

CHARACTERISTICS OF NUCLEAR INTERACTIONS OF PROTONS AND PIONS IN CARBON AT ENERGIES OF ABOUT 50 GeV

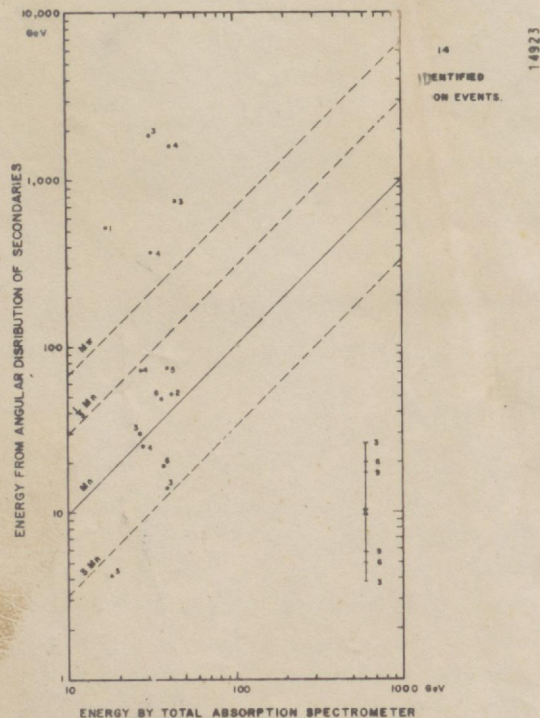
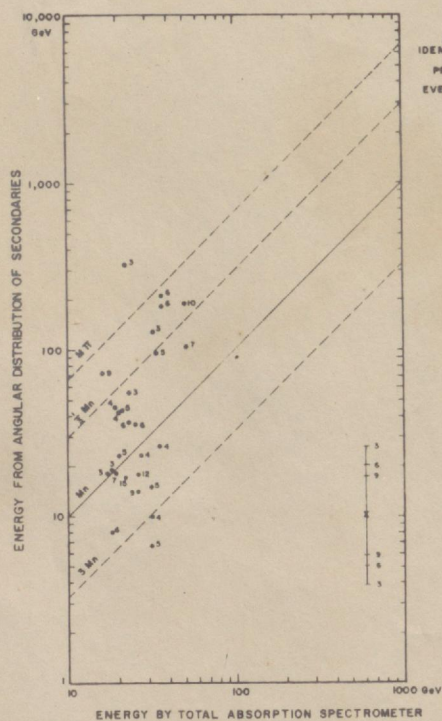
Siddheshwar Lal, R. Raghavan, B. V. Sreekantan, T. N. Rangaswamy, A. Subramanian and S. D. Verma (*)

Tata Institute of Fundamental Research, Bombay

(presented by A. Subramanian)

A study has been made of 125 nuclear interactions in carbon produced by protons and pions of the cosmic radiation at energies of about 50 GeV (in the range of 30-150 GeV) using a multiphase cloud chamber. The experimental arrangement (**) permits the measure-

ment of the energies of the primaries to an accuracy of $\pm 20\%$ in individual cases, and allows the classification of the primaries into protons and pions when they have energies less than 43 GeV by the use of a total absorption spectrometer and an air Cerenkov counter.



Figs. 1 and 2 Plots showing the energy of the primary estimated from the total absorption spectrometer vs. the energy estimated by the method of Castagnoli *et al.* for identified proton (Fig. 1) and identified pion (Fig. 2) events. The numbers near the points indicate the charged multiplicities (n_s) in the events. The error along the ordinate for $n_s = 3, 6$ and 9 is given in the inset.

(*) Now at the University of Chicago on study leave.

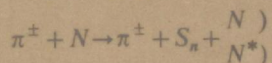
(**) Siddheshwar Lal, R. Raghavan, B. V. Sreekantan, A. Subramanian and S. D. Verma: Journ. of Phys. Soc. of Japan, Vol. 17, Suppl. A-III, 390, (1962).

The relative intensity of pions to protons (at 2.2 km altitude) at about 40 GeV has been found to be $50 \pm 10\%$ with our apparatus.

The events have been examined on plots shown in Figs. 1 and 2. In the case of interactions produced by pions, there appears a group of five events exhibiting extreme angular collimation of the secondaries in the laboratory system (events above the line labelled M_x in Fig. 2). There are in all 21 events of this type in the whole sample of nuclear interactions collected. These are all assumed to be produced by pions. The multiplicity distribution of forward charged secondaries, of total forward secondaries including neutral mesons (geometrically feasible in 16 cases), and other distributions regarding these events, are given in Figs. 3 (a-d). It should be mentioned that in two events there is a relativistic secondary in the backward direction in the laboratory system (probably due to the decay of an isobaric state of the recoiling target nucleon) and four events have one "heavy prong" coming out of the graphite layer in each case. These are not included in the multiplicity distribution.

The most interesting feature of these events is that on the average only $5 \pm 1\%$ of the energy of the primary is transmitted to the neutral mesons. In fact no neutral meson of energy more than 10% of the energy of the primary has been observed. Therefore, these events representing $30 \pm 10\%$ of the collisions of charged pions in the above stated energy region are "peripheral", resulting in no charge exchange, with one outgoing charged pion carrying away 80-90% of the incident energy.

The angular distribution of the secondaries, the energies of the neutral mesons and the multiplicity distributions in Figs. 3 (a and b), lead to a tentative interpretation of the "anomalous" pion events as due to a reaction of the type



DISCUSSION

HERZ: I should like to say first that Dr. Subramanian's results, as he knows, agree extremely well in many parts with the results we obtained at Milan both in a propane bubble chamber and in emulsion using a CERN π^- beam of about 16 GeV. In particular we also find about 30% of events for which one would calculate, if one did so, a very low target

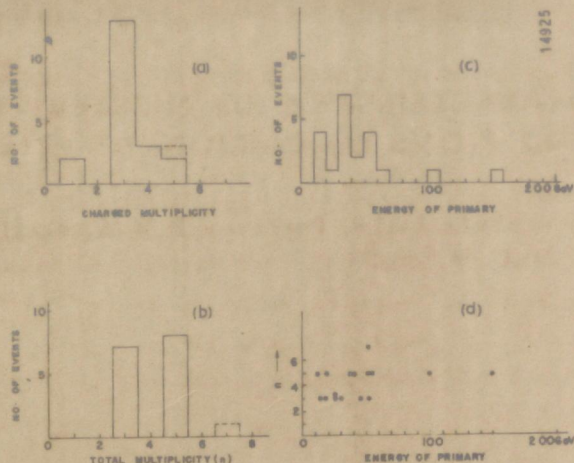


Fig. 3 (a) Distribution of charged multiplicity (n_c) for the anomalous events. (b) Distribution of total multiplicity $n = (n_c + n_n)$ for the same. One event with multiplicity $n_c = 5$ (Fig. a) and $n = 7$ (Fig. b) has a charged secondary which is not clearly distinguishable. (c) Energy distribution of the primaries of the events. The open circle indicates the doubtful multiplicity case. (d) A plot of the total multiplicity vs. energy of the primary producing the events.

where S_n represents a "cloud" disintegrating into n pions, n being most often 2 or 4. The object S_n disintegrates almost symmetrically with a mean total energy of 200^{+25}_{-20} MeV per pion in the centre-of-mass system of the incident pion and the "target pion". This energy of disintegration of S_n is low compared to the mean total energy (evaluated from our data) of 430 ± 80 MeV per pion in the disintegration of "clouds" produced in proton and "normal" pion collisions. Absence of forward charged multiplicity of 2 (and 4 in "good geometry" events) suggest that S_2 and S_4 carry no charge. The above features together with the absence of S_3 probably indicate that S_2 and S_4 are new resonant states of pions with masses ~ 400 MeV and ~ 800 MeV decaying into two and four pions respectively. There seem to be low Q -value "clouds" of multiplicity higher than four in the class of "anomalous" pion interactions.

mass. I am not sure that the 30% is really correct, but this is what we get at the moment. However, we have been trying a number of different explanations for these events (not Dr. Subramanian's). In particular, we have been trying to explain some of these events as one pion exchange with a nucleon; we have been explaining, or trying to explain some of these

THE K.G.F. NEUTRINO PROJECT*)

B.V. Sreekantan,
Tata Institute of Fundamental
Research, Bombay.

I. INTRODUCTION

In 1961-62 a group¹⁾ from the Tata Institute of Fundamental Research, Bombay carried out measurements in the Kolar Gold Fields in South India on the intensity of cosmic-ray particles at large depths underground in the near vertical direction ($> 2,000$ ft). For these measurements large area scintillation counter telescopes were used. At a depth of 4280 m.w.e. with a telescope of area 1.5 m^2 , the counting rate was $\sim 3/\text{day}$. With two telescopes, each of area 1.5 m^2 , the counting rate was \sim one in three days at a depth of 6400 m.w.e. At the largest depth of 8400 m.w.e. no count was registered in 60 days of operation.

This observation of no count at a depth of 8400 m.w.e. in two months of operation clearly set an upper limit to the remanent cosmic-ray muons of atmospheric origin at large depths underground, and opened up the possibility of detecting muons produced by neutrinos with detection systems which are relatively simple and which do not involve elaborate anti-coincidence shields that were thought to be essential for neutrino experiments in the earlier investigations. The feasibility of detecting natural neutrinos, in particular cosmic-ray neutrinos, with arrays comprising parallel detection layers in coincidence mounted vertically at an underground depth around 9,000 ft has been pointed out in two papers by Menon et al.^{2,3)} A more detailed account is available in the review talk given by Menon⁴⁾ at the Jaipur Conference on Cosmic Rays in 1963.

II. NEUTRINO TELESCOPE AT K.G.F.

In the light of the K.G.F. experiments during the last year, we have undertaken to set up large area telescopes designed specifically for detection of the muons produced by neutrinos. The Osaka City University, Japan, and the University of Durham, U.K. have joined us in this project.

The details of the neutrino telescope, the fabrication of which is nearing completion and which will be set up at a depth of 7,500 ft (approx.) at K.G.F., are shown in Fig. 1.

The telescope consists of two vertical walls of plastic scintillators, 3 m high and 2 m long, separated by about 80 cm. In between the plastic scintillator walls there are three vertical columns of neon-flash tubes, between which provision has been made for the introduction of lead bricks of 2.5 cm thickness. The plastic scintillator walls are composed of 24 blocks, each $50 \text{ cm} \times 50 \text{ cm} \times 5 \text{ cm}$. Each square metre of the plastic scintillator wall is viewed by two 5 in. diameter Dumont 6364 photomultipliers mounted centrally and at a distance of about 40 cm from the plastic surface. In all, for each telescope there are 24 photomultipliers. There are two such units.

*) A collaboration between Tata Institute of Fundamental Research, Bombay, Osaka City University, Japan and University of Durham, United Kingdom.

The master pulse that will trigger the flash-tube circuit is obtained as follows: pulses from each pair of photomultipliers which look at the same square metre of plastic scintillator are first put into coincidence after suitable amplification; then, each pair on one side is put into coincidence with any of the six pairs on the opposite side and thus, a four-fold coincident master pulse is generated.

Provision is made for display on a system of four oscilloscopes, the pulse amplitudes of all the photomultipliers, whenever there is a master pulse. A continuous monitoring of the counting rates of all the photomultipliers is also incorporated. The preamplifiers, the main amplifiers, the coincidence circuits, the monitoring circuits etc. are all completely transistorized.

The present site chosen for the experiment is at a depth of 7,500 ft (approximately) below ground and is considered to be quite adequate, since visual detectors are being employed in the apparatus for the detection of the muons produced by neutrinos. Since the experiment has to run for several months - probably for several years - it is essential that the site must be easily accessible from the surface. The present site can be reached in about ten to fifteen minutes from the surface. The temperature at the site is about 90°F and is fairly constant.

III. EXPECTED COUNTING RATES

The counting rates expected obviously depend on the flux of neutrinos and the behaviour of the neutrino interaction cross-section with energy. We reproduce below some of the preliminary calculations that have been made by Menon et al.⁵⁾. The assumptions involved are shown in Table 1.

The flux of muons and the counting rates for an exposure of 10,000 m² day steradians are shown in Table 2.

With our apparatus, which has an effective area of 12 m² and a solid angle of four steradians for isotropic radiation, we can expect an exposure of the order of 10,000 m² day steradians in 200 days of operation.

As can be seen from Table 2, the expected number of events in about six months of operation could be anywhere between 1 and 30. It is only a preliminary run of six months' duration that can really tell us where we stand with respect to the detection of cosmic-ray neutrinos. However, there could well be some surprises either in the behaviour of neutrino interaction cross-section at high energies, or in the extraterrestrial fluxes of neutrinos and antineutrinos. It is to be remembered that so far there has been no experiment which could have detected either of these two possibilities. Many are now in the offing.

The chief merit of the present apparatus is the inclusion of visual detectors, neon flash tubes, which will render the interpretation of the events recorded unambiguous. Dr. Wolfendale will be discussing the role of flash tubes in this apparatus in a paper which is scheduled to be presented later on in this conference.

We hope to start the experiment underground towards the end of February.

Table 1

Assumptions

Neutrino fluxes

- i) Vertical fluxes as given by Zatsepin and Kuzmin [J.E.T.P. 14, 1294 (1962)].
- ii) Fluxes are isotropic.

Elastic collisions

i) $\sigma_{\nu} = 0.74 \cdot 10^{-38} \text{ cm}^2/\text{neutron}$

ii) $\sigma_{\bar{\nu}}$ independent of energy

iii) $\sigma_{\bar{\nu}} = \sigma_{\nu}$

iv) $E_{\mu} \approx E_{\nu}$

Inelastic collisions

i) $\sigma_{\nu} = 0.37 \cdot 10^{-38} \cdot E_{\nu}^n \text{ cm}^2/\text{nucleon}$
up to E_{ν} cut off and constant
at a value $0.37 \cdot 10^{-38} E_{\nu c}^n$ at
higher energies.

ii) $n = 1 \text{ or } 2$

iii) $\sigma_{\bar{\nu}} = \sigma_{\nu}$

iv) $E_{\mu} = \frac{1}{2} E_{\nu}$

Table 2

Neutrino produced muon fluxes deep underground

1. Contribution from elastic collisions: $3.26 \cdot 10^{-14}$ muons/cm² sec sterad
2. Contribution from inelastic collisions:

Flux in units of muons/cm² sec sterad

| Energy dependence of $\sigma_{inel.}$ E_ν cut off (GeV) | $\sigma_{inel} \propto E_\nu^2$ | Number of counts in an exposure of 10,000 m ² days sterad | $\sigma_{inel} \propto E_\nu$ | Number of counts in an exposure of 10,000 m ² days sterad |
|--|---------------------------------|--|-------------------------------|--|
| 1 | $1.63 \cdot 10^{-14}$ | 0.14 | $1.63 \cdot 10^{-14}$ | 0.14 |
| 2 | $4.59 \cdot 10^{-14}$ | 0.39 | $2.84 \cdot 10^{-14}$ | 0.25 |
| 4 | $1.10 \cdot 10^{-13}$ | 0.97 | $4.00 \cdot 10^{-14}$ | 0.34 |
| 10 | $2.90 \cdot 10^{-13}$ | 2.5 | $5.03 \cdot 10^{-14}$ | 0.43 |
| 20 | $5.62 \cdot 10^{-13}$ | 4.8 | $5.91 \cdot 10^{-14}$ | 0.51 |
| 40 | $1.02 \cdot 10^{-12}$ | 8.9 | $6.77 \cdot 10^{-14}$ | 0.59 |
| 60 | $1.42 \cdot 10^{-12}$ | 12 | $7.17 \cdot 10^{-14}$ | 0.62 |
| 100 | $2.06 \cdot 10^{-12}$ | 18 | $7.59 \cdot 10^{-14}$ | 0.65 |
| 150 | $2.66 \cdot 10^{-12}$ | 23 | $7.85 \cdot 10^{-14}$ | 0.68 |
| 200 | $3.06 \cdot 10^{-12}$ | 26 | $7.95 \cdot 10^{-14}$ | 0.69 |

REFERENCES

- 1) S. Miyake, V.S. Narasimham and P.V. Ramana Murthy, Proc.Phys.Soc. (Japan) 3, 318 (1962).
- 2) M.G.K. Menon, P.V. Ramana Murthy, B.V. Sreekantan and S. Miyake, Physics Letters 5, 272 (1963).
- 3) M.G.K. Menon, P.V. Ramana Murthy, B.V. Sreekantan and S. Miyake, Nuovo Cimento, Series X, 30, 1208 (1963).
- 4) M.G.K. Menon, Proceedings of the International Conference on Cosmic Rays (Jaipur), Vol. 6, 152 (1963).
- 5) M.G.K. Menon et al., to be published.

K.G.F. NEUTRINO TELESCOPE

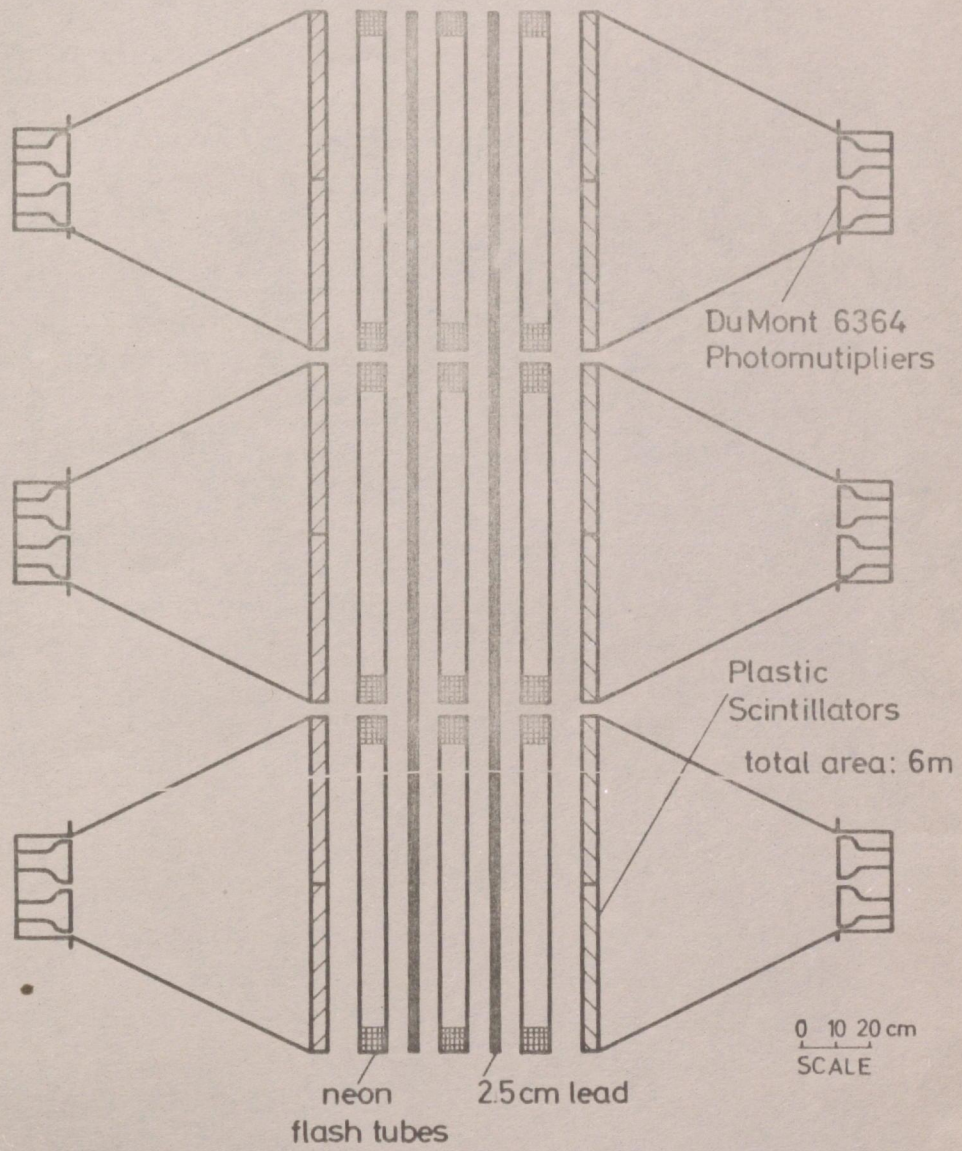


Fig. 1

FIGURE CAPTIONS

Figure 1 : Details of the neutrino telescope.

events as a diffraction process, diffraction disintegration on carbon, and also there is a theory by the Florence group which predicts that there should be one pion exchange with the nucleus as a whole. All these mechanisms are possible and all these mechanisms would combine to give you the sort of results that Dr. Subramanian found, and that we also found; in particular, a large peak of events with three charged secondary pions. The only thing that we do not find is the low energy of the secondaries in highly collimated events. I do not know where this disagreement comes from.

SUBRAMANIAN: I would like to say that with the same technique in other events the energy of the neutral-mesons evaluated agree with the usually accepted value of about 400 MeV. In these events, when we look at the γ rays, we have to be a factor of 2 out in energy in the estimate to make them in agreement with a mean-energy of 400 MeV which we think is not possible.

LOHRMANN: I have two questions regarding the nature of the primary particles producing your interactions. First, what is the percentage of neutral primary particles among your events?

SUBRAMANIAN: All interactions were produced by charged primaries.

LOHRMANN: Second, do you apply any correction for the fact that the proton might be accompanied by an electron and therefore might trigger your air-Cerenkov counter?

SUBRAMANIAN: We have in the trigger system avoided events where there is more than one primary.

MENON: I will give two numbers from an experiment done by Babu, Cowsik, Pal and Rengarajan at Bombay: (a) The charge exchange cross-section for π^- 's of 17 GeV/c in carbon is less than $\cdot 1\text{mb}$. (b) 23 GeV/c proton interactions in carbon have been compared with 17 GeV/c π^- interactions in carbon. The p_\perp of the neutral pions in the proton case is the usual value of about 400 MeV/c and in the pion case about 215 MeV/c. The difference appears to be significant and may reflect on the systems in the two cases which give rise to these pions.

KOBA: I think your interpretation does not mean one pion exchange.

SUBRAMANIAN: We do not know about this one pion exchange, or what really happens. But phenomenologically, from the multiplicity distribution, if one assumes that the neutral meson is a representation of the additional charged secondaries produced, then we are led to this sort of reaction.

KOBA: I said it because you get even multiplicity from an additional cloud.

SUBRAMANIAN: We think that it may be that these are all even numbers and that probably they are neutral. Even multiplicities will not favour one-pion exchange as you have remarked.

EXTENSIVE AIR SHOWER STUDIES OF THE T.I.F.R. (BOMBAY) GROUP

B.V. Sreekantan

(Tata Institute of Fundamental Research, Bombay.)

1. Introduction

Experimental studies in the field of Extensive Air Showers have two important aspects:

(i) To determine the characteristics of nuclear interactions at ultra high energies i.e. at energies greater than about 10^{14} eV where no other method of investigation is feasible.

(ii) To deduce information regarding the nature and properties of the primary cosmic radiation (composition, spectrum, directional anisotropies etc.) again at the very high energy end.

The two aspects belong to entirely different domains of physics but from the point of view of the air shower experimentalist who has to work backwards from his observations at mountain altitude or sea level to the top of the atmosphere through the complex of many generations of nuclear interactions, the two aspects are closely intertwined since information regarding one cannot be obtained without adequate knowledge of the other. The only way he can ultimately hope to segregate the two and derive useful information regarding both is by a systematic study and thorough classification of the detailed properties

Members of the TIFR Air Shower Group:- B.K. Chatterjee, G.T. Murthy, S. Naranan, V.S. Narasimham, P.V. Ramana Murthy, B.V. Sreekantan, M.V. Srinivasa Rao and P.R. Viswanath.

Visiting: K. Hinotani and S. Miyake (Osaka City University, Osaka, Japan)

T. Matano (Institute for Nuclear Study, Tokyo, Japan).

of air showers — he has to determine the structure, the fine structure and the hyperfine structure of air showers, the relative intensities of the various components, the correlations and anti-correlations between these components at different atmospheric depths and zenith angles.

Such a detailed study of air showers has certainly become feasible as far as the electron component is concerned and is being carried out by many workers. It has been demonstrated already that the lateral structure of the electron component is not independent of size and altitude and it is also shown that even at a fixed size there are wide fluctuations in the lateral distribution of the electron component. There is also evidence for fluctuations in the energy carried by the soft component in showers of the same size. These fluctuations are related to many causes — the fluctuation of the level of first collision, composition of primary cosmic radiation, change in the characteristics of nuclear interactions etc. Detailed study of the electron component alone is not sufficient to realize the objectives set forth. Information of a vital nature is certainly contained in other components like the nucleon and muon components. Because of the fact that the intensity of these components is down by a factor of 10 - 100 compared to the electron component and also because of the complexity of the apparatus required to identify these components, it has not been feasible to determine the lateral structure of these components in individual showers. In almost all the experiments the showers are grouped according to electron size and the assumption is made that the lateral distributions of the muon and N-components and their number do not fluctuate from shower to shower. On the basis of such an assumption the shape of the lateral distribution and the total number of muons and N-particles are deduced.

We have reported previously at the Kyoto Conference that our results both at sea level and mountain altitude indicate strongly the presence of wide fluctuations in the density of muons and low energy N-particles in showers of

the same electron size at a specific distance from the core. We also reported a positive correlation in the fluctuations of the densities of muons and N-particles. We could not specifically say at that time whether the fluctuations in the observed densities were due to the fluctuations in the total number of these particles or in the lateral distributions of these particles or, whether they are due to both. Because of the positive correlation between the N and muon components and also because of the extensive nature of the fluctuations, we had assumed that the fluctuations in the density reflected fluctuations in the total number.

We have now analysed our results further and obtained further experimental information with a modified air shower array specifically designed to look at the low energy N and muon components. Our present results show that the total number as well as the lateral distributions of both N and μ -components do fluctuate from shower to shower. There is a clear evidence for the steepening of the lateral distribution of the N-component with increasing size. There is also evidence for a rather interesting correlation between the lateral distributions of the electron, muon and N-components.

II. Experimental Details - Method of Analysis.

The EAS arrays at Ootacamund which have been in operation intermittently for the past three years is shown in Figs. 1 and 2. The method of recording air shower data is shown in Fig. 3. The analysis of air showers is carried out with the electronic computer, TIFRAC

III. The Lateral Distributions of Electron, Muon and N-components.

The lateral distribution function that has been found empirically to fit the observed densities in the distance range 5 - 50 metres and for

showers of size $10^5 - 10^6$ particles is

$$\Delta(r) = C(\alpha_e) N_e r^{-\alpha_e} e^{-r/r_0} \dots (1)$$

where $r_0 = 107$ m (scattering distance for an altitude of 800 gms/cm^2) and α_e is a parameter which indicates the steepness of the lateral distribution function at distances close to the core. The lateral distribution function (1) adopted by us is very close to the N-K function with the relation $s = 2.3 - \alpha_e$ where s is the so-called age parameter in the N-K function. For computer analysis any scintillator which was within a distance of 3 m from the core was excluded in order to avoid bias due to very wide fluctuations which are bound to occur in the core. Four discreet values of α_e were tried out for best fit — 1.3, 1.5, 1.7 and 1.9. The value of α_e that gave the best χ^2 was printed out by the computer.

The histograms in Fig. 4 show the relative frequencies of occurrence of various values of α_e for different size groups. It is necessary to point out that because of varying α_e the area of 100% detection efficiency varies even for showers of the same size. This fact has been taken into account in drawing the histograms in Fig. 4.

The variation of the mean value of α_e with size is shown in Fig. 5.

The important results that follow from Figs. 4 and 5 are:

- (i) At all shower sizes investigated there is a spectrum of α_e values.
- (ii) At sizes of $10^5 - 10^5$ lower α_e 's predominate and fluctuations are considerable (1.3 and 1.5).
- (iii) At sizes larger than 10^6 larger α_e 's predominate (1.7 and 1.9).
- (iv) The mean value of α_e viz. $\bar{\alpha}_e$ changes by about 0.3 for a shower size change of about 5 in the neighbourhood of $N_e = 10^6$.

Since for shower sizes of about 10^5 , there was a pile up of α_e at 1.3 (Fig. 4) in the new analysis of air shower data collected with the

modified array (Fig. 2) the values of α_e that are tried out for best fit are 0.7, 1.0, 1.3 and 1.7. Preliminary results based on the analysis of about 2,000 showers indicate that the mean value of α_e at these sizes is lower than 1.3 — is about 1.1.

At all sizes investigated the lateral distribution of the low energy N-component may be expressed by a power law of the form $r^{-\alpha_n}$ upto a distance of about 40 m. The lateral distribution of the low energy N-component for various sizes is shown in Fig. 6. Evidence for the steepening of the lateral distribution with size is unmistakable. The value of α_n changes by as much as 1.0 in going from shower sizes of 10^5 to 10^7 .

If we classify the showers according to α_e — the parameter indicating the steepness of the electron lateral distribution and then see the corresponding lateral distribution of the N-component, then we find a rather interesting result which is shown in Figs. 7 (a) and 7 (b). At shower sizes less than 10^6 the lateral distribution of the N-component is flat in showers which have a flat electron lateral distribution and steep in showers which have a steep electron lateral distribution.

$$\alpha_n = 1.0 \text{ when } \alpha_e = 1.1$$

$$\alpha_n = 1.8 \text{ when } \alpha_e = 1.7 - 1.9$$

However, surprisingly at shower sizes larger than 10^6 there appears to be only one type of lateral distribution of the N-component.

$$\alpha_n = 1.5 \text{ for } \alpha_e = 1.1$$

$$\alpha_n = 1.65 \text{ for } \alpha_e = 1.7 - 1.9$$

The showers with flat N-component lateral distribution seem to be significantly absent.

This transition appears to be rather sudden in the sense that the change-over of the lateral distribution of the N-component comes about within

a factor of 5 in shower size.

A similar behaviour is also seen in the lateral distribution of the muon component as can be seen from Figs. 8 (a) and 8 (b). However, the difference between the lateral distributions at sizes less than 10^6 and greater than 10^6 is not so very striking as in the N-component. The tendency, however, is quite unmistakable. At shower sizes $2 - 5 \cdot 10^5$ $\alpha_\mu = 1.1 \pm 0.15$ for $\alpha_e = 1.1$ and $\alpha_\mu = 1.5 \pm 0.15$ for $\alpha_e = 1.7 - 1.9$. However, at shower sizes $2 - 5 \cdot 10^6$ $\alpha_\mu = 0.95 \pm 0.15$ for $\alpha_e = 1.1$ and $\alpha_\mu = 1.1 \pm 0.15$ for $\alpha_e = 1.7 - 1.9$. Because of these strong correlations we can conclude that the parameter α_e is a very useful and sensitive parameter for classification of showers of the same size.

Integrating the relevant lateral distributions of the N and μ components up to 50 metres from the core in showers of the same electron size, we find that the showers which have flat lateral distributions ($\alpha_e = 1.1, \alpha_\mu = 1.1, \alpha_n = 1.0$) have more number of N and μ -particles than showers which have steep lateral distributions. Therefore, the observed fluctuation and the positive correlations in the densities of muons and N-particles at a given electron size are a consequence of both the variation of the lateral distribution and the total number.

All the results that we have considered so far are essentially for vertical showers ($\theta < 40^\circ$). A comparison of the number of muons and N-particles at a given size for vertical ($\theta < 40^\circ$) showers and inclined showers ($\theta > 40^\circ$) shows that when the amount of matter is increased by about 300 gms/cm^2 the number of muons increases by a factor of about 1.3 and the number of N-particles decreases by a factor of about 1.7. This is true at all sizes between 10^5 and 10^7 particles. This shows that the effect of the level of first collision would be to give an anti-correlation between the muons and N-particles. The experimentally observed positive correlation between muons and N-components

should therefore be a strong indication of a source which counter-balances the negative correlation that should exist due to level fluctuations even in the vertical direction. One such source can be the presence of heavy nuclei in the primary cosmic radiation at air shower energies.

Ramifications on some of these aspects and also the results on size spectrum, variation of the total number of N-particles and muons with size, differences in the properties of showers triggered by muons etc. will be presented by Dr. Naranan in his talk later on.[†]

IV. Absorption Characteristics of Muons in Extensive Air Showers -

Under-water Experiments.

The muon content of extensive air showers has become an extremely important parameter and has been used particularly in connection with the identification of the nature of primaries of air showers. For example, showers which are particularly rich in muons have been considered to be induced preferentially by heavy primaries and showers which have a low content of muons have become candidates for γ -ray initiated showers. In this connection, it is extremely important to know some of the characteristics of low energy muon component like the energy spectrum, the absorption and lateral spreading characteristics etc.

We have recently determined some of these parameters by a simple but elegant method. This experiment has been carried out in collaboration with Profs. S. Miyake and K. Hinotani of the Osaka City University, Osaka, Japan.

Four plastic scintillators each of area about 1.5 m^2 located at the corners of a square of side 20 m were immersed in a lake at mountain altitude (800 gms/cm^2) to various depths under water and the 4-fold coincidence rates recorded as a function of depth up to a depth of 10 m. The same experi-

[†] See p. 227

mental set-up was then moved to sea level and the counting rates determined in a lake for various depths. A comparison of the rates recorded under similar amount of water at the two atmospheric depths has shown that the rates are attenuated by a factor of about 3 between 800 gms/cm^2 and sea level from which it can be deduced that the absorption of muons in air showers proceeds with a mean free path of about $340 \pm 40 \text{ gms/cm}^2$. This absorption includes losses due to ionisation, decay and lateral spread of muons. The results also indicate that the mean production level of muons of energy $\geq 1 \text{ GeV}$ is about $7 \pm 2 \text{ kms}$ from sea level and the energy spectrum in the energy range $1 - 2 \text{ BeV}$ may be expressed by a power law with an exponent -0.6 ± 0.10 .

The counting rates as a function of different areas of scintillators and also as a function of various separations between them have also been obtained for various depths at both the altitudes. The implications of these measurements will be discussed in a paper that will be presented later on.†

V. Air Shower Studies in Association with Ultra High Energy ($\geq 200 \text{ GeV}$) Muons (K.G.F. Air Shower Project).

We have already stressed on the fact that for a proper utilisation of air shower data, it would be desirable to have simultaneous information on many components of the shower. One such component which can be of immense value is the very high energy muon component. Ultra high energy muons ($\geq 200 \text{ GeV}$) in extensive air showers can arise only through the decay of pions produced very high in the atmosphere in nuclear collisions of energy $> 10^{12} \text{ eV}$. A detailed study (lateral distribution, multiplicity, energy spectrum etc.) of the muons at large depths reflects therefore the characteristics of the first few collisions at the top of the atmosphere. The air shower array at

† See p.277

the surface gives the total energy of the primary interacting at the top of the atmosphere. Since the relevant collisions are confined to a few interaction mean free paths, the nucleon cascade calculations become simple and it becomes feasible to decide the basic characteristics of high energy collisions like inelasticity, multiplicity, angular distribution etc. by such a combined study. From a simple consideration it can be shown that by recording the percentage of association of muons in extensive air showers recorded over a specific area at the surface, it would be possible to obtain the total number of muons in showers of different sizes and by studying the variation of the percentage of association as a function of depth the energy spectrum of very high energy muons can be deduced.

Experimental information regarding multiple muons underground and their relative separation, and the associated shower sizes at the surface should enable us to determine the relative importance of the production of excited baryons which decay into high energy pions at air shower energies.

Multiple muons of high energy can result more easily from heavy primaries because of (i) weak dependence of multiplicity on energy ($n_s \propto E^{0.25}$) and (ii) increase in the probability of occurrence of the first few collisions in the lower density regions of the atmosphere where the $\pi-\mu$ decay probability is higher. Presence of ultra high energy muons, in particular multiple muons, in showers which are relatively rich in low energy muons may, therefore, serve as a more reliable criterion for identification of heavy primary induced showers than the criterion of μ -richness alone adopted so far. The study of the directional distribution of such showers may then reveal any marked anisotropies in the arrival directions of heavy primaries that may exist.

Some of these considerations have prompted us to take up a new project in which we plan to operate a comprehensive EAS array in conjunction with large area muon detectors located at various depths underground. Professor T. Matano of the Institute for Nuclear Study, Tokyo is collaborating with us on this project.

The Extensive Air Shower array will be set up at the Polar Gold Fields where we have carried out recently intensity measurements up to a maximum depth of 3,000 metres below ground. The surface conditions at the mines are ideal for setting up large-scale Extensive Air Shower arrays. Details of the array which is expected to go into operation in a few months are shown in Fig. 9. The Table on the next page gives the calculated rates of association of showers of different sizes with muon detector of 10 m^2 located at depths of 266, 590 and 1120 metres below ground corresponding to association of muons of energy 220, 640 and 1800 GeV respectively.

T A B L E.

| Depth in metres. | Energy of muons in BeV. | Size $\geq 10^4$ particles Effective surface radius = 20 m Surface air shower rate = 4000/day | | Size $\geq 10^5$ particles. Effective surface radius = 60 m Surface air shower rate = 180/day. | |
|------------------|-------------------------|---|---|--|---|
| | | Total Number of muons in the shower. | Expected rate of association in 10 m^2 detector underground | Total Number of muons in the shower. | Expected rate of association in 10 m^2 detector underground |
| 266 | 220 | 18 | 16/day | 87 | 40/day |
| 590 | 640 | 5 | 0.64/day | 25 | 1.6/day |
| 1120 | 1800 | 1 | 1/20 days | 7 | 1/8 days |

Calculations based on:

Flux of showers of size $\geq 10^4 = 3 \times 10^{-5}/\text{m}^2 \cdot \text{sec.st.}$

Flux of showers of size $\geq 10^5 = 1.5 \times 10^{-6}/\text{m}^2 \cdot \text{sec.st.}$

Integral energy spectrum of muons in Air Shower $\propto E_{\mu}^{-1.2}$

* Total number of muons $\geq 75 \text{ GeV}$: $N_{\mu}(\geq 75 \text{ GeV}) = 13$ in 10^3 showers
and $N_{\mu}(\geq 75 \text{ GeV}) = 320$ in 10^5 showers

[* A. Ueda, N. Ogita: Prog. Theor. Phys. 18, 269 (1957).]

Fig. 1

The Extensive Air Shower Array which was in operation till recently at Ootacamund (altitude 2.2 km)

- (i) 12 scintillators spread over an area of 80 m x 80 m to record electron densities.
- (ii) 9 N-particle detectors (BF_3 counter assemblies embedded in lead and paraffin) each of area 0.4 m^2 at the centre of the array.
- (iii) 3 muon detectors each of area 0.6 m^2 (hodoscoped GM counter arrays in brick and lead) separated by about 20 m from each other.
- (iv) A nano second chronotron timing system coupled to 4 fast scintillators for determination of the arrival direction.

EXTENSIVE AIR SHOWER ARRAY I

OOTACAMUND
(2.2 Kms)

- 0.36 m²
- ▣ 0.5 m²
- 1 m²
- CHRONOTRON
- ▨ μ-DETECTOR
- ◻ NEUTRON DETECTOR

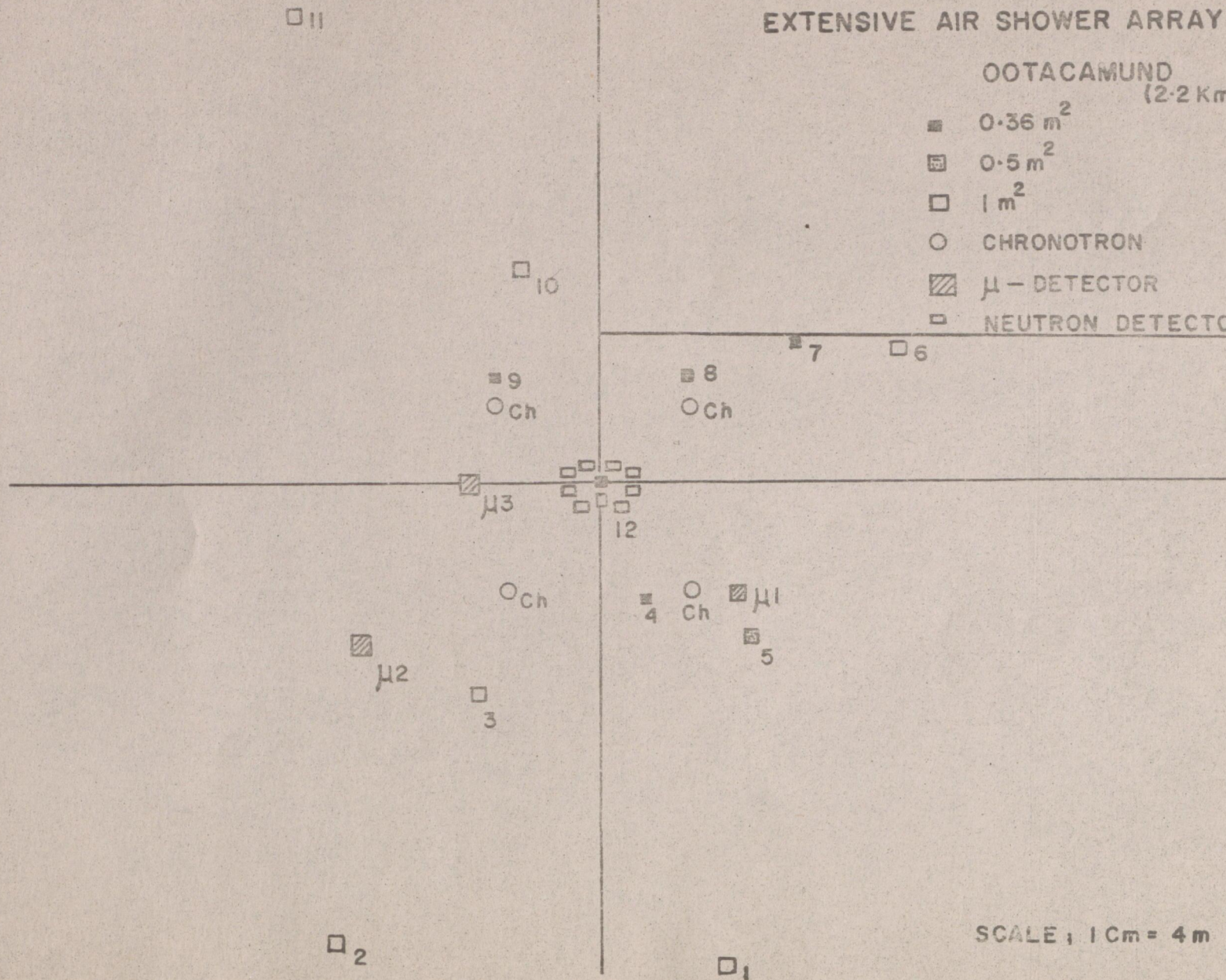


Fig. 2

The Extensive Air Shower array now in operation at Ootacamund.

- (i) 20 scintillators to measure electron densities
- (ii) Two groups of N particle detectors separated by about 20 m, and in all 14 N-particle detectors.
- (iii) 4 muon detectors each of area 1 m^2 (hodoscoped GM counter arrays)
- (iv) 5 fast scintillators (with the central one at a height of 8 m from the ground) for determination of the arrival direction.
- (v) An energy flow detector of area 4 m^2 for the soft component :
4 scintillators each of area 1 m^2 under 2.5 cms lead.
- (vi) Energy flow detector for N-component : 6 scintillators each of area (0.36 sq. m) under 5 ft. of water and 5 cms lead.
- (vii) A total absorption spectrometer of area 1 m^2 to record the nuclear interacting particles of very high energy ($> 100 \text{ GeV}$).

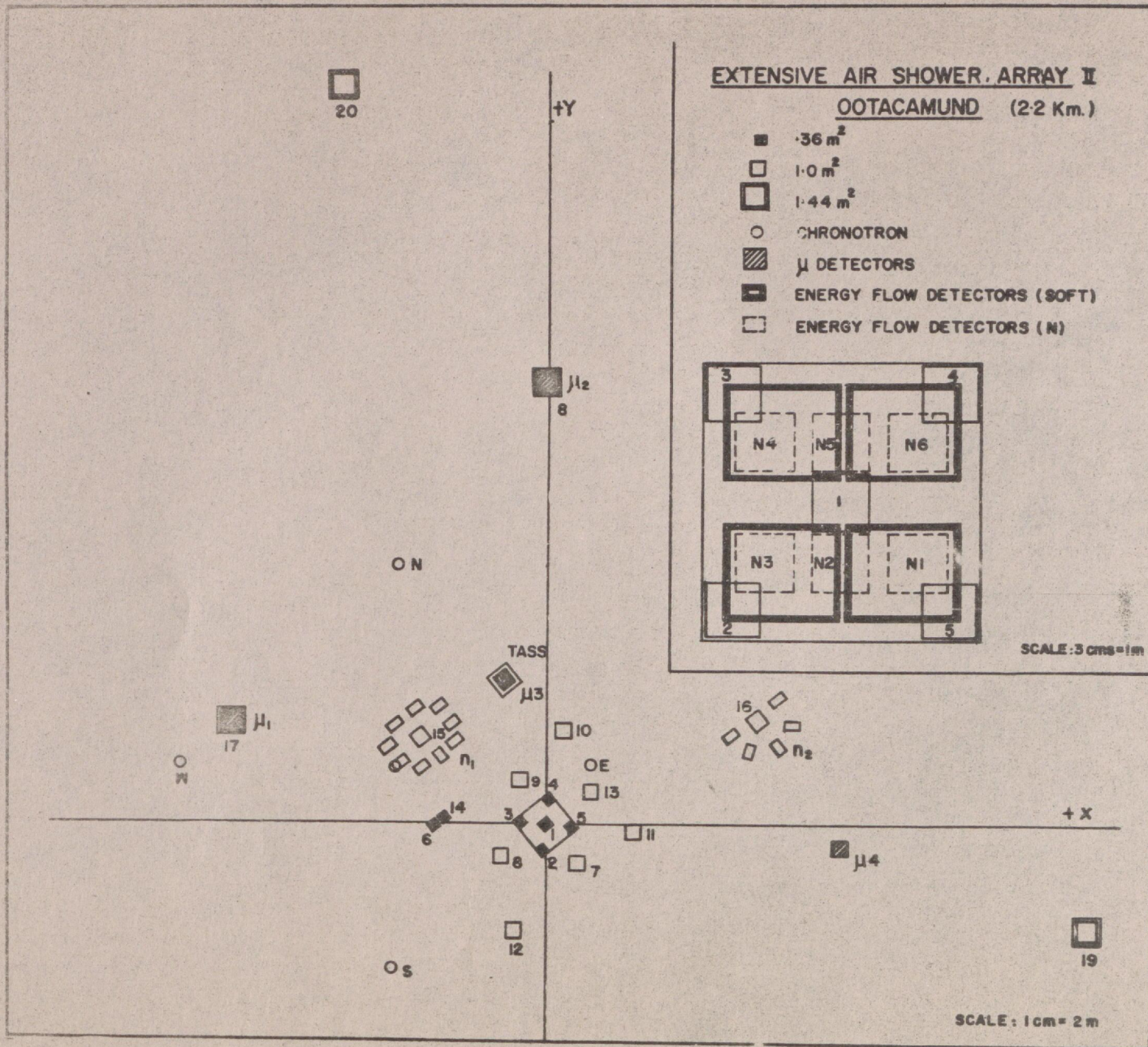


Fig. 2

Fig. 3

Digitised EAS Recording System

The output of each preamplifier belonging to the density measuring scintillators is coupled to a logarithmic amplifier-gated stretching unit, where three decades of pulse height range is compressed logarithmically into a linear ramp range of 10-150 volts, and stretched into a 10 second analog D.C. level by any one of the selection signals. A mercury-wetted-contact relay system triggered by the selection signal consequences the analog levels into an analog-digital encoder whose output is punched on to paper tape, every time the relay system changes on to the next detector in sequence. After the last of density detector informations is punched, a digital sequencing switch starts the punching of the nanosecond timing information of the shower-front timing scintillators, suitably quantised and stored in flip-flops, along with an indexing number for the shower and the local time.

The array is triggered by the following selection systems: (i) electron density — (a) 5-fold coincidence of scintillators 1, 2, 3, 4, 5 with a bias set at 12 particles/m², (b) 5-fold coincidence of scintillators 6, 10, 11, 12, 1 with a bias set at 10 particles/m², (ii) muon density — 4-fold coincidence of muon detectors I, II, III, IV, (iii) selection by total absorption spectrometer — energy of nuclear-active particles greater than 100 BeV, and (iv) energy flow density of the order of 5 GeV in any one of the 4 energy flow scintillators.

DIGITISED EAS RECORDING SYSTEM

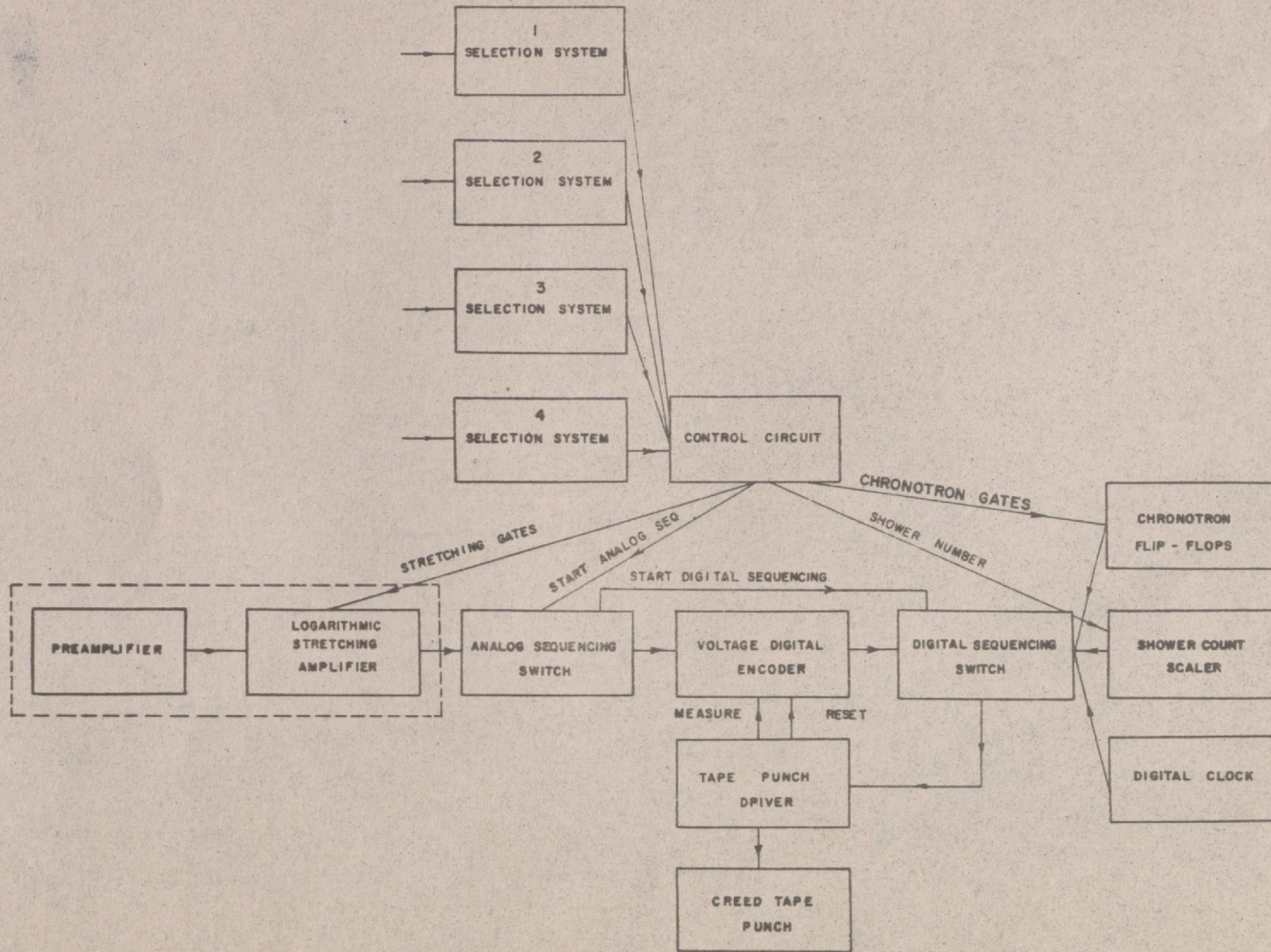
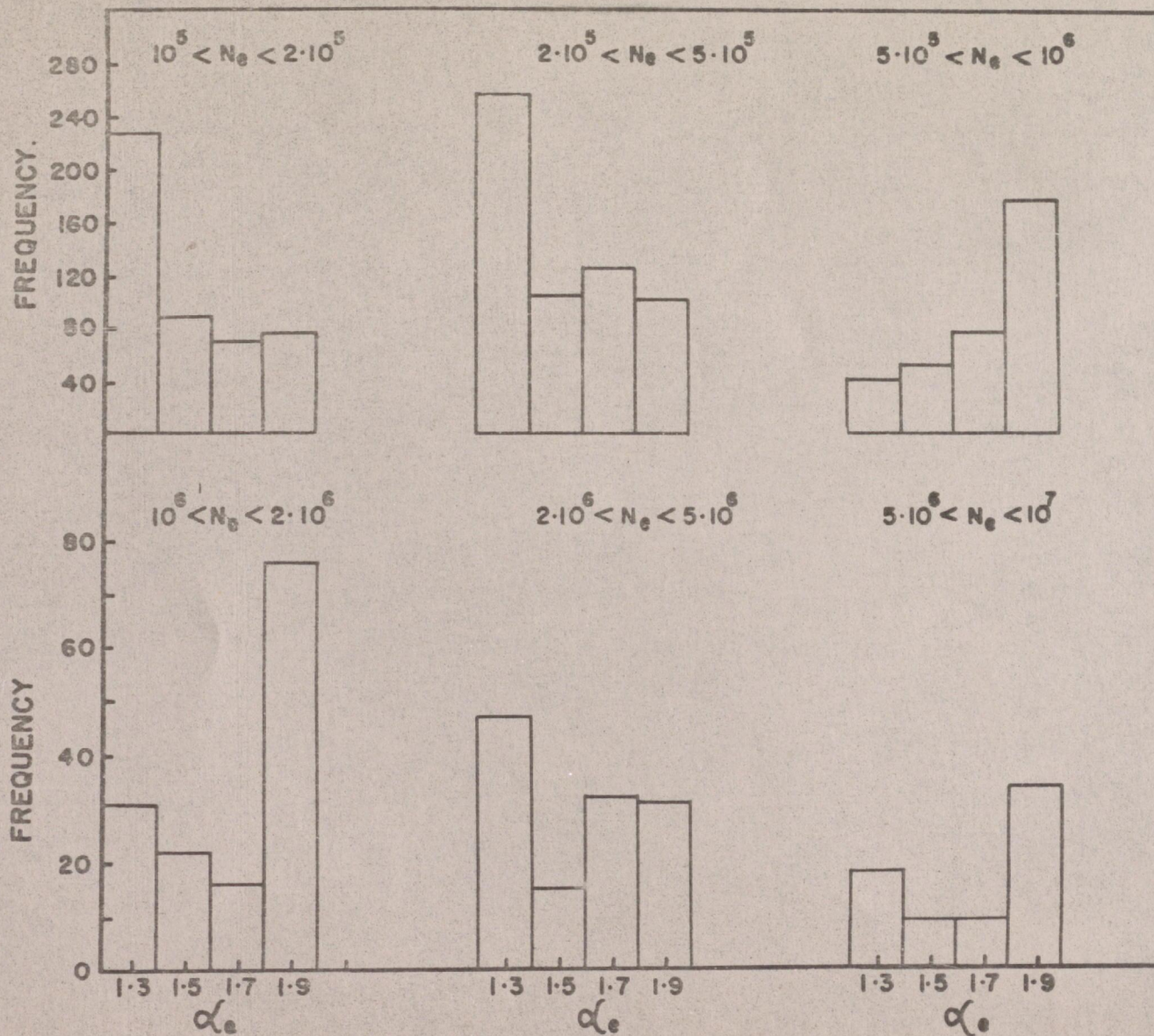


Fig. 3



α_e - DISTRIBUTION IN DIFFERENT SHOWER SIZES.

Fig. 4 : Histogram showing the relative frequency of occurrence of various values of α_e for different shower sizes.

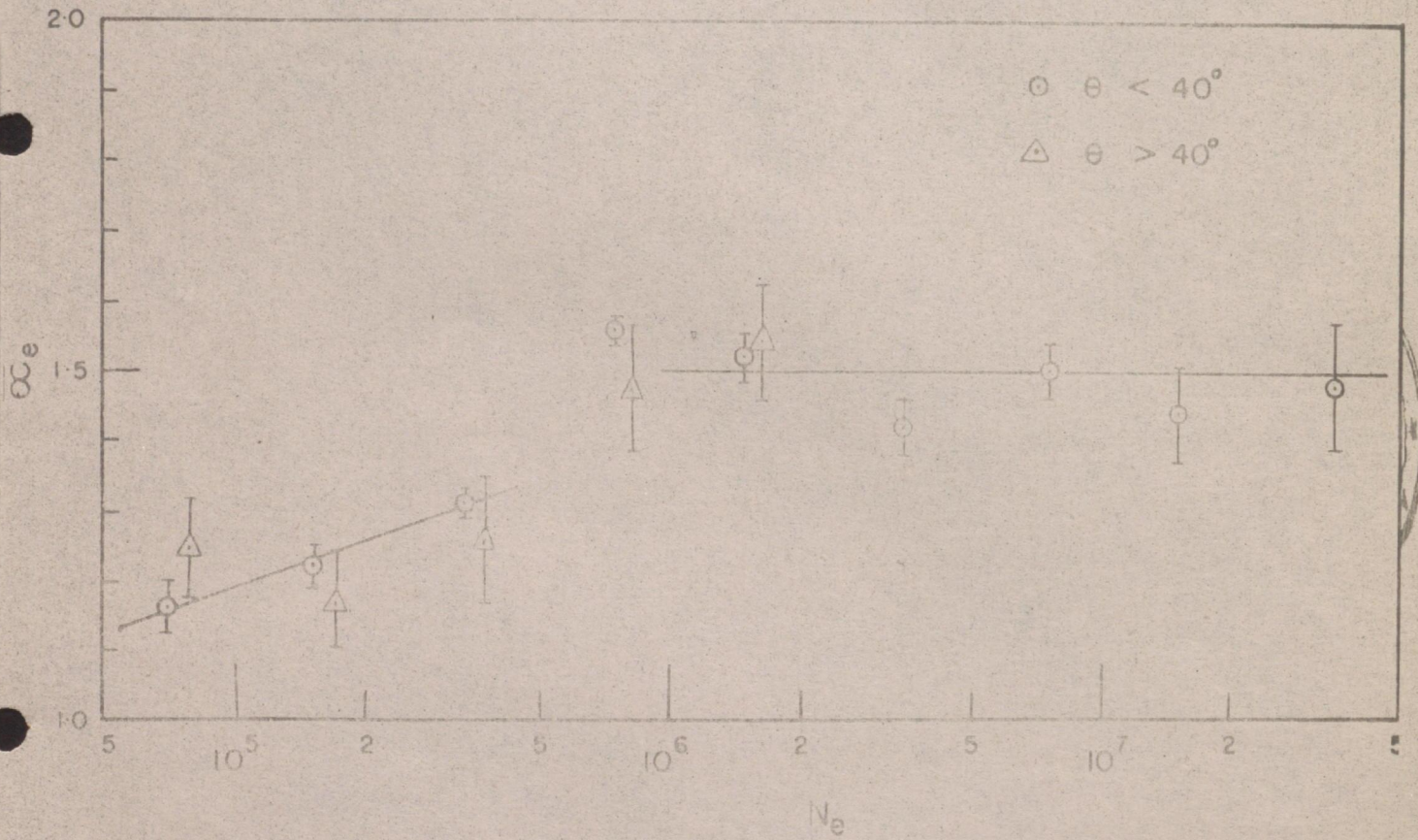


FIG. 5. $\bar{\alpha}_e$ vs. N_e

Variation of the mean value of α_e ($\bar{\alpha}_e$) as a function of shower size.

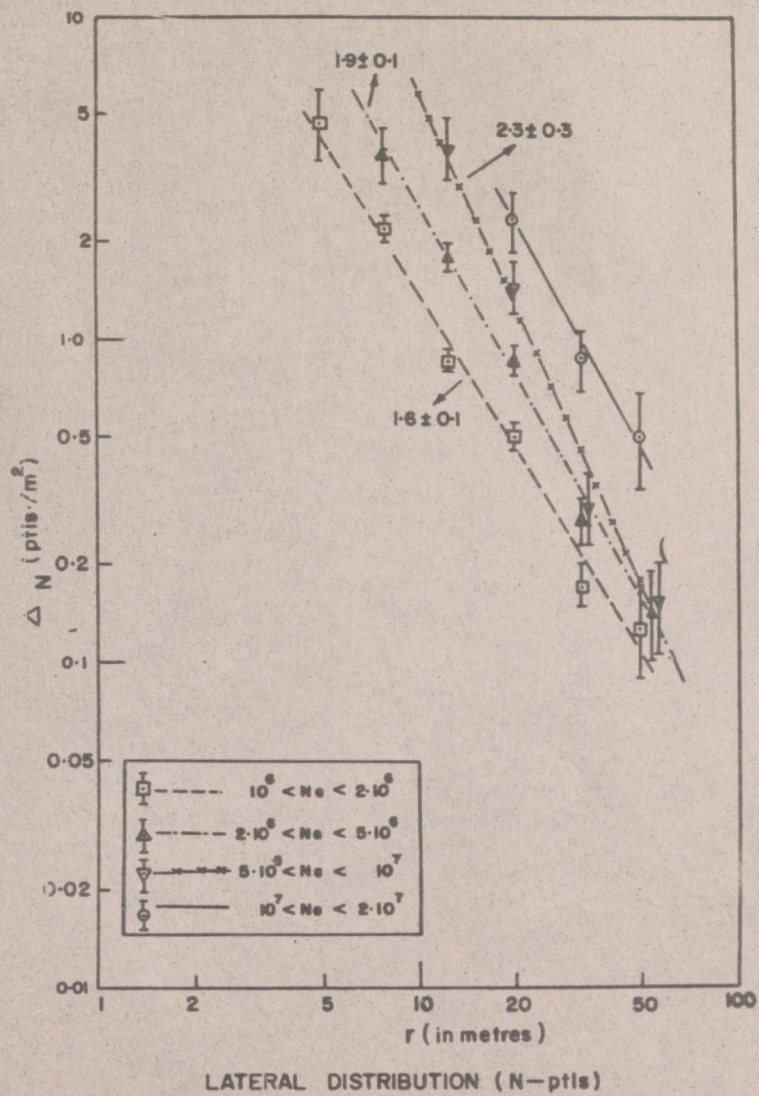
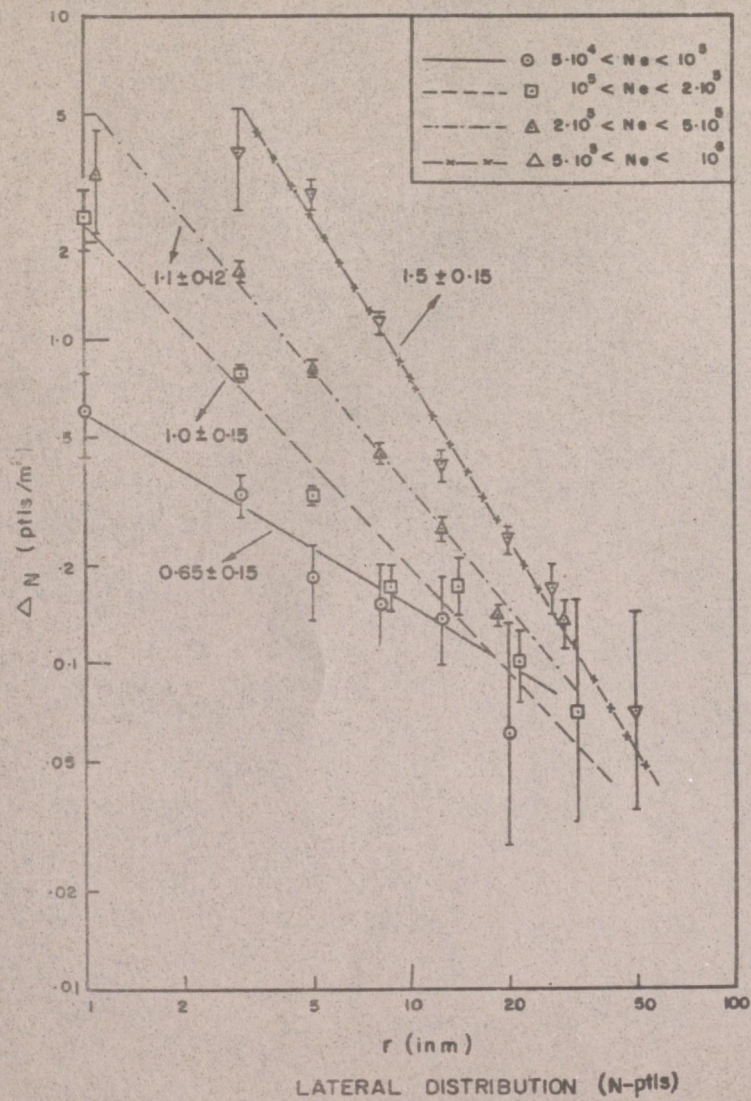


Fig. 6 : Lateral distribution of low energy N-particles as a function of shower size.

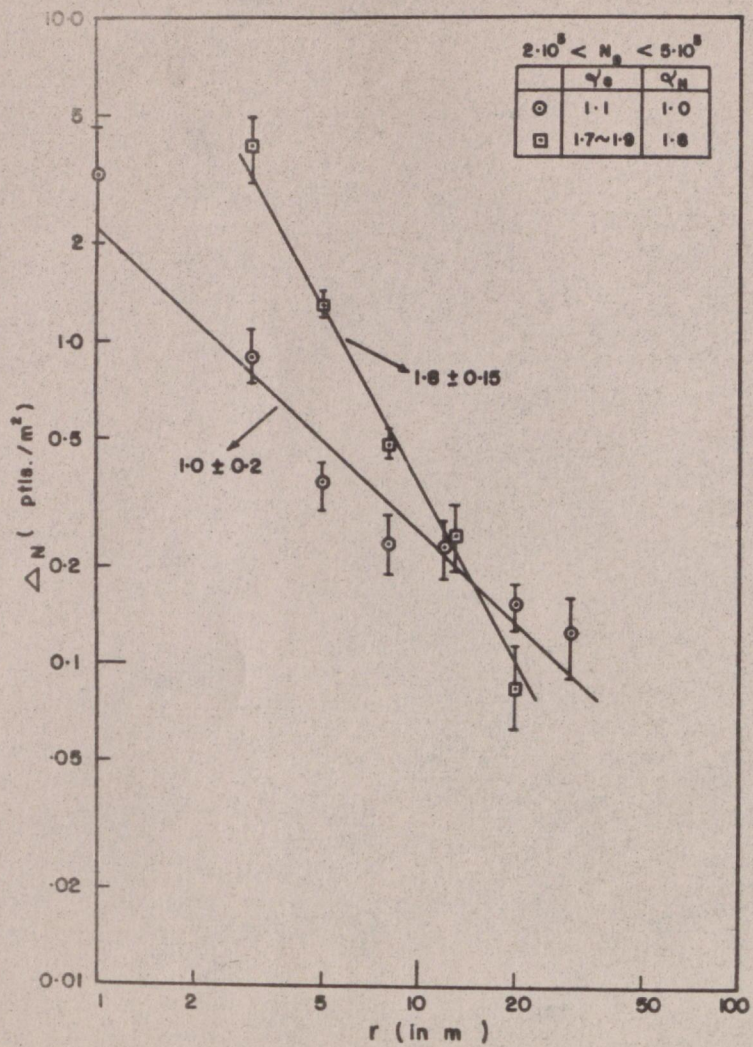


FIG.7(a) LATERAL DISTRIBUTION OF N-PTLS

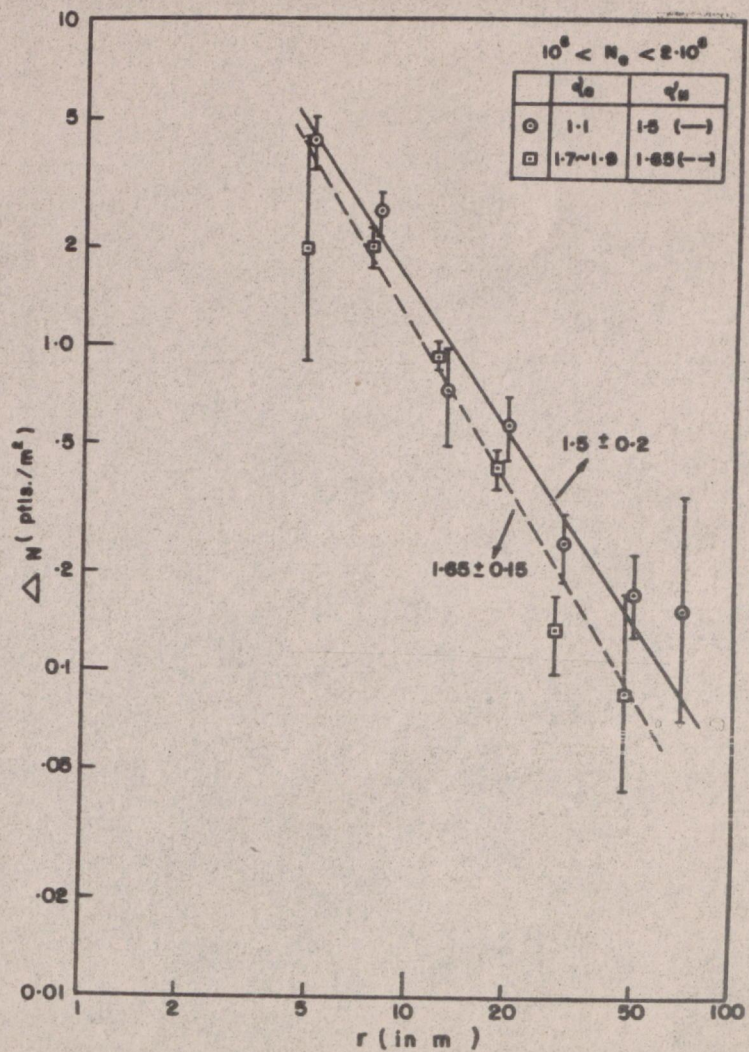


FIG.7(b) LATERAL DISTRIBUTION OF N-PTLS

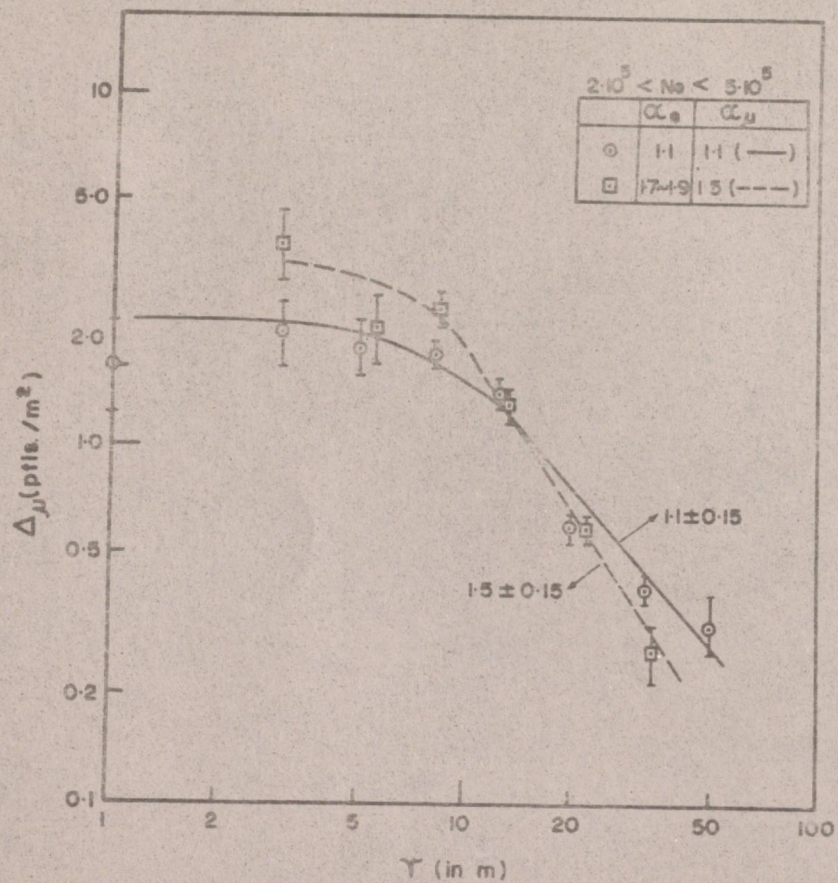


Fig.8(a) LATERAL DISTRIBUTION OF MUONS

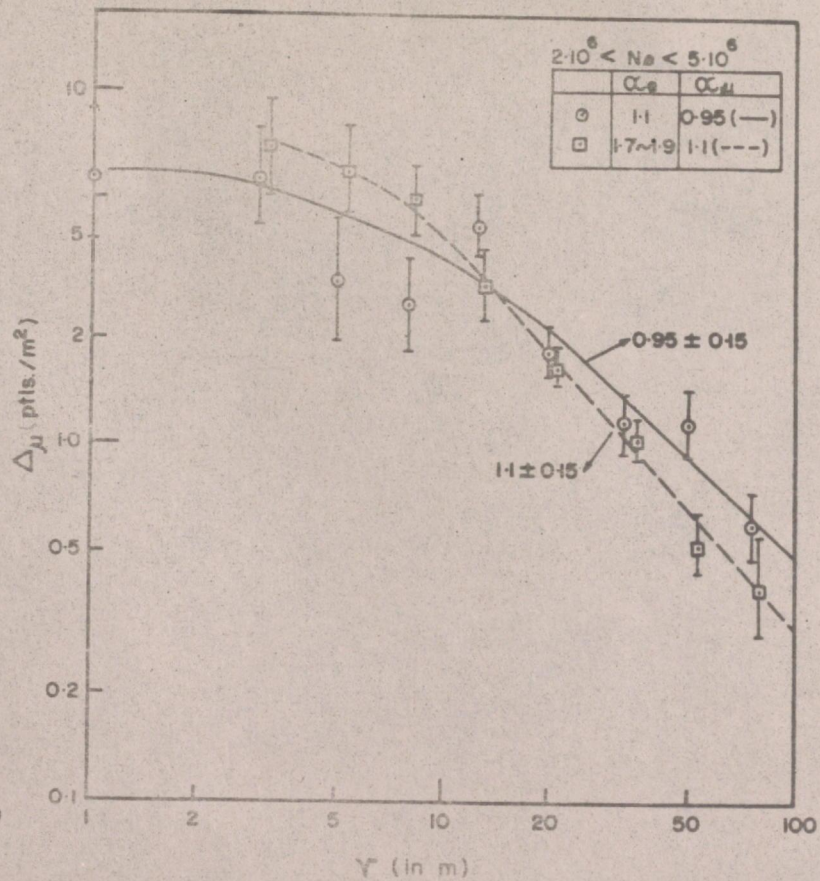


Fig.8(b) LATERAL DISTRIBUTION OF MUONS

Fig. 9

Proposed EAS array to be set up at K.G.F. in conjunction with underground muon detectors.

- (i) 20 scintillators (1 m^2 each) on the surface for measuring shower size.
- (ii) 4 fast timing scintillators for determination of arrival direction of EAS.
- (iii) 15 N-particle detectors
- (iv) 10 m^2 of scintillators on surface under granite to measure muon density ($\sim 1 \text{ GeV}$).
- (v) 30 m^2 of water Cerenkov detectors distributed at depths of 266, 590 and 1116 metres underground to detect muons of energies > 220 , 640 and 1800 GeV respectively.
- (vi) 4 units of multi-layer spark chamber telescopes (each $\sim 1 \text{ m}^2$) at a depth of 266 metres to determine the direction of muons within 0.5° , and investigate multiple muons of small separation.

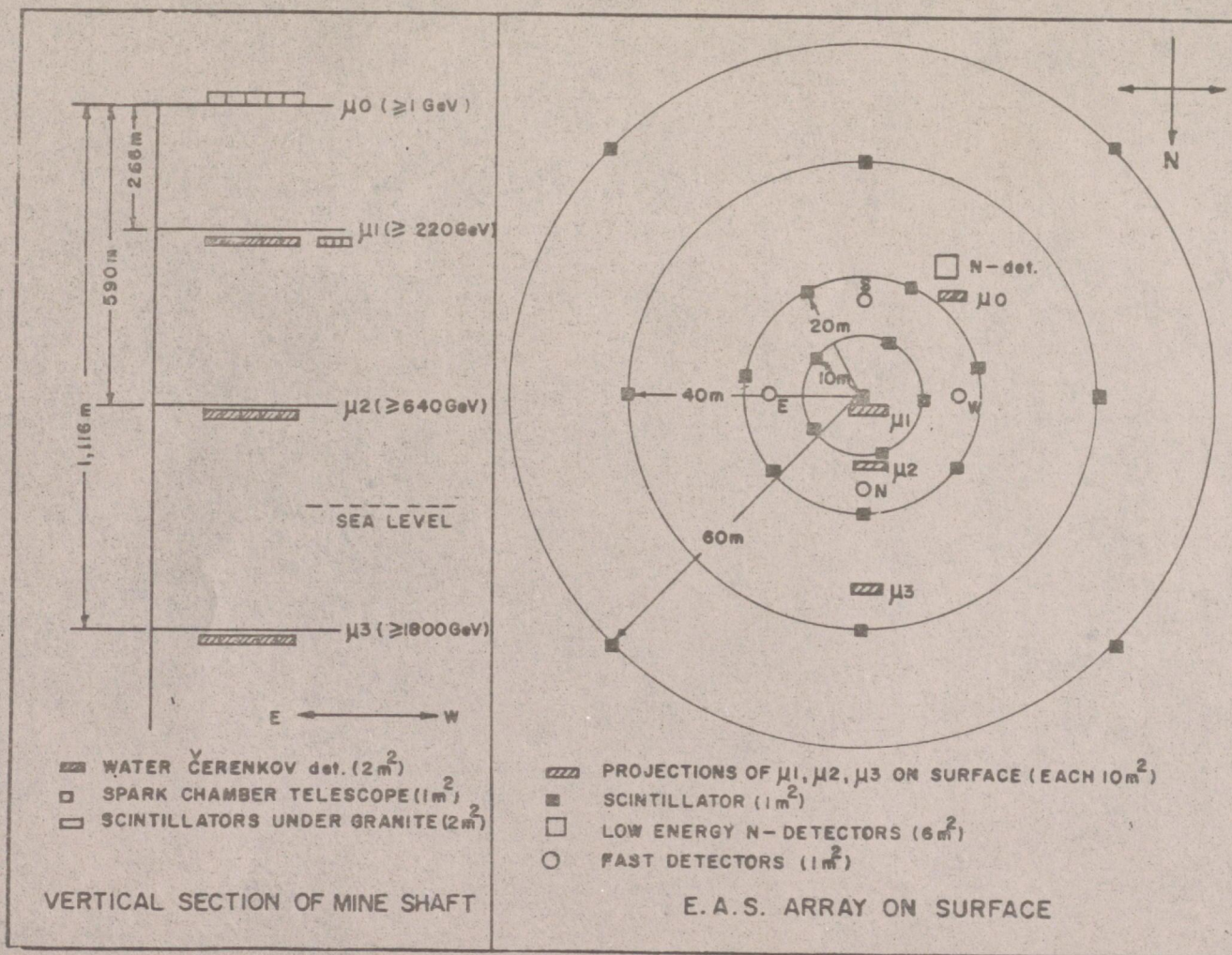


Fig. 9

DISCUSSION

SARABHAI: Have you any more evidence on North-South asymmetry?

SREEKANTAN: We have designed the new timing set-up specifically from this point of view. We have to await the results of analysis with the computer to say anything definite.

YASH PAL: Have you any theories to explain the change in the character of correlations at a shower size of 10^6 ?

SREEKANTAN: We prefer to wait for more experimental results before theorizing.

ODA: Do your results indicate that in showers of $< 10^6$, heavy primaries are predominant?

SREEKANTAN: This is a possible interpretation. We have several types of lateral distributions at $< 10^6$. In the case of heavy primaries, we expect flatter showers, because the energy per nucleon decreases. Also the behaviour of all the components, e, μ and n are similar and is presumably governed by the highest energy nucleons. But we cannot claim this to be a unique interpretation.

Studies on Extensive Air Showers ($10^5 - 10^7$)

at mountain altitude (800 g cm^{-2})*

B.K. Chatterjee, G.T. Murthy, S. Narayan, B.V. Sreekantan
and M.V. Srinivasa Rao

(Tata Institute of Fundamental Research, Bombay)

1. Experimental arrangement

In this paper, we present the experimental results obtained with two Extensive Air Shower arrays that have been in operation successively at Ooty, South India (800 g cm^{-2}). A full description of the air shower arrays (EAS I and EAS II), the recording system, the different triggers used and the method of analysis adopted have already been reported earlier by Prof. B.V. Sreekantan in this Conference⁽¹⁾

The results obtained so far are based on an analysis of 8,000 showers with EAS I, and 2,000 showers with EAS II (Figs. 1 and 2 of Ref. (1)). The shower sizes ranged from 10^5 to 10^7 ; EAS II was specifically designed to cover the smaller size groups. The lateral distribution of electrons, and the total size were determined from plastic scintillators (12 in EAS I and 20 in EAS II) spread over an area 80 m in diameter. The arrival direction of shower was determined by a chronotron timing system coupled to fast scintillators. The low energy n-particles ($\geq 1 \text{ GeV}$) were detected by n-detectors located at the centre in EAS I, and at two different places (10 m and 15 m from centre) in EAS II. The n-detectors were used as 'yes'

* This report covers 3 papers which were combined into one presentation at the Conference: (1) Lateral Distribution of electron component, and size spectrum, (2) Correlations in the fluctuations of the lateral distribution of electron, muon, n-components (3) Average properties of low energy n and muon components in EAS of size $10^5 - 10^7$ at 800 g/cm^2 .

or 'no' detectors to obtain the density of n-particles; the multiplicity of neutron pulses recorded in each event was ignored for the density measurement. Muons of energy > 1 GeV were recorded by a hodoscoped Geiger counter tray (0.6 m^2 in EAS I and 1 m^2 in EAS II) under heavy iron shield. Two similar trays were used under brick-and-concrete and lead shielding to measure densities of muons of energy > 0.5 GeV. In EAS II there was a fourth detector (1 m^2) for muons of > 1 GeV. In this paper only the particle density data for different components are presented. The data from the energy detectors of electron-photon and high energy N-particles have not yet been fully analysed.

2. Experimental Results

2 (A). Lateral distributions of e, n and μ components, and their mutual correlations

At any given size our experimental results show that the lateral distribution functions may be defined by three parameters $\alpha_e, \alpha_n, \alpha_\mu$:

$$\begin{aligned} \Delta_e & \propto e^{-r/r_0} \gamma^{-\alpha_e} \\ \Delta_n & \propto \gamma^{-\alpha_n} \\ \Delta_\mu & \propto \gamma^{-\alpha_\mu} \end{aligned}$$

α_μ is not independent of distance. It is $\approx 0.4 - 0.6$ at $r < 5 \sim 10$ m and ≈ 1.0 for $10 < r < 50$ m. The fluctuations of $\alpha_e, \alpha_n, \alpha_\mu$ at any given size and the variation of their mean values with size have been discussed in Ref. (1). Only the important conclusions will be summarised here.

(a) The lateral structures of all the components (e, n, μ) fluctuate widely and in a similar way. At sizes $< 10^6$, the fluctuations are

wide and positively correlated. At larger sizes ($> 10^6$) α_n and α_μ fluctuations are relatively much less.

(b) At low sizes the lateral structures are on the average flatter than at higher sizes, where they are insensitive to the shower size. There is indication of a significant change in a narrow size interval of ~ 5 around 10^6 .

2 (B). Total number of n-particles (N_n) and muons (N_μ) and their fluctuations

The first conclusion (a) has an immediate bearing on the analysis of the fluctuations in the total number of n-particles and muons - especially in the showers of size $< 10^6$. We had reported at the Kyoto Conference⁽²⁾, that at any given distance from the core, the fluctuations in the densities of n-particles and muons are wider than Poissonian. There was also an indication that the fluctuations were less at larger sizes. The fluctuations in the lateral distributions of n-particles and muons discussed above are found to account for a major part of the density fluctuations at fixed distances from the core. If the lateral distribution of particles is assumed invariant at a fixed size then by interpreting the fluctuations in density at a given distance as a consequence of similar fluctuations in the total number of particles, one is led to an overestimate of the magnitude of fluctuations in the total number. This remark applies to both n-particles and muons -- to a lesser degree for muons. At sizes $> 10^6$, again this is unimportant because of the decrease in the fluctuations of n-particles and muons.

In this experiment, density measurements extend only upto 50 m from the core. By integrating the lateral distributions of n-particles and

that can efficiently select all showers of a given size.

The total number of muons N_μ of energy > 0.5 GeV and > 1 GeV are determined by integration of density distributions from 0 to 50 m. For vertical showers (Fig. 2a, 2b)

$$N_\mu (> 0.5 \text{ GeV}; 50 \text{ m}) = 6,400 (N_e/10^6)^{0.44 \pm 0.04} \quad (3)$$

$$N_\mu (> 1 \text{ GeV}; 50 \text{ m}) = 4,600 (N_e/10^6)^{0.60 \pm 0.04} \quad (1b)$$

For muons of energy > 0.5 GeV,

$$R_\mu = \frac{N_\mu (\theta > 40^\circ)}{N_\mu (\theta < 40^\circ)} \approx 1.3 \quad (2b)$$

N_e fixed

R_μ could not be determined for muons of > 1 GeV, because of the inadequate shielding of the detector for inclined showers.

For showers $\leq 2 \cdot 10^6$, it is found that the ratio of N_n as well as N_μ within 50 m, in "flat" showers ($\alpha_e \approx 1.1$) to the number in "Steep" showers ($\alpha_e \approx 1.7-1.9$) is about $1.3 \sim 1.5$. The ratio will be larger for the total number in the entire shower because beyond $15 \sim 20$ m, flatter showers contain more N-particles and muons than steep showers.

2 (C). Size Spectrum

The effective areas for full efficiency of detecting the air showers were obtained for each size group, taking into account the fact that the effective area depends on α_e . The integral size spectrum in the range 10^5 to $5 \cdot 10^7$ is shown in Fig. 3. From $10^5 - 2 \sim 5 \cdot 10^6$, the spectrum fits a single power law. The three points corresponding to the sizes $5 \cdot 10^6 - 5 \cdot 10^7$ appear to deviate consistently on the lower side from the best-fit line at the lower

muons upto 50 m, it is found that in showers of same size, the numbers N_n and N_μ , fluctuate by a factor less than two and their fluctuations are positively correlated. Therefore it is quite meaningful to relate an average N_n and N_μ within 50 m, to a given shower size.

N_n is plotted as a function of size N_e for vertical ($\theta < 40^\circ$) and inclined ($\theta > 40^\circ$) showers in Fig. 1. Inclined showers correspond to a mean slant atmospheric depth of 1100 g cm^{-2} and should therefore be similar to the showers observed at sea level. The integration of density distribution has been done from 5 to 50 m, because densities within 5 m could not be determined in most of the larger size groups. However, the contribution within 5 m is unlikely to alter the total number appreciably.

For vertical showers, (Fig. 1)

$$N_n (> 1 \text{ GeV}, 50 \text{ m}) = 3,100 (N_e / 2.10^6)^{0.65 \pm 0.05} \quad (1a)$$

For inclined showers, the slope is about the same, and

$$R_n = \frac{N_n (\theta > 40^\circ)}{N_n (\theta < 40^\circ) N_e \text{ fixed}} \approx 0.6 \quad (2a)$$

There is a source of uncertainty in R_n , viz. the detection efficiency of the n-detectors for vertical and inclined showers. But the error on this account is less than the statistical errors.

The measurement at the lowest size group, $5.10^4 - 10^5$ has not been considered here, because the triggering system was heavily biased against such small size showers, especially those with larger α_e . Because of the observed correlation between the electrons and n-particles it is likely that N_n measured for these showers is not the mean, but a biased high value. It is necessary to evaluate N_n with a shower selection system

sizes. If we approximate the spectrum in the two regions by two power-laws, the exponents are respectively -1.45 ± 0.1 , and -1.75 ± 0.15 . Because of statistical errors we have to state that our data could be reconciled to a single power-law of exponent -1.6 ± 0.15 , within the experimental errors. All the three lines are drawn for comparison.

The results are also consistent with a gradually steepening size spectrum. Since the change is very gradual, if at all, we should consider if this can arise from a systematic under-estimate of shower size at larger sizes. One source of such an error could be the steepening of electron density distribution at larger sizes. In our analysis we have used α_e as a variable parameter, and therefore this type of error is small.

3. Discussion

3 (A). Attenuation lengths of electrons, n-particles and muons in air showers

From the measurements of N_n and N_μ summarised in Eqns. 1a, b, 2a, b, it is possible to obtain the relation between the attenuation lengths of the three components. However, we have to make some generally valid assumptions about the development and absorption of these components in the air shower.

First, it is assumed that all the three components reach their maximum at about the same atmospheric depth, and are attenuated exponentially from their maxima, with attenuation lengths Λ_e , Λ_n and Λ_μ respectively. Next, these are assumed to be insensitive to primary energy within a factor ~ 10 . The shift of the depth of shower maximum with increasing primary energy

is ignored. This however does not materially alter the conclusions. It will be clear that the conclusions are insensitive to the details of the model.

For vertical as well as inclined showers (Figs. 1, 2) $N_n \propto N_e^{\beta_n}$, $N_\mu \propto N_e^{\beta_\mu}$, and $\beta_n \approx \beta_\mu \approx 0.6 - 0.65$. It is implicit in the above model that β_n and β_μ are independent of depth; i.e., they are the same at the shower maximum as well as the observation level.

It can be shown easily for fixed N_e , the ratio of n-particles in the inclined showers to the n-particles in vertical showers, R_n is given by

$$R_n = \exp \left[-\Delta_x \left(1/\Lambda_n - \beta_n/\Lambda_e \right) \right] \quad (4a)$$

where Δ_x is the difference in the mean atmospheric depths in the vertical and inclined directions. From (2a), $R_n \approx 0.6$, for $\Delta_x = +300 \text{ g cm}^{-2}$.

Using (4a)

$$1/\Lambda_n - \beta_n/\Lambda_e = +1/600 \quad (5a)$$

Putting $\beta_n = 0.65$, and $\Lambda_e = 150 \sim 200 \text{ g cm}^{-2}$, we find

$$\Lambda_n \approx \Lambda_e \quad (6a)$$

This holds for a wide range of Λ_e values.

For muons, R_μ is given by a relation similar to (4a):

$$R_\mu = \exp \left[-\Delta_x \left(1/\Lambda_\mu - \beta_\mu/\Lambda_e \right) \right] \quad (4b)$$

From (2b) $R_\mu \approx 1.3$ for $\Delta_x = +300 \text{ g cm}^{-2}$. Using (4b)

$$1/\Lambda_\mu - \beta_\mu/\Lambda_e = -1/1150 \quad (5b)$$

Putting $\beta_\mu = 0.5$, we have

$$\Lambda_\mu = (2.5 \sim 3.0) \Lambda_e \quad (6b)$$

$$\text{For } \Lambda_e = 150 \text{ g cm}^{-2}, \quad \Lambda_\mu = 400 \text{ g cm}^{-2}.$$

Summarising, we have the following relations:

$$\begin{aligned} \text{At all depths} \quad N_{\mu,n} &\propto N_e^{0.6} \\ \text{Therefore,} \quad N_\mu &\propto N_n \\ \text{and} \quad \Lambda_n &\approx \Lambda_e \\ \Lambda_\mu &= (2.5 \sim 3.0) \Lambda_e \end{aligned} \quad (7)$$

There is a linear relation between n-particles and muons; both the electron and n-components are absorbed with same attenuation length in a wide range of shower sizes.

In 2(A) we have seen there is a close correlation between the lateral distributions of n-particles and electrons. Combined with the fact that $\Lambda_n \approx \Lambda_e$, we find there is a close similarity in the cascade development of the electron-photon and n-components within 50 m of the core.

It is to be noted that the observed Λ_μ refers to attenuation of muons within 50 m from the core and not of the total number of muons in the shower. The attenuation occurs mainly by a geometrical effect, viz. the lateral divergence of muons from their production level, and to a lesser degree by decay and ionisation loss of muons.

Recently, Hinotani et al⁽³⁾ have measured the coincidence rates of four scintillators immersed under water, at two different altitudes, 800 g cm⁻² (Ooty) and sea-level (Sathanur). They also measured the density

spectrum of muons (1 GeV and 2 GeV) by measuring the rates with scintillators of different areas. These observations did not involve any restriction of distance of muons from shower core. On the basis of a model similar to ours, Λ_μ is deduced as 340 ± 40 g/cm², in good agreement with our value. Hinotani et al have estimated that this value implies a mean production level of muons at 7 km above sea-level (~ 400 g/cm²).

3 (B). Energy spectrum of muons

From eqns. (3) and (1b) we find that $\beta_\mu = 0.44$ for 0.5 GeV muons and $\beta_\mu = 0.6$ for 1 GeV muons. The ratio of 0.5 GeV to 1 GeV muons is 2 at shower size 10^5 , and becomes ≈ 1.0 at 10^7 . At the mean size 10^6 , it is 1.4. For muons of energy > 5 GeV, in a similar size range $\beta_\mu = 0.8 \pm 0.1$ ⁽⁴⁾. This means that the muon energy spectrum continuously becomes flatter with increasing size. At 10^7 , there are practically no muons of energy below 1 GeV.

If we express the integral energy spectrum of muons by a power law: $N(> E_\mu) \propto E_\mu^{-d}$, we find for $N_e \approx 10^6$ $d = 0.5$ ($0.5 < E_\mu < 1$ GeV). Hinotani et al have measured the energy spectrum in 1 to 2 GeV range, by comparing coincidence rates of four scintillators immersed upto 5 m and 10 m under water. They obtain $d = 0.6 \pm 0.1$.

A similar dependence of energy spectrum of n-particles on shower size is also indicated by experiments. For energy ≥ 1 GeV, we get $\beta_n = 0.65$. At energies > 100 GeV, β_n is close to 1.0^(5,6). This brings out another similarity between n-particles and muons, besides the correlations in their lateral structure (2(A)) and the proportionality between N_n and N_μ (3(A)).

3 (C). Fluctuations in n-particles and muons

It is believed that sources of fluctuations in air showers fall under three categories: (1) fluctuations in the depth of first collision of the primary in the atmosphere, (2) the broad mass spectrum of the primary radiation (proton to iron), and (3) fluctuations in the shower development process arising from variations in the nuclear interaction processes.

(1) plays a dominant role for protons, and not for heavy nuclei since a shower due to a heavy nucleus is a superposition of several or more nucleon-induced showers, and the fluctuations in the points of shower origin are averaged out. Therefore (1) and (2) are in a sense mutually exclusive. From general physical considerations we can assess the possible effects of (1) and (2). But, very little can be said about (3), owing to lack of any quantitative knowledge about the nature of fluctuations in the nuclear interactions.

Since protons constitute the major component in the primary radiation, (1) is likely to be a very important source. To understand how fluctuations in starting point of the shower affect the n-particles and muons in showers of same size, we compare the data on the vertical and inclined showers presented in 2 (B). The difference in the atmospheric depth between these two groups of showers is about 300 g cm^{-2} , and one would expect to see clearly the effects of change in the level of shower origin.

For the same size, an increase of 300 g cm^{-2} of atmosphere resulted in an increase of N_{μ} by 1.3 and a decrease of N_n by about 1.7 (Eqns. 2a, b). The effect of a change in the level of the starting point of the

shower with respect to observation level is to produce opposite changes in N_n and N_μ . The validity of this statement in the general case can be seen simply as follows. Combining eqns. (4a, b) and (5a, b), we may rewrite

$$R_n = \exp \left[- \Delta_x / 600 \right] \quad (8a)$$

$$\text{and } R_\mu = \exp \left[+ \Delta_x / 1150 \right] \quad (8b)$$

If $\Delta_x > 0$, $R_n < 1$ and $R_\mu > 1$. If $\Delta_x < 0$, $R_n > 1$ and $R_\mu < 1$.

As a result of fluctuations in the level of shower origin, the numbers of muons and n-particles are altered in opposite directions.

We now ask what kinds of fluctuations are expected in n-particles and muons, due to fluctuations in the mass number of the primary. First, as already mentioned, we can suppose all primaries heavier than protons start the shower in a narrow region at the top of the atmosphere. Second, there is good evidence from many experiments, including the present one, that N_n, N_μ are not proportional to N_e , i.e. β_n and $\beta_\mu \neq 1.0$ (≈ 0.6 at low energies). Since size is proportional to primary energy E_0 , $N_{n,\mu} \propto E_0^\beta$. If we regard the shower produced by primary of mass number A , as a superposition of A proton showers each of primary energy E_0/A , we get $N_{n,\mu} \propto (E_0/A)^\beta \cdot A$, i.e., $N_{n,\mu} \propto A^{1-\beta}$ for fixed size (constant E_0). Therefore N_n and N_μ are higher for larger A . The fluctuations in N_n and N_μ are in the same sense as a result of fluctuations in mass number.

The above discussion shows that fluctuations in starting points of the shower, and the mass number produce opposite correlations in fluctuations of N_n and N_μ . If both these sources exist, then we can expect

to find two classes of showers: (A) in which both N_n and N_μ are higher (or lower) than in an average shower, and (B) in which either N_n or N_μ is higher but the other is lower compared to an average shower.

We have seen that there is some evidence that in vertical showers there is a positive correlation in the fluctuations of N_n and N_μ due to fluctuations in α_e , (2(B)). This would mean that showers of type A do exist. If the fluctuations in α_e (also α_n and α_μ) are entirely due to protons that have originated showers at different altitudes one would expect to find a negative correlation in fluctuations of N_n and N_μ .

We wish to emphasise that the existence of showers of type A cannot by itself constitute a definite proof that they are produced by heavy primaries, since there may be other sources, which may also produce positive correlations in the fluctuations of N_n and N_μ . However, by isolating such showers and studying their detailed properties one can hope to find further proof of the nature of such primaries.

We have attempted to pick out samples of showers resembling A-type and B-type, from the " μ -triggered" showers of EAS II. These showers were selected by muons passing through four widely separated muon detectors. These showers are essentially " μ -rich" for shower sizes upto few times 10^6 . From these, two groups were picked out: (A) those in which both the groups of n-detectors n_1 and n_2 recorded at least one n-particle (A-type) and (B) those in which no n-particles were recorded at all (B-type). By demanding fluctuations in widely separated detectors of muons and n-particles, possible "local" sources of fluctuations are reduced.

The angular distributions of A-type and B-type showers show some interesting features. In each size group, A-showers and B-showers show

distinctly different angular distributions. The proportion of showers f within zenith angle 30° to the total in the size range $10^5 - 10^7$ is given here.

$$\text{A-type : } \quad \text{"}\mu\text{-rich, n-rich"} \quad f = 32/40 = 0.8 \pm 0.2$$

$$\text{B-type : } \quad \text{"}\mu\text{-rich, n-poor"} \quad f = 45/87 = 0.5 \pm 0.1$$

Though the statistical errors are considerable, there is a significant difference in the angular distributions, viz. A-showers are steeper in angular dependence compared to B-showers. This can be seen in conformity with the idea that A-showers could be due to heavy nuclei and B-showers due to protons. Since these are " μ -rich" showers, B-type showers are also presumably produced at the top of the atmosphere, besides the A-type. The mean energy per nucleon of A-showers would be much lower (by several times or more) than the mean energy of the B-showers. One would therefore expect that A-showers would be attenuated faster in the atmosphere than B-showers and, therefore show a steeper angular distribution. A much more detailed analysis of all the properties of A and B-showers is necessary to make any definite identification of the source of fluctuation. This analysis demonstrates that classifying showers into " μ -rich, n-rich" and " μ -rich, n-poor" may lead to meaningful differences in their physical properties, and may help in the understanding of primary composition, and high energy nuclear interactions.

References:

- (1) B.V. Sreekantan: Extensive Air Shower Studies of the TIFR (Bombay) Group, Proc. Jaipur Conference (1963) Vol. 4, 143, (1963)
- (2) B.K. Chatterjee, G.T. Murthy, S. Narayan, T.N. Rangaswamy, B.V. Sreekantan and M.V. Srinivasa Rao: J. Phys. Soc. Japan, Vol.17, Suppl. A-III, 247 (1962).

- (3) K. Hinotani, S. Miyake, and M.V. Srinivasa Rao: Proc. Jaipur Conference (1963) Vol. 4, 277, (1963)
- (4) T. Matano, J. Phys. Soc. Japan, 17, 745, (1962).
- (5) H. Hasegawa, S. Naranan, T. Matano, I. Miura, M. Oda, S. Shibata, G. Tanahashi and Y. Tanaka: J. Phys. Soc. Japan, Vol.17, Suppl.A-III, 189 (1962).
- (6) T. Kameda, Y. Toyoda, and T. Maeda: J. Phys. Soc. Japan, Vol.17, Suppl. A-III, 270 (1962).

DISCUSSION

DOBROTIN: Are your results, particularly on the ratio of nuclear-active particles and electrons in the showers in agreement with the results of other groups?

NARANAN: Our results give $N_n \propto N_e^{0.65 \pm 0.05}$. The value of the exponent is in good agreement with the result of the experiment reported earlier by Prof. Nikolsky, and also the results of Lehane et al at sea-level. Within the experimental errors, we can say that in the shower-size range 10^5 to 10^7 , at 800 g cm^{-2} , the exponent does not change. We have not tried to compare the absolute number of n-particles with other data, since the energy thresholds in different experiments are not well known.

ZATSEPIN: It is very difficult to derive the attenuation length of muons from the angular dependence of N_μ/N_e , because the density of muons depends strongly on distance at which muons are produced, and secondly the production of muons depends on the atmospheric density and is therefore different at different angles.

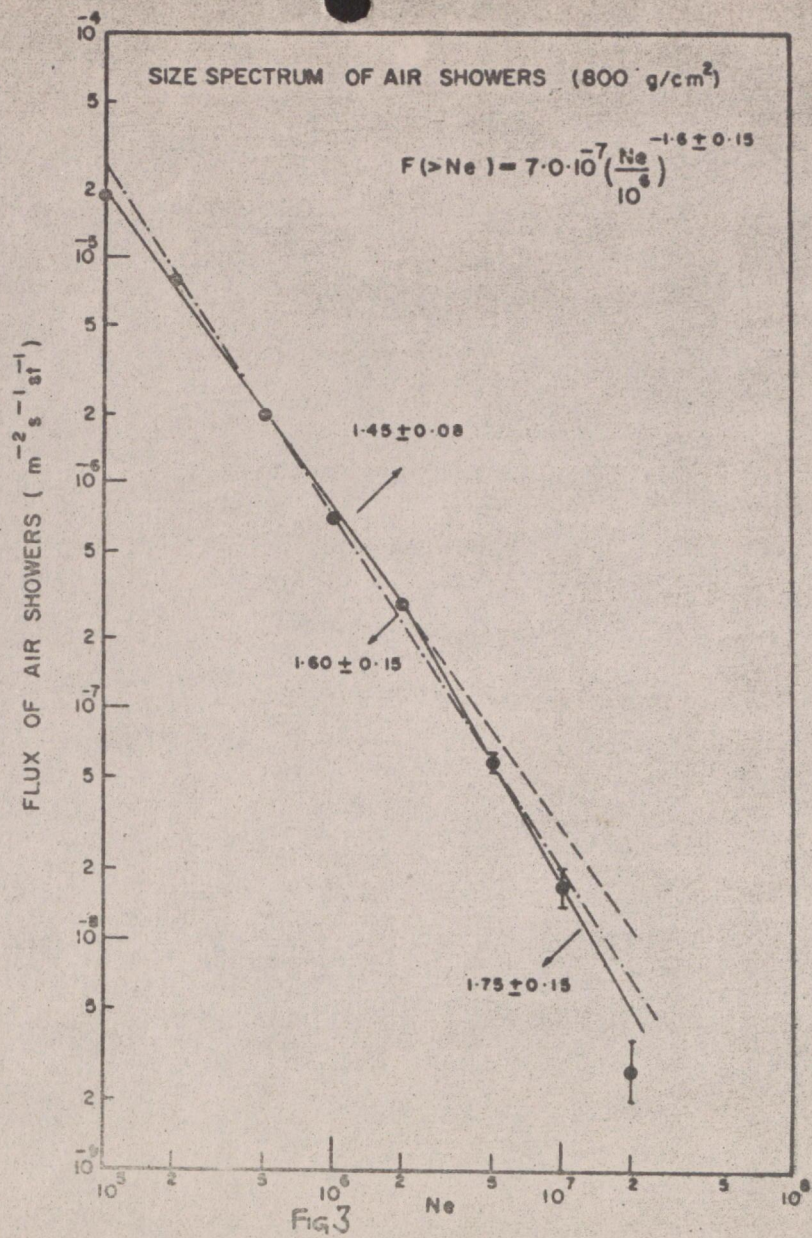
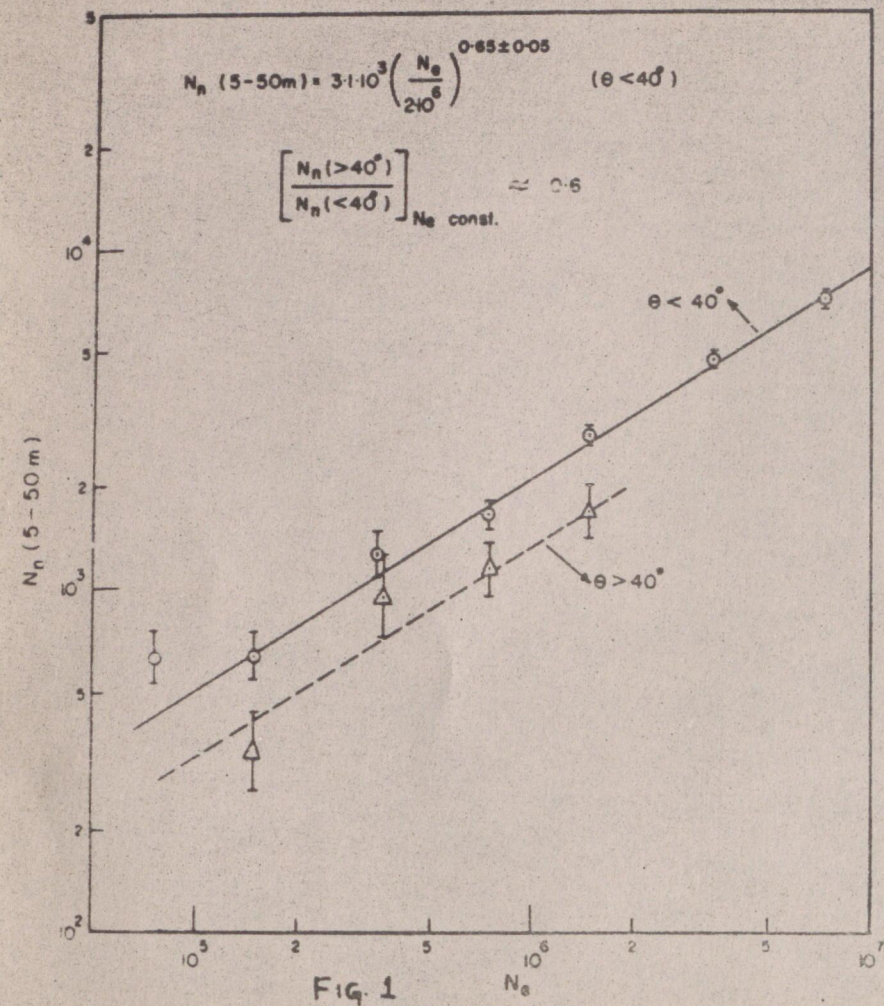
NARANAN: The attenuation length of muons $\sim 400 \text{ g cm}^{-2}$ is only an apparent absorption length, and has to be corrected not only for geometrical spread, but also for loss of muons by ionisation and decay. It is of course necessary to consider the change in atmospheric density with zenith angle. But this correction is quite small for the low energy muons ($\sim 1 \text{ GeV}$) we are considering. This is also indicated by the agreement of our Λ_{μ} with the value obtained by Hinotani et al* by comparing muon coincidence rates at two different vertical depths.

ODA: I think we can avoid the difficulty which comes from the geometrical dilution of density of muons. For the comparison at zenith angles 0 and 45° at sea level the altitude distribution of the density of air turns out so that, whatever be the longitudinal distribution of production of muons in the atmosphere, the ratio of the distance from sea level to the production level of muons remains constant.

SREEKANTAN: We have determined the absorption mean free path of muons by another method: by measuring attenuation rates of muons at two depths in the atmosphere in an under-water experiment, which will be reported later in this Conference.† That experiment also gives the same absorption mean free path.

* See p.277

† See p.277



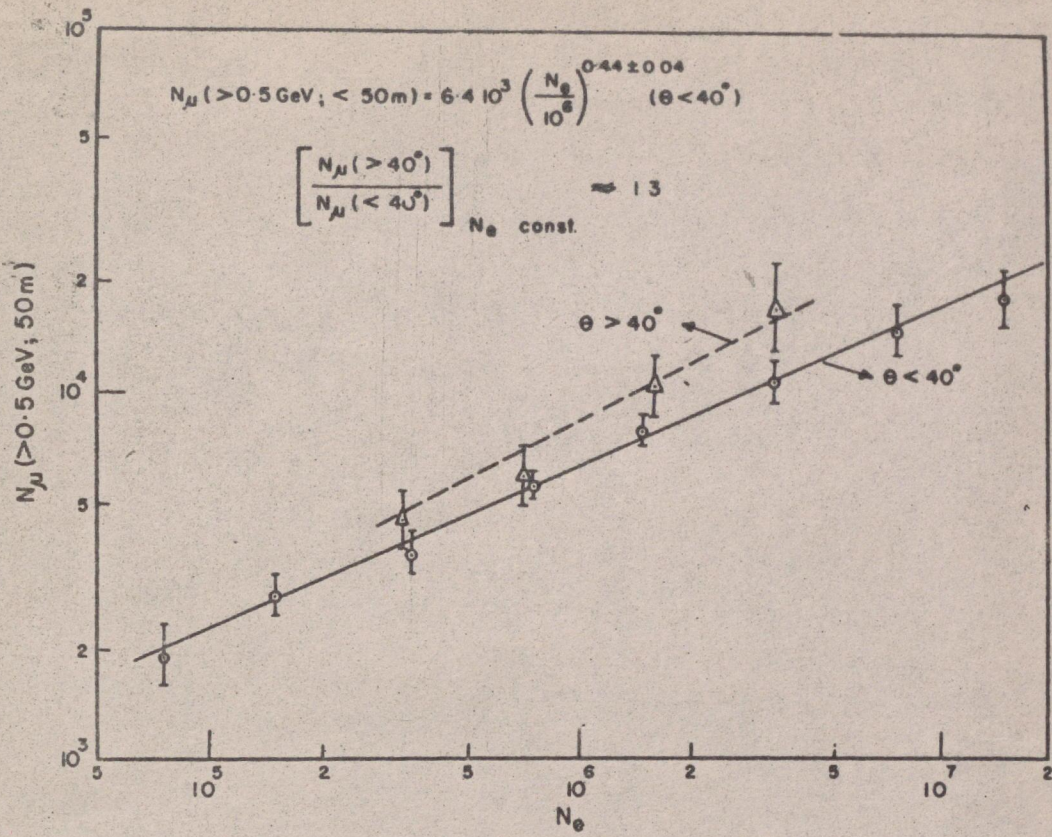


FIG. 2(a) N_{μ} vs N_e

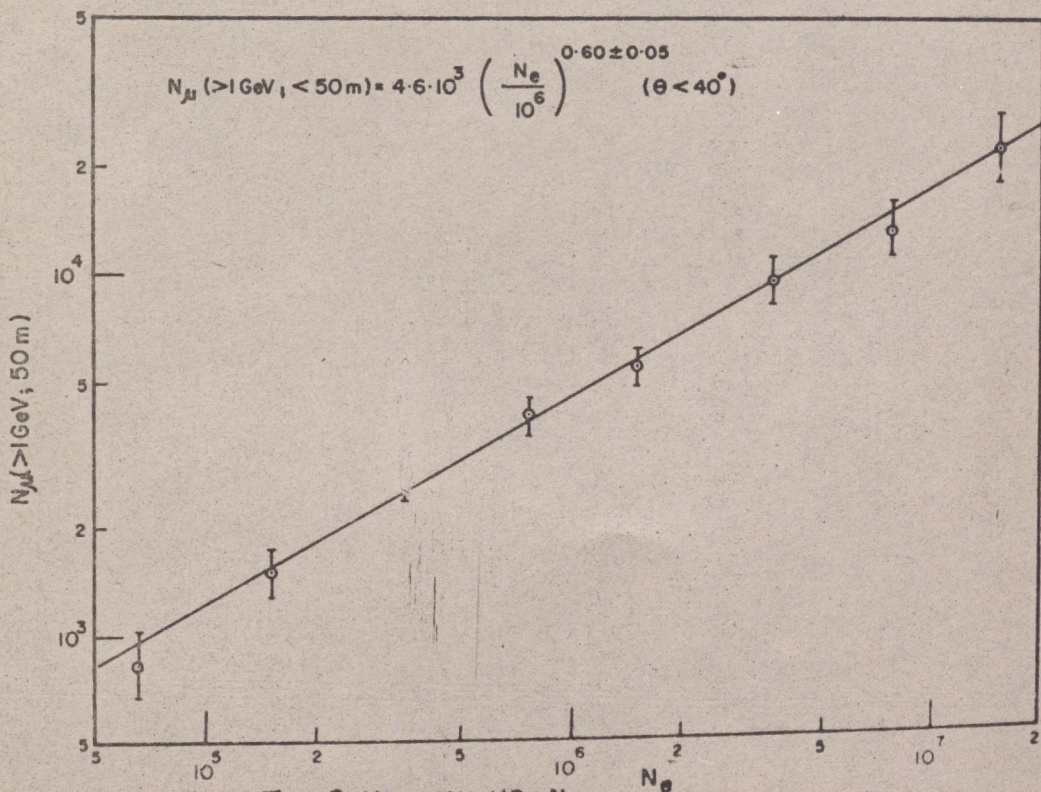


FIG. 2(b) N_{μ} vs N_e

Ratio of Pions to Protons and Ratio of Neutral to Charged
Interacting Particles at Mountain Altitude of 800 gms/cm²

S. Lal, R. Raghavan, T.H. Rangaswamy, B.V. Sreekantan
and A. Subramanian

(Tata Institute of Fundamental Research, Bombay)

In this paper we wish to report on the experimental results that have been obtained on the ratio of neutral to charged interacting particles and the ratio of pions to protons at an altitude of 800 gms/cm² at energies higher than 20 GeV. The experimental arrangement which was principally designed for the study of nuclear interactions produced by pions and nucleons⁽¹⁾ comprised of a multiplate cloud chamber with an air Cerenkov counter above and a total absorption spectrometer below. The air Cerenkov counter⁽²⁾ which was operated at atmospheric pressure at a threshold value of 45 for the Lorentz factor of the charged particles enabled the classification of the charged interacting particles into pions and protons in the energy range 20 - 40 GeV. The energy of the nuclear interacting particles was determined in individual cases to an accuracy of $\pm 20\%$ with the total absorption spectrometer⁽³⁾.

The cloud chamber was triggered with a selection system which selected only charged interacting particles for part of the run and made no distinction between charged and neutral interacting particles for the rest of the operating period. Triggering of the cloud chamber by nuclear interacting particles associated with large air showers or by particles in the cores of small air showers was prevented by a system of anti-coincidence counters of total effective area about a square metre placed by the side of

the cloud chamber.

Experimental Results

(a) Ratio of pions to protons:

During the period (2900 hours) when the cloud chamber was triggered exclusively for charged nuclear interacting particles, 215 events were recorded for which the charged primary was well within the solid angle of the air Cerenkov counter above the cloud chamber and for which the estimated energy from the total absorption spectrometer was in the range 20-40 GeV. Out of these, in 56 cases the air Cerenkov counter gave pulses indicating that the particles were pions. This number, after correction for spurious association of pulses from the Cerenkov counting system and for inefficiency of the Cerenkov counter, becomes 70. This leads to the ratio of pions to protons as 0.48 ± 0.11 in the energy region 20 - 40 GeV.

(b) Ratio of neutral to charged particles (N/C):

During the period of 1550 hours when the chamber was triggered for both charged and neutral interacting particles, 231 nuclear interactions were recorded in the chamber for which one could unambiguously determine whether the interaction was produced by a charged or a neutral particle. Out of the 231 cases in 171 the energy of the interaction as determined with the total absorption spectrometer was in the range 20 - 40 GeV. In these 171 cases it was found that 103 were due to charged primaries giving a value of 0.66 ± 0.1 for the N/C ratio at energies 20 - 40 GeV. In the remaining 60 cases for which the energy was higher than 40 GeV (median energy 60 GeV), 43 interactions were due to charged primaries giving a value of 0.40 ± 0.12 for the N/C ratio.

(c) Ratio of neutrons to protons and probability of charge persistence:

Using the ratio of neutral to charged particles and the ratio of pions to protons we could determine the ratio of neutrons to protons in the energy range 20 - 40 GeV. The value of this ratio comes out to be $0.98 \pm .18$. In the Table below we have given the expected ratio of N/P at an altitude of 800 gm/cm² for various values of the parameters ϵ and λ_{int} . where ϵ is the probability of charge exchange in an inelastic collision of a nucleon with an air nucleus, and λ_{int} is the interaction mean free path of nuclear interacting particles in air.

T A B L E

| ϵ | Expected ratio N/P at 800 gm/cm ² | | | |
|------------|--|--------------------------------------|--------------------------------------|--------------------------------------|
| | $\lambda_{int} = 72 \text{ gm/cm}^2$ | $\lambda_{int} = 80 \text{ gm/cm}^2$ | $\lambda_{int} = 85 \text{ gm/cm}^2$ | $\lambda_{int} = 90 \text{ gm/cm}^2$ |
| 0.5 | 0.98 (0.99) | 0.94 | 0.87 | 0.80 |
| 0.4 | 0.94 (0.96) | 0.88 | 0.80 | 0.71 |
| 0.3 | 0.87 (0.89) | 0.78 | 0.68 | 0.58 |
| 0.2 | 0.71 (0.79) | 0.60 | 0.50 | 0.45 |

In the above Table in column 2 are given within brackets the values of N/P ratio calculated taking into account the presence of heavy nuclei in addition to protons in the primary cosmic ray beam (80% protons and 14% neutrons). It is seen from the Table that the observed value of 0.88 ± 0.1 for N/P excludes the probability of charge persistence being higher than 80% for nucleons of energy ~ 100 GeV (nucleons in the observed energy range of 20 - 40 GeV are expected to arise from the collision of nucleons of energy ~ 100 GeV in the atmosphere).

From the present study the following conclusions may be drawn

regarding nuclear interacting particles not associated with large air showers:

(a) The relative proportion of pions to protons is appreciable at mountain altitudes and sea level at energies above 20 GeV; this ratio is as high as $0.48 \pm .11$ in the energy region 20 - 40 GeV at 800 gms/cm². It may be pointed out that the recent evaluation by the Durham Group⁽⁴⁾ with the magnetic spectrograph of the vertical intensity of pions and protons at sea level indicates a ratio of $\pi/P = 0.57 \pm .21$ at an energy of 27 GeV. This compares well with our value of $0.48 \pm .11$ at 800 gms/cm².

(b) The ratio of neutral to charged particles shows a strong dependence on the energy of the particles. In the energy region 20 - 40 GeV it is found to be $0.66 \pm .11$ and at about 60 GeV it is $0.40 \pm .12$. Such a trend has been found in earlier measurements using visual techniques. This feature suggests that at energies ~ 100 GeV pions are comparable or even more than protons among the nuclear interacting particles at mountain altitudes and sea level. This increase in the contribution of pions with energy may perhaps be due to the regeneration of pions by pions in the atmosphere as pointed out by Subramanian and Verma⁽⁵⁾:

(c) The ratio of neutrons to protons in the energy region 20 - 40 GeV deduced from the ratio of neutral to charged particles is 0.98 ± 0.18 which leads to an upper limit of 80% for the probability of charge persistence of nucleons at energies ~ 100 GeV in collisions with air nucleus. This ratio of neutrons to protons, which is close to unity, also suggests that the charge excess among nuclear interacting particles at mountain altitude is almost entirely due to pions.

References:

1. Siddheswar Lal, R. Raghavan, B.V. Sreekantan, A. Subramanian and S.D. Verma: Journ. of Phys. Soc. of Japan, 17, Suppl. A-III, 390 (1962).
2. A. Subramanian and S.D. Verma: Proceedings of the Cosmic ray symposium Ahmedabad, 1963, p.45.
3. P.V. Ramana Murthy, B.V. Sreekantan, A. Subramanian and S.D. Verma: Nuclear Instruments & Methods 23, 245 (1965).
4. The authors are thankful to Dr. A.W. Wolfendale for private communication of the results obtained by the Durham group.
5. A. Subramanian and S.D. Verma: Nuovo Cimento, 15, 572 (1959).

DISCUSSION

SILVER: The evaluation of the ratio of the numbers of pions and protons from the observed ratio of interactions evidently depends on the choice of mean free paths of the two kinds of particles. Have the mean free paths been determined in this experiment or if not what assumptions have been made for them?

SREEKANTAN: The mean free paths (mostly in bragg) have been assumed to be the same for pions and protons.

LAL: I would like to remark that this kind of measurement is probably one of the best ways of obtaining information on pion-nucleon collisions at high energies because this ratio cannot be as high as reported unless one includes regeneration of pions by pions at mountain altitude. However, in order to obtain definite information on a possible elasticity of pion nucleon collisions, as also on the multiplicity law, we need data at energies which are a factor of two or three higher i.e., around 100 GeV.

Fluctuations in the Angular Distribution of Secondaries Emitted
in High Energy (≥ 30 GeV) Nuclear Collisions in Carbon

S. Lal, R. Raghavan, T.N. Rangaswamy, B.V. Sreekantan
A. Subramanian*, S.C. Tonwar and R.H. Vatcha

(Tata Institute of Fundamental Research, Bombay-5)

I. Introduction

An experimental arrangement^(1,2) consisting of a multiplate cloud chamber, a total absorption spectrometer (T.A.S.) and an air Cerenkov counter has been operated for about 4,000 hours at Ootacamund in South India (altitude 2.2 km, pressure 800 gm/cm²) to study in detail the nuclear collisions of nucleons and pions in a carbon target at energies ≥ 30 GeV. The energies of the particles producing the interactions were estimated to an accuracy of $\pm 20\%$ in individual cases. The air Cerenkov counter enabled distinction between proton and pion primaries at energies less than about 45 GeV.

In this paper, results based on the study of the angular distribution of the secondaries in 250 nuclear interactions showing a total secondary multiplicity of at least 3 are presented.

II. Results and Discussion

In Fig. 1 are given the differential distribution of the events against coordinate of $\log E_c/E_0$; E_c is the "energy" computed by the method of Castagnoli et al⁽³⁾ and E_0 is the primary energy estimated using T.A.S. E_c is a parameter for the degree of collimation of the secondaries in the interactions. In computing E_c , care has been taken to omit a charged secondary

* The next three papers were combined and presented by A. Subramanian.

in the forward direction ("continuing primary") which is emitted within an angle θ in the laboratory system satisfying the condition $\sin\theta = \frac{1}{0.7E_0}$.

The expected distributions shown by dotted curves are based on the assumption of isotropy in the c.m. system (nucleon-nucleon) and are given by the suitably normalised probability distribution $P(E_c/E_0) = \frac{1}{\sqrt{2\pi}\sigma'} \exp\left\{-\frac{(\log E_c/E_0)^2}{2\sigma'^2}\right\}$ where $\sigma' = \frac{\sigma}{\sqrt{n}}$, n being the number of secondaries used in finding E_c . The full line curves have been obtained by shifting the dotted curves by 0.15 on the $\log E_c/E_0$ scale. This shift corresponds to an average overestimate factor of 1.4 in E_c/E_0 which is expected if it is assumed that the secondary pions have on the average a total energy of only ≈ 380 MeV in the c.m. system.

The following are the noteworthy features of the distribution in Fig. 1:

- (a) the tail beyond the ratio of $E_c/E_0 = 8$ (shaded area in the figures) occurs preferentially in pion events compared to proton events ($P(\chi^2) = 0.2 - 0.3$) and to a less significant extent among events produced by neutral primaries compared to proton events ($P(\chi^2) \sim 0.4$).
 - (b) the probabilities of observing the above tail are less than 2×10^{-7} in the case of charged primaries, less than 10^{-5} in the case of pion events and less than 5×10^{-5} in the case of neutral primaries, purely due to fluctuations from isotropic emission in the c.m. system.
- and (c) this tail forms $24 \pm \frac{8}{6}$ % of pion events and $10 \pm 3\%$ in the case of neutral primary events.

To clarify the question whether, leaving aside the tail, the rest of the distributions in Fig. 1 are statistical fluctuations from isotropic

(random) emission in c.m. system, the events have been grouped into three categories: "forward asymmetric" (II) are those with $2 < E_c/E_0 < 8$, "symmetric" (III) are those with $\frac{1}{2} < E_c/E_0 < 2$ and "backward asymmetric" are those with $E_c/E_0 < \frac{1}{2}$. The differential angular distribution of the charged secondaries with respect to $\log \gamma_{CN} \tan \theta$ are shown in Fig. 2 for these three different groups. γ_{CN} is the Lorentz factor of the c.m. system (nucleon-nucleon) corresponding to E_0 and θ denotes the angle of emission in the laboratory system. The widths of these distributions as given in Fig. 2 seem larger than about 0.30, which width is to be expected for isotropic emission of the secondaries in the c.m. system taking into account the fact that pions are not extremely relativistic in that system. If fluctuations in the emission of neutral and charged pions were the cause of selection of events for classification into the above groups, one should have obtained widths even smaller than 0.30. Therefore the conclusion is that these fluctuations occur due to genuine correlated emission of secondaries sometimes either in the forward or backward directions in the c.m. system giving rise to events of groups II and IV. Further support to attributing the fluctuations to some physical origin is given in the Table.

It is possible to conclude from the data presented that the observed fluctuations in the angular distributions of the secondaries are due to correlated emission of secondaries, probably pion resonances, giving rise to different "Q-values" and ratios of γ -rays to charged secondaries and not due to simple motion of fire-balls in the c.m. system.

TABLE

| Groups | II | III | IV |
|--|----------------|-----------------|-----------------|
| Ratio of neutral pions to charged secondaries $(n_{\pi^0}/n_s)^*$ | $0.40 \pm .09$ | 0.22 ± 0.05 | 0.70 ± 0.21 |
| $\langle P_T \rangle$ in MeV/c of γ -rays in the forward hemisphere in the c.m. system. | 135 ± 15 | 158 ± 19 | 105 ± 12 |

* In finding n_{π^0}/n_s , we have removed the so-called "continuing primary" from the observed number of charged secondaries. This ratio has been obtained as $(n_{\gamma}/2n_s)$ for the secondaries emitted within the forward hemisphere in the c.m. system.

References:

1. Siddheshwar Lal, R. Raghavan, B.V. Sreekantan, A. Subramanian and S.D. Verma: Journ. of Phys. Soc. of Japan, Vol. 17, Suppl. A-III, 390 (1962).
2. P.V. Ramamurthy, B.V. Sreekantan, A. Subramanian and S.D. Verma: Nucl. Instruments and Methods, 23, 245 (1963).
3. Castagnoli, G. Cortini, C.F. Franzinetti, A. Manfredini and D. Moreno: Nuovo Cimento, 10, 1539 (1953).

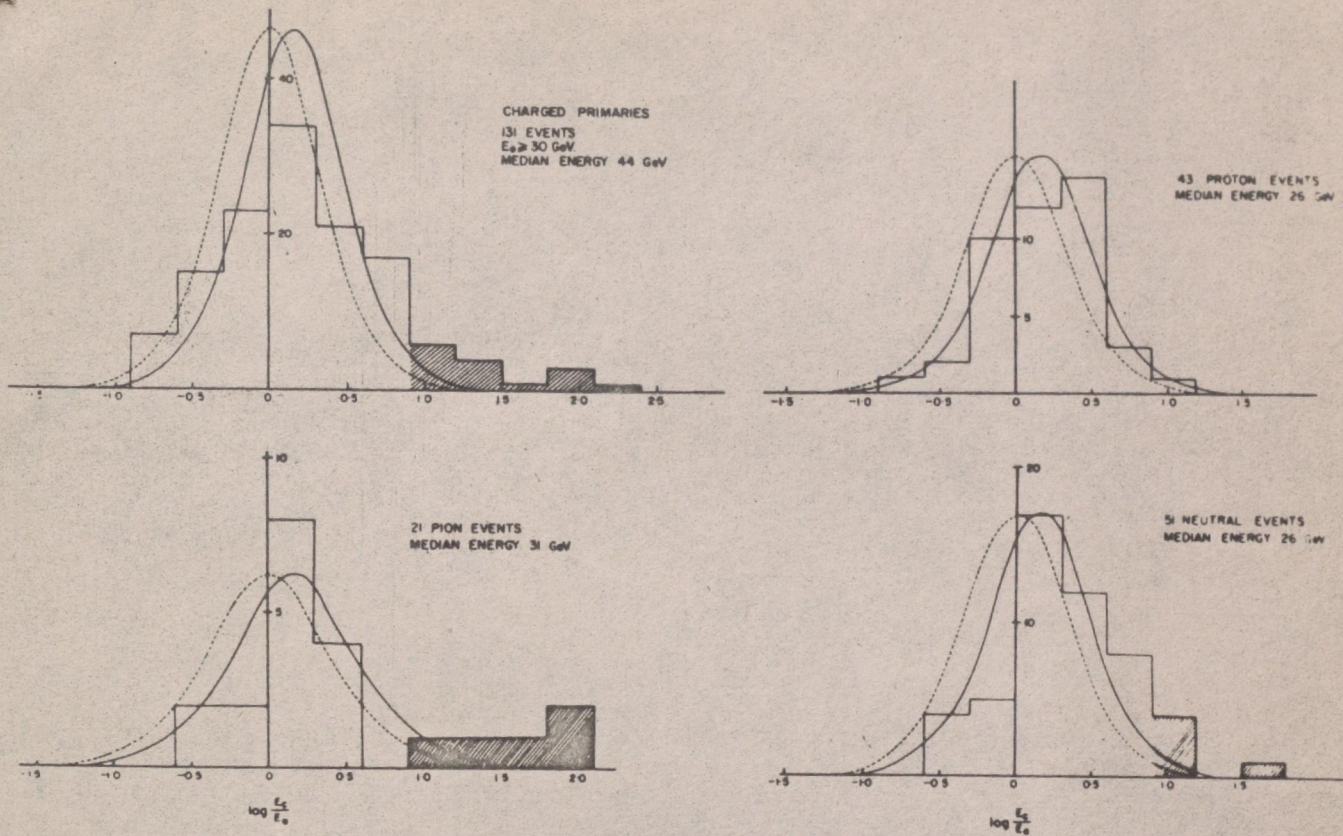


FIG. 1

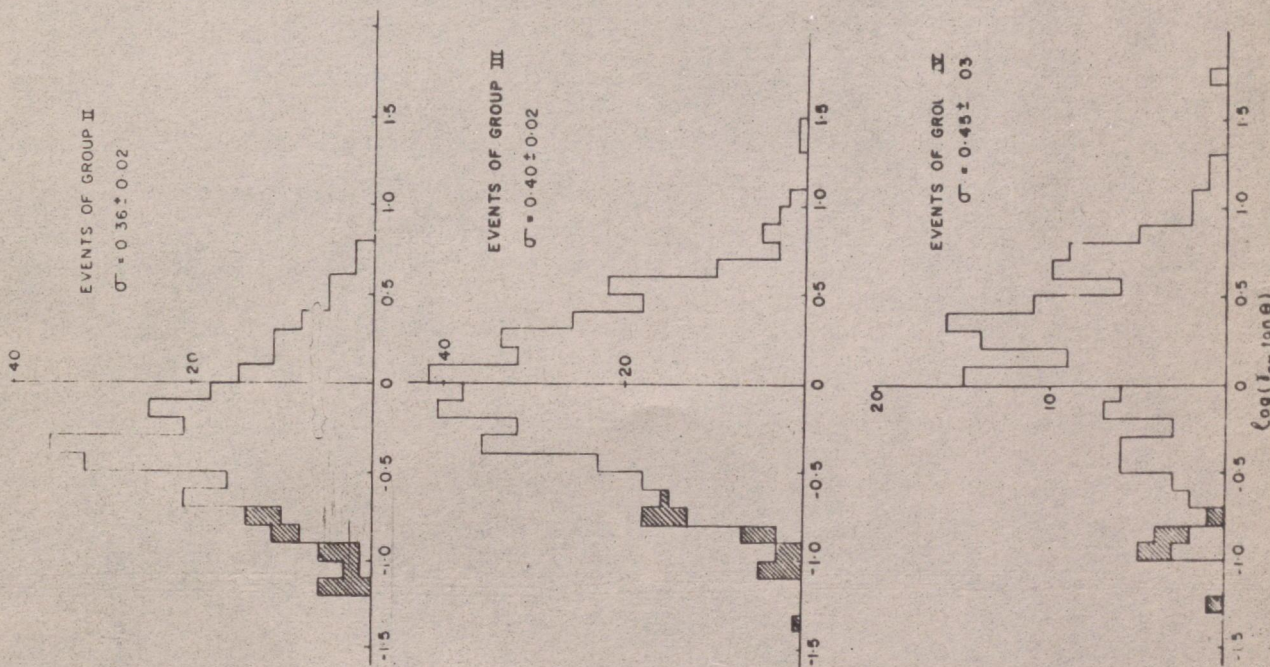


FIG. 2

Extremely Collimated Nuclear Interactions in Carbon Induced by
Cosmic Ray Particles in the Energy Region of about 20 - 100 GeV

S. Lal, R. Raghavan, T.N. Rangaswamy, B.V. Sreekantan

A. Subramanian and S.D. Verma

(Tata Institute of Fundamental Research, Bombay)

I. Introduction

In a paper submitted to this Conference⁽¹⁾, the existence of a group of extremely collimated ("anomalous") nuclear interactions in carbon produced by charged cosmic ray particles has been reported. Preliminary results and tentative interpretation of these events have been reported elsewhere^(2,3). We present here the results and discuss the interpretation of these collisions based on 25 events obtained so far from the interactions of charged primaries and five such events induced by neutral primaries.

II. Characteristics of the "anomalous" events produced by charged primaries

Extremely collimated events have been observed to be predominantly produced by pions, as discussed in ref. (1). Since the expected number of events with $E_c/E_0 \gg 10^*$ due to statistical fluctuations in the angular distribution of the secondaries from isotropy alone in the c.m. system (nucleon as target) is negligible, the above limit is used to define an "anomalous" event. These events constitute $24 \pm 8\%$ ($5/21$) of all interactions produced by pions with total forward secondary multiplicity ≥ 3 . No event with $E_c/E_0 > 10$ in 43 cases of corresponding proton interactions has been observed.

The following are the features of the events:

- i) No high energy γ -ray comparable to the energy of the primary or, a neutral interaction has been found in the forward direction. This

* E_c is the primary energy determined by the "Castagnoli method" and E_0 is the actual energy of the primary estimated by the total absorption spectrometer.

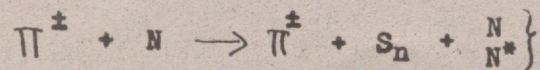
indicates that the particle carrying away the bulk ($\sim 80\%$) of the incident energy is charged. The above high degree of elasticity is arrived at from the observed average energy of the neutral pions produced in these collisions, which are assumed to represent also the average energy of the charged pions produced.

ii) In Fig. 1 is shown the distribution of charged as well as total multiplicity (charged + π^0 's). These multiplicities do not include heavily ionising secondaries (assumed to be recoil protons from the target) and secondaries emitted at angles $> 90^\circ$ in the laboratory system. These latter particles are assumed to originate from an isobar of the recoiling nucleon, since kinematically a created particle of velocity less than the velocity of the c.m. system will always emerge at angles $< 90^\circ$ in the laboratory system.

iii) The transverse momentum distributions of the γ -rays produced in the interactions of different primaries are given in Fig. 2. It is significant to note that both the average and the distribution of the transverse momenta of γ -rays in the case of "anomalous" events are different from those of the rest.

III. Interpretation of the results

In ref. (2), a reaction of the following type was proposed in order to explain the production of such events.



where the incident pion makes a "peripheral" collision, which leads to the production of a low Q-value cloud S_n decaying into n secondaries. The target nucleon may in some cases emerge as an isobar; this is suggested by

the presence of backward secondaries in some of the events. The cloud seems to be neutral and decay into two or four secondaries in most of the cases as judged from Fig. 1. In cases where it decayed into $2\pi^0$'s, the effective mass could be calculated and was found close⁽³⁾ to that of the ABC two-pion resonance⁽⁴⁾. We tentatively interpret the occurrence of S_4 as the production of two S_2 's. On this basis, we calculated the effective mass of two π^0 's in cases of occurrence of S_2 or S_4 . The effective mass calculated in nine such cases is shown at the bottom of Fig. 1. The average mass comes out to be $300 \pm 10 \text{ MeV}^*$ which can be considered to be in agreement with the reported mass of the ABC-particle, which is 317 ± 6 ⁽⁵⁾.

It is of interest to point out that the ratio of π^0/π^\pm produced from S_n is $0.74 \pm 0.18^{**}$.

IV. "Anomalous" events produced by neutral primaries

There are 5 collimated events of the "anomalous" type in a sample of 51 interactions produced by neutral primaries. The total multiplicities that could be associated with these events are $(4 n_s + 0 \pi^0)$, $(6 n_s + 2 \pi^0)$, $(2 n_s + 1 N + 1 \pi^0?)$, $(2 n_s + 1 \pi^0)$ and $(3 n_s + 0)$, where n_s stands for charged multiplicity, and N for neutral secondary. While one can take that the first three events are consistent with multiple ABC production, the other two events may have to be interpreted in a different manner.

* The method of calculation of the mass of S_2 , in ref. (2) was based on the evaluation of the mean energy of neutral pions in the centre of symmetrical emission of secondaries from S_n . This method leads to an overestimate of this mass (quoted before as $\sim 400 \text{ MeV}$) since in cases of $S_n \geq 4$, the kinetic energy of S_2 's in the c.m. system of S_n contributes to an increase of the mean energy of π^0 's.

** If ABC particle has isospin zero, the ratio of π^0/π^\pm expected from its decay is 0.5; but corrected for phase space difference due to the rest masses of charged and neutral pions, this ratio is enhanced to 0.7.

While the above observation may not in itself be very significant, it points to the possibility of detecting a difference between protons and neutrons in their inelastic collisions in carbon at ≥ 30 GeV.

References

1. "Fluctuations in the Angular Distribution of Secondaries Emitted in High Energy (≥ 30 GeV) Nuclear Collisions in Carbon: S. Lal, R. Raghavan, T.N. Rangaswamy, B.V. Sreekantan, A. Subramanian, S.C. Tomwar and R.H. Vatcha (submitted to this Conference). Vol. 5, 363 (1963)
2. Siddheshwar Lal, R. Raghavan, T.N. Rangaswamy, B.V. Sreekantan, A. Subramanian and S.D. Verma: Proceedings of the International Conference on High Energy Physics, CERN, p. 641, 1962.
3. A. Subramanian, Ph.D. Thesis, 1962, University of Madras, India.
4. A. Abashian, N.E. Booth and K.M. Crowe: Phy. Rev. Letters 5, 258 (1960); 7, 35 (1961); Rev. Mod. Phys. 33, 393 (1961).
5. Matts Roos, Rev. Mod. Phys. 35, 313 (1963).

Caption for Figures

Fig. 1 : Distribution of charged and total (charged + neutral) multiplicity in the anomalous events.

In the bottom of the figure is shown the "effective" mass of 2 π -mesons.

Fig. 2 : Differential distribution of transverse momentum of π -rays produced in the "anomalous" events, "normal" pion events, interactions of protons and neutrons.

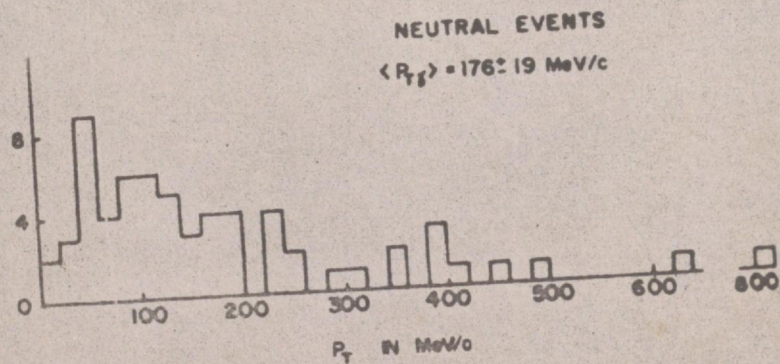
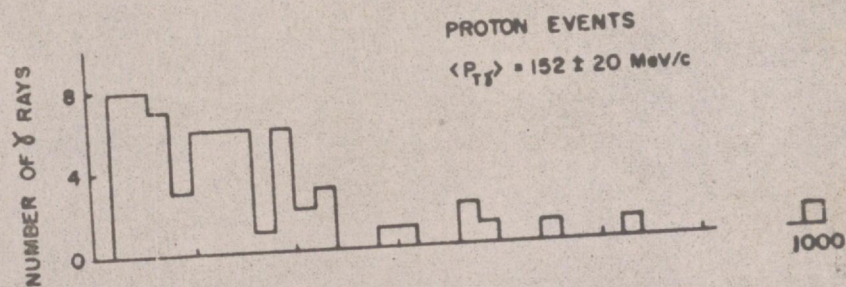
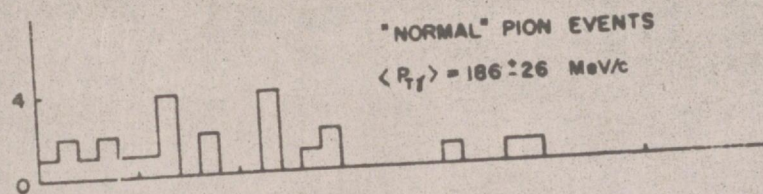
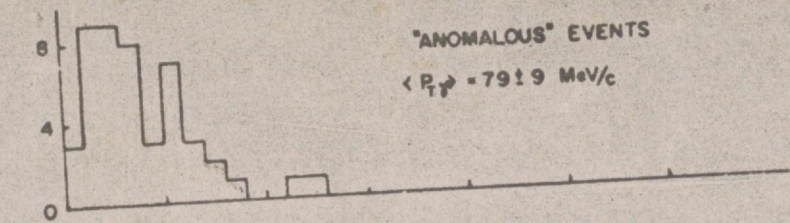
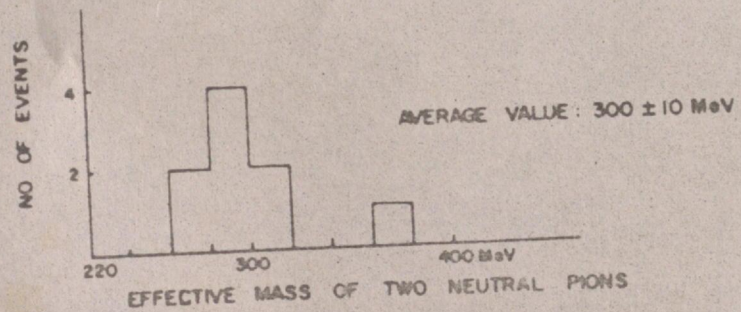
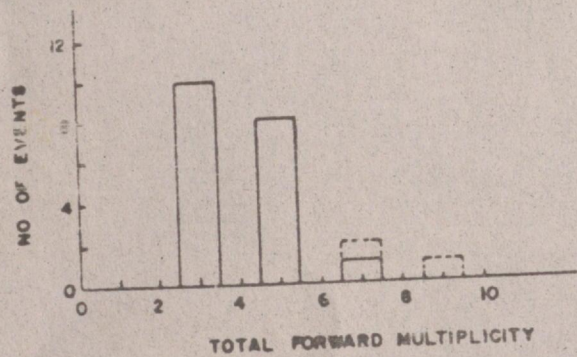
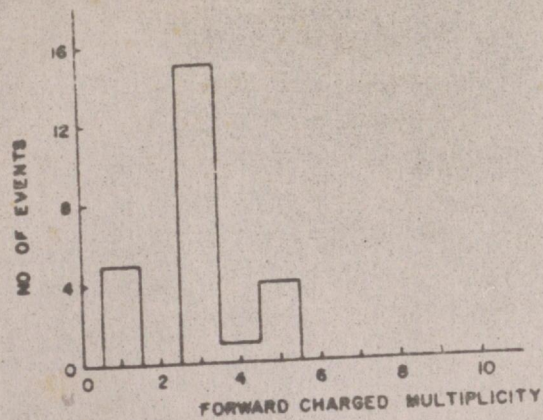


FIG. 1

FIG. 2