~~CONF-650948-3~~

APR - 1 1966

MASTER

Preprints of Papers
presented at the
Ninth International Conference on Cosmic Rays
pertaining to the
Bolivian Air Shower Joint Experiment
(London, September 1965)

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This work was supported in part by the Air Force Office of Scientific Research under Grant No. AF-AFOSR-546-64, and in part by the Japanese Ministry of Education, the Government of Bolivia, and the Atomic Energy Commission under Contract No. AT(30-1)2098.

Massachusetts Institute of Technology

March 4, 1966

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CONF-650948-3

High Energy Nuclearactive Particles in Extensive
Air Showers at 5,200 m Altitude
(Analysis of Bolivian Air Shower Joint Experiment)

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Abstract

Analysing the bursts recorded by 60m^2 shielded scintillation detectors of Bolivian Air Shower Joint Experiment, (BASJE), we obtained information on the high energy nuclear-active particles in extensive air showers, not only near the shower axis but also at large distance up to 100m for the axis. Our conclusions are: (1) The energy flow of nuclearactive particles fluctuates very widely from shower to shower. Below 10^{15}eV , there exists an interaction where the main part of the energy of the primary particle is transferred into the electromagnetic component, and the proportion of this interaction is about 3% at $2 \times 10^{14}\text{eV}$ to $1 \times 10^{15}\text{eV}$. (2) The distribution of the transverse momentum of nuclearactive particles obtained from the bursts at large distance is consistent with $f(p_t) = \exp [-p_t/p_0] p_t/p_0^2$ up to 1 GeV/c . However, there is evidence for the possible existence of large transverse momenta of more than 2 GeV/c .

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I. Introduction

In the center of BASJE array, (Suga et al. 1962) there is a 60m^2 scintillation detector shielded by 165 g cm^{-2} of galena, 132 g cm^{-2} of concrete and 23 g cm^{-2} of lead. The 60m^2 detector consists of 15 units of scintillation detectors of 4m^2 area. When the core of a shower hits the detector, the nuclearactive particles (N-particles) produce nuclear interactions in the shielding material and bursts are observed in the scintillation detectors. When the core of a shower hits the ground at a large distance, the muons penetrate the shielding material and we measure the number of muons. Occasionally a shower, even with its core at a large distance, produces a nuclear burst in the scintillation detector. The relation between the burst size (Δb) and the energy of the N-particle is not so simple, since the burst size may fluctuate according to the level of the interaction of the N-particle in the shielding material. Tanahashi (1965) gave a conversion factor of the energy of 1 GeV per one burst particle, assuming the N-particle interacts at the top of the shielding material. We estimate that a conversion factor of 0.2 GeV per one burst particle yields the minimum estimate for the energy of the N-particle.

2. Nuclearactive particles near the shower axis

Fig. 1 shows the burst sizes in each of 15 detectors for showers whose cores hit the 60m^2 detector. The burst size is represented by the number of relativistic particles.

Comparing two showers, we see a large fluctuation of burst sizes or energy flow of N-particles of each shower. We selected the showers whose cores were incident upon any one of the central three detectors (No. 5, 8, and 11) and whose zenith angles were equal to or less than 30° . The fluctuation of the energy flow of N-particles for a given shower was obtained from the median burst size of the 15 detectors. Fig. 2 shows the distribution of the energy flow of N-particles thus obtained. The ordinate is the number of showers per logarithmic interval of the median burst size, and the abscissa is the median burst size normalized to the size of showers of 10^5 . The breadth of the fluctuation is about two decades for shower sizes greater than 5×10^5 , but the breadth is more than two decades for sizes less than 5×10^5 .

We constructed the expected distribution of the energy flow of N-particles according to Tanahashi's Monte Carlo calculation (1965). Fig. 3 shows the distribution for two sizes of showers, namely 5×10^5 and 5×10^3 . He took into account not only the fluctuation in the depth of the first interaction of the primary particle but also fluctuations in the depths of successive interactions of the survival nucleon down to the level of 500 g/cm^2 . At the size of 5×10^5 , the breadth of the expected fluctuation is about two decades and is consistent with the experimental result. But even at the size of 5×10^3 , the expected breadth is only two decades and is

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still narrower than the breadth of the experimental result at the size of 3×10^4 to 5×10^5 . This suggests that at lower size than 5×10^5 (at lower energy than 10^{15} eV) there occurs an interaction where the main part of the energy of the primary particle is transferred to the electromagnetic component. We estimated the relative proportion of this type of interaction from the proportion of observed showers which have an energy flow of N-particles less than that defined by two decades of fluctuations. It turns out to be about 3% over the energy range of 2×10^{14} eV to 1×10^{15} eV.

3. Nuclearactive particles far from the shower axis.

3.1 Lateral distribution of N-particles and the total number of N-particles

Analysing the bursts recorded by the 60m^2 detector, we obtained the lateral distribution of the bursts up to ~ 100 m for smaller burst size and up to 20 m even for the largest burst size observed. In these regions, the observed bursts are produced by N-particles in shielding materials and the contribution of muon bursts is negligibly small. Fig. 4 shows an example of the lateral distribution of the bursts. The lateral distribution of N-particles $f_N(r)$ is well approximated by the exponential function

$$f_N(r) \propto \exp(-r/r_0),$$

where r_0 is a parameter depending on the burst size and the shower size, except for the region very near the core and the

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region far from the core (≥ 50 m). The value of r_0 decreases with increasing burst size (Δb) and increases with the shower size N , as is generally expected. For example, for the shower size $N = 1 \sim 3 \times 10^6$, r_0 decreases from 5.0 ± 0.6 m for $\Delta b = 200 \sim 500$ per 4m^2 to 3.0 ± 0.6 m for $\Delta b = 2000 \sim 5000$ per 4m^2 . For the shower size $N = 1 \sim 3 \times 10^7$, $r_0 = 8.0 \pm 0.6$ m for $\Delta b = 200 \sim 500$.

The total number of N -particles per shower is obtained by integration of $f_N(r)$ over the whole area. Fig. 5 shows the integral spectrum of the burst $F(\geq \Delta b)$ involved in one shower. The burst size dependence of $F(\geq \Delta b)$ is represented by a power function $\Delta b^{-(0.9 \pm 0.1)}$ in a range of $5000 \geq \Delta b \geq 100$ and in a range of shower size $N = 1 \times 10^5 \sim 3 \times 10^7$. The shower size dependence of $F(\geq \Delta b)$ is $N^{0.8 \pm 0.1}$.

Thus we get

$$F(\geq \Delta b) = 10 (N/10^6)^{0.8 \pm 0.1} (\Delta b/1000)^{-0.9 \pm 0.1}$$

The total number of the bursts per shower agrees with Tanahashi's result within a factor 2. The burst size dependence and shower size dependence are also consistent with his results (Tanahashi, 1965).

3.2 Transverse momentum of N -particles

The lateral distribution of N -particles $f_N(r)$ is determined by the distribution of the production height of the N -particles and the distribution of the transverse momentum p_t . We shall assume a simple model, without loss of generality,

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and extract information about the distribution of p_t from the observed lateral distribution of N-particles $f_N(r)$.

Let us assume the distribution of the production height of N-particles with energy E as follows:

$$Q(E, x') dx' \propto \exp[-x'/L] \cdot x'^{a+1} dx' \quad (1)$$

where x' is the thickness of the atmosphere measured from the top in units of gcm^{-2} , L is the nuclear m. f. p. of N-particles, and a is a parameter depending on the energy E and the shower size N. The probability that a N-particle produced in the layer $(x', x' + dx')$ survives to a depth x is

$$p(E, x', x) = \exp \left[-\frac{x-x'}{L} - \frac{m_\pi c}{\tau_\pi E} (h' - h) \right] \quad (2)$$

where h and h' (in units of km) are the heights corresponding to the depths x and x' (in unit of gcm^{-2}) respectively, m_π the pion rest mass, τ_π the pion mean life, and c the light velocity. Tentatively we assume the distribution of transverse momentum p_t at the production of N-particles is expressed by an exponential form:

$$f(p_t) = \exp[-p_t/p_0] \cdot p_t/p_0^2 \quad (3)$$

An average transverse momentum $\langle p_t \rangle = 2p_0 = 0.4 \text{ GeV}/c$ is adopted. From (1), (2), and (3), one obtains a relation for the lateral distribution of the N-particles $f_N(r)$,

$$f_N(r) 2\pi r dr \propto \int_{p_t=0}^{\infty} Q(E, x') p(E, x', x) f(p_t) dp_t \frac{x' b E}{p_t} dr$$

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with help of a geometrical relation $p_t/E = r/(h' - h)$ and a semiempirical formula $x' = x \exp [-b(h' - h)]$ with $b^{-1} = 7$ km. Substitution of the arguments by $x \equiv p_t/p_0$ and $\rho \equiv [b(a + 1) + (m_\pi c/\tau_\pi E)] (E \cdot r/p_0)$ gives

$$f_N(r) 2\pi r dr \propto d\rho \int_0^\infty \exp [-x - (\rho/x)] dx. \quad (4)$$

Here the ρ means the reduced distance from the core and x the reduced transverse momentum. Integrand in (4) has a sharp peak at $x = \sqrt{\rho}$. This means the following: Among the N-particles falling at a certain ρ value, the number of N-particles with large p_t is very small because of the steeply decreasing character of the exponential function $f(p_t)$. On the other hand, the number of N-particles with small p_t is also small since their production height is too high. Therefore, the distribution of transverse momentum of N-particles falling at a certain ρ value has a sharp peak around the most probable p_t determined by the equation

$$p_t = p_0 \sqrt{\rho}.$$

Thus, one sees the true p_t -distribution in reference to the assumed exponential p_t -distribution, by comparing an observed lateral distribution $f_N(r)$ with the calculated one (4).

Fig. 6 shows an example of the analysis. Here a conversion factor of 0.2 GeV/particle and parameter $a = 1$ were adopted. Calculations were done by supposing that $r = 2$ m corresponds to $\rho = 1$. Errors of p_t indicated are taken as a half width of p_t -distribution of N-particles which come at

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the respective ρ value. From this figure one can see that in a range of $p_t \leq 1$ GeV/c the observed lateral distribution $f_N(r)$ is consistent with an exponential p_t -distribution (3) in the interaction.

3.3 Possible evidence for the existence of large transverse momentum

Among 5000 showers of large size ($N \geq 5 \times 10^6$), we found two large bursts very far from the core. One is a burst of size $\Delta b \sim 6,300$ 81 m from the core of a shower of size $N \sim 7.6 \times 10^6$. Another is a burst of size $\Delta b \sim 4,900$ 62m from the core of a shower of size $N \sim 2.8 \times 10^7$. Taking into account the nonlinearity of photomultiplier response for large bursts ($\Delta b \geq 3,000$) and with a conversion factor 0.2 GeV/particle, the minimum estimates of energy of N-particles producing the observed bursts are 4000×0.2 GeV = 800 GeV and 3000×0.2 GeV = 600 GeV, respectively. In order to obtain the minimum estimates of p_t -values, we adopted the parameter a as 1 and found that $\rho = 90$ in the former case and $\rho = 50$ in the latter case, which means that the most probable values of p_t are p_t of 1.9 GeV/c and 1.4 GeV/c, respectively.

If the p_t -distribution is of an exponential type (3), a relative probability of finding a N-particle with a certain value of ρ or more in a shower can be obtained by the integration of (4) from ρ to infinity. The results are 3×10^{-7} and 2×10^{-5} , respectively. Now, the total number of bursts

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with size of $\Delta b \geq 5000$ per shower is 10 in the former case, and 30 in the latter case. Hence, the expected frequencies of such bursts per shower are 3×10^{-6} and 6×10^{-4} respectively. On the other hand, the observed frequency is $1/5000 = 2 \times 10^{-4}$. From a comparison of these figures, it is suggested that N-particles which have transverse momentum of about 2 GeV/c or more are about 100 times as abundant as those expected from the p_t -distribution of an exponential type (3).

It is to be noticed that the above mentioned p_t values are the most probable p_t values computed from an assumed exponential p_t distribution. If the tail of p_t distribution at large p_t is less steep than the exponential function (3), the most probable p_t value of N-particles observed at a certain ρ value is much higher than the value given by (4). The result of the above analysis seems to support the INS result (Shibata et al. 1965) which shows the existence of high p_t event of more than 5 GeV/c from the analysis of double core events observed by the $20m^2$ spark chambers.

Acknowledgements

The authors wish to express their appreciation to Drs. H. Bradt and M. LaPointe of the Massachusetts Institute of Technology for the computation of the size of showers and the location of the shower axes. They are also grateful to all BASJE people in constructing and running of the equipment.

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Captions of Figures

- Fig. 1 Two examples of the pattern of bursts observed in each 4m^2 detector for showers with approximately same size. The axis of the shower hit No. 11 detector for both showers.
- Fig. 2 Fluctuation of the energy flow of N-particles. The abscissa is the median burst size normalized to the size of showers of 10^5 . The ordinate is the observed number of showers per logarithmic interval of the abscissa.
- Fig. 3 Fluctuation of the energy flow of N-particles calculated by Tanahashi (1965).
- Fig. 4 Lateral distribution of the bursts observed in 4m^2 detector.
- Fig. 5 Integral burst size spectrum. Parameter in the figure is the size of shower.
- Fig. 6 Distribution of the transverse momentum p_t . The full curve is drawn by $f(p_t) = \exp [-p_t/p_0] \times p_t/p_0^2$.

YEAR 3 DAY 653 2694
 SIZE 1.59×10^5 ZA 30°

YEAR 4 DAY 748 225
 SIZE 1.27×10^5 ZA 18°

$$\frac{\text{MEDIAN BURST SIZE}}{\text{SIZE} / 10^5} = 206$$

$$\frac{\text{MEDIAN BURST SIZE}}{\text{SIZE} / 10^5} = 6.9$$

1 110.7	2 25.1	3 16.0
4 143.9	5 67.6	6 35.9
7 7538.9	8 330.3	9 466.1
10 2076.2	11 32539.7	12 328.9
13 6970.6	14 1675.6	15 87.1

1 0.0	2 6.4	3 0.0
4 1.4	5 0.0	6 0.0
7 13.5	8 4.9	9 8.9
10 140.7	11 36.0	12 7.9
13 8.7	14 9.3	15 15.8

Fig. 1 EAS-8

DISTRIBUTION OF ENERGY FLOW
OF NUCLEAR ACTIVE PARTICLE

Fig.2 EAS-8

DISTRIBUTION OF ENERGY FLOW OF NUCLEAR ACTIVE PARTICLE

Fig. 3 EAS-8

Fig. 4 EAS-8

Fig. 5 EAS-8

Fig. 6 EAS-8

CONF-650948-4

A Monte Carlo Simulation of the
Nuclear Active Cascade in EAS*

(Analysis of Bolivian Air Shower Joint Experiment)

by

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* This work was supported in part by the Air Force Office of Scientific Research under Grant No. AF-AFOSR-546-64 and by the Atomic Energy Commission under Contract No. AT(30-1) 2098.

ABSTRACT

We have carried out a three dimensional Monte Carlo simulation of the nuclear cascade of extensive air showers of energy 1.8×10^{14} ev and have studied the spatial and energy distribution of the nuclear active particles (n.a.p.) at the atmospheric depth of Mt. Chacaltaya (530 g/cm^2) with the following results:

(1) The total energy deposited by the n.a.p. of a single shower fluctuates much less from shower to shower in the case of Fe primaries than for proton primaries. The model of nuclear interaction, two center or isobar, does not significantly affect the distribution.

(2) The radial distribution of n.a.p. within 8 m in the core is presented for the case of a distribution of transverse momentum,

$$f(p_t) \propto p_t e^{-p_t^2/p_o^2}; \quad \langle p_t \rangle_{av} = 350 \text{ Mev/c}; \quad (p_t)_{max} = 1000 \text{ Mev/c}$$

(3) A large proportion of the highest energy n.a.p. in a cascade are nucleons if the primary particle is a complex nucleus.

Finally, we have used the artificial burst patterns to simulate the burst patterns in the 60 m^2 mosaic of fifteen shielded detectors on Mt. Chacaltaya with the following results:

(1) The burst patterns undergo extreme fluctuations which render remote the possibility of consistently identifying the primary particles of individual cascades. However an occasional pattern can be so identified.

(2) The spatial and energy distribution of the burst pattern is presented and, on the average, the burst patterns for Fe primaries exhibit a predominance of large bursts within 4 m of the core relative to cascades arising from proton primaries.

(3) At the present state of analysis, comparison with the actual data from the Bolivian Air Shower Joint Experiment does not yield conclusive results concerning the interaction model or primary composition.

The study of the nuclear core of extensive air showers at high altitudes potentially can yield important information concerning the composition of the primary cosmic rays and possibly also the nature of the high energy nuclear interactions at energies above 10^{14} ev. However, such an analysis is quite complicated because of the existence of 6-7 nuclear mean free paths of atmosphere between the primary beam and, for instance, the detectors of the Bolivian Air Shower Joint Experiment (BASJE) on Mt. Chacaltaya at 530 g/cm^2 atmospheric depth. It thus has become necessary for comparison purposes to generate artificial nuclear cascades using various compositions of the primary flux and also various interaction models and taking into account the several sources of fluctuations as they are presently understood. The recent Monte Carlo calculations of the nuclear cascade by Tanahashi (1965) took into account the fluctuations in the distances between the successive interactions of the primary particle. We have expanded his calculations to take into account (1) the transverse momentum and hence the spatial patterns of the nuclear active particles (n.a.p.) at 530 g/cm^2 . (2) the fluctuations in the

in the distance between the interactions of every n.a.p.; and (3) fluctuations in inelasticity.

We have used Monte Carlo techniques on an electronic computer to carry out these simulations of the nuclear cascade at the primary energy of 1.8×10^{14} ev. The computer was programmed to follow, in three dimensional space, each n.a.p. to its interaction point and in turn to follow each of the secondaries to their respective interaction points, and to continue this process down to the atmospheric depth of 530 g/cm^2 . The energy and spatial distributions of the simulated n.a.p. at 530 g/cm^2 may then be compared to the nuclear burst data obtained from the 60 m^2 shielded mosaic of fifteen detectors of the Bolivian Air Shower Joint Experiment (BASJE) which is described by Hasegama, et. al. (1965).

To properly represent the several fluctuations, we used a random number generator (one of the computer's library subroutines) to select:

(1) The interaction point of each particle assuming a mean free path of 80 g/cm^2 for protons, neutrons, and pions and 15 g/cm^2 for Fe nuclei.

(2) The direction of emission of every particle emerging from an interaction relative to the direction of the incident particle assuming a uniform azimuthal distribution and the

distribution of transverse momentum:

$$f(p_t) \propto p_t e^{-p_t^2 / p_0^2} ; \langle p_t \rangle_{av} = 350 \text{ Mev/c}; (p_t)_{max} = 100 \text{ Mev/c}$$

and finally,

(3) The inelasticity of protons and neutrons assuming an even distribution from 0.25 to 0.75. We adopted an inelasticity of 1.0 for pions. Further, we approximated the effect of the decay of charged pions by a low energy cutoff at 5.6×10^{10} ev. The energy spectrum of the secondary pions was fixed for a given available energy (inelasticity x incident energy) and was taken directly from Tanahashi's (1965) numerical approximations of the 2 center model (Type 1) and the isobar model (Type 2). We further assumed that other than the residual incident particle, the only secondaries were pions and that in every interaction the number of charged pions amounted to 2/3 of the total number of pions. In the case of heavy primaries we assumed complete breakup at the first interaction.

We have generated about 400 artificial cascades using the two above mentioned interaction models and two pure primary compositions (pure Fe and pure p) as shown in Table I.

TABLE I

<u>No. Events</u>	<u>Primary Composition</u>	<u>Primary Energy</u>	<u>Interaction Model</u>
99	pure proton	1.8×10^{14}	two center
99	pure iron	1.8×10^{14}	two center
99	pure proton	1.8×10^{14}	isobar
99	pure iron	1.8×10^{14}	isobar

Our results are indicated in Figures (1-3). Figure (1) illustrates, for proton events, the large fluctuations in the pattern and total energy of the n.a.p. at 530 g/cm^2 . The same characteristic fluctuations are immediately apparent for Fe events even though an analysis of the entire sample indicates that they are less severe. Figure (2) presents the distribution of total energy deposited at 530 g/cm^2 per shower for each of the four combinations of primary composition and interaction model. It is noted that the distribution for Fe primaries is much narrower than that for proton primaries, a phenomenon closely related to the fact that the Fe cascade is largely controlled by 56 distinct nucleons of high elasticity which as a group must convert their energy to pions more or less continuously throughout the atmosphere. In contrast, the proton cascades have only one such particle which can suffer large fluctuations in the number and atmospheric depth of its interactions. There is no pronounced effect due to the choice of interaction model. Figure (3) presents the lateral distributions close to the core of the number of n.a.p. in several ranges of fixed energies for the 99 proton primary, 2 center model simulated events.

The 400 artificial cascades were used to simulate the nuclear burst patterns in the 60 m^2 BASJE shielded detector. The core location was chosen randomly to be on or near the mosaic of fifteen 4 m^2 detectors. The conversion to burst size was obtained from an independent but similar Monte Carlo

calculation, the preliminary results of which indicate that

$$\text{Burst size (particles)} = E_{\text{n.a.p.}} (\text{ev}) \times 10^{-9} \pm 60\%$$

is a reasonable calibration for our purposes. In fact, the extreme fluctuations may exceed 60%, especially at lower energies. We assume that the fluctuations obey a flat distribution law within the 60% limits, and we chose each particular burst size with the random number generator. Figures (4-6) illustrate the distribution of bursts in radius and in size.

For the 2 center model particularly (Fig. 4) we note that, relative to the proton events, the Fe events yield many large bursts in the radial interval 2-4 meters and fewer detectors with small or with no bursts in the 0-4 meter interval. This observation is apparently equivalent to the previous observation that the Fe cascades tend to deposit a significant and consistent amount of energy at 530 g/cm^2 and to the fact that the Fe cascade generally will consist of many n.a.p. These effects yield both a flat-peaked pattern and large bursts in the finite size (4 m^2) detectors. This distinction is less clear for the isobar model (Fig. 5). Also, we note that comparison of the energy distribution of bursts near the core for the two proton plots shows a large number of high energy events for the isobar model relative to the 2 center model.

The actual BASJE data (Fig. 6) yields distributions which are similar to the artificial distributions but which are not

markedly identical to any particular one of them. At the present state of our analysis, it is not appropriate to draw conclusions from this comparison. However, it appears that such conclusions might be possible once we have included in our computations: (1) the decay of charged pions, (2) fluctuations in the $\pi^{\pm}/\pi^0$ ratio, and (3) the 2-3 meter uncertainty in the core location of the real showers which derive from the fitting of the electromagnetic component to a theoretical lateral distribution. Item (1) above and underestimated fluctuations in the conversion of low energy n.a.p. to burst size suffice to explain the marked absence of small bursts in the simulated distributions.

A visual inspection of individual burst patterns yield no qualitative systematic difference between an iron cascade pattern and a proton cascade pattern. However, we do note that when large amounts of energy are deposited in the 60 m² array by an Fe cascade, the peaks are invariably more flat topped, or less peaked, than they are for proton events which deposit large amounts of energy in the array. Also, we have tabulated (Table II) the number of double and triple peaks for the simulated iron and proton cascades and for the real data. A peak was defined as a burst in one or two adjacent detectors, whose average burst size exceeded by a factor of two, each of the bursts in each of the adjacent detectors of the 60 m² mosaic of fifteen detectors. We also required in

each case that the shower core be incident upon the 60 m^2 array. No clear distinction in the patterns for the two interaction models was apparent, so we grouped all proton events together for comparison with all the Fe events. The results presented in Table II show no apparent change with primary composition in the distribution of multiple peaked events in the BASJE detectors.

TABLE II

Percentage Distribution of Double and Triple Peaks in the 60 m^2 BASJE array

No. of Events:	Real Events	Artificial Events	
	36 <u>Run 591</u>	88 <u>Proton</u>	95 <u>Fe</u>
Flat or no peak	25%	10%	11%
1 peak	47	63	59
2 peaks	22	26	26
3 peaks	6	1	4

Finally, we have generated several cascades at $5.6 \times 10^{15} \text{ ev}$ for Fe, C, and proton primaries using an isobar interaction model. We find that for C and Fe cascades there is a large proportion of nucleons among the n.a.p. of energy greater than 10^{12} ev at the atmospheric depth of 530 g/cm^2 . The results are presented in Table III. This result did not include the effect of fluctuations in inelasticity. However, because the effect is so pronounced, it appears possible to identify individual showers initiated by complex nuclei by the identification of neutral n.a.p. in the core of EAS at Mr. Chacaltaya.

Such an experiment has been suggested by the Japanese group (Koshiha et.al. 1965).

TABLE III

Relative numbers of nucleons among all n.a.p. of energy $\geq 10^{12}$ ev and incident at atmospheric depth of 530 g/cm^2 upon an area of 9 m^2 about the core location; seven simulated events for various primary particles each of energy 5.6×10^{15} ev.

<u>Type Primary</u>	<u>No. Nucleons</u>	<u>Total No. n.a.p.</u>
Fe	13	13
Fe	12	12
C	7	15
C	7	12
p	1	3
p	1	1
p	1	3

ACKNOWLEDGEMENTS

The authors wish to thank Dr. K. Suga and Dr. K. Kamata for rewarding discussions concerning the paper, and Mr. Paul Scheffler for his assistance with the calculations. Also the authors wish to express gratitude to the staff of the Laboratorio de Fisica Cosmica of the Universidad Mayor de San Andres, La Paz and to the staff of the Laboratory for Nuclear Science at the Massachusetts Institute of Technology for their assistance.

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FIGURE CAPTIONS

- Figure 1 Spatial distribution of nuclear active particles at the atmospheric depth of 530 g/cm^2 for four simulated proton initiated events at $1.8 \times 10^{14} \text{ ev}$ and using the two centered model. Upper events are extreme fluctuations: left, the primary survived to 530 g/cm^2 without interaction; and right; the primary interacted 12 times above 530 g/m^2 .
- Figure 2 Distribution of total energy of nuclear active particles deposited per shower at 530 g/cm^2 for approximately 400 simulated events of energy $1.8 \times 10^{14} \text{ ev}$.
- Figure 3 Radial distribution of the number of nuclear active particles in the specified energy range. The ordinate is the cumulative number of particles incident in the appropriate radial interval for 99 EAS.
- Figure 4 Radial and size distributions of bursts in the BASJE 60 m^2 detector array for simulated nuclear cascades initiated by a proton and Fe primary respectively, each of energy $1.8 \times 10^{14} \text{ ev}$, and using the two center model. The projected impact point of the primary particle (the core position) was allowed to fall randomly on or near the rectangular 60 m^2 array. The histogram at the bottom indicates the distribution of bursts of zero size (i.e. no n.a.p. was present). The absence of bursts of size between 1 and 10 arise from our use of a fixed low energy cutoff in lieu of pion decay.
- Figure 5 Same as Figure 4 except the isobar interaction model is used herein.
- Figure 6 50 real events. The core location is determined from the electromagnetic component with an uncertainty of about two meters. To allow direct comparison with the simulated cascades, the events were selected according to the following criteria: (1) core within 2 meters of the 60 m^2 array; (2) zenith angle less than 30° ; and (3) $4.8 \leq \log_{10} (\text{size}) \leq 5.2$.

1200002 - P2C

• $5.6 \times 10^{10} - 5.6 \times 10^{11}$ ev

X $5.6 \times 10^{11} - 5.6 \times 10^{12}$

Y $5.6 \times 10^{12} - 5.6 \times 10^{13}$

Z $5.6 \times 10^{13} - 5.6 \times 10^{14}$

Z

1200003 - P2C

Spatial Distribution of Four
Events (Proton-2 center)

1200033 - P2C

Y.

1200020 - P2C

Fig.1 EAS-11

Fig. 2 EAS-11

Fig. 3 EAS-11

Fig 5 EAS-11

Fig. 6 EAS-11

Title: Low- μ Showers

CONF-650948-5

1. Distribution of arrival directions of pure electromagnetic air showers of energy 10^{14} to 10^{16} eV.
2. Experimental upper limit on intergalactic cosmic rays at 2×10^{17} eV.
3. Evidence for pure proton composition of primary cosmic rays above 10^{17} eV.

(Bolivian air shower joint experiment)*

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* This work was supported in part by the Air Force Office of Scientific Research under Grant No. AF-AFOSR-546-64, and in part by the Japanese Ministry of Education, the Government of Bolivia, and the Atomic Energy Commission under Contract No. AT(30-1)2098.

Abstract

The accumulation of extensive air showers with extremely few penetrating particles (low mu showers) has been continued. The low proportion of penetrating particles in these showers is consistent with that expected for nearly pure electromagnetic showers generated by primary gamma rays.

The distribution in right ascension of the arrival directions of low mu showers of energy 10^{14} to 10^{16} eV shows a peak between 200° and 220° .

Among about 10,000 showers in the energy range from 10^{16} to 10^{17} eV we have observed none which have sufficiently few penetrating particles to be classed as of possible gamma ray origin. This result places a significant upper limit on the rate of production of high energy gamma rays in intergalactic space in collisions between cosmic rays above 2×10^{17} eV and thermal photons. With the assumption of an intergalactic thermal photon flux characterized by a 5800°K black body spectrum and an energy density of 0.1 eV cm^{-3} , this upper limit implies that the average intensity of cosmic rays above 2×10^{17} eV in intergalactic space is less than 6.5×10^{-2} times their intensity near the earth.

In showers above 10^{17} eV, the distributions of number of muons at mountain altitudes and at sea level suggest that most of the primary cosmic rays above 10^{17} eV are protons.

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1. Introduction

The search for primary cosmic gamma rays of 10^{14} eV to 10^{17} eV (Suga et al. 1962, Suga et al. 1963) has been continued. The experimental approach, which has been described previously, is based on the idea that a shower produced by a primary gamma ray should contain a much smaller proportion of muons (about 1/30 to 1/100) than an ordinary shower produced by a primary charged cosmic ray.

The apparatus of the Bolivian Air Shower Joint Experiment (BASJE) consists of the following components: a 60 m^2 scintillation detector shielded by 165 g cm^{-2} of galena, 132 g cm^{-2} of concrete and 23 g cm^{-2} of lead to observe the number of muons; twenty scintillation detectors, each of 0.9 m^2 area, to observe the density of electrons; five fast timing scintillation detectors, each of 1 m^2 area, to determine the arrival direction; and seven lead glass total absorption Cerenkov detectors, each of 0.2 m^2 area, to observe the energy flow of electrons and photons. Fig. 1 shows the present arrangement of the detectors. The diameter of the array was recently expanded to 300 m by the addition of five scintillation detectors, each of area 0.9 m^2 , in order to increase the rate at which data on large showers can be obtained. An automatic system has been installed for recording the data from the fast timing detectors as well from all of the other detectors.

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2. Low-mu showers of 10^{14} to 10^{16} eV.

2.1 Existence of a separate group of showers with extremely few muons.

At the international Conference on Cosmic Rays at Jaipur, India (Suga et al. 1963) we reported evidence for showers with extremely few muons. This result has been confirmed with additional data obtained since that Conference. Fig. 2 is a plot of the frequency of showers versus the ratio of the number of muons to the number of electrons over the 60 m^2 detector for showers in the size range from 5×10^5 to 5×10^6 particles and with cores landing more than 25 m from the center of the 60 m^2 detector. As in our previous result there is a well defined peak in the lowest interval of the muon to electron ratio. The relative frequency of the "low mu" showers that give rise to this peak is about 5×10^{-4} in comparison to all showers in the same size range. This is in agreement with our previous result. As these low mu showers are nearly pure electromagnetic showers and since their longitudinal development through the atmosphere is different than that of ordinary showers, their relative frequency compared to ordinary showers of the same primary energy turns out to be about 2×10^{-4} for the energy range from 10^{15} eV to 10^{16} eV. However, from what is presently known regarding high energy interactions, it appears possible that low mu showers may be produced by primary charged cosmic rays which undergo extreme fluctuations in their first inter-

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action and transfer nearly all of their energy to a few neutral pions. Thus, without additional supporting evidence as to the nature of the primaries of low mu showers, the value of 2×10^{-4} must be taken only as an upper limit on the relative frequency of gamma rays.

2.2 Possible anisotropy of low mu showers

The clearest evidence for the existence of gamma rays among the primaries of low mu showers would be the observation of an anisotropy in the distribution of their arrival directions. It is well known that the distribution of the arrival directions of primary charged cosmic rays is highly isotropic. Thus, if low mu showers are, in fact, produced by primary charged cosmic rays, then the distribution of their arrival direction should also be isotropic. On the other hand, we can assume that high energy gamma rays are produced by the decay of neutral pions that arise in the collisions of charged cosmic rays with interstellar matter. The distribution of interstellar matter is certainly not isotropic on the scale of the galaxy nor possibly on the scale of a local super-cluster of galaxies. The distribution of cosmic rays in interstellar space may also be similarly anisotropic. Thus, we may well expect the distribution of the arrival directions of high energy gamma rays to be anisotropic.

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In order to test for the possible existence of an anisotropy, we selected showers with muon to electron ratios that were less than a certain value which was set so as to accept a group whose relative frequency in comparison to all showers was 10^{-3} . The selection criteria were described in detail previously (Suga, et al., 1963). The arrival directions of these showers (148 in number) in celestial coordinates are shown in Fig. 3. Fig. 4 shows the distribution of the arrival directions in right ascension. Between 200° and 220° there is a peak containing 21 showers. The expected number in the interval is 8.8 events on the assumption that the primaries have an isotropic direction distribution, and taking into account the observation time and the zenith angle distribution of the showers. The probability of occurrence of a statistical fluctuation of such a magnitude in any of the specified intervals of right ascension is 6×10^{-3} . We do not see any significant anisotropy of the showers in declination or in galactic coordinates. A peak in the same interval of right ascension was previously observed (Suga et al. 1963) but its amplitude was not as statistically significant. It is worth noting that the peak is in the interval of right ascension that includes a portion of the galaxy cluster that has been characterized as the local Super galaxy (De Vaucouleurs 1958).

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3. Low mu showers of 10^{16} eV to 10^{17} eV.

Hayakawa (1962) has pointed out that the predominant process for the production of primary gamma rays above 10^{16} eV is neutral pion production in collisions of ultra-high energy cosmic rays ($\geq 10^{17}$ eV) with thermal photons in intergalactic space. Therefore, the intensity of primary gamma rays above 10^{16} eV is related to the intensity of cosmic rays above 10^{17} eV and the density of thermal photons in intergalactic space.

We have observed 12,638 showers with sizes greater than 5×10^6 . Unlike the situation at lower energies, no separate group of showers with extremely few muons is distinguishable. Fig. 5 is a plot of the frequency of showers versus the muon to electron ratio over the 60 m^2 detector for sizes greater than 5×10^6 . We have estimated the expected number of primary gamma rays which would produce showers with sizes greater than this same lower limit following the discussion of Hayakawa and Yamamoto (1963). We have assumed 1) that the intensity of the intergalactic cosmic rays is the same as the intensity of cosmic rays observed at the earth, 2) that the energy density of the thermal photons in the intergalactic space is 0.1 eV cm^{-3} , and 3) that the energy spectrum is represented by black-body radiation of temperature $5,800^\circ\text{K}$. The expected number of primary gamma rays is about 15, and the average energy is about 3×10^{16} eV. The absorption of gamma rays of this energy in photon-photon collisions in intergalactic space was estimated to be negligible. According to Yamamoto's calcu-

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lation (1964), the energy of a proton which produces a gamma ray of energy 3×10^{16} eV is sharply peaked at 2×10^{17} eV. Therefore, the upper limit of the intensity of the intergalactic cosmic rays at 2×10^{17} eV is about $1/15 \approx 6.5 \times 10^{-2}$ of the intensity of the cosmic rays observed at the earth at the same energy. Fig. 6 shows the experimental upper limit on the ratio of the intergalactic intensity to the local intensity of cosmic rays obtained in this experiment together with the result obtained at a high energy at the Institute for Nuclear Study, University of Tokyo (INS) (Matano et al. 1965).

An alternative point of view is to ask what upper limit can be set from these data on the intergalactic thermal photon energy density. Let us take for the intensity of intergalactic cosmic rays the value determined by an extrapolation to lower energies of the spectrum of the ultra high energy primaries above 10^{18} eV which we may, for the sake of discussion, assume to be entirely extragalactic in origin. Using the data of Linsley (1963) on the spectrum above 10^{18} eV we find an upper limit for the energy density of the thermal photons of 1.1×10^{-2} eV cm⁻³.

4. Composition of primary cosmic rays above 10^{17} eV.

Fukui et al. (1960), have pointed out that a study of the number of muons in air showers can give information regarding the presence of heavy nuclei among the primary particles. If the number of muons n_μ depends on the size N according to the relation $n_\mu \propto N^p$ with $p < 1.0$, then an air

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shower produced by a heavy primary should contain a larger proportion of muons than one of the same size produced by a proton. The dependence of the number of muons in an air shower produced by a heavy primary on the mass number A is expressed by the relation $n_{\mu} \propto A^{1-p}$.

Fig. 7 is a plot of the number of showers versus the median number of muons in the 15 muon detectors adjusted to take into account variation with shower size and distance from the core and finally normalized to the average. The plot includes those showers with sizes larger than 5×10^7 (average about 1×10^8) corresponding to primary energies larger than 1×10^{17} eV (average about 2×10^{17} eV). The distribution can be fitted with a Gaussian distribution having a 25% standard deviation as would be expected on the assumption that the primary composition is pure and that the fluctuations are due to the Poisson fluctuation in the observed numbers of muons (average number ≈ 100) and instrumental errors amounting to 15 to 20%. The dotted curve is the distribution expected on the assumption that the composition is the same as that measure at lower energy (Ginzburg, Syrovatskii, 1964). In this calculation we used for the exponent p the value 0.8 which was obtained in this experiment. These results indicate that the composition above 1×10^{17} eV is quite different from that at lower energies and is pure (only protons or only heavy nuclei).

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The showers of size 5×10^7 observed at 5,200 m altitude are attenuated as they pass through the atmosphere so that the size of these showers at sea level is less than 10^7 . Fukui et al. (1960) showed that the large fluctuations in the number of muons in air showers of size less than 10^7 observed at sea level could be attributed to fluctuations in the depth of the first interaction of the primary particles provided they are protons. If the primary nuclei were heavy the fluctuations in the depth of the first interaction would be appreciably smaller. The evidence therefore supports the conclusion that the primary particles of energy more than 1×10^{17} eV are mainly protons. This conclusion is consistent with that of Linsley (1962).

Acknowledgements

The authors wish to acknowledge the assistance of Mr. H. Akiyama and Mr. A. Mogro in running the air shower equipment. They are also grateful to many others for their contribution to the construction, installation and operation of the equipment in the Laboratory for Nuclear Science of the Massachusetts Institute of Technology, the Laboratorio de Fisica Cosmica of Universidad Mayor de San Andres and the Institute for Nuclear Study of University of Tokyo. Professors B. Rossi and M. Oda have made the essential contributions in planning

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this project. This experiment is being supported in part by the United States Air Force Office of Scientific Research, by the U.S. Atomic Energy Commission, by the Ministry of Education of Japan, and by the Bolivian Government.

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Captions of Figures

- Fig. 1 BASJE array at Mt. Chacaltaya 5,200 m above sea level.
- Fig. 2 Distribution of the frequency of showers versus the muon to electron ratio in 60 m^2 for showers of sizes 5×10^5 to 5×10^6 and with core at least 25 m from the center of the detector array.
- Fig. 3 Arrival directions of low mu showers in celestial coordinates.
- Fig. 4 Distribution of the arrival directions of low mu showers in right ascension.
- Fig. 5 Distribution of the frequency of showers versus the muon to electron ratio in 60 m^2 for showers of size greater than 5×10^6 and with core at least 20 m from the center of the detector array.
- Fig. 6 Proportion of the intergalactic cosmic rays to the cosmic rays observed at the earth estimated from the intensity of gamma rays.
- Fig. 7 Distribution of the number of showers versus the median number of muons in the 15 muon detectors adjusted to a fixed shower size and fixed distance from the core, and finally normalized to the average.

BASJE ARRAY

(From October 1964)

Fig.1 EAS-29

Fig. 2 EAS-29

Fig. 3 EAS-29

Fig. 4 EAS-29

Fig. 5 EAS-29

Fig.6 EAS-29

Fig.7 EAS-29

The Primary Energy Spectrum
from 8×10^{14} ev - 4×10^{17} ev⁺

CONF-650948-6

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- + This work was supported in part by the Air Force Office of Scientific Research under Grant No. AF-AFOSR-546-64 and by the Atomic Energy Commission under Contract No. AT(30-1)-2098.

ABSTRACT

The number of extensive air showers obtained with the Bolivian Air Shower Joint Experiment on Mt. Chacaltaya in Bolivia has increased more than ten fold since the Jaipur meeting. The detector array has recently been enlarged to allow measurements on showers of up to 10^8 particles in size. With this new data, we have derived size spectra at Chacaltaya at various zenith angles and from them have deduced the energy spectrum. The spectrum is substantially the same as that reported at Jaipur except that our best estimate of the logarithmic slope is now $-2.2 \pm .15$.

We have made an estimate of the effect upon our result of fluctuations in the longitudinal development of EAS and in the depths of the depths of the first interactions. The effect is small and is included in the quoted slope.

At the Jaipur Conference Clark, et al. (1963) reported a primary energy spectrum which was based on air shower data recorded at El Alto (4,200 m.a.s.l.) and on early results obtained with the array of the Bolivian Air Shower Joint Experiment (BASJE) on Mt. Chacaltaya (5,200 m.a.s.l.). Since that report the number of showers recorded at Chacaltaya has been increased by an order of magnitude and part of this data was obtained with the recently enlarged detector array (Toyoda, et al., 1965). Several showers of size 10^8 or more particles are now being accumulated each day.

The input data from the many thousands of showers have been fitted by an iteration process to obtain a size, core location, and arrival direction for each shower. Showers were selected from the processed data using criteria which insured that the detection probability was close to 100%. The accepted showers were divided into subgroups according to zenith angle. From each of these subgroups we constructed an integral size spectrum which took into account the projected effective areas for different sizes, the solid angle included in each zenith angle interval, and the total observation time. Each size spectrum spans a narrow interval of atmospheric depth and effectively describes the integral intensity of showers of size greater than N particles at a fixed atmospheric depth x , $S(N,x)_{x = \text{const.}}$

The integral size spectrum for near vertical showers is shown in Figure 1. In this instance, the characteristic slope change is from -1.4 near size 10^5 to -2.3 near size 10^7 . This change in slope may be interpreted as an indication that for smaller showers the average depth of development lies above the level of observation while showers of size 10^7 or more reach their average maximum development below the level of observation. The knee might also reflect a change in the primary energy exponent in this region.

A comparison between the El Alto results and the present experiment can best be made by comparing the size spectra of the two experiments at the same atmospheric depth. This comparison is shown in Figure 2. The agreement is close above size 2×10^6 . At the smaller sizes the results from the two experiments might be expected to differ slightly since the El Alto size determinations were derived from density measurements made at typically larger distances from the core. Our results do not depend critically upon size determinations below 2×10^6 .

Obtaining an energy spectrum from air shower data is rendered difficult by the lack of precise knowledge of the nucleonic cascade which governs the development of the shower. The average parameters involved in high energy nuclear interactions are not well known and fluctuations add to the complexity. The effects of these uncertainties are minimized if showers are observed near the average depth of maximum develop-

ment. Most theoretical models predict an almost linear relationship between the energy and the maximum size. The models predict that showers of from 10^6 to 10^8 particles reach their maximum development at mountain altitudes.

The series of integral size spectra, $S(N, x)_{x = \text{const}}$ for several atmospheric depths, x , may be cut at the same integral intensity giving several values of the function $N(S, x)_{S = \text{const}}$. Figure 3 shows the results for several such cuts. One series of points (for an intensity of $10^{-15} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$) has been retained from the El Alto results and a comparison between the experiments is made at the intensity of $10^{-14} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$.

Over a range of four decades in intensity, the size at maximum development may be estimated without resorting to a particular model of shower development. Figure 4 is a plot of the intensity versus the estimated size at the maximum of the smooth curves drawn through the points in Fig. 3. Over the size range from 10^6 to 10^8 a power law with an exponent of -2.3 provides the best fit. Below 10^6 the uncertainty in estimating the size at maximum becomes large.

In order to transform the size spectrum into a primary energy spectrum we have assumed that the size at shower maximum is proportional to the primary energy, in that the proportionality constant is $2 \times 10^9 \text{ ev/particle}$. This value is within 30% of estimates based on average development curves.

computed for various models (Ueda 1960) (Tanahashi 1965). The value is also close to the empirical estimates of Greisen ((1960) and Nikolsky (1962) which are based on the average energy dissipation of the various components of air showers. Ignoring the effect of fluctuations, we would conclude that the primary spectrum has the same logarithmic slope as our size spectrum, namely -2.3. Taking into account the fluctuations in the depths of the first interactions and in the development of individual showers as described below, the logarithmic slope of the primary energy spectrum would appear to be -2.2 ± 0.15 .

A composite energy spectrum is plotted in Fig. 5. The portion covered by the present results differs only slightly from the presentation at Jaipur (Clark et al., 1963). This portion can be represented by

$$J(>E) = 2.0 \pm .4 \times 10^{-14} (E/10^{17})^{-2.2 \pm 0.15} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$$

for $8 \times 10^{14} < E < 4 \times 10^{17}$ ev.

In order to understand better the relation of this derived energy spectrum to the true primary energy spectrum, we have simulated the generation of showers by primaries with a given energy spectrum with the aid of an electronic computer. We have assumed two forms of the longitudinal development curves and have allowed for fluctuations in the depths of the first interactions and in the maximum size-energy relation. With these assumed fluctuations we have generated size spectra at

various atmospheric depths and from these have derived a primary energy spectrum using the constant intensity method of analysis and a linear maximum size-depth relation. Preliminary results from these calculations show a slight tendency for this method of analysis to steepen the logarithmic slope of the energy spectrum, and it is for this reason that we have made the correction mentioned above.

ACKNOWLEDGEMENTS

The authors wish to thank the staff of the Laboratorio de Fisica Cosmica for their efforts in behalf of the BASJE experiment. Particular gratitude is due Mr. H. Akiyama and Mr. A. Mogro who bear the difficult task of maintenance at the mountain laboratory. Acknowledgement is also gratefully made to the computation Center of the Massachusetts Institute of Technology for the considerable use of their facilities in processing the data. Finally, we thank the staff of the Laboratory for Nuclear Science of the Massachusetts Institute of Technology for their assistance throughout the course of this experiment and in particular Mr. Charles Forline and Mr. Paul Scheffler for their thoughtful and energetic assistance with the data analysis.

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FIGURE CAPTIONS

- Figure 1 Integral size spectrum of EAS observed at Mt. Chacaltaya with arrival directions near the vertical, i.e. such that $1.0 < \sec \theta < 1.1$ where θ is the zenith angle.
- Figure 2 Comparison of size spectra at Mt. Chacaltaya (5200 m altitude) and El Alto (4200 m). The zenith angles (θ) are chosen so that both observations are at the same effective atmospheric depth.
- Figure 3 Longitudinal development curves obtained from constant intensity cuts on the plots of the size spectra obtained for various zenith angles, or effective atmospheric depths. The smooth curves are drawn to fit the data points.
- Figure 4 Integral intensity as a function of shower size at the maximum in the longitudinal development curves of Figure 3.
- Figure 5 Composite primary energy spectrum. The heavy line refers to the spectrum obtained in this work. Volcano Ranch data is from J. Linsley, Proceedings of the Eighth International Cosmic Ray Conference Jaipur, 4, 77 (1963).

Fig. 1 EAS-31

Fig.2 EAS-31

Fig. 3 EAS-31

Fig. 4 EAS-31

Fig. 5 EAS-31