OBSERVATIONS ON THE PENETRATING COMPONENT OF EXTENSIVE AIR SHOWERS

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Summary

The variation in the composition of the penetrating component of extensive air showers at sea-level has been investigated as a function of shower density. The proportion of N-particles in the penetrating component was observed to decrease as the shower density decreased. It is suggested that this behaviour is due to the filtering action of the atmosphere on the more absorbable particles in the nuclear cascade which has passed maximum development.

The zenith angle distribution of the penetrating μ-mesons in air showers has been found to be of the form $\cos^8 \theta$ which is consistent with that expected for shower axes, and gives no evidence for the broader distribution reported at mountain altitudes.

An anomalous deficiency of penetrating μ-mesons with zenith angles less than 5° has been found in air showers of median density 10 m^{-2}.

I. Introduction

The data on the penetrating component of extensive air showers reported in this paper were collected during an experiment in which the penetrating component was searched for delayed particles (Officer and Eccles 1954). Analysis of hodoscope pictures taken under 15 cm of lead gave information on the composition of the extensive shower penetrating component, the zenith angle distribution of the penetrating μ-mesons, and the dependence of these on shower density.

Since the early work on the penetrating particles in air showers discussed by Broadbent and Jánossy (1948), there have been many investigations on this subject. These include researches by Cocconi, Cocconi Tongiorgi, and Greisen (1949), Mitra and Rosser (1949), Ise and Fretter (1949), Cocconi and Cocconi Tongiorgi (1950), McCusker (1950), Greisen, Walker, and Walker (1950), Sitte (1950), McCusker and Millar (1951), Sitte (1952), Hodson (1953), and Kasnitz and Sitte (1954). There is general agreement that at sea-level about 2 per cent. of shower particles can penetrate 20 cm of lead, and there seems to be a slow increase in this proportion as the shower density decreases. Most of the penetrating particles are μ-mesons and the remainder called the N-component, are nuclear interacting particles such as neutrons, protons, and π-mesons. However, the composition of the penetrating component and its abundance as a function of distance from the shower core and of shower age, have not been fully investigated, as shown by the following apparently conflicting results. Several workers (Sitte 1950, 1952 ; Hodson 1953 ; Piccioni and Cool 1953) have reported

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proportionality between the penetrating particle and electron densities. Recently Kasnitz and Sitte (1954) working at an altitude of 3260 m have found the abundance of the penetrating component to increase with shower age, due mainly to an increase in the proportion of N-component. The results of the present experiment carried out at sea-level show that there is a marked decrease in the proportion of N-component as shower density decreases.

The zenith angle distribution of air shower axes has usually been studied by examining the inclination of approximately parallel electron tracks in cloud chamber pictures. The direction of the penetrating μ-mesons in air showers should be close to that of the shower axis, but Brown and McKay (1949) and Sitte (1950) working at mountain altitudes found broader zenith angle distributions for the penetrating particles than for the shower electrons at the same altitudes. The present distribution for the penetrating μ-mesons is in agreement with that expected for the shower axes as calculated from the altitude dependence of air showers by Kraybill (1954).

The zenith angle distribution for the penetrating μ-mesons has been examined for three ranges of shower density. An anomalous deficiency of zenith angles less than 5° compared with the numbers expected for a cosine power law, has been found in the group with a median density of 10 particles/m^2.

II. Experimental Arrangement

The showers were detected by a threefold coincidence arrangement consisting of trays of Geiger counters at the vertices of a 2 m triangle. One tray, 359 cm^2 in area, was shielded with 15 cm of lead and the other two trays, 450 cm^2 and 583 cm^2 in area, were unshielded. The resolving time was approximately 1 μsec. Immediately above and below the shielded tray were two trays of counters connected to a hodoscope, and below these were arranged alternately, three 5 cm lead layers and three trays of hodoscope counters. The ends and sides of the array were shielded with 10 cm of lead. The remaining five channels of the 50 channel hodoscope were connected to a simple form of shower density detector consisting of one sensitive area of 500 cm^2, three of 90 cm^2, and one of 15 cm^2. The apparatus is described in detail by Officer and Eccles (1954).

III. Composition of the Penetrating Component

(a) *Classification of the Hodoscope Pictures*

The hodoscope pictures of shower components penetrating 15 cm of lead were divided into four main classes, μ-mesons, N-component with range $R > 25$ cm of lead, N-component and electronic event mixture with $15 < R < 25$ cm of lead, and a class containing photons and oblique particles. The criteria used in classifying the pictures were as follows.

(i) *Samples of Penetrating Component containing one or more μ-Mesons.*—Most of the pictures in this class showed the track of a single penetrating non-interacting particle. The discharge of two or several adjacent counters under one of the 5 cm layers of lead was allowed for inclusion in the class, but the frequency of these occurrences was consistent with the production of knock-on electrons and knock-on showers by μ-mesons. There were 240 of these single particle pictures and an additional small group of 11 pictures that could have been very oblique particles in the top cavity. A group of 71 pictures, showing an otherwise single track accompanied by an apparent knock-on event in the top lead cavity immediately below the upper 15 cm lead shield, was included. The frequency of these events was such that at least half of them must have represented coincidences in the top cavity between μ-mesons and other particles from the air showers, probably of electronic nature. Also included was a group of 31 pictures showing parallel penetrating tracks. One picture showed four tracks, two showed three tracks, and the rest had only two parallel tracks. Two of these particles were N-particles but the rest were considered to be μ-mesons.

(ii) *Samples containing N-component.*—Penetration of at least 25 cm of lead was required. The pictures usually showed several counters discharged in most of the layers traversed, but any particle which gave rise to an interaction with penetrating secondaries was included. In addition to 136 events of this type 32 events in which most of the counters in each layer were discharged were included. In some cases all 45 shielded hodoscope channels registered a hit. Samples of penetrating component in this class thus contained one or more N-particles and an unknown number of μ-mesons.

(iii) *Mixed Samples of N-component and Electronic Events.*—This class contained 31 events with ranges between 20 and 25 cm of lead or with a lower limit of 20 cm due to escape from the side of the array. They resembled N-component pictures but identification was less certain than for the longer-range N-component. Also included were 58 pictures showing showers or groups of two or more particles in the top cavity only. As the thickness of lead above this cavity was only 15 cm they could have been produced by a mixture of electronic events and short range N-component.

(iv) *Oblique Particles and Photons.*—Pictures in this class of 143 usually showed no shielded hodoscope counters discharged at all. A considerable number had one counter discharged in the top cavity only, and a few had one or two counters discharged anywhere in the array. These events could not have been accidental coincidences between a background count in the shielded timing tray and a shower striking the two unshielded trays, as these were calculated to have negligible frequency. Also the time interval distribution for this class would have been spread uniformly over the 1 μsec resolving time if they had been accidental coincidences, but it was sharply peaked (Officer and Eccles 1954). These events were considered to be a mixture of photons and very oblique particles. The photons could have come from burnt-out cascades in the 15 cm of top lead, and the oblique particles must have come through the 10 cm side shielding. If photons were responsible the abundance of the events should have increased with shower density since high energy electrons are more abundant at high densities, but in fact it decreased. This suggests that oblique penetrating particles in low density showers were mainly responsible, and the suggestion fits in with the explanation of a few significant time lags in this group reported earlier (Officer and Eccles 1954).

The classification of the penetrating component samples is summarized in Table 1. In order to obtain the percentage composition of the penetrating component several corrections to these results would have to be made. As we are at present more interested in the variation of the composition with shower density, these corrections will not be made in full. Firstly, a correction should be made for non-recognition of charged N-particles which do not interact in the thickness of lead traversed. As the 25–30 cm of lead is about two mean free paths thick for N-particles the correction will not be large. Secondly, only those neutrons that interact in the 15 cm upper lead shield will be detected. Greisen, Walker, and Walker (1950) give 1·5 as the ratio of charged to neutral particles in the air shower N-component at 4260 m. Thirdly, the proportion of μ-mesons in the samples containing one or more N-particles is unknown. With large enough samples of penetrating component an N-particle would be included almost invariably, and the present method of classification would yield 100 per cent. N-component. A correction is made for this effect in Section III (*b*), where it is found to be of importance for only the highest shower density classes recorded.

Table 1

Classification of Penetrating Samples

Class	No. of Samples	Percentage of Samples
One or more μ-mesons	353	$45\cdot_8 \pm 2\cdot_4$
N-component (one or more N-particles and unknown μ-meson content)	168	$21\cdot_8 \pm 1\cdot_7$
N-component and electronic event mixture	89	$11\cdot_6 \pm 1\cdot_2$
Oblique particles and photons	143	$18\cdot_6 \pm 1\cdot_6$
Miscellaneous	17	$2\cdot_2 \pm 0\cdot 5$
Total	770*	

* The total number of detected showers was 782, but in a few cases there was no hodoscope record or the timing record was obscured by a ghost image.

(*b*) *Variation of the Composition of the Penetrating Component with Shower Density*

Each class of penetrating component samples was analysed according to the combination of large, medium, and small density detector counters discharged. The result of this analysis is shown in Table 2. Rarely discharged density detector combinations have been omitted. Calculation showed that accidental coincidences between background counts in the density detector counters and shower master pulses were insignificant compared with statistical errors in the counter combination totals, in spite of the fact that the resolving time was 20 μsec.

In order to obtain the median shower densities corresponding to the various density detector counter combinations, several numerical integrations were performed. Firstly, the fraction ε of shower particles able to penetrate 15 cm of lead was found from

$$N=\int_0^\infty K\Delta^{-\gamma}(1-e^{-S_1\Delta})(1-e^{-S_2\Delta\varepsilon})(1-e^{-S_3\Delta})d\Delta \quad \text{hr}^{-1},$$

where the observed shower rate $N=0\cdot50_6\pm0\cdot01_8$ hr^{-1}, the values of K and γ were taken from Singer (1951), S_1 and S_3 are the areas of the unshielded trays and S_2 is the area of the shielded tray. K and γ were assumed to be independent of shower density Δ. ε was found to be $2\cdot8_6$ per cent. and can be compared with $2\cdot60$ per cent. found by Cocconi, Cocconi Tongiorgi, and Greisen (1949) under $17\cdot8$ cm of lead at an altitude of 260 m. The present higher value could be due to some electronic component penetrating 15 cm of lead.

TABLE 2

ANALYSIS OF SAMPLE CLASSES ACCORDING TO DENSITY DETECTOR COUNTER COMBINATIONS DISCHARGED

	Counter Combination					
	0	L	LM	L2M	L3M	L3MS
μ-Mesons	65	64	64	41	38	21
N-component	11	17	29	29	25	29
N-component and electronic event mixture	13	8	17	10	12	8
Oblique particles and photons	30	24	19	21	10	6
Miscellaneous	2	4	5	2	3	—
Totals	121	117	134	106	88	64

Secondly, the frequency of discharge of each counter combination by detected showers was calculated as a function of shower density. The frequency of discharge of a given combination at a density Δ is given by the product of the integrand in the expression for N and the probability of discharging that combination in a shower of density Δ. The probability of discharging the combination L3M is, for example,

$$(1-e^{-S_L\Delta})(1-e^{-S_M\Delta})^3e^{-S_S\Delta},$$

where S_L, S_M, and S_S are the areas of the large, medium, and small density detector counters. For each combination the median density was found as the bisector of the area under the frequency of discharge versus density curve.

It is known that both γ and ε vary slowly with density (Cocconi and Cocconi Tongiorgi 1949 ; Cocconi, Cocconi Tongiorgi, and Greisen 1949). The median densities calculated as described will therefore be in error, but this will not upset the main conclusions of this experiment as the exact values of median density are not important. However, these uncertainties do make it difficult to express the results as the variation of the absolute abundance of the various penetrating constituents with density. The variation with density of the percentage composition of the penetrating component is therefore presented.

The data of Table 2 concerning penetrating samples are shown in Figure 1 as percentage composition plotted against median shower density. The increase in the proportion of N-component with increasing density is striking, but part of this rise is due to the inclusion of μ-mesons in the N-component samples.

If it is assumed that μ-mesons and N-particles are both distributed at random in the plane of the detector a simple correction can be applied. The assumption of random mixing of the particles should be valid except for those produced close to the apparatus. If ε_1 and ε_2 are the absolute abundances of

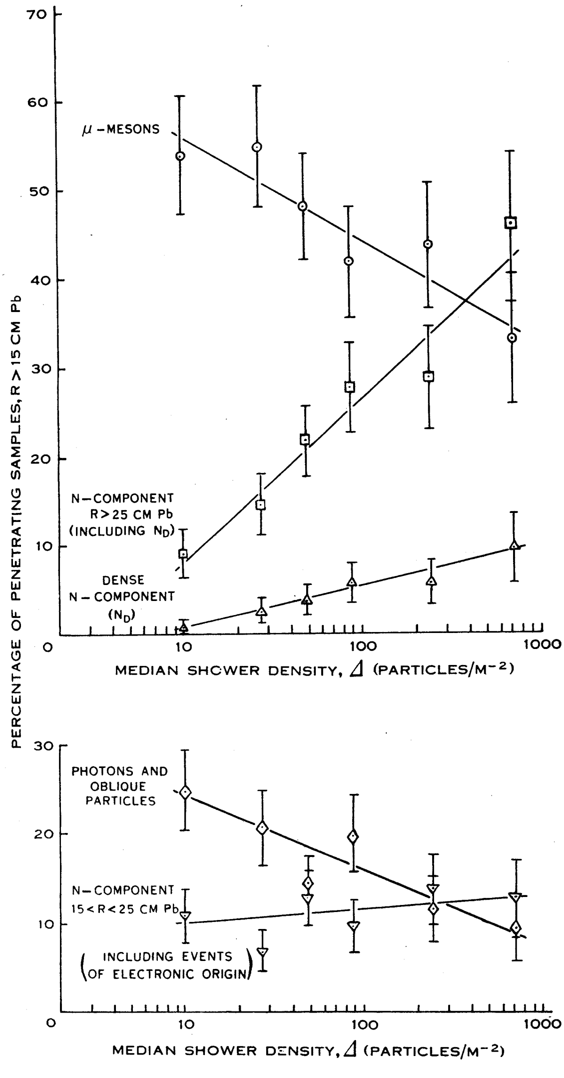

Fig. 1.—Composition of the penetrating component (uncorrected data).

μ-mesons and N-particles at a shower density Δ, the fraction β of penetrating samples observed to contain one or more N-particles will be

$$\beta=\frac{1-e^{-S\Delta\varepsilon_2}}{1-e^{-S\Delta(\varepsilon_1+\varepsilon_2)}},$$

where S is 1200 cm^2 ,the area of the hodoscope trays. With the total abundance of penetrating component assumed independent of Δ and given the value $2 \cdot 8_6$

per cent. deduced earlier, $\varepsilon_1+\varepsilon_2$ can be found from Figure 1 for each Δ and corrected values of ε_1 and ε_2 computed. Besides correcting for μ-mesons included in the N-component samples this procedure also corrects for the fact that the μ-meson samples may contain one or more particles. Figure 2 shows the corrected results for μ-mesons and N-component only. The increase in the proportion of N-component with increasing density is reduced but it is still marked, being a factor of ≈ 3 in the density range 10–710 m^{-2}.

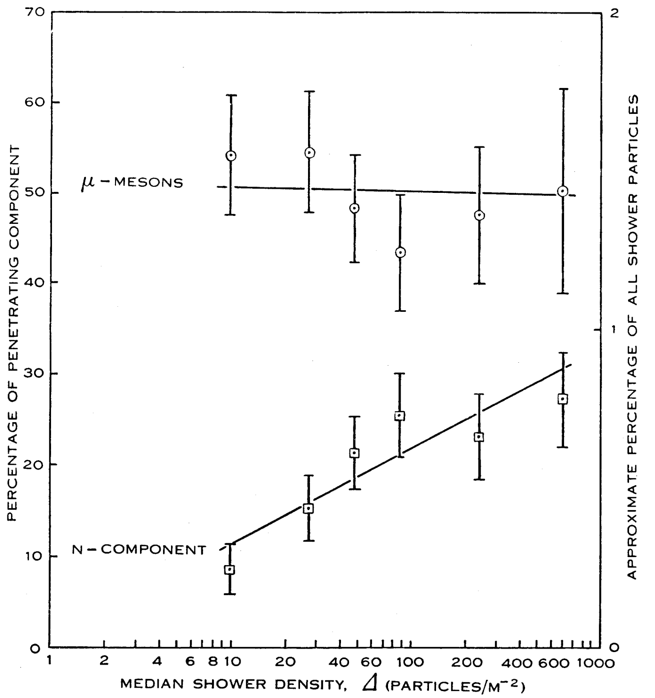

Fig. 2.—Variation with shower density of the percentage of μ-mesons and N-particles in the air shower component penetrating 15 cm of lead (corrected data).

(c) *Discussion*

As the shower density is reduced, contributions to the counting rate of the present apparatus will come from showers of greater age, and also from points at greater distances from the core in showers that are not necessarily older. It can be shown (Ise and Fretter 1949 ; Singer 1951) that any shower arrangement which is triggered predominantly by showers in a narrow density range will detect mostly showers whose cores strike nearby. This should apply to the present arrangement which includes a shielded tray, unless there is a marked increase in the abundance of penetrating component as distance from the core increases. As other workers have found no evidence for such an increase in the present density range, it is plausible to consider that in Figure 2 decreasing shower density means decreasing shower size (i.e. total number of particles) and thus increasing shower age.

This brings the present results into apparent conflict with those of Kasnitz and Sitte (1954), who found when working at an altitude of 3260 m that the proportion of N-component increased slowly with shower age. They deduced that the nuclear cascade reaches maximum development somewhat later than the electron cascade. They made special efforts to detect low energy N-component, and they suggested that this could continue to multiply after it had ceased to feed energy into the electron cascade via the production of π^0-mesons. At sea-level, however, both cascades will have passed maximum development and it is probable that we are observing the progressive filtering of the products by the atmosphere as shower age increases. If the process is continued to completion, the low density showers composed chiefly of μ-mesons observed by McCusker and Millar (1951) should be obtained by the absorption of all the less penetrating particles. The present results probably represent an intermediate stage in the process.

IV. The Zenith Angle Distribution of the Penetrating μ-Mesons

The zenith angles projected on a vertical plane perpendicular to the hodoscope counters were measured for the single penetrating non-interacting particles in the air showers. The projected zenith angle could usually be determined from the hodoscope record to $\pm 3°$ and occasionally much more accurately when

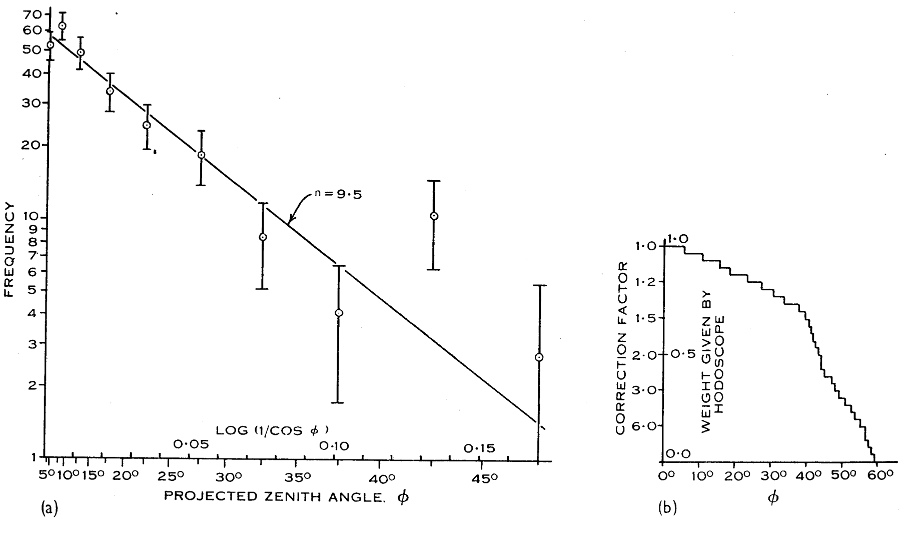

Fig. 3 (a).—Zenith angle distribution of single penetrating μ-mesons in air showers, corrected for geometrical bias of the hodoscope array, but not corrected to a spherical detector.

Fig. 3 (b).—Hodoscope zenith angle sensitivity.

a track passed between two counters in a layer. A few tracks which passed through the top lead cavity only had errors in their zenith angles up to $\pm 5°$, but statistical errors provided the main uncertainties in the distribution.

Figure 3 (a) shows a logarithmic plot of the data corrected for a geometrical bias of the hodoscope array favouring small projected zenith angles. In Figure

3 (*b*) the weight given by the hodoscope array to each angle is shown. This weight distribution was obtained by the summation of the angular sensitivities, found from the geometry, for tracks passing through each of the small nickel timing counters, a hit on the timing tray being essential for the triggering of the apparatus. The errors shown in Figure 3 (*a*) are those of statistical origin only. It can be seen that a straight line representing a $\cos^{9\cdot5}\varphi$ law is consistent with the corrected data.

As shown by Brown, McKay, and Palmatier (1949) a zenith angle distribution which can be represented tolerably well by a $\cos^n\theta$ law gives rise to a projected angle distribution which is still a cosine power law of the same power but with a new multiplying constant depending on n. Consequently it can be stated that the results are consistent with a zenith angle distribution of the form $\cos^{9\cdot5}\theta$. This applies to showers detected by event-selecting trays which can be represented approximately by three unequal horizontal areas arranged at the vertices of a 2 m triangle and discharged by one or more hits on each. The effect of 15 cm of lead over one tray and the selection of single penetrating particles through it by means of the hodoscope can be regarded as an approximate 100-fold reduction in its area.

It is usual to state the zenith angle distribution with reference to a spherical detector, and a theorem given by Cocconi, Loverdo, and Tongiorgi (1946) enables this to be done. They showed that, for shower trays of equal area connected in coincidence, reduction of the tray areas by a factor f results in a shower rate reduced by a factor $f^{\gamma-1}$, where $-\gamma$ is the power of the differential shower density distribution. The theorem can be shown to hold also in the present case where trays of unequal area all have the same effective area reduction factor, $\cos\theta$, as the zenith angle is increased. The zenith angle distribution that would be observed with a spherical detector is thus of the form $\cos^8\theta$ since $\gamma=2\cdot5$.

(*a*) *Discussion*

It is to be expected that most of the penetrating μ-mesons observed in extensive air showers at sea-level will travel close to the direction of the shower axis. There will be little scattering of these mesons on account of their high average energy, in the vicinity of several kMeV, and most of them will have been produced at high altitudes such as 5–20 km. Since they are detected amongst the electrons within tens of metres from the shower core, few of them can have large angular deviations from the direction of the shower axis. Kraybill (1954) has calculated the zenith angle distribution of shower axes at sea-level using experimental data on the altitude dependence of air showers. He obtained a cosine power law with the power $n=7\cdot5$, and his result agrees with direct measurements on the electrons at sea-level by Deutschmann (1947). The present value of $n=8$ is consistent with these results.

However, two previous determinations of the zenith angle distribution of penetrating particles in air showers have been carried out at mountain altitudes, and these are not in agreement with the shower axis distributions expected at those altitudes. Brown and McKay (1949) working at an altitude of 3260 m found $n=3$ for all penetrating particles under 15 cm of lead, except those which appeared to have been generated in the lead shield. They found $n=5$ for the electron component and Kraybill (1954) has calculated $n=5\cdot5$ at 3500 m for

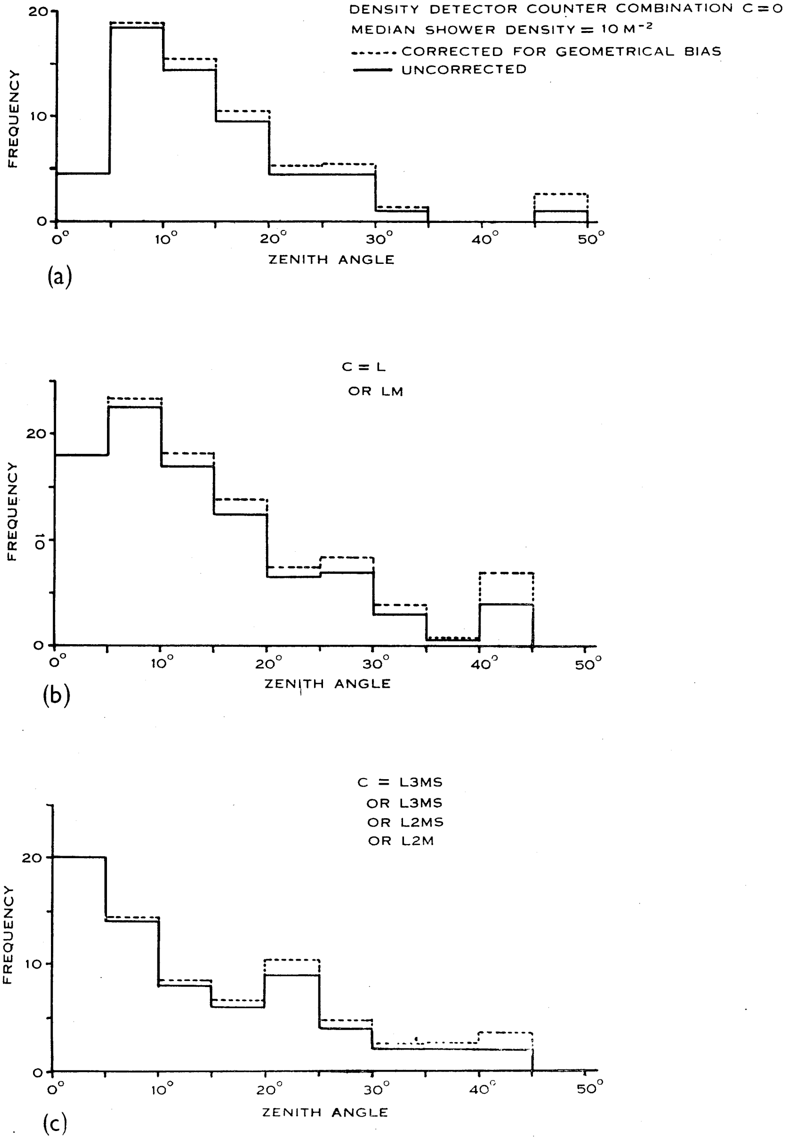

Fig. 4.—Penetrating μ-meson zenith angle histograms for three ranges of shower density.

the shower axes. They suspected that local production of penetrating particles in the lead shield may have broadened the distribution. Sitte (1950), who worked at the same altitude, found the zenith angle distribution for penetrating non-interacting particles only. He found $n=3\cdot8$.

The present results do not agree readily with a value of n less than the sea-level shower axis value of $7 \cdot 5$. This is probably accounted for by the present method of observation being insensitive to penetrating particles produced in the lead shielding. Only tracks which appeared single under 15 cm of lead were used, and they frequently penetrated one to three additional 5 cm layers, always without noticeable scattering. It is also possible that at the mountain altitudes, where the nuclear cascade is still developing, there are more wide angle penetrating particles arising from local production in the air than would be expected at sea-level.

It should be noted that Bassi, Clark, and Rossi (1953) have recently obtained a value of n that does not agree with Kraybill's calculated result. They found $n = 15 \pm 1 \cdot 2$ by a new method in which the inclination of shower fronts was found by timing methods.

(*b*) *Dependence of the Zenith Angle Distribution on Shower Density*

Figure 4 shows the zenith angle observations grouped according to shower density. The combinations of density detector counters discharged are: zero in Figure 4 (*a*) ; L and LM in Figure 4 (*b*) ; and L2M, L2MS, L3M, and L3MS in Figure 4 (*c*). The main feature of interest is the small number of observations falling in the 0–5° class in the lowest density group (Fig. 4 (*a*)). This group has a median density of 10 m^{-2}. The difference between this class and its neighbour of $14 \pm 4 \cdot 8$ is $2 \cdot 9$ times its standard error and could be regarded as significant, but more experimental evidence would be desirable. Two other teams, Cresti, Loria, and Zago (1953) and Hazen, Williams, and Randall (1954), have investigated the zenith angle distribution of shower electrons for different densities or shower sizes. They have not reported an anomaly of this kind, but their observations were not restricted to such a narrow range of low densities. Hazen and co-workers were not able to measure zenith angles for shower densities $\leqslant 200\ \mathrm{m}^{-2}$ because the spread in the directions of the individual electron tracks observed in the cloud chamber was too great.

V. μ-Meson Residual Range Data

Only 32 mesons appeared to stop in the three 5 cm layers of lead arranged below the 15 cm upper layer. After corrections for particles escaping at the ends and sides of the array, the data were consistent with a uniform distribution of residual ranges in the interval 170–339 $\mathrm{g/cm^2}$ of lead, as found by Sitte (1950) at an altitude of 3260 m in the interval 280–680 $\mathrm{g/cm^2}$ of lead.

VI. Conclusions

The observed decrease in the proportion of N-particles in the penetrating component of air showers at sea-level as shower density decreases is probably the result of progressive filtering of the products of the almost spent nuclear cascade by the atmosphere, leaving the less strongly interacting particles.

The zenith angle distribution of penetrating μ-mesons in air showers at sea-level is consistent with that expected for the shower axes, and gives no evidence of a broader distribution as found at mountain altitudes by other workers.

VII. Acknowledgment

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