

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

## Time lags of nuclear interacting particles in extensive air showers

B. K. CHATTERJEE, G. T. MURTHY, S. NARANAN, B. V. SREEKANTAN, M. V. SRINIVASA RAO and S. C. TONWAR  
Tata Institute of Fundamental Research, Bombay, India

**Abstract.** An experiment has been carried out at 2.2 km altitude to determine the time lags with respect to the shower front of nuclear interacting particles of various energies. For this purpose a total absorption spectrometer of area  $1.4 \text{ m}^2$  has been operated at the centre of an air shower array. Delays of interacting particles of energy not less than 5 GeV have been measured up to a maximum delay of about 300 nsec. The results show: (i) that the peak of all nuclear interacting particles of energy above 5 GeV is displaced with respect to the shower front by about 20 nsec, (ii) the average delay is a function of the average energy of the particles, and (iii) while nearly 30% of the particles of energy above 5 GeV are delayed by more than 50 nsec, only about 0.4% are delayed beyond 100 nsec. The tail extends right up to 250 nsec.

These features quite definitely rule out the possibility that nuclear active particles of energy not less than 5 GeV are predominantly pions. They suggest the production of a large number of nucleon-antinucleon pairs in air showers.

An experiment has been carried out at 2.2 km altitude to determine the time lags with respect to the shower front of nuclear interacting particles of various energies. For this purpose a total absorption spectrometer of area  $1.4 \text{ m}^2$  has been operated at the centre of an air shower array. The array (Chatterjee et al. 1965) which is shown in figure 1, comprises: (i) fifteen scintillators distributed in concentric rings over an area of radius 40 m for the measurement of the density of soft particles; (ii) four fast scintillators coupled to a 45-channel nanosecond chronotron system for measurement of the arrival direction of the showers. The nuclear interacting particles are detected and their energy and delay measured using the total absorption spectrometer which works on the following principle. The nuclear interacting particle is allowed to pass through an appreciable amount of condensed matter; it interacts several times in this medium losing energy to secondary particles which are mostly pions. The charged pions further interact and produce more pions and lead to the development of a nucleon cascade. The neutral pions produced in the various collisions decay instantaneously into  $\gamma$  rays and lead to electromagnetic cascades; energy is thus fed continuously into the electromagnetic cascade from the nucleon cascade. The nucleonic and electromagnetic cascade particles lose their energy continuously by ionization in the medium, thus transforming practically all the energy into energy of ionization. The energy of ionization is sampled by the introduction of a number of scintillators in the absorber.

The total absorption spectrometer operating at Ootacamund (Ramana Murthy et al. 1963) consists of 25 layers of iron (in all  $800 \text{ g cm}^{-2}$ ), each of area  $120 \text{ cm} \times 120 \text{ cm}$  and thickness 3.5 cm, which are stacked one above the other on spacers in such a way that there is a gap of 4 cm between the adjacent layers. In the gap between the iron plates there are liquid scintillation tanks of horizontal dimensions  $114 \text{ cm} \times 64 \text{ cm}$ . The height of the tanks varies in a step-wise manner from 1.9 cm at the front to 3.2 cm at the rear. This step-wise design makes it possible to obtain uniformity of light response at the photomultipliers which are placed at a distance of about a metre from the front of the scintillation tanks, as shown in figure 2. The tanks are made of aluminium sheets and are fitted with glass windows in the front side for light transmission. The scintillating liquid used is Shellsol A with  $3.5 \text{ g l}^{-1}$  of para-terphenyl and  $5 \text{ mg l}^{-1}$  of POPOP. The photomultipliers that view the tanks from the opposite ends are arranged as shown in the figure; there are five photomultipliers on each side; reckoning from the top the first two tanks are viewed by one photomultiplier, the next two by the second, the next six by the third, the following seven tanks by the fourth and the last eight tanks by the fifth photomultiplier. The spectrometer is shielded on the top by 2.5 cm of lead up to about  $45^\circ$ . It is

calibrated by recording the pulse heights of fast muons passing through the entire spectrometer. Further details on the design features, the method of estimation of energy and corrections for unsampled energy losses are available in the paper by Ramana Murthy et al. (1963).

In the present experiment only the two bottom sections, C and D of the total absorption spectrometer, were used both for measurement of delay and for measurement of energy. Therefore the nuclear interacting particles could be detected either after they passed through the top sections or when they entered the spectrometer from the sides. For these reasons the estimate of energy in the present experiment is not so accurate as claimed in the paper by Ramana Murthy et al. (1963). The passage of a minimum ionizing particle through C or D would release an energy in ionization equivalent to 350 MeV. This therefore is the absolute minimum energy release per particle in C or D. It is estimated that unseen energy losses are of comparable magnitude at these energies. This factor, however, is subject to large uncertainties, particularly at low energies. The energy estimate may be taken to be accurate to within a factor of 2.

The delay is measured with respect to one of the chronotron scintillators. The maximum delay measured is 300 nsec.

The selection system for the air showers consisted of a three-fold coincidence of three scintillators (6, 10, 13—see figure 1) whose centre is at a distance of about 10 m from the spectrometer. Showers are recorded at the rate of about 200/hour. The spectrometer is biased for an energy release corresponding to the passage of about three minimum ionizing particles through either one of the bottom sections C and D of the spectrometer. The percentage of association with this bias was approximately 45%. After running the experiment for a few days at the rate of 200/hour a delayed coincidence trigger was introduced to take a long run for particles which arrive in the interval 60-300 nsec with respect to the shower front.

Detailed analysis of the showers for size, core position, arrival angle etc. has not yet been completed.

Preliminary results on the delay distributions of nuclear interacting particles of estimated energy above 5 GeV obtained in an operating period of about 330 hours are shown in figure 3. In practically all these cases comparable energy releases were seen in both the C and D sections of the spectrometer and therefore these events could not be due to possible neutron stars in the scintillators. From the figure the following features are evident: (i) the peak of the nuclear interacting particles is displaced with respect to the shower front by about 20 nsec; (ii) nearly 30% of the particles of energy above 5 GeV

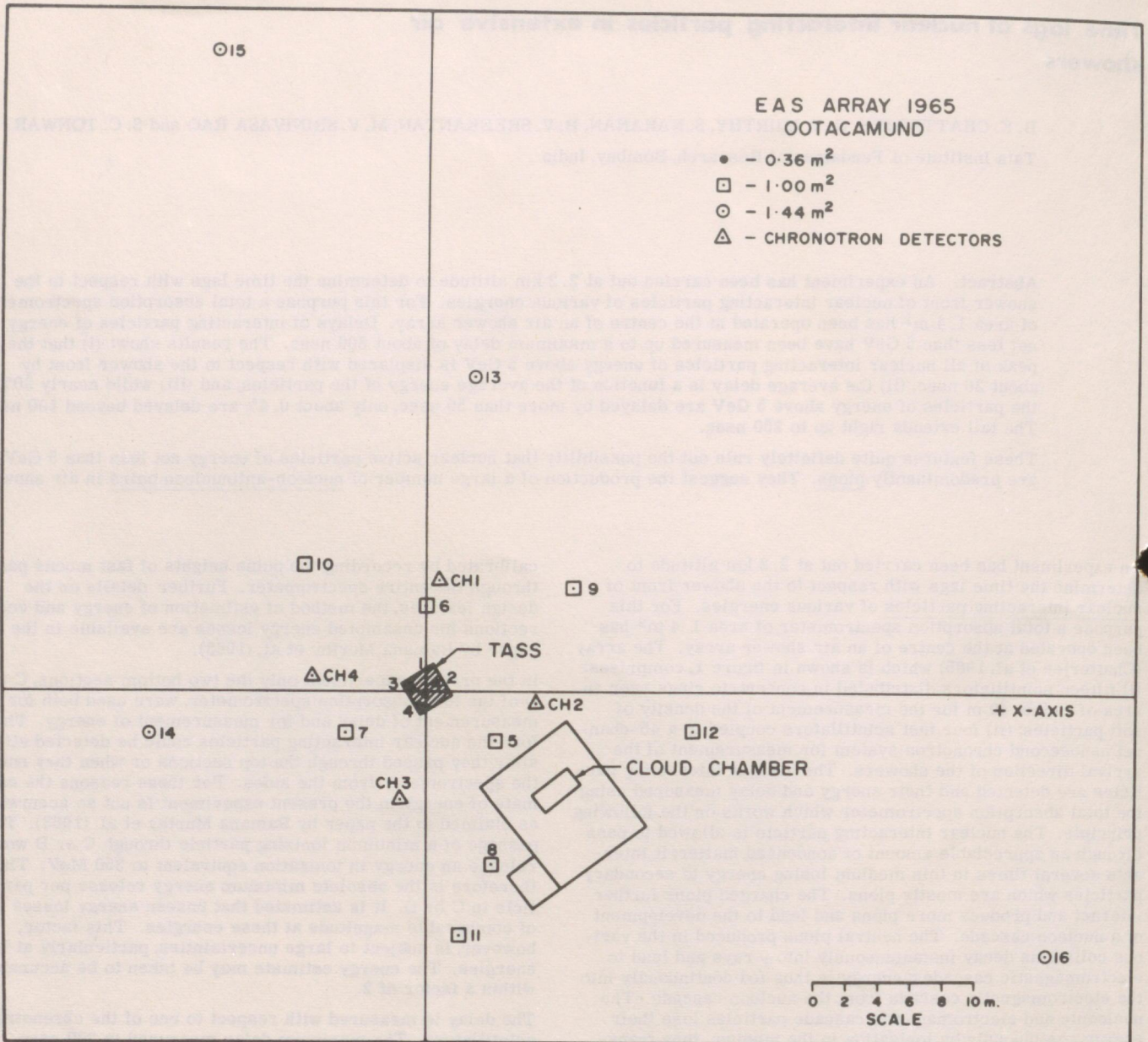


Fig. 1 Extensive air shower array at Ootacamund (altitude 2.2 km). Scintillators 1 to 15 are for measurement of densities. CH<sub>1</sub> to CH<sub>4</sub> are fast scintillators for determining the arrival direction of showers.

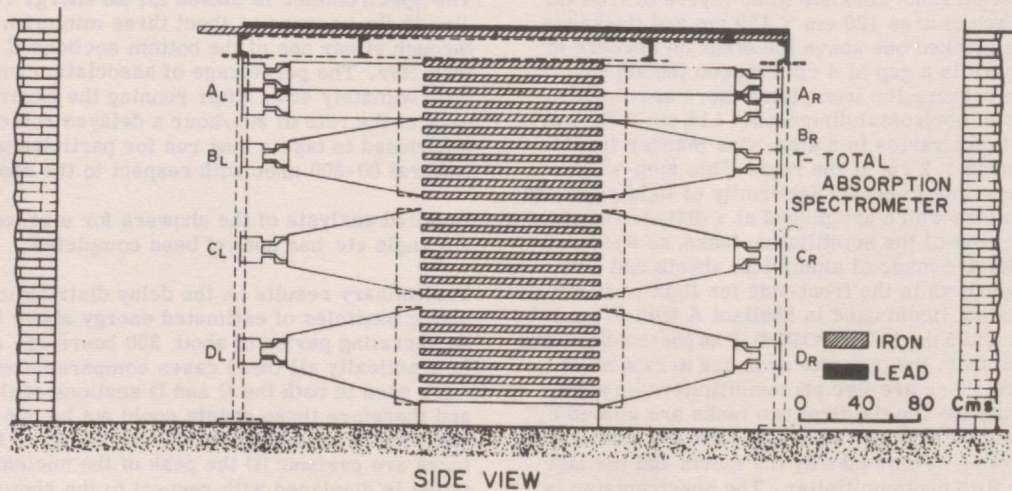


Fig. 2 Cross sectional view of the total absorption spectrometer.

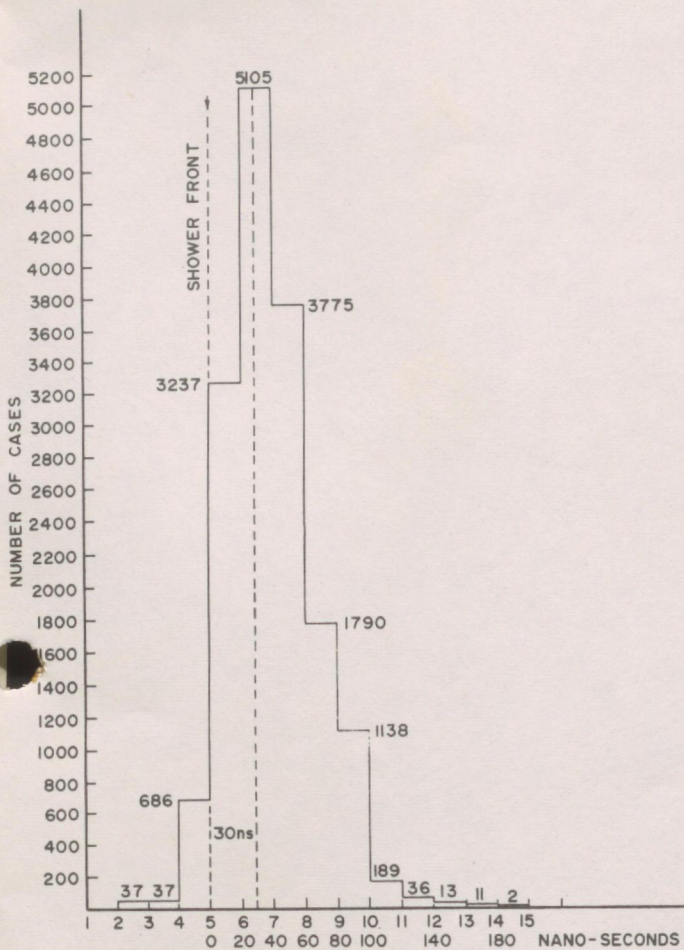


Fig. 3 Delay distribution of nuclear interacting particles of energy above 5 GeV recorded at an altitude of  $800 \text{ g cm}^{-2}$  for showers of size greater than a few times  $10^4$ - $10^7$  particles.

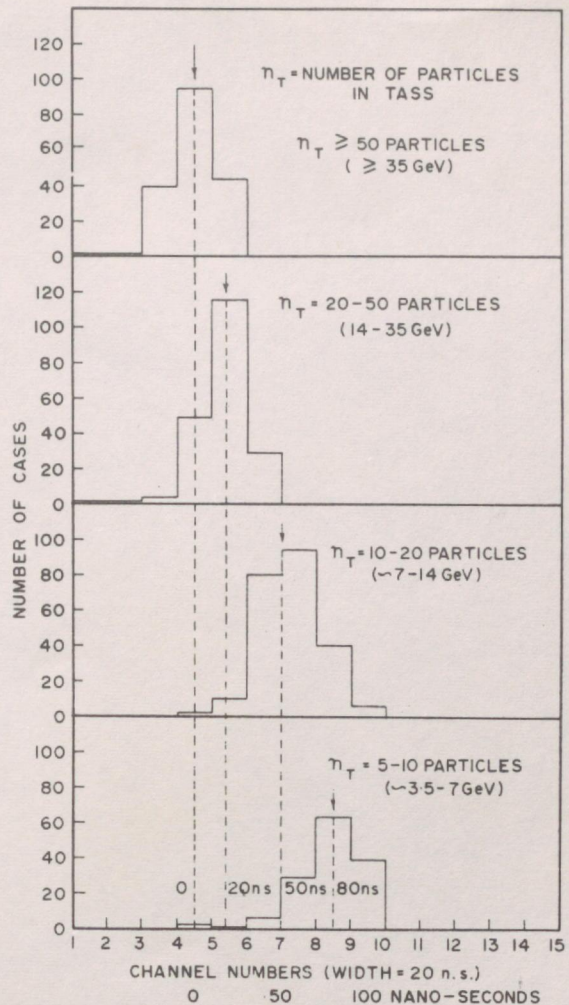


Fig. 4 Delay distribution of nuclear interacting particles as a function of energy greater than 3 GeV. It is to be noted that the energies given should be taken only as indicative of the order of magnitude. [The first and second histograms from the top must be shifted to the right by one channel. The shifts in the peak are therefore 20, 30 and 60 nsec instead of 20, 50 and 80 nsec.]

are delayed by more than 50 nsec while only about 0.4% are delayed beyond 100 nsec. The tail extends right up to 250 nsec.

In figure 4 are given the preliminary results on delay distributions for nuclear interacting particles of different energies. It is seen from the figure that the average delay is a function of the average energy of the particles. For example, while particles of energy not less than 7 GeV are delayed by about 30 nsec, particles of energy above 3.5 GeV are delayed by about 60 nsec.

If the nuclear interacting particles recorded were predominantly pions, then such a broad distribution as seen in figure 4 cannot be understood. In fact, pions of energy 5 GeV have a  $\gamma$  factor of 35 and so will have negligible delays with respect to the shower front. The broad distribution and the fact that the peak shifts with energy can, however, be understood if a large percentage of the nuclear interacting particles of energy

greater than 5 GeV are nucleons. We estimate that at least 50% of the nuclear interacting particles of energy 5 GeV will have to be nucleons. This means that in showers of size of order  $10^5$ , we should have at the level of observation at least 50 nucleons of energy above 5 GeV or, at the cascade maximum, approximately 500 nucleons. Since the recoil nucleons are known to have energies less than 1 GeV, we surmise that these high energy nucleons can only come through the production of nucleon-antinucleon pairs in air showers.

References

Chatterjee, B. K., et al. 1965, this Conference, Chap. 8, EAS 38.  
 Ramana Murthy, P. V., Sreekantan, B. V., Subramanian, A., and Verma, S. D., 1963, Nucl. Instrum. Meth., 23, 245-254.

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

# Search for heavy mass particles in air showers

B. K. CHATTERJEE, G. T. MURTHY, S. NARANAN, B. V. SREEKANTAN, M. V. SRINIVASA RAO and S. C. TONWAR  
Tata Institute of Fundamental Research, Bombay, India

**Abstract.** Recently there have been theoretical speculations on the production in high energy collisions of particles much heavier than nucleons. Such particles are expected to behave like nuclear interacting particles in air showers with the difference that even at high energies they will be considerably delayed with respect to the shower front and transfer a much smaller fraction of their energy in nuclear collisions.

An experimental search has been made at Ootacamund (2.2 km altitude) employing a total absorption spectrometer at the centre of an air shower array for the presence of delayed high energy interacting particles in the interval 60-300 nsec. In 449 hours of observation (about 80 000 showers of size  $10^4$ - $10^7$ ) there is no evidence for the passage of a heavy mass particle through the total absorption spectrometer of approximate area 1.5 m<sup>2</sup>. A heavy mass particle would have been detected if it had a mass of about 5-10 GeV, energy 40-100 GeV, interacted with a mean free path of about 80-100 g cm<sup>-2</sup>, transferred 5-10% of its energy in nuclear collisions, and was not more than about 20 m away from the core.

## 1. Introduction

In recent years some theorists (Gell-Mann 1964, Gursev et al. 1964) have speculated on the production in high energy collisions of particles much heavier than the nucleon. Such heavy mass particles can be produced with appreciable cross section only at very high energies. Obviously, one of the best places to look for them is the air shower which is itself the product of many generations of high energy collisions. Because of the heavy mass of these particles, even if they are produced with high energy they will not be sufficiently relativistic and so will lag behind the shower front which is defined by the photons and ultra-relativistic electrons. Simple calculations show that particles of mass 5-10 GeV lag behind the shower front by as much as a few hundred nanoseconds. Since these particles are expected to be produced in strong interactions, it is reasonable to expect that the particles themselves are interacting and, therefore, should behave like N particles in air showers. Because of their heavy mass they naturally will transfer a much smaller fraction of their energy in an encounter with a nucleon (say, about 5%).

On the basis of some simple assumptions the average delay with respect to the shower front of nucleons and of particles of mass approximately 10 GeV have been calculated for different kinetic energies and given in figure 1. The considerations that have gone into these calculations are: (i) the interaction mean free path is the same for both types of particles ( $\lambda = 80$  or  $100$  g cm<sup>-2</sup>); (ii) the inelasticity  $\eta$  for nucleons is assumed to be 0.45 while for heavy mass particles it is taken to be 0.05; (iii) while the fluctuations in the points of collisions have been ignored; (iv) the particles which degenerate to the energy observed at the observational level are assumed to be produced either at the top of the atmosphere or at the cascade maximum (400 g cm<sup>-2</sup>); (v) calculations have been made for both mountain altitude and sea level.

It is seen from figure 1 that a nucleon of kinetic energy 10 GeV is delayed with respect to the shower front, on average, by not more than about 20 nsec while a heavy mass particle of mass 10 GeV is delayed by more than 500 nsec. A nucleon of energy 20 GeV is delayed by about 10 nsec while a heavy mass particle of the same kinetic energy is delayed by at least 400 nsec. It is, therefore, apparent that if the energy of the nuclear interacting particle is determined fairly accurately and the delay measured with respect to the shower front then, depending upon the absolute frequency of production, their lateral distribution etc., it should, in principle, be possible to detect these heavy mass particles in air showers.

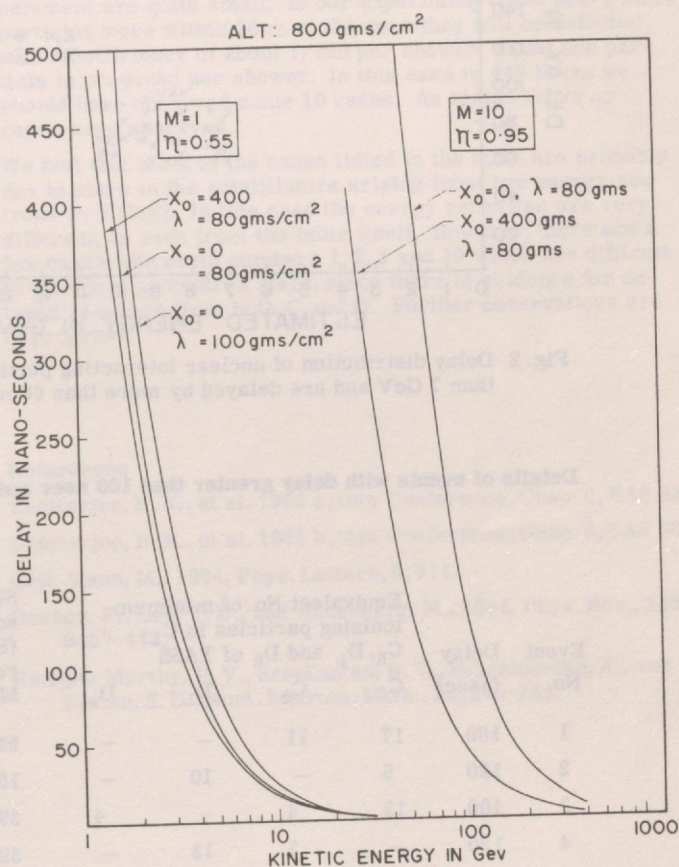


Fig. 1 Average delay of nuclear interacting particles (nucleons and particles of mass 10 GeV) as a function of kinetic energy calculated for mountain altitude (2.2 km) assuming  $\lambda = 80$  or  $100$  g cm<sup>-2</sup> and production height 0 or 400 g cm<sup>-2</sup>. The calculations have been made by the Monte Carlo method.

Based on these considerations, an experiment is in progress at Ootacamund (2.2 km) and the preliminary results are described below.

2. Experimental details

The search for heavy mass particles was carried out with the air shower array at Ootacamund (Chatterjee et al. 1965 a). The details of the array are shown in figure 1 of the previous paper (EAS 58 a). The four fast scintillators coupled to the chronotron timing system enable the determination of the angle of arrival of showers with an accuracy of about 5°. The fifteen scintillators spread over an area of 40 m radius around the total absorption scintillation spectrometer (TASS) enable the determination of the size and core position of the showers.

The total absorption spectrometer (Ramana Murthy et al. 1963) determines the energy of nuclear interacting particles by transforming practically all the energy into energy of ionization through nuclear collisions, decay of  $\pi^0$  mesons, develop-

ment of nucleonic and electromagnetic cascades and ultimately ionization of all charged particles in a large iron absorber ( $800 \text{ g cm}^{-2}$ ) which is interspersed with 25 layers of liquid scintillators that sample the ionization energy. Some relevant details of the spectrometer are shown in figure 2 of the previous paper (EAS 58 a). The design features, method of calibration of the spectrometer, determination of energy, correction for unseen energy losses etc. are available in the paper by Ramana Murthy et al. (1963).

For measurement of the delay of N particles, in the present experiment only the two bottom sections C and D (see figure 2 of the previous paper) of the spectrometer were used. The accuracy of energy determination is estimated to be better than a factor 2.

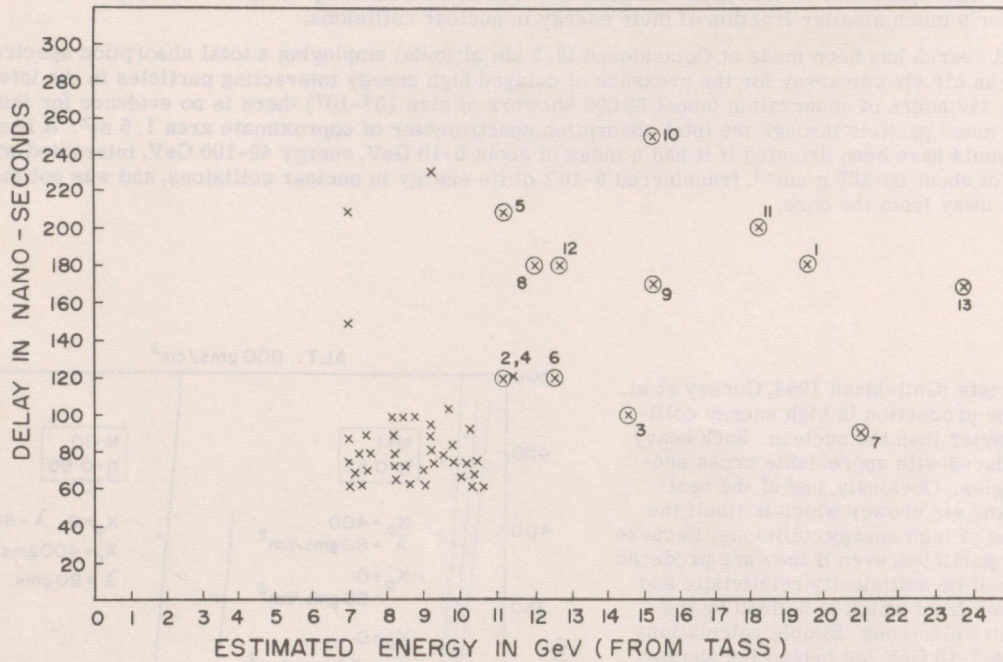


Fig. 2 Delay distribution of nuclear interacting particles which have energy greater than 7 GeV and are delayed by more than 60 nsec.

Details of events with delay greater than 100 nsec and energy (apparent) above 7 GeV recorded in 449 hours

Event No.	Delay (nsec)	Equivalent No. of minimum ionizing particles in $C_L, C_R, D_L$ and $D_R$ of TASS				Star in scintillator (Energy release MeV)	Interaction of high energy nucleon (Energy of nucleon in GeV)	Interaction of a heavy mass (> 10 GeV) particle (Energy of the particle in GeV)
		$C_L$	$C_R$	$D_L$	$D_R$			
1	180	17	11	—	—	510, 330	19.6	76
2	120	5	—	10	—	150, 300	11.2	45
3	100	13	4	—	4	390, 120, 120	14.7	58
4	120	—	3	13	—	390	11.2	45
5	210	3	13	—	—	90, 390	11.2	45
6	120	—	18	—	—	540	12.6	50
7	110	2	26	2	—	60, 780, 60	21	84
8	180	2	—	15	—	60, 450	12	48
9	170	—	1	19	2	30, 560, 60	15.4	61
10	250	2	2	2	16	60, 60, 60, 480	15.4	61
11	200	—	26	—	—	780	18.2	77
12	180	1	—	13	4	30, 390, 120	12.6	50
13	170	30	3	—	2	900, 90, 60	23.0	92

The delay was measured with respect to one of the fast scintillators, CH<sub>1</sub> (see figure 1 of previous paper), used for measuring the angle of arrival of the showers. A 15-channel chronotron timing system with channel width of 20 nsec was used to measure the delay with respect to the shower front in the interval 0-300 nsec.

To reduce the frequency of association of prompt particles through the TASS and also to favour the detection of heavy mass particles which may have a very much flatter lateral distribution compared with nucleons, a selection system which was not quite central to the TASS was chosen. This consisted of a threefold coincidence of the scintillators 6, 10 and 13 in the array. The rate of showers so selected was about 200/hour. Showers recorded were mostly in the size range a few times 10<sup>4</sup>-10<sup>7</sup> particles with core distances about 20 m for showers of size about 10<sup>5</sup>. The spectrometer was biased so that a triggering pulse was available from it only when there was an energy release corresponding to the passage of at least three minimum ionizing particles through either C or D or both. With this requirement it was found that the percentage of showers in which there was an associated pulse from the TASS was about 44%. The electronic system for recording delays was such that if more than one interacting particle passed through C or D, then only the delay of the earlier one was measured. This percentage of association ensured that there was at least a 50% chance for large delays to be registered.

### 3. Results

First a fast run was taken for a few days at the rate of about 200/hour. The delay distribution of N particles of energy above 5 GeV could be obtained quite accurately from this run up to about 80 nsec. Later a delayed coincidence circuit to record all cases with delays in the interval 60-300 nsec was used and the run continued for about 20 days at a rate of 20/hour. The combined distribution of the delay of N particles is shown in figure 3 of the previous paper.

It is seen from the figure that nearly 30% of N particles of energy above 5 GeV are delayed by more than 50 nsec while only 0.4% are delayed beyond 100 nsec.

Since the showers have not yet been analysed on the computer for core position, shower size etc., it has not been possible to determine the distributions for various shower sizes and distance intervals.

The delay distribution of N particles which have an energy above 7 GeV and delayed by more than 60 nsec is given in figure 2. This distribution has been obtained in a total effective time of operation of 449 hours. In the figure those cases which have an energy release corresponding to more than 10 GeV and delayed by more than 100 nsec have been circled and numbered. The relevant details of these cases, which in the first instance may be considered as large energy release, large delay cases, are given in the table.

It has been shown in the previous paper (Chatterjee et al. 1965 b) that the delay distribution shown in figure 4 of the

previous paper cannot be understood if the majority of N particles of energy above 5 GeV in air showers are pions, but the distribution can be understood if they are nucleons. In this case appreciable production of nucleon-antinucleon pairs in air showers is indicated.

A characteristic feature of a heavy mass particle passing through TASS would be to release comparable energy in both sections C and D of the spectrometer, since each of the sections C and D offers at least two interaction mean free paths and a heavy mass particle is expected to transfer only about 5% of its energy. It is clear from the table that there is not even a single case in which appreciable energy release is seen in both the C and D sections of the spectrometer. This observation means that in 449 hours (about 80 000 showers) in an area of about 1.5 m<sup>2</sup> there is no indication of the passage of a heavy mass particle with the following properties: (i) mass 5-10 GeV, (ii) energy at the observation level 40-100 GeV, (iii) interaction mean free path 80-100 g cm<sup>-2</sup>, (iv) inelasticity 5-10%.

However, it is to be pointed out that the above observation cannot be taken as evidence against the production of heavy mass particles. The efficiency of detection of these particles in air showers critically depends on the lateral distribution of these particles with respect to the core of the shower. If these particles are produced very high in the atmosphere, then it is reasonable to expect that they will be found away from the core and could even be at distances of several hundred metres. In this case the chances of recording them in the present experiment are quite small. In our experiment if the heavy mass particles were within 20 m of the core they will be detected with an efficiency of about 1/800 per shower, if just one particle is produced per shower. In this case in 449 hours we should have observed some 10 cases. As stated above no cases were observed.

We feel that most of the cases listed in the table are probably due to stars in the scintillators arising from low energy neutrons (~ 1 GeV). In this case the energy estimates are very different, as seen from the table itself. However, there are a few cases like event numbers 1, 2, 3 and 10 which are difficult to interpret as neutron stars, since there is evidence for delayed response from both C and D. Further observations are in progress.

### References

- Chatterjee, B. K., et al. 1965 a, this Conference, Chap. 8, EAS 38.
- Chatterjee, B. K., et al. 1965 b, this Conference, Chap. 8, EAS 58A.
- Gell-Mann, M., 1964, Phys. Letters, 8, 214.
- Gursey, F., Lee, T. D., and Nauenberg, M., 1964, Phys. Rev., **135**, B467-477.
- Ramana Murthy, P. V., Sreekantan, B. V., Subramanian, A., and Verma, S. D., Nucl. Instrum. Meth., **23**, 245-254.

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

## The Kolar Gold Field neutrino experiment

C. V. ACHAR, \* M. G. K. MENON, \* V. S. NARASIMHAM, \* P. V. RAMANA MURTHY, \* B. V. SREEKANTAN, \* K. HINOTANI, † S. MIYAKE, † D. R. CREED, ‡ J. L. OSBORNE, ‡ J. B. M. PATTISON ‡ and A. W. WOLFENDALE ‡

\* Tata Institute of Fundamental Research, Bombay, India

† Osaka City University, Osaka, Japan

‡ University of Durham, Durham, England

**Abstract.** Two telescopes designed for the detection of muons produced by neutrinos have been set up at a depth of 7500 m w.e. in the Kolar Gold Fields in India. Each telescope consists of two vertical walls of plastic scintillators 2 m long and 3 m high separated by 80 cms. Between the scintillator walls there are three columns of neon flash tubes; 5 cms lead can be introduced in between. Each square metre of scintillator is viewed by two adjacent 5-inch diameter photomultipliers. The fourfold coincidence of any two opposite pairs triggers the voltage on the flash tubes. With the use of visual detectors in the form of flash tubes it is possible to determine the zenith angle of the muon to an accuracy better than  $2^\circ$  and thereby to correct for the contribution due to remanent atmospheric muons which leak through; the latter have a steep angular distribution, arriving mostly vertically, whilst the neutrino-induced muons are much more isotropic. One unit with 5 cm lead and another without any lead are in operation. Results up to the time of the Conference are presented.

Underground neutrino energy spectra have been derived as a function of zenith angle and the expected cross sections for neutrino interactions have been calculated from theoretical predictions and accelerator experiments. These data are used to give predicted rates and angular distributions of neutrino-induced muons detected by the telescopes of the Tata Institute-Osaka City-Durham collaboration experiment at a depth of 7500 m w.e. in the Kolar Gold Fields.

The interpretation of the observed events will be given.

### 1. Introduction

Following the early work carried out at great depths underground in the Kolar Gold Mines in India (Miyake et al. 1964, Menon et al. 1963 a, b, Menon 1963 and Achar et al. 1965 a), we have specifically designed an experiment for the detection of the interactions of cosmic ray neutrinos; (Sreekantan 1965 and Wolfendale 1965). The first phase of this experiment was meant to be exploratory in character; the main objective has been to see if the fluxes of cosmic ray neutrinos (either of terrestrial or of extraterrestrial origin) and the high energy behaviour of neutrino interaction cross sections are consistent with the expectations based on various estimates. Preliminary results obtained in the first 3000 m<sup>2</sup> day sterad of operation were reported in Physics Letters (Achar et al. 1965 b, c). Here we wish to present results obtained up to the time of the Conference.

### 2. Experimental details

The experiment has been in operation since March 1965 in the Kolar Gold Mines in South India at a depth of 7600 ft (equivalent to 7500 m w.e.\* in the case of standard rock with  $Z^2/A = 5.5$ ).

We have used two identical telescopes, each consisting of two vertical walls of plastic scintillators, 2 m long and 3 m high, separated by 80 cm, as shown in figure 1. Each 'scintillator element', one square metre in area, is viewed by two adjacent 5-inch diameter photomultipliers; fourfold coincidences are recorded between a pair of photomultipliers on one wall and any pair on the other wall. Between the scintillator walls there are three arrays of neon flash tubes; in each array there are four columns of flash tubes. There are two walls of lead absorber, each 2.5 cm in thickness, in between the flash tube arrays. When fourfold coincidences occur, the photomultiplier pulses are recorded on oscilloscopes, and after a delay of about 30  $\mu$ sec a high voltage pulse is applied to the electrodes of the neon flash tube arrays.

\* At Kolar  $Z^2/A = 6.5$  and rock density is  $3.02 \text{ g cm}^{-3}$ , and accordingly the depth of 7600 ft corresponds to 7000 m w.e. for Kolar rock.

### K.G.F. NEUTRINO TELESCOPE

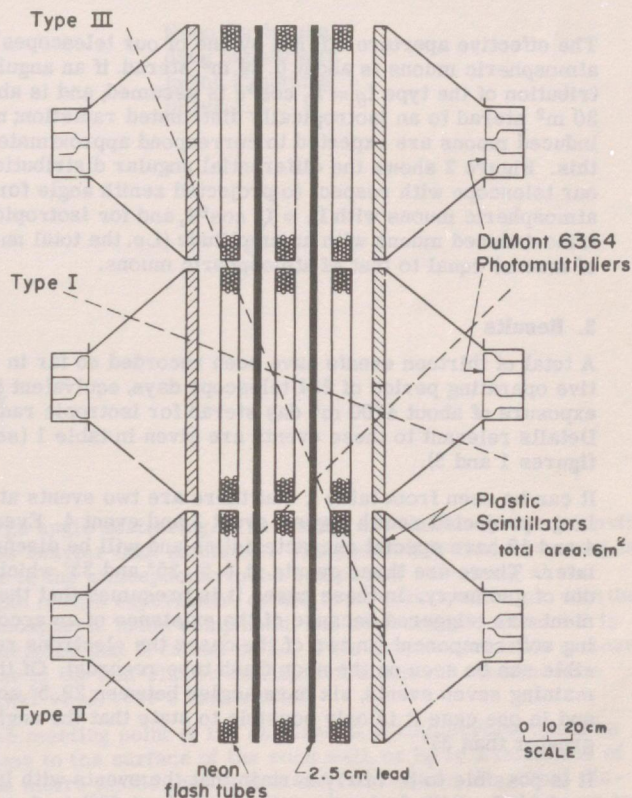


Fig. 1 Front view of one of the Kolar Gold Field neutrino telescopes.

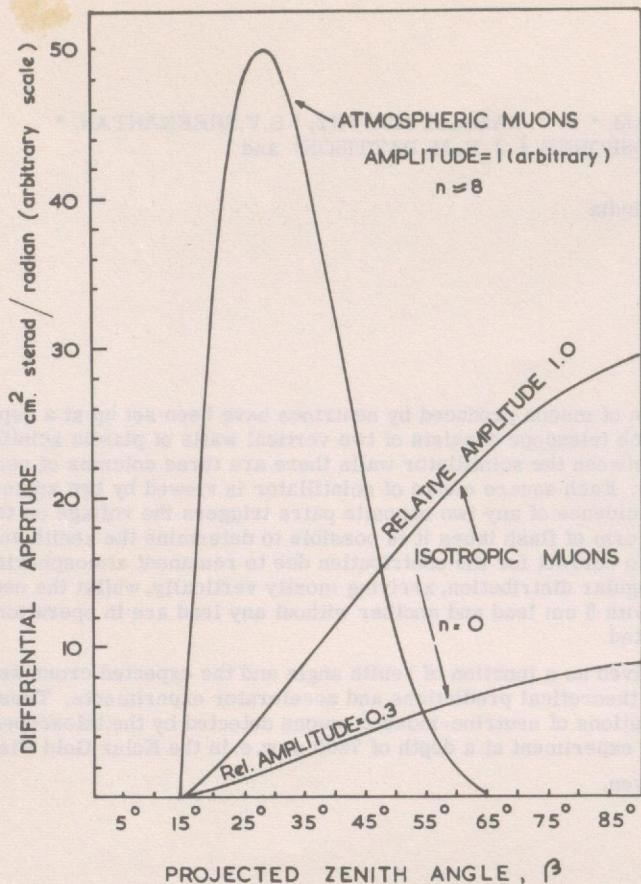


Fig. 2 The differential angular distributions for the neutrino telescopes.

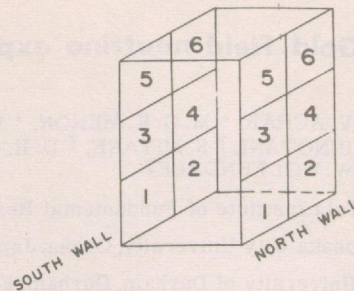
The effective aperture offered by one of our telescopes to atmospheric muons is about 0.29 m<sup>2</sup> sterad, if an angular distribution of the type  $I_{\theta} = I_0 \cos^8 \theta$  is assumed, and is about 20 m<sup>2</sup> sterad to an isotropically distributed radiation; neutrino-induced muons are expected to correspond approximately to this. Figure 2 shows the differential angular distributions for our telescope with respect to projected zenith angle for atmospheric muons with  $I_{\theta} = I_0 \cos^8 \theta$ , and for isotropic neutrino-induced muons with an amplitude (i.e. the total number of muons) equal to that of atmospheric muons.

3. Results

A total of thirteen events have been recorded so far in an effective operating period of 234 telescope days, equivalent to an exposure of about 4700 m<sup>2</sup> day sterad for isotropic radiation. Details relevant to these events are given in table 1 (see also figures 1 and 3).

It can be seen from table 1 that there are two events at very large projected zenith angles, event 3 and event 4. Event nos. 4 and 13 have special characteristics and will be discussed later. There are three events at 8.5°, 25° and 33° which are all out of geometry. In these cases it is presumed that the equipment was triggered because of the existence of an accompanying soft component (in two of the cases the electrons responsible can be seen on the neon flash tube records). Of the remaining seven events, six have angles between 29.5° and 48° and in one case it is only possible to state that the angle is greater than 37°.

It is possible to be fairly certain that the events with large projected zenith angles (greater than about 65°) such as event nos. 3 and 4, are due to neutrino-induced muons (see figure 2); on the other hand, one is not sure if an event with a zenith angle smaller than about 60° is to be attributed to a neutrino interaction or to an atmospheric muon (see figure 2). We have



TYPE I EVENTS: (N<sub>1OR2</sub> + S<sub>1OR2</sub>) OR (N<sub>3OR4</sub> + S<sub>3OR4</sub>) OR (N<sub>5OR6</sub> + S<sub>5OR6</sub>)  
 TYPE II EVENTS: (N<sub>3OR4</sub> + S<sub>1OR2</sub>) OR (N<sub>3OR4</sub> + S<sub>5OR6</sub>) OR (N<sub>5OR6</sub> + S<sub>3OR4</sub>) OR (N<sub>1OR2</sub> + S<sub>3OR4</sub>)  
 TYPE III EVENTS: (N<sub>1OR2</sub> + S<sub>5OR6</sub>) OR (N<sub>5OR6</sub> + S<sub>1OR2</sub>)  
 N MEANS NORTH; S MEANS SOUTH

Fig. 3 Nomenclature for the various types of events.

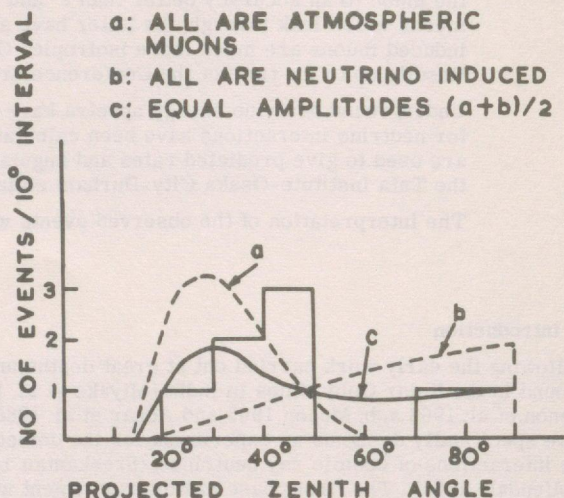


Fig. 4 The frequency distribution of measured projected zenith angles.

made attempts to estimate in several ways the fraction of events which can be attributed to neutrino interactions.

The relative percentages of events of types I, II and III (as defined in figure 3) for events induced by neutrinos are very different from those in the case of events due to atmospheric muons; the relevant values are shown in table 2. This difference in the relative percentages arises from the different angular distributions of the two categories of muons. Let us assume that the total number of neutrino-induced muons is x times that of atmospheric muons. By dividing the muons of the two categories into various types by the respective ratios given in table 2, one can derive the expected ratios, in terms of x, for type I/all, type II/all and type III/all. By comparing these ratios with the experimentally observed ratios, one can solve for x. From such an analysis we conclude that about five of all the observed events are neutrino-induced and the rest are due to atmospheric muons (see figure 4).

When a sufficiently large number of events has been observed, one can directly compare the observed projected zenith angle distributions with a mixture in known proportions of the two distributions shown in figure 2, and thereby obtain the best estimate of the relative amplitudes. An attempt in this direction, shown in figure 5, indicates that about 5-6 of the events are due to  $\nu$ -induced muons. The rate of neutrino-induced muons which follows from this is approximately equal to  $1.2 \times 10^{-12}$  particles/cm<sup>2</sup> sec sterad (for an isotropic distribution of neutrinos).

Table 1

Events obtained in the Kolar Gold Field neutrino experiment up to the end of August 1965

Event No.	Date and time I.S.T.	Coincidence	Event type	Projected zenith angle	Remarks
1	5 Apr. 1965 2004 h	S <sub>4</sub> N <sub>4</sub> tel. 2	I	> 37°	Neon flash tubes not present
2	27 Apr. 1965 1826 h	S <sub>1</sub> N <sub>1</sub> tel. 1	I	48° ± 1°	Only two extreme trays of neon flash tubes present
3	25 May 1965 2003 h	S <sub>6</sub> N <sub>6</sub> tel. 2	I	75° ± 10°	Only the central tray of neon flash tubes present
4	3 Jul. 1965 1230 h	S <sub>1</sub> N <sub>1</sub> tel. 2	I	96.2° ± 0.8° 99.2° ± 0.3°	Double track event
5	13 Jul. 1965 1613 h	S <sub>3, 5, 6</sub> N <sub>4</sub> tel. 2	II	45° ± 1°	
6	18 Jul. 1965 0252 h	S <sub>1, 2</sub> N <sub>3, 6</sub> tel. 1	Out of geom.	8.5° ± 1°	
7	24 Jul. 1965 1147 h	S <sub>3</sub> N <sub>6</sub> tel. 1	II	37.5° ± 1°	
8	27 Jul. 1965 0324 h	S <sub>3</sub> N <sub>6</sub> tel. 1	II	29.5° ± 1°	
9	29 Jul. 1965 1907 h	S <sub>3</sub> N <sub>1</sub> tel. 2	II	32.5° ± 2.5°	
10	1 Aug. 1965 2100 h	— tel. 1	Out of geom.	25° ± 1°	Oscilloscope data not available
11	2 Aug. 1965 0338 h	S <sub>4</sub> N <sub>6</sub> tel. 1	II	47° ± 1°	
12	11 Aug. 1965 1737 h	S <sub>3</sub> N <sub>4</sub> tel. 1	Out of geom.	33° ± 1°	
13	12 Aug. 1965 1138 h	S <sub>1, 2, 6</sub> N <sub>2, 4, 6</sub> tel. 1 S <sub>1, 2, 3, 4, 5, 6</sub> N <sub>4</sub> tel. 2	? ?	? ?	Neon flash tube data; big shower in tel. 2; nothing in tel. 1.

Table 2

Category of muons	Assumed angular distribution	Type of events		
		I	II	III
Neutrino-induced	isotropic	0.67	0.31	0.02
Atmospheric	cos <sup>8</sup> θ	0.08	0.65	0.27

It should be emphasized at this stage that the curve shown in figure 2 is based on an assumed angular distribution  $I_{\theta} = I_0 \cos^8 \theta$  for atmospheric muons; we have used this as a conservative estimate. The indications are that the distribution is probably steeper but in view of uncertainties with regard to the scattering behaviour at very high energies there is some uncertainty in the estimate of the fraction of  $\nu$ -induced muons amongst the total number observed.

### 3.1. Event No. 4

In this event, a sketch of which is shown in figure 5, there are two tracks, one at a projected zenith angle of 99° and the other at 96°. By a detailed reconstruction of the event from the photographs of flash tube arrays and oscilloscopes, it can be shown that both the particles responsible for the tracks penetrated more than 9 radiation lengths without multiplication or

large angle scattering. The tracks are therefore due to particles heavier than electrons. The possibility that this event is due to the atmospheric muon component remaining at the depth of this experiment, or due to pions in equilibrium with the atmospheric muon component, has been considered and it is concluded that it cannot be so. This event represents a clear case of the non-elastic collision of a natural neutrino (see Achar et al. 1965 c for details).

The meeting point of the two tracks, within errors, could be close to the surface of the rock wall, or up to a thickness of one metre inside the rock; in the latter case, the actual distance traversed by the particles through rock would be up to about 1.7 metres. The uncertainty in the traversal through rock of each of the tracks, namely 0 to 1.7 m, does not allow us to say if both the tracks are due to muons, or if one of the tracks is due to a muon and the other due to a pion. The point

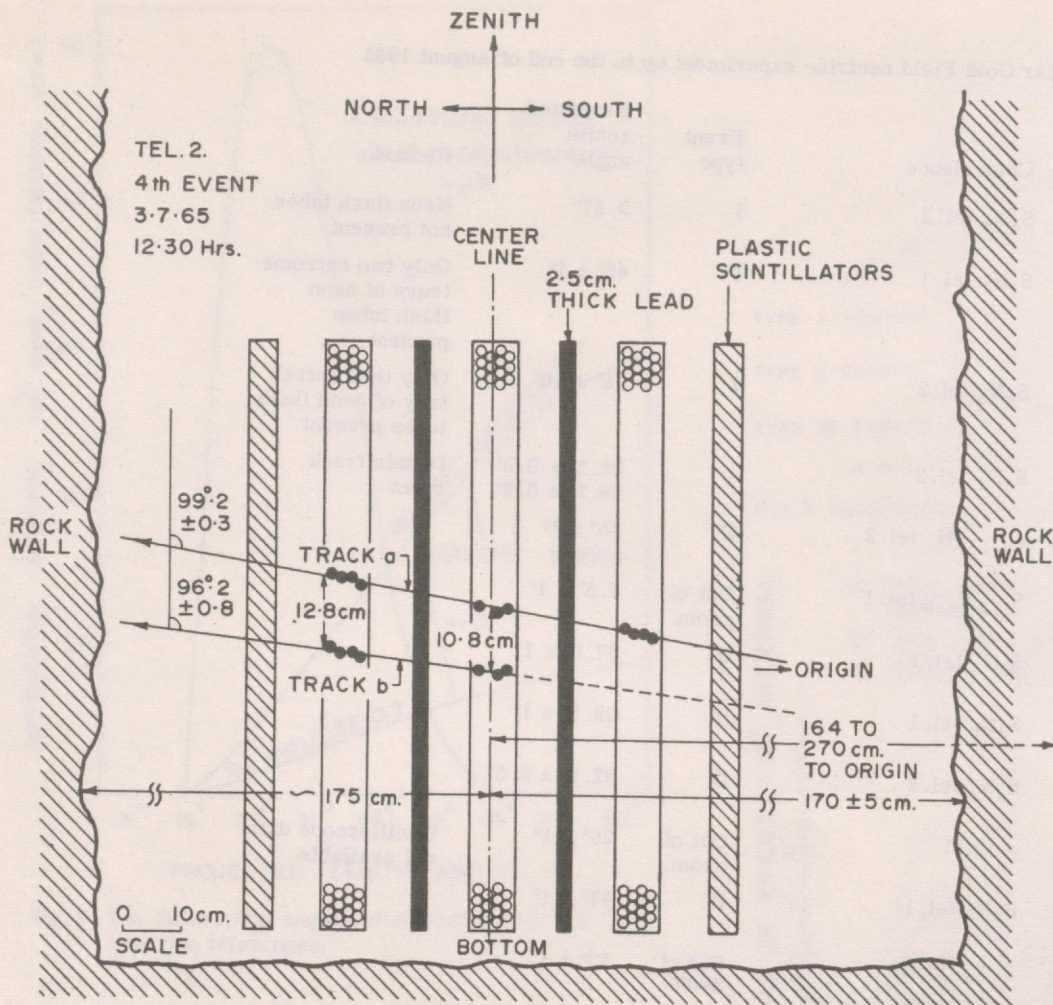


Fig. 5 Details of the double track event (no. 4) showing the bottom third of telescope no. 2.

Table 3

Expected number of neutrino-induced muons in an exposure of 4700 m<sup>2</sup> day sterad

Process	Expected number	
(a) Elastic	0.28	
Inelastic collisions		
(b) $\sigma_{inel} \propto E_\nu$ up to $E_\nu = 10$ GeV and saturates	0.74	
(c) $\sigma_{inel} \propto E_\nu$ up to $E_\nu \gg 10$ GeV	1.26	
Intermediate boson W		
(d) $M_W = 1.8$ GeV	A	B
(e) $M_W = 2.5$ GeV	1.24	4.4
	0.56	2.0
Glashow resonance		
(f) $M_W = 1.8$ GeV	0.37	
(g) $M_W = 2.5$ GeV	0.08	
Total lower limit (a) + (b)		
$\sigma_{inel}$ saturates at $E_\nu = 10$ GeV; W does not exist or $M_W \gg 2.5$ GeV	1.02	
Total upper limit (a) + (c) + (d) + (f)		
$\sigma_{inel}$ does not saturate, $M_W = 1.8$ GeV	3.15	6.31

of interest here is that if the penetration in the rock of both the tracks is several nuclear interaction mean free paths, then one would have been able to assert with high probability that both of them are due to muons; if this were so it would be probable that the event corresponds to the production of an intermediate boson.

### 3.2. Event No. 13

This event was primarily observed in telescope no. 2. All 'scintillator elements' on the southern side ( $S_{1-6}$ ) and one scintillator element ( $N_4$ ) on the north side showed large pulses; other scintillator elements on the north also showed pulses, but these were small. The photograph of the neon flash tube arrays is unfortunately incomplete; because of a defect in the film winding system a part of the picture showing details of the top section of the telescope overlapped with the previous photograph and some of the relevant details are thus lost. A reconstruction of the event based on the photograph of the bottom two thirds of the telescope shows that practically all the flash tubes on the southern side had discharged. In the central array a few well-separated large clusters of tubes which had discharged can be seen. On the north side, only a few tubes had been discharged; a few clusters can also be seen here. A remarkable feature is that three scintillator elements on the north wall ( $N_2, N_4, N_6$ ) and an equal number on the south wall ( $S_1, S_2, S_6$ ) of telescope 1 also showed pulses in coincidence; the pulses on the north wall were rather small but those on the south wall large. The flash tube arrays of telescope 1 were visible but showed very few flashes. This is the only event in which both telescopes have been triggered simultaneously.

This event is undoubtedly the most complex one which we have yet seen. It can be immediately stated, on the basis of the sizes and shapes of the scintillator pulses, and the manner in which the neon flash tube arrays have discharged, that this event was not due to instrumental effects and that we are dealing with a genuine event involving a large number of particles, probably generated through electromagnetic processes. The most likely explanation, on the basis of a geometrical reconstruction of the event, is that it was due to an electromagnetic shower arising in the southern rock wall and travelling at a small angle to the plane of the rock, so that in addition to the primary effects in telescope 2 it could also be seen in telescope 1. It is difficult to assign an exact value to the zenith angle since there is no track of a clearly penetrating particle which can be unambiguously defined. It is possible to ascribe plausible directions for many of the particles in the cascade as seen in the neon flash tube array and from this it appears likely that the zenith angle was quite large; if the zenith angle is sufficiently large the event would correspond to a neutrino interaction. From the size of the cascade, it is estimated that the total energy involved is more than several hundred GeV. We draw attention to this event to indicate the types of phenomena which are observable with arrays of the type we have used. The analysis of such events, though no doubt complicated, will be of great interest from the viewpoint of high energy muon and neutrino physics.

### 4. Discussion

The estimated number of neutrino-induced muons can be compared with the theoretically expected number calculated on the basis of the calculated atmospheric neutrino fluxes and neutrino interaction cross sections which have been measured up to energies of several GeV at CERN and Brookhaven and concerning which assumptions can be made for higher energies.

The fluxes of neutrinos produced in the terrestrial atmosphere have been calculated for various energies by Greisen (1960), Zatsepin and Kuzmin (1962), Cowsik et al. (1963, and to be published) and Osborne et al. (1965). The general approach in all of these calculations has been to deduce the production spectrum of the parents of the muons from the observed energy spectrum of muons at sea level, and then to deduce the neutrino spectra from the production spectra of the parents of the muons. The neutrino intensities estimated by Zatsepin and Kuzmin (1962) were on the basis of pion and muon decays alone. In the papers of Cowsik et al. and Osborne et al. account has

been taken of the production of K mesons in high energy nuclear collisions; the intensities calculated by these two groups agree to better than 20%. The contribution from extraterrestrial neutrinos is considered later.

We have considered the following processes for evaluating the expected interaction cross sections:

(i) Elastic collisions:

$$\nu_\mu + N \rightarrow \mu + N. \quad (1)$$

(ii) Inelastic collisions:

$$\nu_\mu + N \rightarrow \mu + N + \pi\text{'s etc.} \quad (2)$$

(iii) Production of intermediate boson W:

$$\nu_\mu + P \rightarrow P + \mu + W \quad (\text{incoherent production}) \quad (3)$$

$$\nu_\mu + Z \rightarrow Z' + \mu + W \quad (\text{coherent production}) \quad (4)$$

$$\bar{\nu}_e + e^- \rightarrow W^- \quad (\text{Glashow resonance}). \quad (5)$$

In each of the reactions (3), (4) and (5), it is assumed that W decays within a very short time by a leptonic mode (into  $\mu$  or  $e$ ) or by a non-leptonic mode, i.e.

$$W \rightarrow \mu + \nu_\mu \quad (6)$$

$$W \rightarrow e + \nu_e \quad (7)$$

$$W \rightarrow \pi, K, Y \text{ etc.} \quad (8)$$

The cross section for process (1) has been taken to be  $0.75 \times 10^{-38}$  cm<sup>2</sup> per n-p pair, independent of neutrino energy for  $E_\nu \geq 1$  GeV (Block et al. 1964); it is assumed further that  $E_\mu \approx E_\nu$ . The CERN bubble chamber observations (Block et al. 1964) indicate that  $\sigma_{\text{inel}} = 0.45 \times 10^{-38} E_\nu$  cm<sup>2</sup>/nucleon over the range from one to several GeV. Since there are no data on the behaviour of  $\sigma_{\text{inel}}$  at higher energies we have considered two alternatives:

- (a)  $\sigma_{\text{inel}} = 0.45 \times 10^{-38} E_\nu$  in the range  $1 < E < 10$  GeV, and equal to  $0.45 \times 10^{-37}$  at  $E_\nu > 10$  GeV, i.e. the cross section is proportional to  $E_\nu$  up to 10 GeV, and then saturates.  
 (b)  $\sigma_{\text{inel}} = 0.45 \times 10^{-38} E_\nu$  at all energies.

It is further assumed that  $E_\mu = \frac{1}{2} E_\nu$  up to  $E_\nu = 10$  GeV and  $E_\mu = E_\nu$  above 10 GeV in case (a);  $E_\mu = \frac{1}{2} E_\nu$  at all energies in case (b).

The cross sections for the processes (3), (4) and (5) depend on the mass of the intermediate boson  $M_W$ . It is known from the CERN and Brookhaven experiments (Bernardini et al. 1964, Burns et al. 1965) that  $M_W > 1.8$  GeV. The W production cross section for both incoherent and coherent interactions used here is that given by Wu et al. (as quoted by Burns et al. 1965) up to  $E_\nu = 20$  GeV, together with the asymptotic expression of von Gehlen (1963) which is valid down to about 100 GeV. One may interpolate easily between these two energies. At energies near threshold, reaction (3) dominates over (4); at higher energies the situation is reversed. Process (5) contributes very little compared with (3) and (4), mainly because at the resonance energies ( $E_\nu \approx 1000 M_W^2$  GeV if  $M_W$  is in GeV) the  $\bar{\nu}_e$  fluxes are quite small. The flux of muons underground from this interaction has been calculated by Zagrebin and Zheleznykh (1964, preprint, Lebedev Institute, Moscow) and we apply their results to the Kolar Gold Field apparatus. By folding the cross sections for processes (3) and (4) into the energy spectrum of neutrinos, it can be seen that the maximum contribution to the counting rate comes from the interactions of neutrinos with energies around 100 GeV.

There is considerable uncertainty concerning the fractional energies carried by the prompt muon  $E_{\mu p}$  in reactions (3) and (4) and by the delayed muon  $E_{\mu d}$  resulting from the decay of the W meson in reaction (6). It may be pointed out that the counting rates are directly proportional to the effective target thicknesses, and these in turn are proportional to the energy the muon receives. It follows that the counting rates are proportional to the factor  $f$  given by

$$f = (E_{\mu p} + b E_{\mu d})/E_\nu$$

where  $b$  is the branching ratio of W decaying by the muon mode. For production of intermediate bosons by comparatively

low energy neutrinos the momentum transfer to the nucleon is large and the energy spectrum of prompt muons is strongly affected by the form factor of the nucleon. The spectrum is strongly peaked at

$$E_\nu M_\mu / (M_W + M_\mu)$$

corresponding to the minimum momentum transfer  $M_W^2/2 E_\nu$ . This is the situation which applies for  $M_W = 1.8$  GeV and  $E \sim 10$  GeV. For very high energies the asymptotic formula given by Lee et al. (1961) gives  $\bar{E}_\mu \sim \frac{1}{2} E_\nu$ ; von Gehlen (1963) indicates that the interaction cross sections correspond to the asymptotic formula only at energies greater than  $10^4$  GeV.

The median energy effective in our experiment is of the order of 100 GeV and the question we face is: what form of energy sharing between the prompt muon and W should be valid at these energies? There is no specific theoretical analysis of this problem at present. However, considering that  $M_W > 1.8$  GeV and that the interaction cross section corresponds to the asymptotic formula only above  $10^4$  GeV, the energy sharing should be closer to the lower limit, i.e.  $E_\mu \sim E_\nu/20$  for  $M_W = 2$  GeV.

We assume that the muon decay mode of the W has a branching ratio of 40%. According to Uberall (1964) the W is strongly polarized and the muon comes out predominantly backwards in the centre-of-mass system. If one accepts this then the delayed muon retains, on the average, a quarter of the boson energy. These considerations would lead to  $f \approx 0.15$  as a lower limit for  $M_W = 1.8$  GeV. The upper limit would be  $f \approx 0.55$ , on the basis of the asymptotic formula; the values calculated by Cowsik et al. (to be published) are based on this.

Contributions to the expected number of neutrino-induced muons by the various processes considered above for an exposure of 4700 m<sup>2</sup> day sterad have all been listed in table 3. Contributions arising from W-meson production are given for the energy sharing between the prompt  $\mu$  and W corresponding to the lower limiting case; these are marked A. The true values will be greater than this but are likely to be close to them. The maximum possible contributions corresponding to the asymptotic formula of Lee et al. are shown purely for comparison; these are marked B. Also shown in the table are the absolute lower limits to the predicted number (obtained by assuming that W does not exist and  $\sigma_{inel}$  saturates around 10 GeV), and the absolute upper limit obtained by assuming that  $\sigma_{inel}$  does not saturate,  $M_W \approx 1.8$  GeV and energy sharing is as given by the asymptotic formula. It is seen that the estimated number ( $\approx 5$ ) of  $\nu$ -induced muons lies in between these two limits.

On the basis of table 3 we draw the following conclusions:

- (i) If W does not exist, the theoretically predicted number of events is low compared with the experimentally estimated number.
- (ii) This would imply that either: (a) the fluxes derived by various authors are too low by a substantial extent or (b) that  $\sigma_{inel}$  increases with energy much faster than  $\sigma_{inel} \propto E_\nu$ . Since the evidence from the accelerator experiments is that  $\sigma_{inel}$  does not rise much faster than  $\sigma_{inel} \propto E_\nu$  up to  $E_\nu = 10$  GeV it would then be necessary for  $\sigma_{inel}$  to rise faster than  $E_\nu$  for  $E_\nu > 10$  GeV.
- (iii) A possible explanation of (ii) (b) above would be that intermediate bosons exist with masses not much greater than 1.8 GeV.

It is difficult to see how the flux calculations of neutrinos of terrestrial origin can be in great error, i.e. by a factor of two or more, unless hitherto unknown processes come into play. As far as extraterrestrial sources are concerned, the calculations (Greisen 1960) show that they are extremely small. This view is further confirmed by the observations on primary  $\gamma$  ray fluxes, which are genetically related to neutrino fluxes in the sense that both are derived from pion decays. There is of course the possibility that unknown processes exist wherein high energy neutrinos are produced, but not high energy  $\gamma$  rays, or that  $\gamma$  rays may have been attenuated by unexpectedly large

factors before arriving at the Earth. Light can be thrown on these points by studying the neutrino arrival directions in celestial coordinates; as yet, the observed number of events is too small to say if there is any dominant region in the sky from which the neutrinos could have come. Our plans in the immediate future include a study of these possibilities. Cowsik et al. (to be published) have also discussed some of these aspects.

Reines et al. (1965), from their deep mine neutrino experiment, have reported events attributable to the interactions of natural neutrinos in the surrounding rock. Their observed rate, namely  $0.6 \times 10^{-12}$  particles/cm<sup>2</sup> sec sterad compares reasonably with the rate we have reported here, namely  $1.2 \times 10^{-12}$ , which is within the statistical weights of the two observations.

### 5. Vertical intensity of atmospheric muons (at a depth of 7500 m w.e. of standard rock)

As discussed earlier in section 3, eight out of the thirteen observed events are due to atmospheric muons. Only five out of these eight are within the geometry. If the angular distribution of atmospheric muons at this depth is approximately taken to be  $I_\theta = I_0 \cos^n \theta$ , then the rate attributed to atmospheric muons divided by the aperture offered by the telescope for a radiation with  $n = 8$  yields a value for the vertical intensity  $I_\nu \approx 0.9 \times 10^{-10}$  particles/cm<sup>2</sup> sec sterad at the depth of our experiment, namely 7500 m w.e. of standard rock with  $Z^2/A = 5.5$ . This value is in reasonable agreement with the extrapolated value from the data hitherto available only up to a depth of 6930 m w.e. of standard rock (Menon and Ramana Murthy 1965).

### 6. Conclusions

Events which can be definitely shown to be due to the interactions of natural neutrinos in the rock surrounding the apparatus have been reported. Two events involving charged particles at large zenith angles have been seen and one can be fairly sure that these represent  $\nu$ -induced interactions. It is estimated that a further 2-4  $\nu$ -induced muons are contained amongst the events with projected zenith angles ranging from 29.5° to 48°. Based on an estimated five  $\nu$  events in 4700 m<sup>2</sup> day sterad, the muon flux resulting from neutrino collisions deep underground is derived as about  $1.2 \times 10^{-12}$  particles/cm<sup>2</sup> sec sterad. This rate, when interpreted in terms of the fluxes of neutrinos produced in the terrestrial atmosphere and the high energy behaviour of neutrino interaction cross sections suggests one (or more) of the following possibilities:

- (a) There are sources of high energy neutrinos (terrestrial or extraterrestrial) which yield fluxes comparable with (or greater than) the atmospheric fluxes which have been calculated from pion, muon and kaon decays.
- (b)  $\sigma_{inel}$  rises much faster than  $\sigma_{inel} \propto E_\nu$  at energies beyond several GeV.
- (c) A possible reason for (b) would be that W mesons exist with masses not very much greater than 1.8 GeV.

These results should be treated as tentative since this paper is only meant to be a status report on this experiment for this Conference. The statistical weight of the observations needs to be enhanced; towards this we are expanding the size of the array by a factor of 2. The great interest of the present observations is that we seem to be encountering new physical phenomena; an exact and definite interpretation is not possible at this stage; one would have to carefully evaluate various phenomena which could come into play at such depths. What is clear is that a continuation and enhancement of the experiment is of considerable value.

### References

- Achar, C. V., et al. 1965a, Proc. Phys. Soc., **86**, 1305.  
 — 1965b, Phys. Letters, **18**, 196-199.  
 — 1965c, Phys. Letters, **19**, 78-81.

- Bernardini, G., et al. 1964, Phys. Letters, **13**, 86-91.
- Block, M., et al., 1964, Phys. Letters, **12**, 281-285.
- Burns, R., et al., 1965, Phys. Rev. Letters, **15**, 42-45.
- Cowsik, R., Pal, Y., Rengarajan, T.N., and Tandon, S.N., 1963, Proc. Int. Conf. Cosmic Rays, Jaipur, 1963, **6**, 211-214.
- von Gehlen, G., 1963, Nuovo Cim., **30**, 859-877.
- Greisen, K., 1960, Proc. Int. Conf. for Instrumentation for High Energy Physics, Berkeley (New York: Interscience), p. 209.
- Lee, T. D., Markstein, P., and Yang, C. N., 1961, Phys. Rev. Letters, **7**, 429-433.
- Menon M. G. K., 1963, Proc. Int. Conf. Cosmic Rays, Jaipur, **6**, 152-181.
- Menon, M. G. K., and Ramana Murthy, P. V., 1965, Progress in Cosmic Ray and Elementary Particle Physics, Vol. 9 (Amsterdam: North Holland).
- Menon, M. G. K., Ramana Murthy, P. V., Sreekantan, B. V., and Miyake, S., 1963 a, Nuovo Cim., **30**, 1208-1219.
- 1963 b, Phys. Letters, **5**, 272-274.
- Miyake, S., Narasimham, V. S. Ramana Murthy, P. V., 1964, Nuovo Cim., **32**, 1505-1540.
- Osborne, J. L., Said, S. S., and Wolfendale, A. W., 1965, Proc. Phys. Soc., **86**, 93-99.
- Reines, F., et al., 1965, Phys. Rev. Letters, **15**, 429-433.
- Sreekantan, B. V., 1965, Proc. Informal Conf. on Experimental Neutrino Physics, CERN (Geneva: European Organization for Nuclear Research), in the press.
- Uberall, H., 1964, Phys. Rev., **133**, B444-453.
- Wolfendale, A. W., 1965, Proc. Informal Conf. on Experimental Neutrino Physics, CERN (Geneva: European Organization for Nuclear Research) in the press.
- Zatsepin, G. T., and Kuzmin, V. A., 1962, Soviet Physics—JETP, **14**, 1294-1299.

## Discussion

K. GREISEN. I wish to ask two questions about the computation of the expected neutrino flux: (i) is there considerable uncertainty owing to doubt about the role played by kaons in the neutrino production; and (ii) instead of using an isotropic neutrino distribution in sorting out the neutrino-induced events from those made by atmospheric muons, should one not have taken an angular distribution having a peak in the horizontal direction?

J. L. OSBORNE. The neutrino flux used in the calculations of predicted rates of neutrino-induced events assumes a  $K/\pi$  ratio of 20%. Calculations have been made, however (Osborne et al. 1965), of the variation of flux for  $K/\pi$  from 0 to 40%. It is found that the variation is smallest for large zenith angles and low energy. For energies and directions relevant to this experiment the uncertainty in the muon-neutrino flux caused by the uncertainty in the  $K/\pi$  ratio must be less than 20%.

To answer the second of Professor Greisen's questions, the calculated atmospheric neutrino flux is indeed slightly peaked towards the horizontal direction. The integral intensity of neutrino-induced muons is thus also peaked in this direction but the ratio of horizontal to vertical intensity is less than 2 (the exact value depends on the form of the cross section for the particular neutrino interaction). The predicted angular distribution is therefore only slightly different from that obtained assuming an isotropic neutrino flux. The allocation of the present events into atmospheric and neutrino-initiated categories is not altered if this weakly anisotropic flux is used.

J. C. BARTON. Could you please give more information about the 'out-of-geometry' events?

P. V. RAMANA MURTHY. In the three 'out-of-geometry' events which we have observed we find that the tracks, as seen in the neon flash tube arrays, when extrapolated do not pass through one of the scintillator walls. A fourfold coincidence from the two scintillator walls is necessary to satisfy the triggering interior and it is assumed that normally this is due to the same particles traversing both the walls. In the 'out-of-geometry' events we do see pulses from the scintillator walls on the oscilloscopes though tracks apparently do not pass through them. This is presumably due to the soft component generated by the muon in the rock entering the scintillator wall. Indeed, in two of the cases, we see in the flash tube photographs evidence for the electron component associated with the muons.

P. H. FOWLER. I would like to know how you estimate that the maximum contribution to the counting rate in your experiment is due to neutrinos with energies around 100 GeV.

Y. PAL. The effective neutrino energy is close to 100 GeV only when one is considering the production of intermediate bosons of mass around 2 GeV. In other words the product of the cross section and the flux has a maximum at about this energy. If there is no boson and one is considering only energy-dependence of the cross section, the effective energy is much lower.

A. W. WOLFENDALE. It is important to point out that if we divide the tracks seen according as  $\theta$  greater or less than  $45^\circ$  then of the former only one out of five is associated with an electron. On the other hand, for  $\theta < 45^\circ$ , three out of four of the particles are associated with electron showers. These facts add weight to the identification of particles: particles near the vertical are ultra-high energy muons and the others are lower energy muons due, presumably, to neutrino interactions.

G. D. ROCHESTER. Have you any results on the azimuthal distribution of the neutrino events?

M. G. K. MENON. We have an accuracy to about  $\pm 1^\circ$  in zenith angle determination with the flash tube arrays; at present we have only horizontal flash tubes. As regards azimuth, we have no information from the flash tubes. Here we have only very

crude estimates obtained from the 'scintillator elements'. To remedy this situation and to ensure that on every event we can have reliable zenith as well as azimuth angle determinations, our next development, in addition to an expansion of the array, is to include in each telescope two vertical columns of neon flash tubes. We have, however, even now a very crude plot of the events seen on the celestial sphere but I would urge the greatest caution in interpreting this.

J. B. M. PATTISON. The six  $\nu$  events are distributed in sidereal time as follows: one, 0-1 hours; one, 6-7 hours; two, 8-9 hours; and two, 11-12 hours. There are no events between 12-24 hours.

S. A. COLGATE. Have you calculated the theoretically expected number of electron-neutrino events?

J. L. OSBORNE. Because the effective target thickness of rock for electron events is restricted to a few radiation lengths the predicted rate of these events is much smaller than that of muon events. Approximate calculations give rates for each type of interaction below 1% of the corresponding muon rate.

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

## Ultra-high energy muons (> 200 GeV) in extensive air showers

B. K. CHATTERJEE, S. LAL, T. MATANO,\* G. T. MURTHY, S. NARANAN, K. SIVAPRASAD,  
 D. V. SREEKANTAN, M. V. SRINIVASA RAO and P. R. VISHWANATH.

Tata Institute of Fundamental Research, Bombay, India

**Abstract.** The absolute number of muons of energy above 220 GeV and above 640 GeV have been estimated in showers of size  $10^5$ - $10^6$  (primary energy  $10^{15}$ - $10^{16}$  eV), using a large air shower array on the surface and muon detectors deep underground in the Kolar Gold Mines, India ( $11^\circ\text{N}$ ,  $920 \text{ g cm}^{-2}$ ). The number of muons may be expressed as

$$n_\mu(N, > E_\mu) = 1.6 \times 10^5 \left(\frac{N}{10^5}\right)^{0.47 \pm 0.1} E_\mu^{-1.5 \pm 0.1}.$$

The implications, in particular the slow increase of  $n_\mu$  with size, with reference to the multiplicity of pions in nuclear collisions are discussed. The frequency of multiple muons is consistent with a mean production height of 10 km with  $\langle p_T \rangle = 0.4$ - $0.6 \text{ GeV}/c$ . The distribution of arrival directions of showers with high energy muons in right ascension shows no deviation from a uniform distribution.

### 1. Experimental arrangement

The basic aim of the experiment is to study pion production (multiplicity, energy spectrum etc.) in high energy nucleon collisions in the energy range  $10^{14}$ - $10^{17}$  eV; such information can be obtained at present only from a study of high energy muons in extensive air showers. Various other aspects of such a study, including some astrophysical aspects, were discussed at the Jaipur conference by Sreekantan (1963).

\* Permanent address: Institute of Nuclear Study, Tokyo University, Tokyo, Japan.

The apparatus consists of: (i) the air shower array on the surface and (ii) the muon detectors deep underground.

(i) The air shower array (figure 1) consists of 20 plastic scintillators, each of area  $1 \text{ m}^2$ ; 19 are laid out in concentric circles up to a maximum radius of 100 m and one is located 200 m from the centre. An air shower is recorded only if a minimum of two particles are registered in any four of the 19 scintillators. Particle densities are converted to a logarithmic scale and recorded digitally on paper tape (figure 2).

(ii) The muon detectors are located at two depths, 270 m ( $U_1$ ) and 600 m ( $U_2$ ) (figure 1). There are four plastic scintillators,

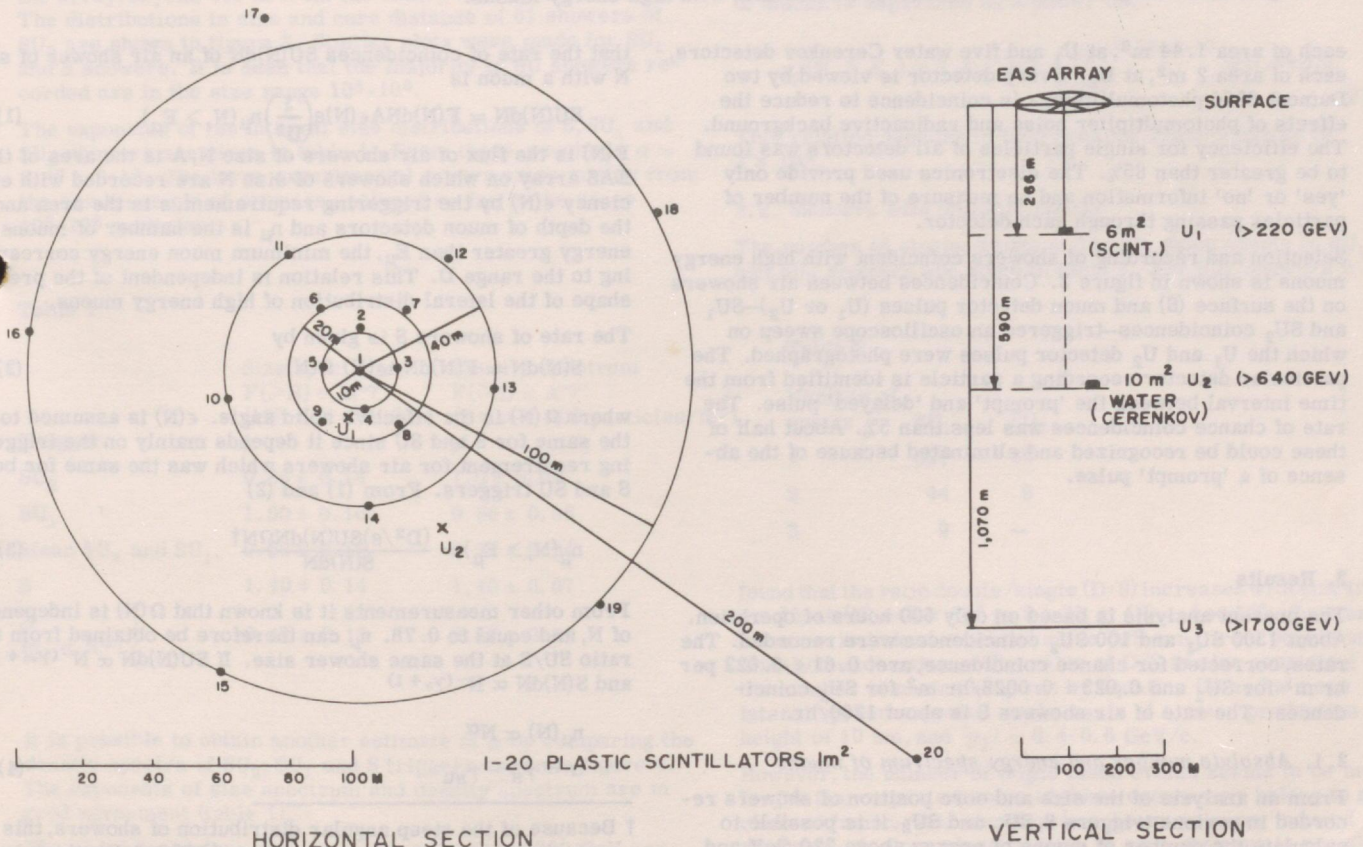


Fig. 1 The extensive air shower array in the Kolar Gold Mines.

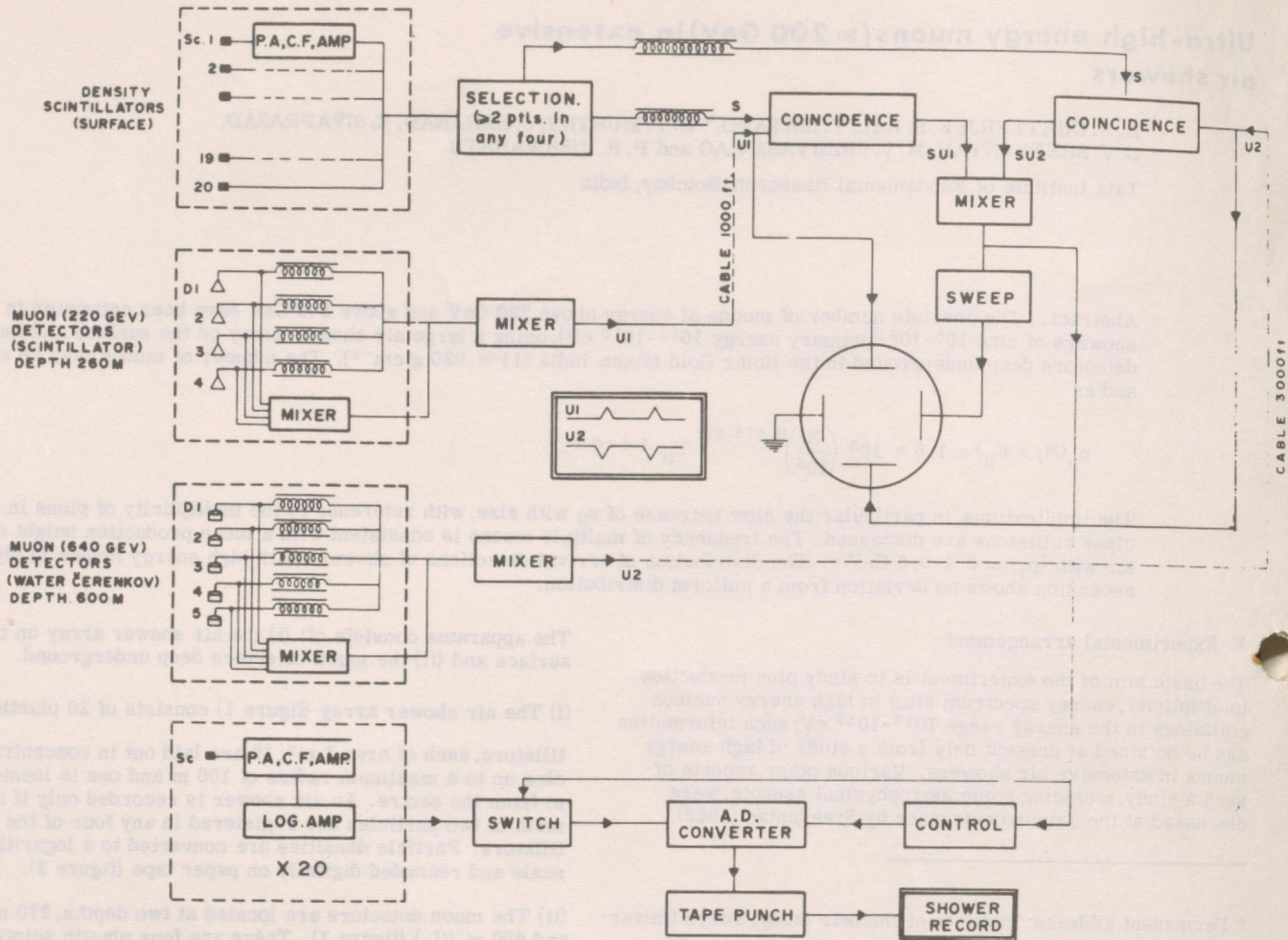


Fig. 2 Recording of extensive air showers coincident with high energy muons.

each of area  $1.44 \text{ m}^2$ , at  $U_1$  and five water Čerenkov detectors, each of area  $2 \text{ m}^2$ , at  $U_2$ . Every detector is viewed by two Dumont 6364 photomultipliers in coincidence to reduce the effects of photomultiplier noise and radioactive background. The efficiency for single particles of all detectors was found to be greater than 85%. The electronics used provide only 'yes' or 'no' information and no measure of the number of particles passing through each detector.

Selection and recording of showers coincident with high energy muons is shown in figure 2. Coincidences between air showers on the surface (S) and muon detector pulses ( $U_1$  or  $U_2$ )— $SU_1$  and  $SU_2$  coincidences—triggered an oscilloscope sweep on which the  $U_1$  and  $U_2$  detector pulses were photographed. The particular detector recording a particle is identified from the time interval between the 'prompt' and 'delayed' pulse. The rate of chance coincidences was less than 5%. About half of these could be recognized and eliminated because of the absence of a 'prompt' pulse.

## 2. Results

The present analysis is based on only 500 hours of operation. About 1300  $SU_1$  and 100  $SU_2$  coincidences were recorded. The rates, corrected for chance coincidence, are:  $0.61 \pm 0.022$  per hr  $\text{m}^2$  for  $SU_1$  and  $0.023 \pm 0.0023$ /hr  $\text{m}^2$  for  $SU_2$  coincidences. The rate of air showers S is about 1200/hr.

### 2.1. Absolute number and energy spectrum of muons

From an analysis of the size and core position of showers recorded in various triggers S,  $SU_1$  and  $SU_2$ , it is possible to calculate the number of muons of energy above 220 GeV and above 640 GeV per shower of a given size. It can be shown

that the rate of coincidences  $SU(N)dN$  of an air shower of size N with a muon is

$$SU(N)dN = F(N)dN A \epsilon(N) s \left(\frac{1}{D^2}\right) n_\mu(N, > E_\mu). \quad (1)$$

$F(N)$  is the flux of air showers of size N, A is the area of the EAS array on which showers of size N are recorded with efficiency  $\epsilon(N)$  by the triggering requirement, s is the area and D the depth of muon detectors and  $n_\mu$  is the number of muons of energy greater than  $E_\mu$ , the minimum muon energy corresponding to the range D. This relation is independent of the precise shape of the lateral distribution of high energy muons.

The rate of showers S is given by

$$S(N)dN = F(N)dN A \epsilon(N) \Omega(N) \quad (2)$$

where  $\Omega(N)$  is the effective solid angle.  $\epsilon(N)$  is assumed to be the same for S and SU since it depends mainly on the triggering requirement for air showers which was the same for both S and SU triggers. From (1) and (2)

$$n_\mu(N, > E_\mu) = \frac{(D^2/s)SU(N)dN\Omega(N)\dagger}{S(N)dN} \quad (3)$$

From other measurements it is known that  $\Omega(N)$  is independent of N, and equal to 0.78.  $n_\mu$  can therefore be obtained from the ratio  $SU/S$  at the same shower size. If  $SU(N)dN \propto N^{-(\gamma_{su}+1)dN}$  and  $S(N)dN \propto N^{-(\gamma_s+1)}$

$$\begin{aligned} n_\mu(N) &\propto N^\alpha \\ \alpha &= \gamma_s - \gamma_{su} \end{aligned} \quad (4)$$

† Because of the steep angular distribution of showers, this expression needs a correction for  $n_\mu (> 220 \text{ GeV})$  which has been applied. The correction is negligible for  $n_\mu (> 640 \text{ GeV})$ .

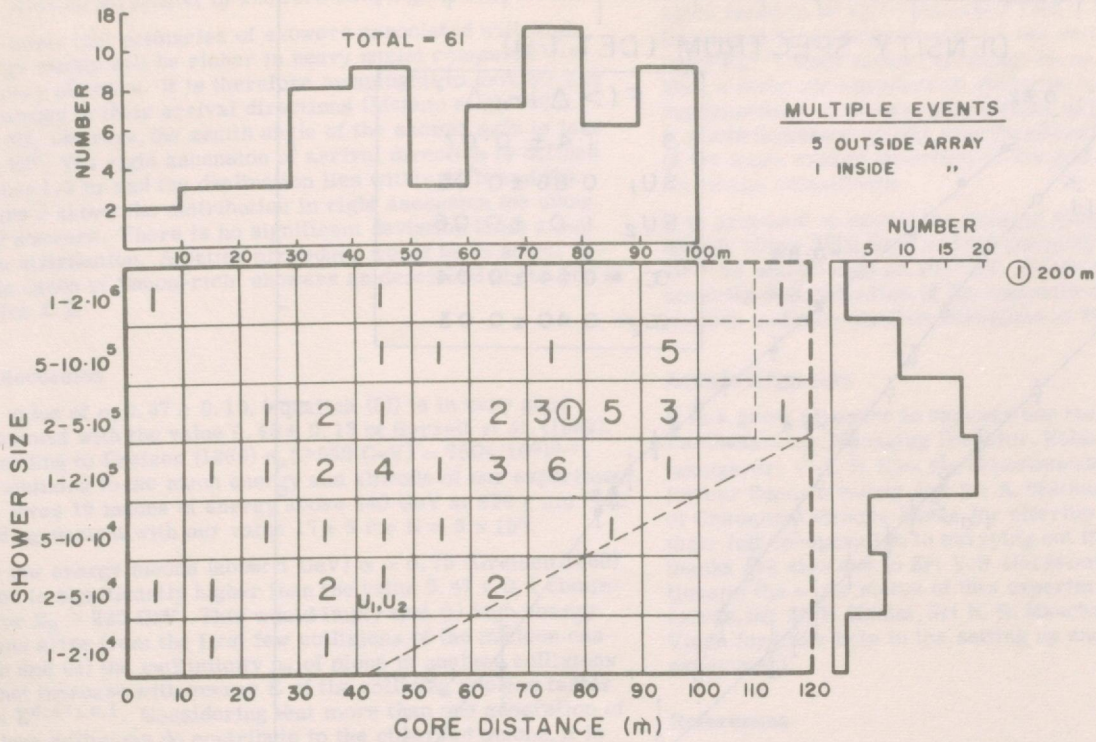


Fig. 3 Distributions in shower size and core distance of  $SU_2$  showers.

All the  $SU_2$  showers (100), 175 showers of  $SU_1$  and 400 of S triggers have been analysed so far for size and core location. The particle densities are fitted to the lateral structure function given by Greisen (1960) graphically. Further analysis will be carried out with the electronic computer CDC 3600.

About 30% of  $SU_2$  and 20% of  $SU_1$  and S showers fell outside the array, beyond 100 m from the centre and were discarded. The distributions in size and core distance of 61 showers of  $SU_2$  are shown in figure 3. Similar plots were made for  $SU_1$  and S showers. It is seen that the majority of SU showers recorded are in the size range  $10^5$ - $10^6$ .

The exponents of the integral size distributions of S,  $SU_1$  and  $SU_2$  showers are given in table 1. From these, we obtain  $\alpha = 0.47 \pm 0.16$ . The large experimental errors arise mainly from the small sample of showers analysed so far in the range  $10^5$ - $10^6$  particles.

Table 1

Trigger	Size spectrum $F(>N) \propto N^{-\gamma}$ ( $10^5 < N < 10^6$ )	Density spectrum $F(>\Delta) \propto \Delta^{-\gamma'}$ ( $2 < \Delta < 100$ particles/m <sup>2</sup> )
$SU_2$	$0.86 \pm 0.14$	$1.0 \pm 0.04$
$SU_1$	$1.00 \pm 0.10$	$0.86 \pm 0.05$
Mean $SU_2$ and $SU_1$	$0.93 \pm 0.12$	$0.93 \pm 0.04$
S	$1.40 \pm 0.14$	$1.40 \pm 0.07$
$\alpha$ ( $n_\mu \propto N^\alpha$ )	$0.47 \pm 0.16$	$0.47 \pm 0.08$

It is possible to obtain another estimate of  $\alpha$  by comparing the density spectra of  $SU_2$ ,  $SU_1$  and S triggers shown in figure 4. The exponents of size spectrum and density spectrum are in good agreement (table 1).

The absolute number of muons of energy above 220 GeV and energy above 640 GeV can be expressed as

$$n_\mu(>220 \text{ GeV}) = 50 \left( \frac{N}{10^5} \right)^\alpha$$

$$n_\mu(>640 \text{ GeV}) = 10 \left( \frac{N}{10^5} \right)^\alpha$$

where  $10^5 < N < 10^6$  and  $\alpha = 0.47 \pm 0.10$ . The experimental error for  $n_\mu$  is about 30%. If the integral energy spectrum of muons is expressed as a power law

$$n_\mu(N, > E_\mu) = 1.6 \times 10^5 \left( \frac{N}{10^5} \right)^{0.47 \pm 0.10} E^{-1.5 \pm 0.1}$$

This relation appears to hold even for lower sizes up to  $2 \times 10^4$ .

### 2.2. Showers with multiple muons

The number of single, double and triple muon events in  $SU_1$  and  $SU_2$  showers are given in table 2. For  $SU_1$  showers it is

Table 2

Number of muons	$SU_1$	$SU_2$
1	621	60
2	44	6
3	9	—

found that the ratio double/single (D/S) increases with size from  $4 \pm 1\%$  at  $\langle N \rangle = 5 \times 10^4$  to  $8 \pm 2\%$  at  $\langle N \rangle = 5 \times 10^5$ . Such an increase is indeed expected since  $D/S \propto n_\mu$  from purely statistical considerations. The value of D/S is also consistent with the number of muons as given by equation (5) and a mean lateral spread expected on the basis of a mean production height of 10 km, and  $\langle p_T \rangle = 0.4$ - $0.6$  GeV/c.

However, the number of triple muon events seems to be much larger than expected; some of these events may belong to a class of 'muon-rich' showers (e.g. heavy primary induced showers). A clear classification of such showers is possible with more data.

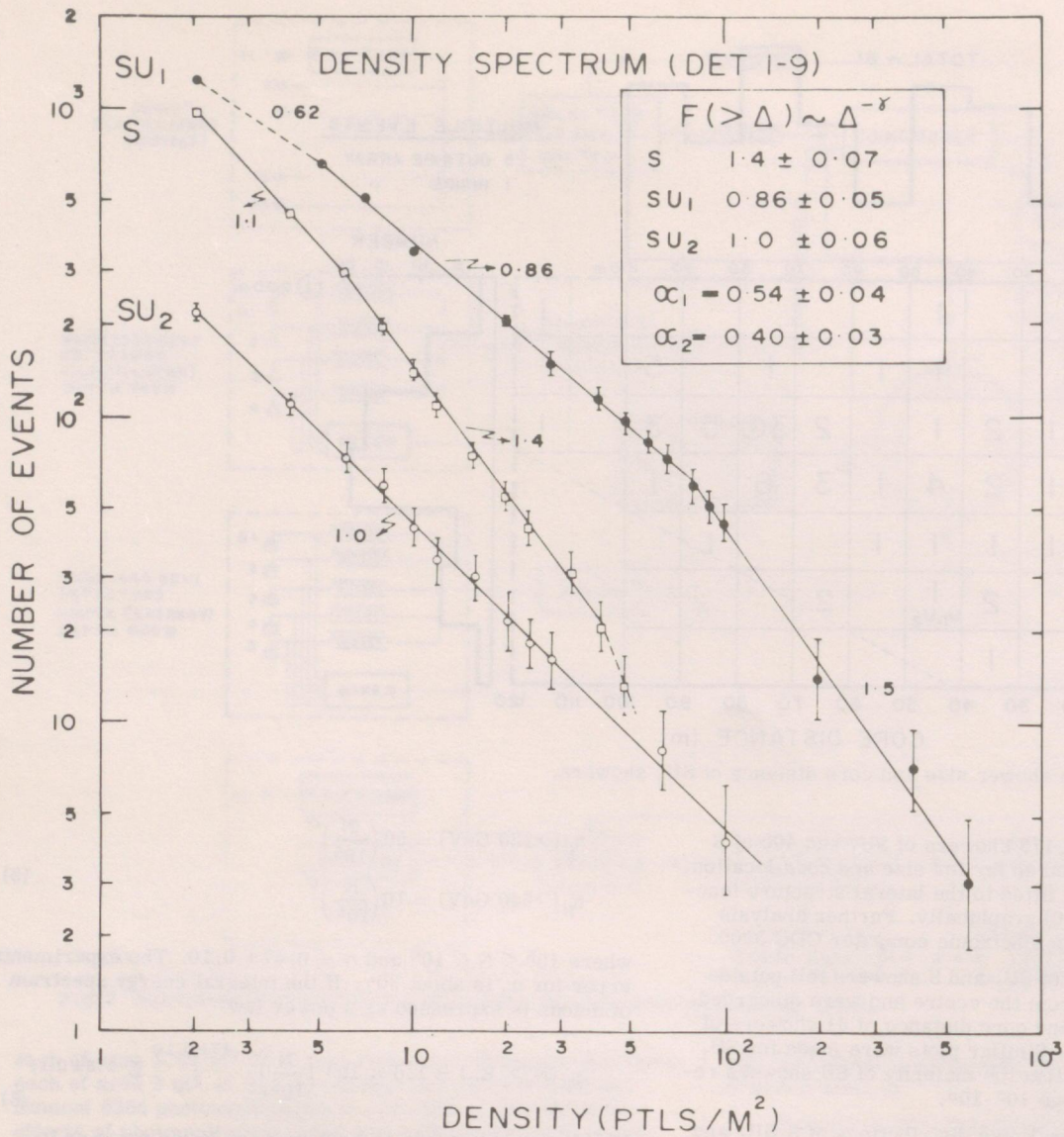


Fig. 4 Density spectrum of showers recorded in triggers S, SU<sub>1</sub> and SU<sub>2</sub>.

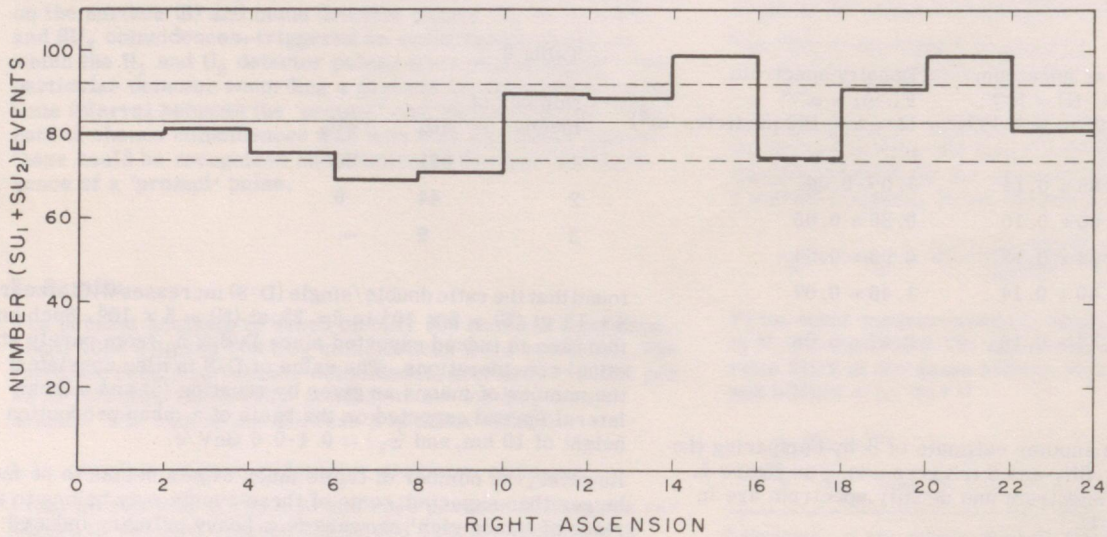


Fig. 5 Distribution in right ascension of the directions of showers with high energy muons.

### 2.3. Arrival directions of showers with high energy muons

It is likely that primaries of showers associated with high energy muons will be richer in heavy nuclei compared with ordinary showers. It is therefore meaningful to look for any anisotropy in their arrival directions (Matano et al. 1963). For  $SU_1$  showers, the zenith angle of the shower axis is less than  $20^\circ$ . The right ascension of arrival direction is defined within  $\pm 1.3$  hr and the declination lies within  $31^\circ N$  and  $9^\circ S$ . Figure 5 shows the distribution in right ascension for about 1000 showers. There is no significant deviation from a uniform distribution. A better procedure would be to select definite cases of 'muon-rich' showers as described at the end of section 2.2.

### 3. Discussion

Our value of  $\alpha$ ,  $0.47 \pm 0.10$ , (equation (5)) is in very good agreement with the value  $0.45 \pm 0.13$  of Barrett et al. (1952). According to Greisen (1960)  $n_\mu (>560 \text{ GeV}) = 75(N/10^6)^{0.7}$ . Normalizing to the muon energy and altitude of our experiment, this gives 19 muons of energy above 640 GeV at  $920 \text{ g cm}^{-2}$  in good agreement with our value  $17 \pm 3$  for  $N = 3 \times 10^5$ .

For low energy muons (about 1 GeV)  $\alpha = 0.75$  (Greisen 1960) which is significantly higher than the value  $0.47 \pm 0.1$  obtained for  $E_\mu > 220 \text{ GeV}$ . This would imply that (i) high energy muons arise from the first few collisions of the nucleon cascade and (ii) the multiplicity  $n_\pi$  of pions in nuclear collisions cannot increase with energy  $E$  of the colliding nucleon faster than  $E^{0.47 \pm 0.1}$ . Considering that more than one generation of nuclear collisions do contribute to the observed muons, it is probable that the actual variation is slower, viz.  $n_\pi \propto E^{0.25}$ . It is possible to explain the observed energy spectrum and variation with size of high energy muons by such a multiplicity law.

The integral energy spectrum of muons above 220 GeV is  $E_\mu^{-1.5}$ . The integral spectrum of the parent pions (above 300 GeV) is therefore  $E_\pi^{-0.5}$  after allowing for  $\pi \rightarrow \mu$  decay probability which is proportional to  $1/E_\pi$  at these energies. For

low energy muons (about 1-20 GeV), the integral spectrum is again found to be  $E_\mu^{-1.4}$  (Greisen 1960). However, in this case the parent pion spectrum will be the same as the muon spectrum  $E_\pi^{-1.4}$  since almost all pions decay at these low energies. Such a steep pion production spectrum would result from the superposition of several generations of pions in the cascade. It would therefore appear that the observed constant exponent of the muon energy spectrum at low and high energies is a fortuitous coincidence.

It is proposed to extend the present measurements to muons of energy above 2000 GeV, and for primary energies as low as  $10^{14}$  eV and as high as  $10^{17}$  eV. These would enable a more accurate determination of the characteristics of nucleon-nucleon and pion-nucleon collisions at high energies.

### Acknowledgments

It is a great pleasure to express our thanks to Sri M. H. Parthasarathy, Managing Director, Kolar Gold Mines Undertakings, Sri V. V. R. Rao, the Superintendent, Mr. A. Cave, the former Superintendent and Sri A. Seetharam, Chief Engineer of Champion/Mysore Mines for offering all the facilities and their full co-operation in carrying out these experiments. Our thanks are also due to Sri V. S. Narasimham for his contributions in the early stages of this experiment and to Sri F. Gon-salves, Sri M. P. Kamat, Sri N. R. Manchanda and Sri A. M. Vinze for their help in the setting up and daily operation of the experiment.

### References

- Barrett, P. H., Bollinger, L. M., Cocconi, G., Eisenberg, Y. and Greisen, K., 1952, *Rev. Mod. Phys.* **24**, 133-178.
- Greisen, K., 1960, *Ann. Rev. Nucl. Sci.*, **10**, 63-107.
- Matano, T., et al., 1963, *Proc. Int. Conf. Cosmic Rays, Jaipur*, **4**, 129-136, 248-251.
- Sreekantan, B. V., 1963, *Proc. Int. Conf. Cosmic Rays, Jaipur*, **4**, 143-167.

### Discussion

K. SUGA. Could you tell me what is the criterion for muon-rich air showers?

S. NARANAN. We have plotted the distribution in right ascension for all showers associated with at least one high energy muon of energy above 220 GeV. Primaries responsible for such showers are likely to have a larger proportion of heavy nuclei than ordinary showers, since  $\alpha = 0.47$ .

Similar plots for showers with at least one muon of energy greater than 640 GeV (100 events) and showers with 2 or more muons of energy above 220 GeV (60 events) also showed no departures from isotropy within the limited statistics available.

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

## Properties of extensive air showers rich in muons

B. K. CHATTERJEE, G. T. MURTHY, S. NARANAN, B. V. SREEKANTAN, M. V. SRINIVASA RAO and S. C. TONWAR

Tata Institute of Fundamental Research, Bombay, India

**Abstract.** The properties of extensive air showers selected by the fourfold coincidence of four muon detectors mutually separated by about 20 m without any restriction on the associated electron component have been studied at mountain altitude. It is found that the zenith angle distribution of mu triggered showers is very flat compared with the showers selected by requirements of electron density, particularly at sizes lower than  $10^6$ , indicating that the showers selected by mu trigger are relatively rich in muons.

A plot of the arrival direction of showers in celestial coordinates does not reveal any marked anisotropies in either the electron triggered or mu triggered showers in the size range  $10^5$ - $10^6$ . This is also true of higher sizes.

A study of the variation of the energy flow in the soft component and in the nuclear active component close to the core reveals that in showers of size less than  $10^6$  the energy flow in both the components is much lower in mu triggered showers than in electron triggered showers. This difference is more conspicuous in the case of the N component.

As stated elsewhere (Chatterjee et al. 1965) one of the selection criteria for recording air showers with the array in operation at Ootacamund was the simultaneous passage of at least one muon through each of the 4 muon detectors (each of area  $1 \text{ m}^2$ ) mutually separated by about 20 m (see figure 2 in paper EAS 38). This selection criterion imposed no restrictions whatsoever on the associated electron component and was therefore specially suited for recording showers that were relatively rich in muons.

The fourfold coincidence rate was about 4 per hour. A total of 2500 showers was recorded in an effective operation period of 600 hours.

The zenith angle distributions of showers of various size selected by the mu trigger have been compared in figure 1 with the zenith angle distributions for showers selected by the electron trigger. For this purpose only those mu triggered showers which lie within the 100% areas of electron triggered showers for the various sizes were considered. It is seen that at sizes less than  $10^6$  the zenith angle distribution of mu triggered showers is very flat compared with that of electron triggered showers. At a shower size of about  $10^5$  the average muon density at the mu detectors is such that an individual muon detector is triggered once in about 5 showers. Therefore the fourfold coincidence rate due to fluctuations in density is expected to occur in about 0.5% of the showers selec-

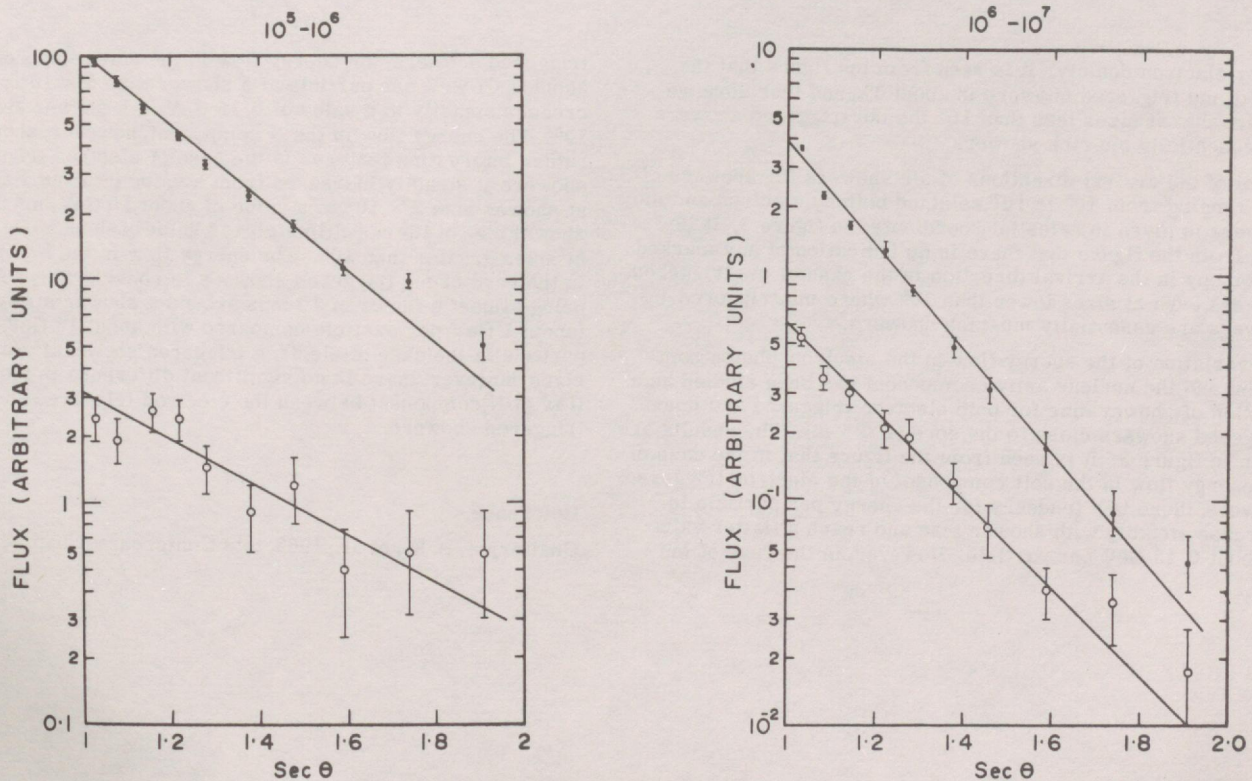


Fig. 1 Comparison of zenith angle distributions of muon triggered and electron triggered showers.

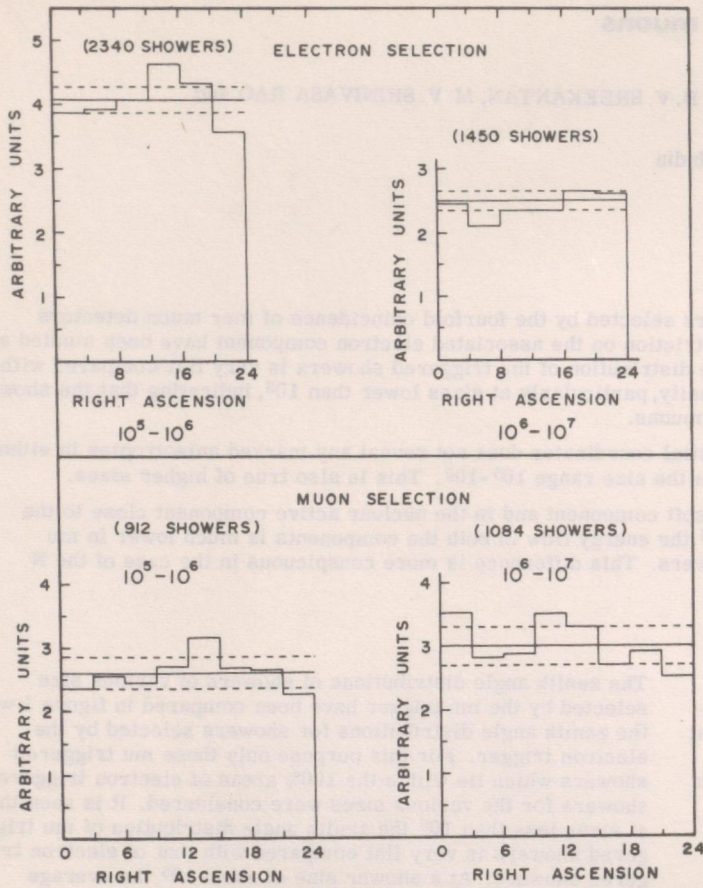


Fig. 2 A plot of arrival directions in celestial coordinates of air showers of size  $10^5$ - $10^7$  particles selected by both electron and mu triggers.

ted by electron density. It is seen from the figure that the rate of mu triggered showers is about 3%, and therefore we believe that at sizes less than  $10^6$  the mu triggered showers are essentially mu rich showers.

A plot of the arrival directions of air showers for showers of size ranging from  $10^5$  to  $10^7$  selected both by electron and mu triggers is given in celestial coordinates in figure 2. It is seen from the figure that there is no indication of any marked anisotropy in the arrival direction in the case of mu triggered showers even at sizes lower than  $10^6$  where mu triggered showers are essentially mu-rich showers.

The variation of the energy flow in the electron-photon component and the nuclear active component has been studied as a function of shower size for both electron triggered and muon triggered showers close to the core ( $r < 5$  m). The results are given in figure 3. It is seen from the figure that in the case of the energy flow in the soft component of the electron triggered showers, there is a tendency for the energy per particle to decrease steadily with shower size and reach a flatter value of about 0.15 GeV per particle. However, in the case of mu

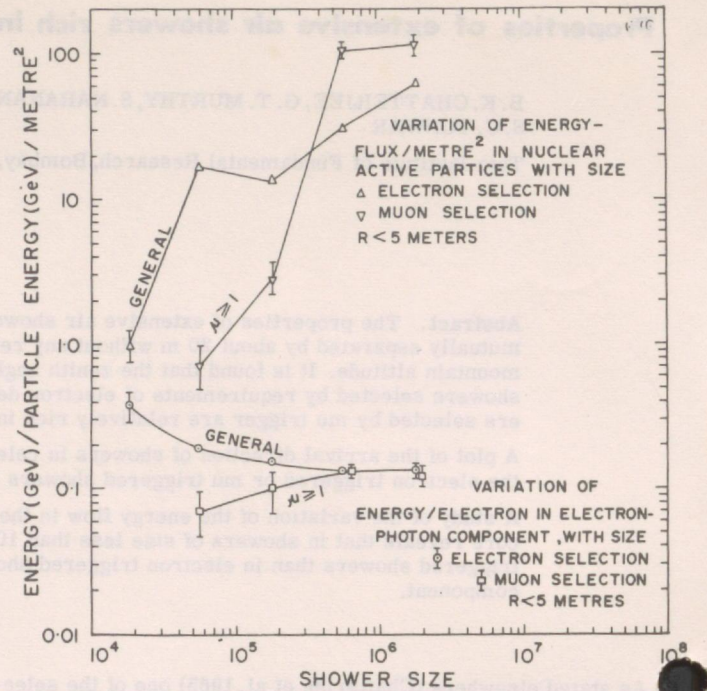


Fig. 3 Variation of the energy flow in the electron-photon component and nuclear active component with size for electron and mu triggered showers.

triggered showers, the energy flow in the soft component is about 0.07 GeV per particle at a shower size  $5 \times 10^4$  and increases steadily to a value of 0.15 GeV at a shower size of  $10^6$ . The energy flow in the N component, however, shows a rather interesting feature. In the case of electron triggered showers it steadily increases from a value of about 1 GeV/m<sup>2</sup> at shower size  $2 \times 10^4$  to a value of about 10 GeV/m<sup>2</sup> at a shower size of  $10^5$  and ultimately to a value of about 50 GeV/m<sup>2</sup> at sizes greater than  $10^6$ . The energy flow in the N component in the case of mu triggered showers is considerably lower being almost a factor of 10 less around a shower size of  $10^5$  (about 1 GeV per particle compared with about 15 GeV per particle in the case of electron triggered showers). At high sizes, however, there is no significant difference in the energy flow of N component between the electron triggered and mu triggered showers.

Reference

Chatterjee, B. K., et al., 1965, this Conference, Chap. 8, EAS 38.

*Reprinted from*

**THE PROCEEDINGS OF  
THE NINTH INTERNATIONAL CONFERENCE  
ON COSMIC RAYS**

LONDON, 1965

### Correlations between the electron, muon and N components in extensive air showers

B. K. CHATTERJEE, G. T. MURTHY, S. NARANAN, B. V. SREEKANTAN, M. V. SRINIVASA RAO, S. C. TONWAR and R. H. VATCHÁ

Tata Institute of Fundamental Research, Bombay, India

**Abstract.** With the air shower array at Ootacamund (altitude 2.2 km) the energy spectrum of high energy N particles above 50 GeV has been determined for showers of size ranging from a few times  $10^4$  to  $10^7$  particles and classified according to shower size and steepness of the electron lateral distribution. It is found that the number of high energy N particles within 10 m is significantly less in showers which have a flat electron lateral distribution than steep showers of the same size (strong correlations in the lateral distributions of N particles, muons and electrons have been reported earlier). It is also found that the variation of the total number of N particles with size may be expressed as  $N_n \propto N^m$  where m has a value of about 0.7. The low energy N component and muon component also have a similar dependence on shower size.

#### 1. Introduction

At the Jaipur Conference in 1963 we presented experimental results from our air shower array at Ootacamund on the fluctuations in the lateral distributions of electrons, muons and N particles in showers of size  $10^4$ - $10^7$  particles and emphasized the close correlations that exist between the lateral distributions of the various components (Sreekantan 1964, Chatterjee et al. 1964). The main results presented which are relevant to the present investigation may be summarized as follows:

(i) The lateral distribution of electrons in showers of size  $10^4$ - $10^7$  in the distance range 5-50 m can be fitted very well by an empirical formula of the type

$$\Delta(r) = C(\alpha_e) r^{-\alpha_e} \exp\left(-\frac{r}{r_0}\right)$$

where  $\alpha_e$  is a parameter which indicates the steepness of the lateral distribution and  $r_0$  has a value of 107 m at  $800 \text{ g cm}^{-2}$

(ii) At any given size  $\alpha_e$  has a spectrum of values.

(iii) The lateral distributions of low energy N component and muon component may be expressed by relations of the type  $r^{-\alpha_n}$  and  $r^{-\alpha_\mu}$  with  $\alpha_n$  and  $\alpha_\mu$  varying from 1 to 1.8.

(iv)  $\bar{\alpha}_n$  and  $\bar{\alpha}_\mu$  steadily increase with size.

(v) At sizes less than about  $10^6$ , showers which have a flat electron lateral distribution (low  $\alpha_e$ ) have a flat lateral distribution of N particles and muons, and similarly showers which have a steep electron lateral distribution have a steep lateral distribution of N particles and muons.

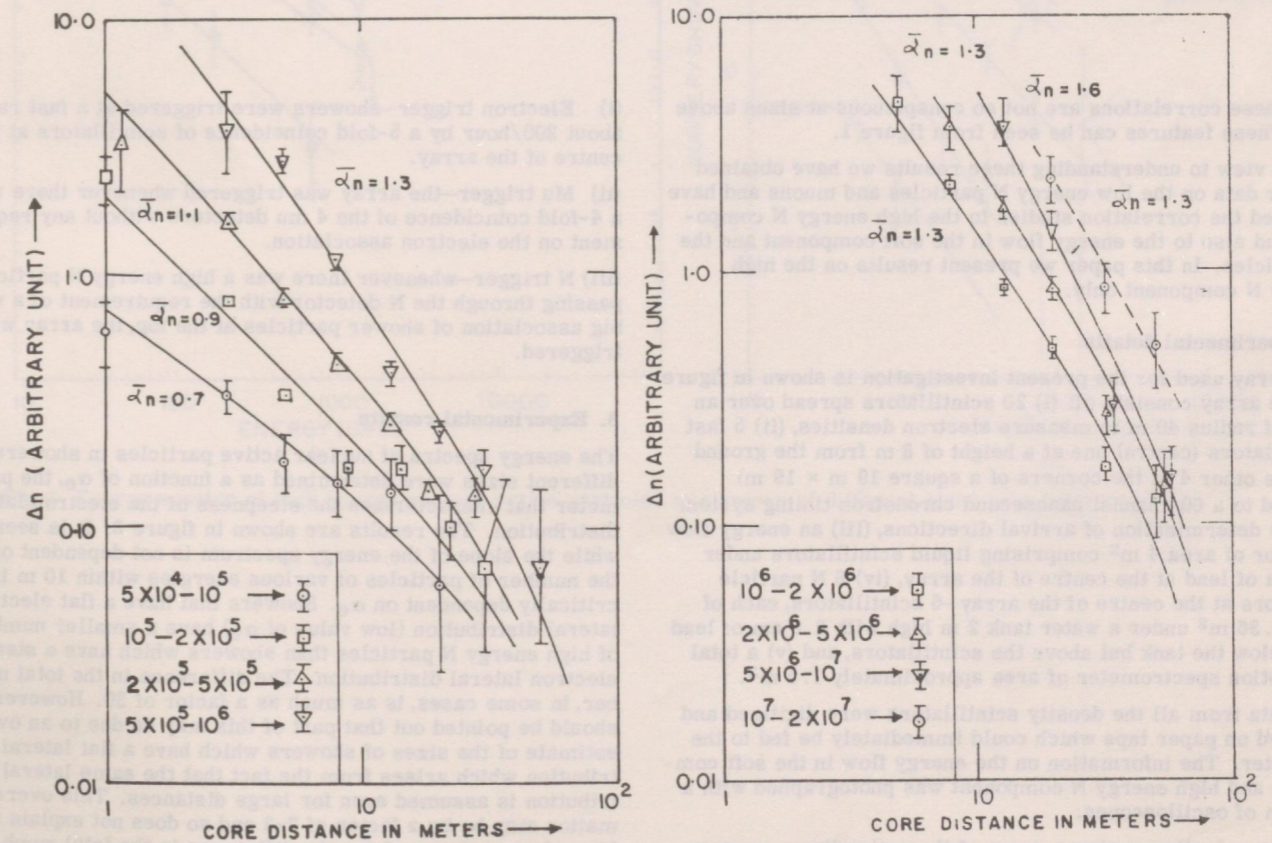


Fig. 1 Average lateral distribution of N particles in showers of various size.

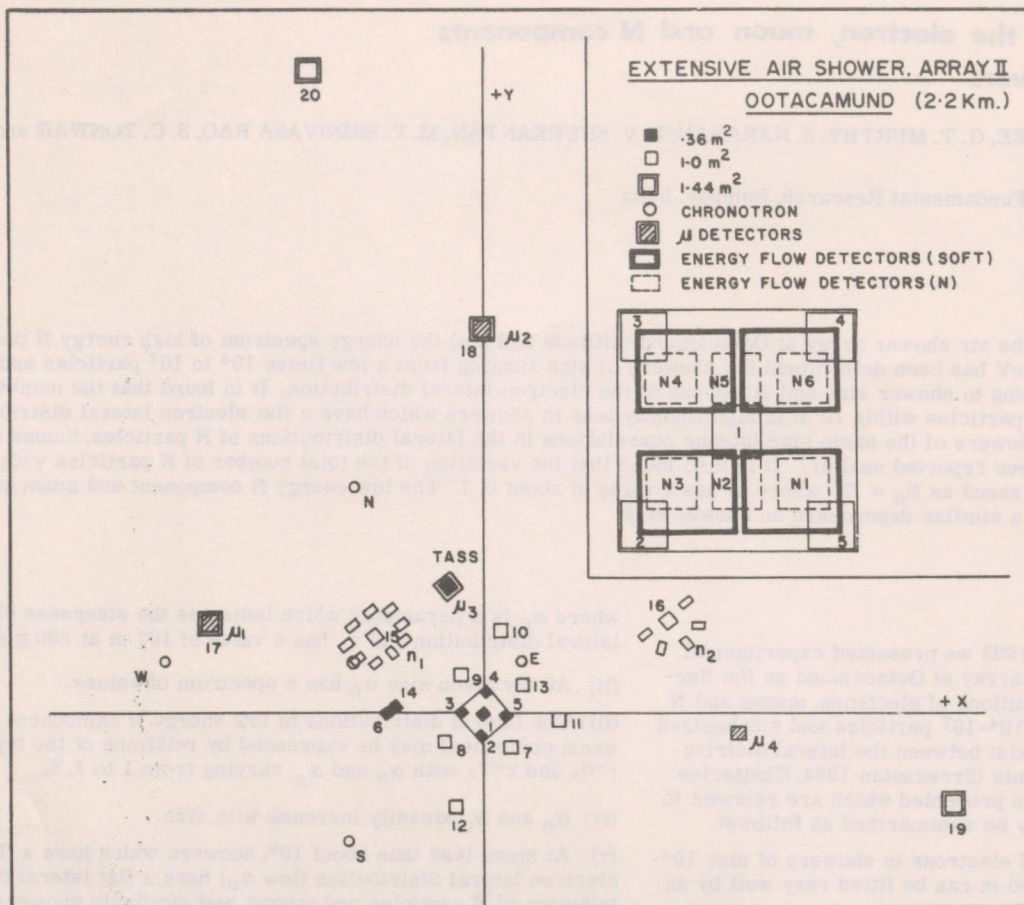


Fig. 2 The extensive air shower array at Ootacamund.

(vi) These correlations are not so conspicuous at sizes above  $10^6$ . These features can be seen from figure 1.

With a view to understanding these results we have obtained further data on the low energy N particles and muons and have extended the correlation studies to the high energy N component and also to the energy flow in the soft component and the N particles. In this paper we present results on the high energy N component only.

## 2. Experimental details

The array used for the present investigation is shown in figure 2. The array consists of: (i) 20 scintillators spread over an area of radius 40 m to measure electron densities, (ii) 5 fast scintillators (central one at a height of 8 m from the ground and the other 4 at the corners of a square  $19\text{ m} \times 19\text{ m}$ ) coupled to a 60 channel nanosecond chronotron timing system for the determination of arrival directions, (iii) an energy flow detector of area  $4\text{ m}^2$  comprising liquid scintillators under 2.5 cm of lead at the centre of the array, (iv) 6 N particle detectors at the centre of the array—6 scintillators, each of area  $0.36\text{ m}^2$  under a water tank 2 m high with 2.5 cm of lead just below the tank but above the scintillators, and (v) a total absorption spectrometer of area approximately  $1.5\text{ m}^2$ .

The data from all the density scintillators were digitized and punched on paper tape which could immediately be fed to the computer. The information on the energy flow in the soft component and high energy N component was photographed with a system of oscilloscopes.

Various selection systems, some of them simultaneous, were used:

(i) Electron trigger—showers were triggered at a fast rate of about 200/hour by a 5-fold coincidence of scintillators at the centre of the array.

(ii) Mu trigger—the array was triggered whenever there was a 4-fold coincidence of the 4 mu detectors without any requirement on the electron association.

(iii) N trigger—whenever there was a high energy N particle passing through the N detector with the requirement of a very big association of shower particles at the top, the array was triggered.

## 3. Experimental results

The energy spectra of nuclear active particles in showers of different sizes were determined as a function of  $\alpha_e$ , the parameter that characterizes the steepness of the electron lateral distribution. The results are shown in figure 3. It is seen that while the slope of the energy spectrum is not dependent on  $\alpha_e$ , the number of particles of various energies within 10 m is critically dependent on  $\alpha_e$ . Showers that have a flat electron lateral distribution (low value of  $\alpha_e$ ) have a smaller number of high energy N particles than showers which have a steep electron lateral distribution. The difference in the total number, in some cases, is as much as a factor of 30. However, it should be pointed out that part of this may be due to an overestimate of the sizes of showers which have a flat lateral distribution which arises from the fact that the same lateral distribution is assumed even for large distances. This overestimation may be by a factor of 2-3 and so does not explain the large factor observed for the difference in the total number of N particles.

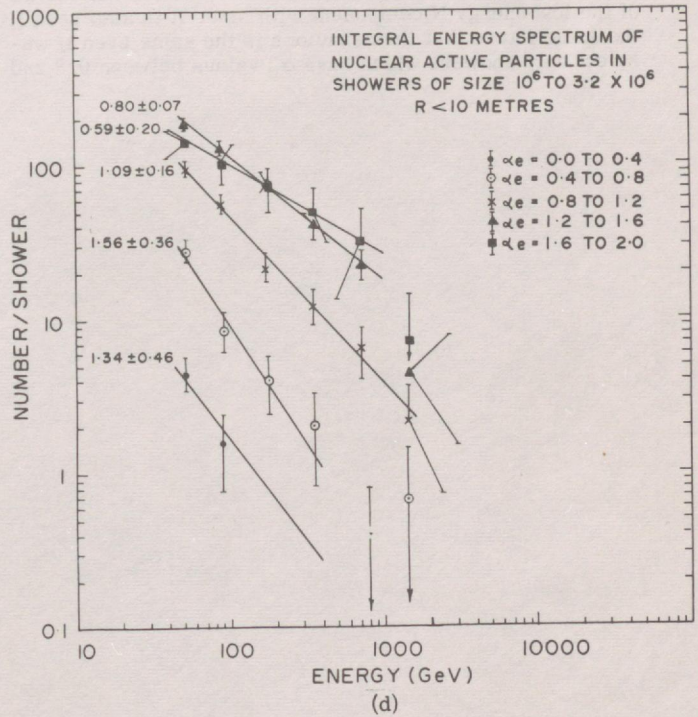
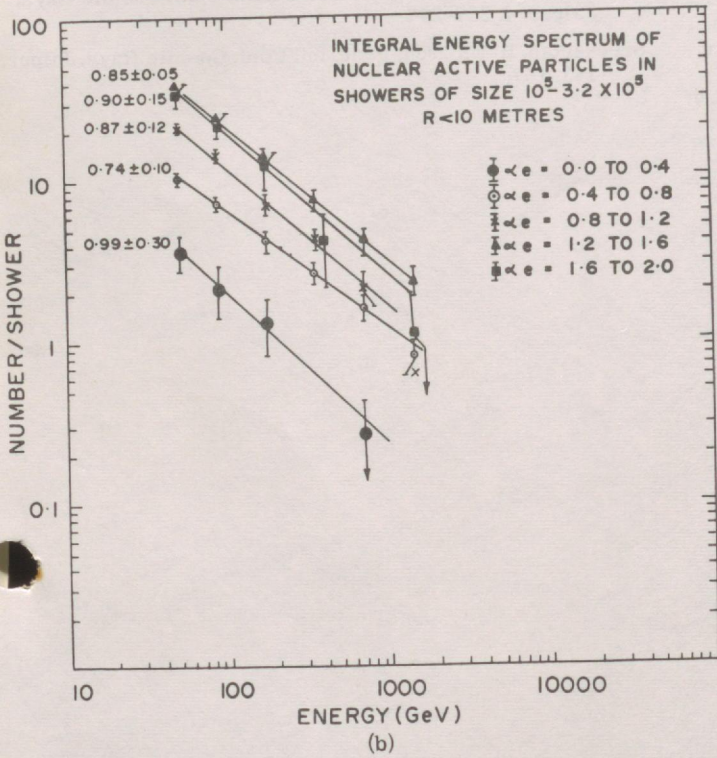
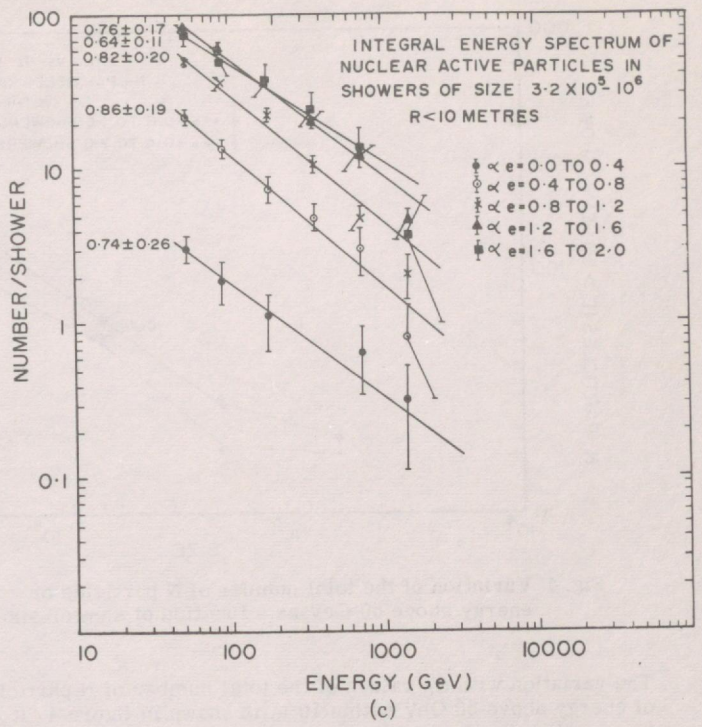
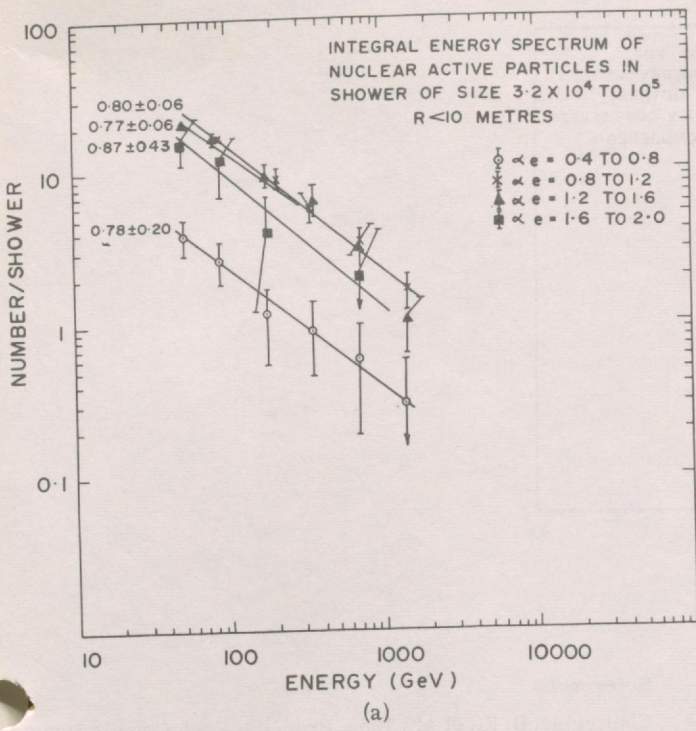


Fig. 3 Energy spectra of high energy nuclear active particles in showers of different sizes as a function of  $\alpha_e$ .

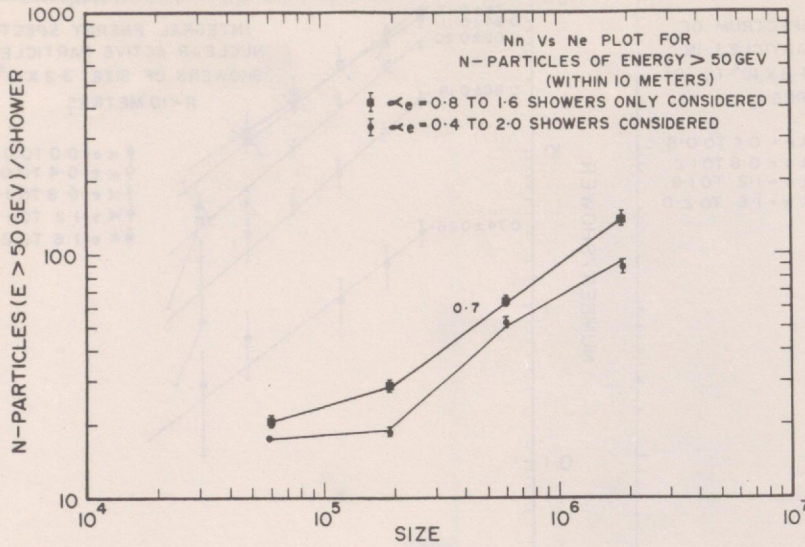


Fig. 4 Variation of the total number of N particles of energy above 50 GeV as a function of shower size.

The variation with  $\alpha_e$  values of the total number of N particles of energy above 50 GeV within 10 m is shown in figure 4. It is seen that the slope of this curve is not 1.0 but close to 0.7 and is almost similar to the slope observed for the variation of the low energy N component with size. It is also seen from the same figure that the behaviour is the same even if we select only showers which have  $\alpha_e$  values between 0.8 and 1.6.

**References**

Chatterjee, B. K., et al., 1964, Proc. Int. Conf. Cosmic Rays, Jaipur, 4, 227-247.  
Sreekantan, B. V., 1964, Proc. Int. Conf. Cosmic Rays, Jaipur, 4, 143-167.

OBSERVATION OF A NON-ELASTIC COSMIC RAY NEUTRINO INTERACTION

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM,  
P. V. RAMANA MURTHY and B. V. SREEKANTAN  
*Tata Institute of Fundamental Research, Bombay, India*

K. HINOTANI and S. MIYAKE  
*Osaka City University, Osaka, Japan*

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE  
*University of Durham, Durham, U.K.*

Received 18 August 1965

In a recent communication to this journal [1] we have described briefly our experimental arrangement for the detection of muons produced in the interaction of "natural" (cosmic ray) neutrinos deep underground; and discussed three events, recorded in 50 days of observation, some at least of which were due to natural neutrino interactions. The neutrino telescopes have been in operation since March, 1965 at a depth of 7600 ft below ground in the Kolar Gold Mines in South India.

Since we communicated our earlier paper, eight further events have been observed, making a total of eleven events so far. The fourth event is characterized by features which make it a clear case of a non-elastic natural neutrino interaction. In this note we wish to describe and discuss this particular event in some detail. (The other events will be reported in a later more detailed publication.)

For information concerning the experimental set-up in the mines, operational features and classification of events into various types, the earlier paper [1] may be referred to.

A sketch of the fourth event, based on the flash-tube array photograph, is shown in fig. 1. In table 1 we give relevant details concerning the event, using the nomenclature of the earlier paper.

Table 1

Event no.	Type of coincidence	Projected zenith angle	Date	Time
4	TEL. 2 N <sub>1</sub> + S <sub>1</sub>	Track 'a' 99.2° ± 0.3° Track 'b' 96.2° ± 0.8°	3.7.65	12.30

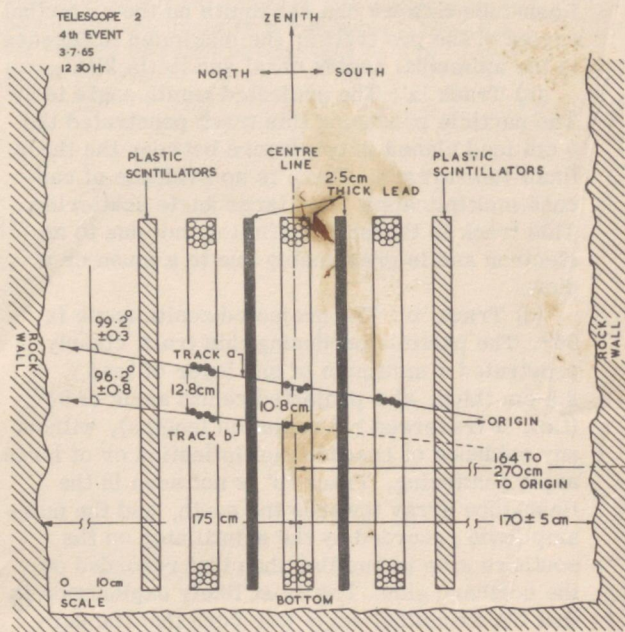


Fig. 1. A sketch of the event based on the flash-tube array photograph showing the relative position of plastic scintillators and lead layers with respect to the arrays of flash-tubes. The black dots show the discharged tubes; (only the bottom 1/3 section of the telescope is shown in the figure). As indicated in the figure, the meeting point of the two tracks could be either in air close to the rock wall on the southern side or inside the rock up to a thickness of one meter.

The main features of the event that can be deduced from the flash-tube photograph and the oscilloscopic display system are the following:

(a) Convergence of the two tracks: The two tracks 'a' and 'b' shown in fig. 1 converge to a point \* below the horizontal plane on the south side; (the projected zenith angle between the tracks is  $3^\circ \pm 1^\circ$ ). The point of interaction therefore appears to be in the southern rock wall. Because of the uncertainties that exist in the determination of the zenith and azimuthal angles, the exact location of the point at which the two tracks converge cannot be determined accurately. Within the errors, the point could be close to the surface of the rock wall, or up to a thickness of one meter inside the rock; in the case of the latter possibility, the actual distance traversed by the particles through rock would be up to 1.7 meters.

(b) Azimuthal angles: From the scintillator and flash-tube data we can set limits on the azimuthal angles of the two tracks; the maximum difference in the azimuthal angles of 'a' and 'b' is  $21^\circ$ .

(c) Track 'a': The projected zenith angle is  $99^\circ$ . The particle producing this track penetrated the 5 cm lead placed in two layers between the three flash-tube arrays. There is no evidence of cascade multiplication or of large angle scattering. This track is therefore definitely not due to an electron and is presumably due to a muon or a pion.

(d) Track 'b': The projected zenith angle is  $96^\circ$ . The particle producing this track clearly penetrated a minimum of one layer of lead, 2.5 cm thick, at a projected zenith angle of  $96^\circ$ , (i.e., it traversed  $\geq 5$  radiation lengths), without any evidence of cascade multiplication or of large angle scattering. Track 'b' is not seen in the flash-tube array towards the south, and the pulse amplitude recorded by the scintillator on the southern side is smaller than that recorded on the northern side. The most likely explanation is that the azimuthal angle was such that the particle missed the southern flash-tube array and associated scintillator. By a detailed geometrical reconstruction of the limiting possibilities for the track configurations, as defined by the scintillator and flash-tube data, it can be shown that track 'b'

also almost certainly travelled a minimum of 5 cm of lead, provided the direction of travel is taken to be from south to north. It is most unlikely therefore that particle 'b' was an electron; and, again, it was presumably a muon or a pion.

(e) Possibility that the interaction occurred in the northern wall: There is the less likely possibility that the interaction took place in the northern rock wall and one of the two particles diverging into the telescope was scattered in the rock itself thereby giving rise to the configuration observed. In this case no geometrical reconstruction can be carried out to define the point of interaction.

If the interaction did occur in the northern rock wall, it could be asked whether track 'b' might be an electron which was scattered in the rock wall. We consider this extremely unlikely since for this the electron would have to undergo both a large angle scattering in the rock wall and traverse eight or more radiation lengths in the rock plus lead without any evidence of multiplication.

From what has been said above, it is clear that the two tracks are almost certainly due to pions or muons; and this is true whether the interaction occurred in the southern or northern rock wall. The event in question follows as a non-elastic interaction.

The most significant feature of the event is the fact that the zenith angles of the two tracks are very large, i.e.,  $96^\circ$  and  $99^\circ$ . We can now proceed to consider the nature of the primary particle that could have given rise to such a non-elastic interaction at such a large zenith angle and at a depth of 7 600 ft below ground. There are the following three possibilities:

(A) A photonuclear interaction of an atmospheric muon travelling at the required zenith angle: the muon and a created pion could then constitute the two particles 'a' and 'b' of the event.

(B) An interaction caused by a pion travelling at the required zenith angle; the pion, in turn, was produced in a photonuclear process by an atmospheric muon near the level of observation; for this, the pion would have had to suffer a large angle scattering to the observed - almost horizontal - direction from the direction of maximum intensity of muons, which is the vertical. The particles 'a' and 'b' would then both be pions.

(C) An interaction caused by a natural neutrino.

The first two possibilities can be ruled out on the following grounds: (i) the very low vertical

\* At the depth of operation, single tracks are recorded in one of our telescopes at the rate of one in  $2 \times 10^6$  seconds; the probability of observing two unrelated tracks in the same picture can be shown to be  $\lesssim 10^{-10}$ . Since we have so far seen only 11 events, the probability that the event discussed here is due to two unrelated tracks is vanishingly small.

intensity of atmospheric muons at this depth \*; (ii) the steep angular distribution of atmospheric muons, as a result of which the intensity at the large zenith angle in question is quite negligible; (iii) the small cross section for the production of pions by muons in photonuclear processes; (iv) the small probability for the required large angle scattering of the pion. We therefore consider it extremely improbable that the event is due to an atmospheric muon or the pion component in equilibrium with it.

We consider that the event is a clear example of the non-elastic interaction of a natural neutrino travelling approximately in the horizontal direction; in all probability the neutrino travelled upwards from below the horizontal.

The two most likely explanations of the event could be:

(i) Production and decay of an intermediate boson:  $\nu_{\mu} + Z \rightarrow Z' + \mu + W$  and subsequent leptonic (or non-leptonic) decay of W. The two observed tracks would then most probably be due to muons.

(ii) Production of a pion in an inelastic interaction:  $\nu_{\mu} + N \rightarrow \mu + N' + \pi + \dots$

The two tracks would then be due to a muon and a pion.

If the point of interaction was well inside the rock - say a few meters inside - then the secondaries would necessarily have to be muons to be able to penetrate the rock and pass through the telescope. In the present event the uncertainties in the estimated point of origin and in the amount of matter traversed by the two particles are too large to decide with certainty between the two alternatives cited above. The accumulation of more events should clearly enable a decision to be made.

#### Reference

1. C.V. Achar et al., Physics Letters 18 (1965) 196

\* From our own observations in this experiment, we deduce that the intensity of atmospheric muons in the vertical direction at this depth is  $\approx 10^{-10}$  particles/cm<sup>2</sup> sec.sr.

\* \* \* \* \*

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINOS  
DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY  
and B. V. SREEKANTAN,  
*Tata Institute of Fundamental Research, Colaba, Bombay*

K. HINOTANI and S. MIYAKE,  
*Osaka City University, Osaka, Japan*

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE  
*University of Durham, Durham, U.K.*

Received 12 July 1965

Following the early work [1] carried out at great depths underground in the Kolar Gold Mines

in South India, we have specifically designed an experiment for the detection of muons produced

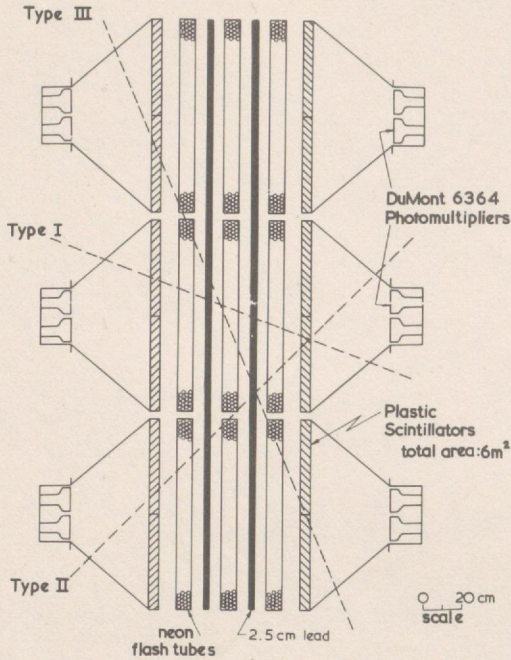


Fig. 1. Neutrino telescope.

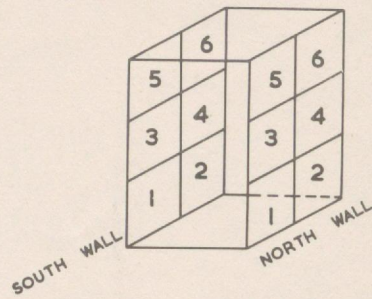
in the interactions of cosmic ray neutrinos; for preliminary reports concerning the experimental set-up see refs. 2 and 3. This experiment has been in operation in the Kolar Gold Mines at a depth of 7600 ft. (equivalent to 7500 m.w.e. \* of standard rock with  $Z^2/A = 5.5$ ) since March 1965.

For the initial phase of the experiment we have used two telescopes, each consisting of 2 vertical walls of plastic scintillators 2 m long and 3 m high separated by 80 cm as shown in fig. 1. Each "scintillator element", one square meter in area, and composed of 4 plastic scintillator blocks, is viewed by 2 adjacent 5" diameter photomultipliers; four-fold coincidences are

Table 1

Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL.2 N <sub>4</sub> +S <sub>4</sub>	37°	30.3	20.04
2	TEL.1 N <sub>1</sub> +S <sub>1</sub>	48 ± 1°	27.4	18.26
3	TEL.2 N <sub>6</sub> +S <sub>6</sub>	75 ± 10°	25.5	20.03

\* At Kolar  $Z^2/A = 6.5$  and rock density = 3.02 g/cm<sup>3</sup> and accordingly the depth of 7600 ft. corresponds to 7000 m.w.e. for Kolar rock.



TYPE I EVENTS: (N<sub>1</sub>OR2 + S<sub>1</sub>OR2) OR (N<sub>3</sub>OR4 + S<sub>3</sub>OR4)  
OR (N<sub>5</sub>OR6 + S<sub>5</sub>OR6)  
TYPE II EVENTS: (N<sub>3</sub>OR4 + S<sub>1</sub>OR2) OR (N<sub>3</sub>OR4 + S<sub>5</sub>OR6)  
OR (N<sub>5</sub>OR6 + S<sub>3</sub>OR4) OR (N<sub>1</sub>OR2 + S<sub>3</sub>OR4)  
TYPE III EVENTS (N<sub>1</sub>OR2 + S<sub>5</sub>OR6) OR (N<sub>5</sub>OR6 + S<sub>1</sub>OR2)

N MEANS NORTH : S MEANS SOUTH

Fig. 2.

recorded between a pair of photomultipliers on one wall and any pair on the other wall. Between the scintillator walls is space for three arrays of neon flash tubes with 4 columns of tubes in each array and also for 2 walls of lead absorber, each 2.5 cm in thickness. During the period over which the data presented in this note were obtained the telescopes were still incomplete, one having two (extreme) arrays of flash-tubes and lead (telescope 1) and the other containing only one (central) array of flash-tubes (telescope 2) without lead. When 4-fold coincidences occur, the photomultiplier pulses are recorded on oscilloscopes and after a delay of about 30 microseconds a high voltage pulse is applied to the electrodes of the flash-tube arrays.

For each square meter of detector area looked at by one pair of photomultipliers the counting rate was adjusted to be 20/hour, almost all of which was due to background gamma rays of radioactive origin. Hence the accidental chance coincidence rate for 4-fold coincidence is about 1 in 7 years and the coincidence rate due to double Compton effect of gamma rays is

Table 2

Category of muons	Type of events		
	I	II	III
Atmospheric muons	5.5%	61.3%	33.2%
Muons from neutrino interactions	72.6%	25.9%	1.5%

Table 3  
Summary of results  
Number of events in 100 telescope-days ( $\approx 2140 \text{ m}^2 \text{ days steradians}$ )

Class		I	II	III	
Observed number		3	0	0	
Expected number of muons from neutrino interactions	(a) Elastic collisions	0.08	0.03	0.002	
	Inelastic collisions				
	(b) $\sigma_{\text{inel}} \propto E_\nu$ up to $E_\nu \gg 10 \text{ GeV}$	0.36	0.13	0.007	
	(c) $\sigma_{\text{inel}} \propto E_\nu$ up to $E_\nu = 10 \text{ GeV}$ and saturates thereafter	0.21	0.08	0.004	
	Assuming existence of intermediate boson				
	(d) $M_W = 1.8 \text{ GeV}$	0.36	0.13	0.007	
	(e) $M_W = 2.5 \text{ GeV}$	0.16	0.06	0.003	
	With Glashow resonance				
	(f) $M_W = 1.8 \text{ GeV}$	0.10	0.04	0.003	
	(g) $M_W = 2.5 \text{ GeV}$	0.023	0.008	0.0005	
Total upper limit (a + b + d + f)					
		0.90	0.33	0.019	
Total lower limit (a + c)					
		0.29	0.11	0.006	
Expected number of atmospheric muons		0.065	0.80	0.47	

Summary of interactions:

Elastic collision	$\nu_\mu + N \rightarrow \mu + N'$ ; Cross section = $0.75 \times 10^{-38} \text{ cm}^2$ per neutron-proton pair; $E_\mu \approx E_\nu$ .
Inelastic collisions	$\nu_\mu + N \rightarrow \mu + N' + \text{created particles such as pions}$ ; cross section = $0.45 \times 10^{-38} E_\nu \text{ cm}^2$ , (i.e., linear dependence on energy; $E_\nu$ in GeV), up to a cut off energy and constant above this energy. $E_\mu \approx \frac{1}{2} E_\nu$ below cut off and $E_\mu \approx E_\nu$ above cut off.
Intermediate boson	Production of an intermediate boson and a muon by a muon neutrino in the Coulomb field of a nucleus $\nu_\mu + Z \rightarrow Z' + \mu + W$ with subsequent decay of the boson, a fraction of which produce a second muon.
Glashow resonance	Resonance production of an intermediate boson by a $\bar{\nu}_e$ on an atomic electron with subsequent decay via the muon mode $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \bar{\nu}_\mu + \mu^-$ .

estimated to be less than 1 for 10 years, for each telescope.

Since the amplitudes of the pulses from all the "scintillator elements" are displayed on oscilloscopes, it is possible to classify the events into the three types I, II and III as shown in figs. 1 and 2; it may be noted that information relating to azimuth, though somewhat crude, is also available.

In about 50 days of operation (100 telescope days  $\approx 2140 \text{ m}^2 \text{ days steradians}$ ) three events have been recorded; details concerning these are given in table 1. In each case only one scintillator element was traversed on each side of the telescope. All the three events are of type I

and no event was recorded of type II or III. The first event occurred before the flash-tubes were installed and it was therefore not possible to have an accurate measure of the projected zenith angle of the charged particle responsible for the event. However, on the basis of information from the oscilloscope, the angle has to be necessarily larger than  $37^\circ$ . The other two events occurred when the telescopes had been partially loaded with flash-tubes and showed tracks of single unambiguous particles. Of these two events the first one was recorded in telescope 1; the particle must therefore have penetrated 5 cm of lead besides the plastic scintillators; since there was no indication of any shower develop-

ment it is most probably not an electron. The other event was recorded in telescope 2 in which there was no lead; the particle could therefore be either an electron or a muon. It is interesting to point out that after the introduction of flash-tubes not a single case has been recorded by the scintillator telescope without a corresponding indication in the flash-tube array.

The observed events could arise from either atmospheric muons which have come from ground level through the overlying rock, or muons arising from the interactions of cosmic ray neutrinos in the surrounding rock. The greatest depth so far for which atmospheric muon intensity measurements exist is 6930 m.w.e. of standard rock (Miyake et al. [1] at Kolar Gold Mines). One has to extrapolate and surmise to arrive at the expected counting rate due to atmospheric muons at the depth of our present experiment; this counting rate is thus subject to some uncertainty. The angular distribution of atmospheric muons is very steep, being of the form  $I_{\theta} = k \cos^n \theta$  with  $k \approx 10^{-10}$  muons/cm<sup>2</sup> sec · sterad and  $n \approx 9$ ; their contribution to the observed events is therefore negligible at large zenith angles. Table 2 shows the relative percentages of events of types I, II and III that should be expected in the case of atmospheric muons (on the basis of the angular distribution just indicated) and in the case of charged particles secondary to the more or less isotropic flux of cosmic ray neutrinos.

In table 3 we show the expected number of events of type I, II and III in 100 telescope days due to atmospheric muons and due to muons arising from neutrino interactions.

It will be seen that we have made different assumptions regarding the neutrino interaction cross section. For the case where the production of the intermediate bosons of mass  $m_W$  is postulated, the cross sections are based on the predictions of Wu et al. [4] for neutrino energies up to 10 GeV, combined with the high energy asymptotic expression of Von Gehlen [5].

The actual numbers given in table 3 are based on the neutrino intensities estimated by Osborne et al. [6].

With regard to neutrino intensities, there is, among the various computations that exist today, general agreement at lower energies. But at higher energies the estimates depend on parameters such as the  $K/\pi$  production ratio. The expected counting rates due to neutrino interactions which are shown in table 3 should be taken only as approximate and indicative of the magnitude to be expected for the various processes.

The fact that all the three events recorded are

of type I and that none has been recorded of type II or III is particularly significant. This, it seems to us, rules out the possibility that all the events recorded are due to the remanent atmospheric cosmic ray muons. The probability that an atmospheric muon recorded by the telescopes is of type I is only  $\sim 5\%$ , while the probability of its being of type II or III is 95%. There is thus strong evidence that events have been detected which are attributable to neutrino interactions.

If all the observed events are attributed to neutrinos, then it is clear that none of the processes envisaged in table 3 is ruled out from the present observations. In fact, if the present rate of events, namely 3 in 2140 m<sup>2</sup> days steradians, is maintained, it will be necessary for the neutrino cross section to rise faster than  $E_{\nu}$ , or for the neutrino intensities to be appreciably higher than the present estimates.

The authors are deeply indebted to the Kolar Gold Mining Undertakings and several of the individual officers for considerable cooperation and help extended to us, without which this experiment would not have been possible.

We are grateful to Dr. S. Naranan of the Tata Institute for discussions on various aspects, and to Professor G. D. Rochester F. R. S. for his support.

The authors of the Osaka group express their sincere thanks to the I. U. P. A. P. Cosmic Ray Commission for encouraging the continuation of international collaboration at Kolar Gold Fields, and to Professor S. Tomonaga and the "Japanese Society for the Promotion of Science" for their financial support of part of the experiment.

The Science Research Council (U. K.) are also thanked for their financial support.

#### References

1. S. Miyake, V. S. Narasimham and P. V. Ramana Murthy, Proc. Phys. Soc. (Japan), Vol. 3 (1962) 318; Nuovo Cimento 32 (1964) 1505; M. G. K. Menon, P. V. Ramana Murthy, B. V. Sreekantan and S. Miyake, Phys. Lett. 5 (1963) 272; Nuovo Cimento 30 (1963) 1208.
2. B. V. Sreekantan, Proc. Informal Conf. on Experimental neutrino physics, CERN 1965, to be published.
3. A. W. Wolfendale, Proc. Informal Conf. on Experimental neutrino physics, CERN 1965, to be published.
4. A. C. T. Wu, Chen-Ping Yang, K. Fuchel and S. Heller, Phys. Rev. Lett. 12 (1964) 57.
5. G. Von Gehlen, Nuovo Cimento 30 (1963) 859.
6. J. L. Osborne, S. S. Said and A. W. Wolfendale, Proc. Phys. Soc. (1965) to be published.