MULTIPLE MUON EVENTS OBSERVED UNDERGROUND

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Abstract

Observations are reported on events involving multiple penetrating particles recorded in a scintillator-neon flash tube telescope, at a depth of 1500 hg/cm^2 in the Kolar Gold Mines. From these, it is shown that: (1) the cross-section for nuclear interaction of muons of average energy ~ 200 GeV is $\sim 6 \times 10^{-30}$ cm^2/nucleon; (2) the decoherence curve for events involving two parallel muons is uniform over the range of distances from 0 to 2 metres; and (3) the angular distribution of double-parallel muons closely resembles that of single muons, implying that these two types of events are probably produced in the atmosphere in a similar manner.

Introduction

We have recently completed an experiment, using a scintillator-neon flash tube telescope, to determine the angular distribution of muons at a depth of 1500 hg/cm^2 (Kolar) in the Kolar Gold Fields (KGF) in South India. The apparatus employed and the results obtained on the angular distribution have been described in detail in an earlier paper by Krishnaswamy *et al.* (1968). In this paper we wish to report and discuss the multiple muon events observed in this experiment.

Apparatus

Figure 1 shows the KGF muon telescope. Since it has been described fully by Krishnaswamy *et al.* (1968) we shall only briefly recapitulate the essential features. There is a horizontal layer of plastic scintillator, 2 metres $\times$ 2 metres in area, below which there are four boxes of neon flash tubes (NFT); the five horizontal layers of particle detectors are interleaved with four layers of absorber ($\frac{1}{2}''$ thick lead + $\frac{1}{4}''$ thick iron). The pulse from the plastic scintillator is used as the trigger to photograph, with the NFT array, the trajectories of the traversing particles. The spacial angles of the trajectories can be determined with the system since the alternate NFT boxes have been arranged in crossed geometry; the accuracy in the definition of zenith angle is about $\pm 1 \cdot 5°$ in the vertical direction.

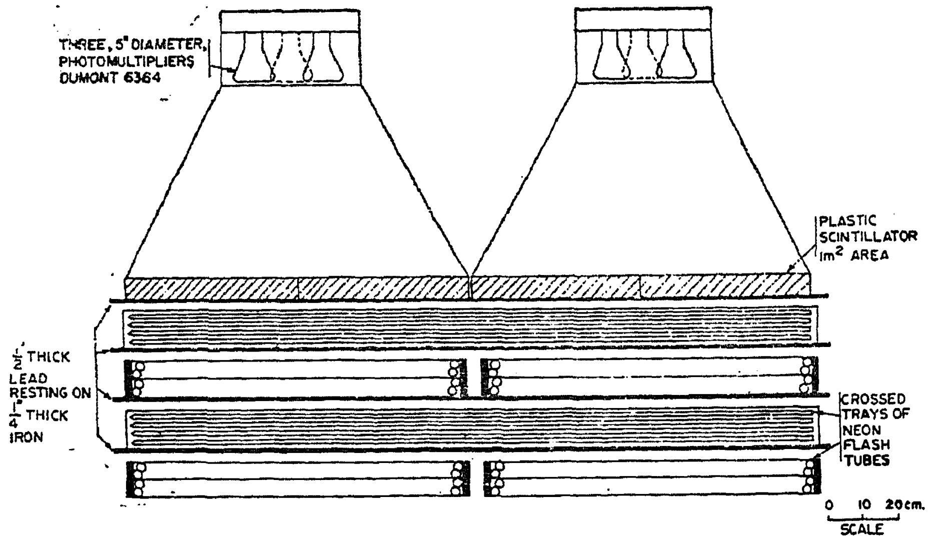

FIG. 1. Experimental arrangement.

TYPES OF EVENTS OBSERVED

In a period of observation of $4 \cdot 08 \times 10^6$ seconds we have recorded the following types of events:

(i) 6×10^4 cases have been seen of single tracks due to penetrating particles muons), traversing the telescope within a defined geometry; these have been discussed at length by Krishnaswamy *et al.* (1968).

(ii) 77 cases have been of rock showers due to the nuclear interactions of muons in the surrounding rock; these are characterized by several (two or more) tracks which can be traced to a common point of origin within a few metres of overlying rock; in these cases there are also complicated trajectory patterns caused by accompanying soft component;

(iii) 243 cases have been of events involving two or more tracks due to penetrating particles traversing the telescope that can be stated to be parallel within the accuracy of our angular measurement;

(iv) a large number of electromagnetic events have been recorded, arising mainly through the Bremsstrahlung of high energy muons.

We will discuss in this paper only our observations on events in the categories (ii) and (iii). We would like to recall here the earlier experiment done at Kolar (Creed *et al.*, 1965) on muon interactions far underground; in that work the electromagnetic events were divided into various categories and analysed as a function of depth. Creed *et al.* also discussed the multiple penetrating particles observed by them and concluded that at depths of a few thousand hg/cm^2, the main contribution is from muons associated with extensive air-showers.

Rock Showers

In analysing rock showers one comes across several ambiguities such as the efficiency of detection, ranges of the secondary particles, threshold energy for an event to be detected, etc.; these are difficult to estimate precisely. Therefore, for the present we shall compare our observations directly with those of Barrett *et al.* (1952) involving a similar analysis. They obtained for the ratio of the number of rock showers to the number of single muons a value of $8 \pm 1 \cdot 7 \times 10^{-3}$; and assuming a range of 300 gms/cm^2 for the secondary particles, they concluded that the interaction cross-section of muons at about this depth is $4 \pm 2 \times 10^{-29}$ cm^2/nucleon. Our value for the ratio of the number of rock showers to the number of single muons is much smaller, $1 \cdot 3 \pm 0 \cdot 15 \times 10^{-3}$; and with the same assumption as made by Barrett *et al.* we obtain $6 \pm 0 \cdot 7 \times 10^{-30}$ cm^2/nucleon for the cross-section, $\sigma_{\mu N}$, for the nuclear interaction of muons. From this, we estimate that the cross-section for photonuclear interaction in the relevant energy range is of the order of 10^{-28} cm^2/nucleon. The average energy of muons at this depth is about 185 GeV.

Our value of $\sigma_{\mu N}$ is approximately six times smaller than that of Barrett *et al.* We would like to point out that our detector system employed small-diameter visual detectors with good spacial resolution; this makes it possible to sort out the various categories of complex events that are observed; Barrett *et al.* used large diameter G.M. counters and with these there are problems in distinguishing between rock showers and electromagnetic events. Further, we have used a detector of fairly large area, 2 m. $\times$ 2 m., and the average height of the roof above it was only $\sim 1 \cdot 4$ m.; thus, the efficiency for the detection of rock showers originating at points distributed within a distance of a few metres from the rock surface is rather good.

PARALLEL MUONS

We define as " parallel muons " all events in which tracks of penetrating particles are observed which are parallel to one another within the experimental error in measurement of angle. When these tracks are traced upwards, their meeting point above the apparatus is estimated to be $\gtrsim 30$ metres for an event with a horizontal separation of ~ 1 m.

We have observed 243 cases of parallel muons; of these in 215 cases there are 2 muons, in 19 cases there are 3 muons, in 5 cases there are 4 muons, in 3 cases there are 5 muons and in 1 case there are 6 muons. These numbers are shown in Fig. 2, along with the observed frequency of single muons. A possible fit to the data is shown by dashed lines.

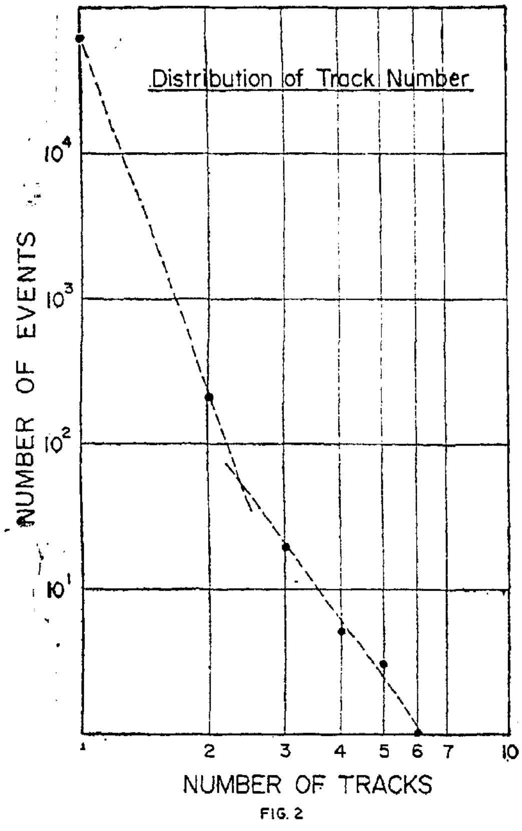

FIG. 2. Distribution showing the frequency of occurrence of events with different *numbers* of parallel muons.

The zenith angle distribution of parallel events involving 2 muons is shown in Fig. 3. In the same figure, we have shown the corresponding distribution for single muons with a suitable reduction in the scale; at this depth, the angular distribution for single muons can be expressed as $2 \cdot 8$ $\cos \theta$. The two distributions, for single muons and double-parallel muons appear to be quite similar. From this we may conclude that double-parallel muons originate through the decays of pions and kaons, similar to the single muons.

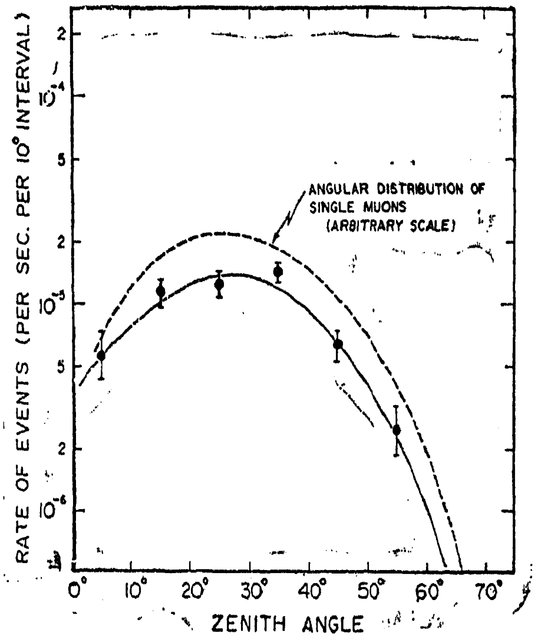

FIG. 3. Angular distribution of events containing parallel muons.

In Fig. 4 we show, for parallel events involving 2 muons, by the dotted-line histogram, the number of events we have observed with various values of separation, r, in intervals of 25 cm. When this dotted-line histogram is corrected for the efficiency for the detection of events with various separations, we obtain the solid-line histogram. In order to make a comparison with the decoherence curve of Barrett *et al.* (1952), we have treated the solid-line histogram in the following manner: the frequency at each value of separation, r, has been divided by the corresponding area $2\pi r\, dr$. The finally obtained histogram is shown shaded in Fig. 4; the units are arbitrary. Except for a small increase between 0 and 25 cm., the distribution is almost flat over the complete range of values of r. The flat distribution can be understood if the muons are produced in the atmosphere and not locally through interactions in the rock, since the scattering of muons of energy about 1 TeV, in passing through 1,500 hg/cm^2 will, on the average, give rise to a displacement of about 40 cm from the original direction. The slight increase at close distances may possibly be due to a small amount of local production of muons in the rock. This observation is in disagreement with the results of Barrett *et al.*, which show a sharp increase of frequency in their de-coherence curve at distances of less than about 2 metres; from this, they had concluded that the interactions occurred in the rock at a considerable rate. Even if we consider the effects on the shaded histogram of Fig. 4 due to multiple muon events involving more than 2 muons, such a steep increase in the frequencies at close separations is difficult to understand.

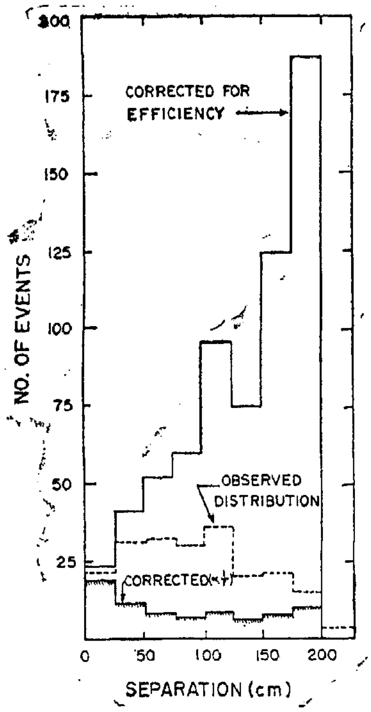

FIG. 4. Distribution of separation of double-parallel muons.

DISCUSSIONS AND CONCLUSIONS

From our present observations, we conclude :

(*a*) that the nuclear interaction cross-section of muons at this depth (where the average muon energy is about 185 GeV) is of the order of $6 \cdot 0 \times 10^{-30}$ cm^2/nucleon; this implies a value of $\sim 10^{-28}$ cm^2/nucleon for the photo-nuclear interaction cross-section, in fair agreement with what is expected on the basis of experiments at lower energies at the accelerators;

(*b*) there is very little, if any, local production of muons as can be seen from the relatively flat distribution in Fig. 4 of the frequency of events for various values of separation r for double-parallel muons.

From our analysis of the angular distribution of single muons observed in this experiment (Krishnaswamy *et al.*, 1968), we have shown that there is a sec θ enhancement in the number of muons observed at various zenith angles, θ, as is to be expected if the muons arise wholly in the decays of pions and kaons, according to the normally assumed cosmic ray picture, Again, in the deep underground neutrino experiments (Menon *et al.*, 1968; Reines *et al.*, 1968), it is assumed that the tracks observed at large zenith angle are due to neutrino-induced muons. Since the detector systems employed in all of these experiments have relatively low threshold energies, it has been questioned whether some of the tracks observed at large angles might not be due to muon interactions in the surrounding rock, including rock showers. The low frequency that we have observed in our current experiment for the ratio of the number of rock showers to the number of single muons and the corresponding low values for the nuclear interaction cross-section of muons, as well as our observations on the double-parallel muons, render this possibility very unlikely.

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