

Experiments by Piccioni[13] indicate that the particles produced in penetrating showers are mostly π-mesons. We are thus confronted with too few scatterings, according to present theories, by a factor of ten or so. It may be that when these particles scatter they nearly always produce a nuclear disruption, and thus count, not as an anomalous scattering, but as a nuclear event. Most of the nuclear events were high energy, however, and the question of the low cross section for scattering remains unresolved.

A final remark should be made concerning the comparisons which have been made between the observed data and the various meson theories. Because of the uncertainties in the meson coupling constants, none of the numerical comparisons can be considered as rigorous. In addition to this uncertainty, it is often necessary to jump from one meson theory to another in order to get any kind of agreement at all between theory and experiment. Thus, any numerical comparisons which have been made in this paper have been for illustrative purposes only, and cannot be considered as proof that any particular theory is correct.

ACKNOWLEDGMENTS

We are indebted to Mr. Carl P. Russell, Superintendent, Yosemite National Park, and to the National Park Service men who were so helpful to us during the summer at Tioga Pass, and without whose cooperation our work would have been impossible. Professor R. B. Brode's continuing interest and support, and the help of John Ise, Jr., and Andrew Yeiser in taking the pictures, are also gratefully acknowledged.

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[13] O. Piccioni, Phys. Rev. 75, 1281 (1949).

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On the Mechanism of Production of the Neutron Component of the Cosmic Radiation

VANNA COCCONI TONGIORGI
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

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Experiments have been performed on the neutron component of the cosmic radiation, with a system of BF$_3$ proportional counters embedded in paraffin, capable of recording neutrons in the energy range between $\sim$2 and $\sim$15 Mev. The neutron rate recorded with such a detector is due to both neutrons locally produced inside the detector and neutrons produced outside the detector, i.e., in the surroundings and in the atmosphere.

The local neutron production is due to a radiation which in the great majority does not consist either of photons or μ-mesons.

The intensity of such a radiation increases with altitude with a mean free path in air of 120–130 g/cm^2, which is confirmed by the fact that it shows a barometric coefficient ≈ -11 percent per cm Hg. At mountain elevation (4000 m) the intensity of this radiation is close to that of the total ionizing cosmic radiation. This suggests that it consists principally of fast neutrons.

The locally produced neutrons are mostly produced in multiples, with multipliticy depending upon the material. In lead the average multiplicity observed was close to 8, in carbon smaller than 2.

The rates of neutron production in different materials are satisfactorily described by a cross section proportional to the $\frac{2}{3}$ power of the mass number of the material.

The results indicate that the main source of all the neutrons present in the cosmic radiation are "stars," though high energy processes like penetrating and extensive showers do contribute to neutron production.

I. INTRODUCTION

FOR more than ten years neutrons have been known to exist in the atmosphere as a component of the cosmic radiation and many experiments have been performed to study their properties.

In the last few years the importance of the strongly interacting radiations (neutrons, protons, heavy mesons) for the general understanding and interpretation of the cosmic-ray phenomena has been steadily growing. Recently the phenomena concerning the neutron component have been framed in a picture in which stars, penetrating showers, bursts and extensive showers also find their places.

According to this picture, the presence of neutrons in the atmosphere can be justified somewhat as follows. As neutrons have a finite lifetime, they cannot be primaries, hence they must originate within the atmosphere. The primary radiation (say protons and heavy ions), when it collides with air nuclei, produces fast neutrons in association with fast protons, heavy mesons and photons. High energy processes of this kind can be thought of as the origin of extensive showers, bursts and penetrating showers. The fast neutrons and