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The Kolar Gold Fields neutrino experiment
I. The interactions of cosmic ray neutrinos

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Final results are presented of an experiment to study the interactions of cosmic ray neutrinos deep underground, at a depth of 7.6×10^5 g cm^{-2} (standard rock).

Clear examples have been recorded of neutrino-induced muons, including cases of upward moving particles and neutrino interactions within the detector assembly itself.

The observed rate of events is compared with expectation and conclusions are made about the variation of the inelastic cross-section with energy and the lower limit to the mass of the intermediate boson.

An examination has also been made of the celestial coordinates of the detected neutrinos and details are presented.

1. Introduction

Before their actual detection, it had long been recognized that there should be high energy neutrinos in the secondary cosmic radiation. This followed from the knowledge that there were high energy pions and muons in the secondary cosmic ray beam and the assumption that the neutral particles involved in the $\pi-\mu$ and $\mu-e$ decays were neutrinos. But it was only about a decade ago that the first calculations of the intensity of these high energy neutrinos were reported and the feasibility of carrying out cosmic ray experiments to study their interactions was realised. In particular, this question was discussed by Markov (1960), Greisen (1960), and Kuzmin *et al.* (1962). These authors suggested that the experiments be carried out far underground to reduce the effects of cosmic rays other than neutrinos. They envisaged experiments of very large magnitudes; Greisen considered unit detectors 10 m cube in volume and Kuzmin *et al.* installations of area 300 m^2. In view of the size of these experiments, Greisen (1960) suggested that it would be advisable to await results from the experiments then planned at the accelerators in order to be sure about the magnitude of the neutrino interaction cross-section.

In 1962, the accelerator experiment of Danby *et al.* at Brookhaven demonstrated two important features: (i) the difference between the electron and muon

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neutrino (ν_e and ν_μ) and (ii) the comparatively large cross-section for neutrino-nucleon interactions, $\sigma_{\nu N} \approx 10^{-38}\,cm^2$/nucleon. Shortly afterwards, the experiment of Miyake *et al.* (1964) showed that at a depth of 2804 m below ground the vertical intensity of atmospheric muons was less than $10^{-7}\,m^{-2}\,s^{-1}\,sr^{-1}$ (by 'atmospheric' muons is meant muons which are generated by the decay of parent particles in the atmosphere). On the basis of these observations Menon *et al.* (1963) concluded that the atmospheric muon intensity had been attenuated to such an extent as to be of the same order as that expected for muons arising from neutrino interactions and therefore experiments on high energy atmospheric neutrinos would be feasible at such great depths with relatively modest detector arrays.

In view of this, in early 1965 an experimental programme was initiated, involving groups from the Tata Institute of Fundamental Research (India), Osaka City University (Japan), and the University of Durham (U.K.), to investigate at a great depth underground in the Kolar Gold Fields the interactions produced by high energy cosmic ray neutrinos (ν_μ) in the rock surrounding the detector assembly.

On account of the rarity of neutrino phenomena and the need to extract maximum information from each event, as also the need for good direction resolution, it was clear that visual detectors would be essential for such investigations. In particular, it was decided to use neon flash tubes since these appeared to be particularly suitable for use over extended time periods in the difficult operating conditions encountered deep underground; further, extensive experience concerning these had been accumulated over the years by the Durham Group (see for example, Gardener *et al.* 1957; Ashton *et al.* 1959; Coxell & Wolfendale 1960). Prior to the neutrino experiment, a small experiment was carried out by the Durham and T.I.F.R. groups (Achar *et al.* 1965*a*) in which neon flash tube arrays were successfully employed for work at various depths underground to measure the muon intensity and angular distribution. This work was important in that it confirmed that the atmospheric muon component was behaving as expected, particularly with regard to its angular distribution.

Simultaneously with the experiment in the Kolar Gold Fields, Reines *et al.* (1965) initiated a similar experiment deep underground in a gold mine in South Africa. Evidence for muons produced in the interactions of cosmic ray neutrinos were reported by both groups in 1965.

A number of progress reports on the Kolar Gold Field neutrino experiment work have been given during the course of the experiment and the reader is referred to them, particularly for details of the apparatus (Achar *et al.* 1965*b, c, d*; Menon *et al.* 1967, 1968; Krishnaswamy *et al.* 1968, 1969). The purpose of the present paper (part I) is to summarize the final results of the K.G.F. experiment with regard to neutrinos; the results on atmospheric muons are considered in the following paper (part II).

2. Experimental details

2.1. *Location and disposition*

In this experiment we employed five telescopes (telescopes 1, 2, 3, 4 and 5) and two magnet spectrographs (spectrographs 1 and 2). These were located as shown in figure 1, at the 80th level, Heathcote Shaft, in the Champion Reef Mines of the Kolar Gold Mining Undertaking (latitude 12° 57′ N, longitude 78° 18′ E). The tunnel is at a depth of 2316 m below the earth's surface; this corresponds to 7000 hg $\mathrm{cm^{-2}}$ of Kolar rock (1 hg $\mathrm{cm^{-2}}$ = 10^2 g $\mathrm{cm^{-2}}$) for which $\langle Z/A \rangle = 0.495$, $\langle Z^2/A \rangle = 6.3$ and mean density $\rho = 3.02\ \mathrm{g\ cm^{-3}}$.

The detectors were designed to record charged penetrating particles traversing them, predominantly at large angles to the vertical, and arising through the interactions of neutrinos in the surrounding rock; additionally, they would record, but with much smaller aperture, atmospheric muons that have penetrated to this depth and which are known to arrive predominantly in the vertical direction.

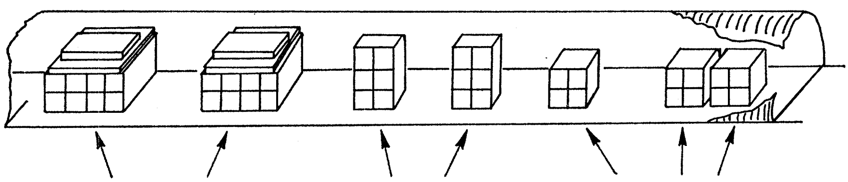


Figure 1. Disposition of apparatus in the Neutrino Experiment at K.G.F.

2.2. *Description of telescopes and spectrographs*

The three types of detectors employed are shown diagrammatically in figure 2. In each of the seven detectors there were two walls of plastic scintillators separated horizontally; in telescopes 1 and 2, the walls were of area (3 m × 2 m) in telescopes 3, 4 and 5 of area (2 m × 2 m) and in spectrographs 1 and 2, of area (2 m × 4 m); the walls were separated in the three cases by 80, 130 and 100 cm respectively. Between these walls of scintillators were located arrays of neon flash tubes; the flash tubes were of length 2 m and external diameter 1.8 cm. In telescopes 1 and 2 and in spectrographs 1 and 2 the flash-tubes were placed horizontally; with this arrangement only the projected zenith angle could be measured. In telescopes 3, 4 and 5 the flash-tube arrays were placed in a crossed geometry and hence the spatial angles could be measured. With the flash-tube arrays the error in the measurement of the angle was ± 1°.

Vertical walls of absorber were used in all the seven detectors. Two 2.5 cm thick lead walls were employed in telescopes 1 and 2, four 7.5 cm thick iron walls in telescopes 3, 4 and 5, and a 40 cm thick iron block, in the form of a central magnet, in the spectrographs. With these layers of absorber it was possible to distinguish between electrons and heavier particles (pions and muons) traversing the detector

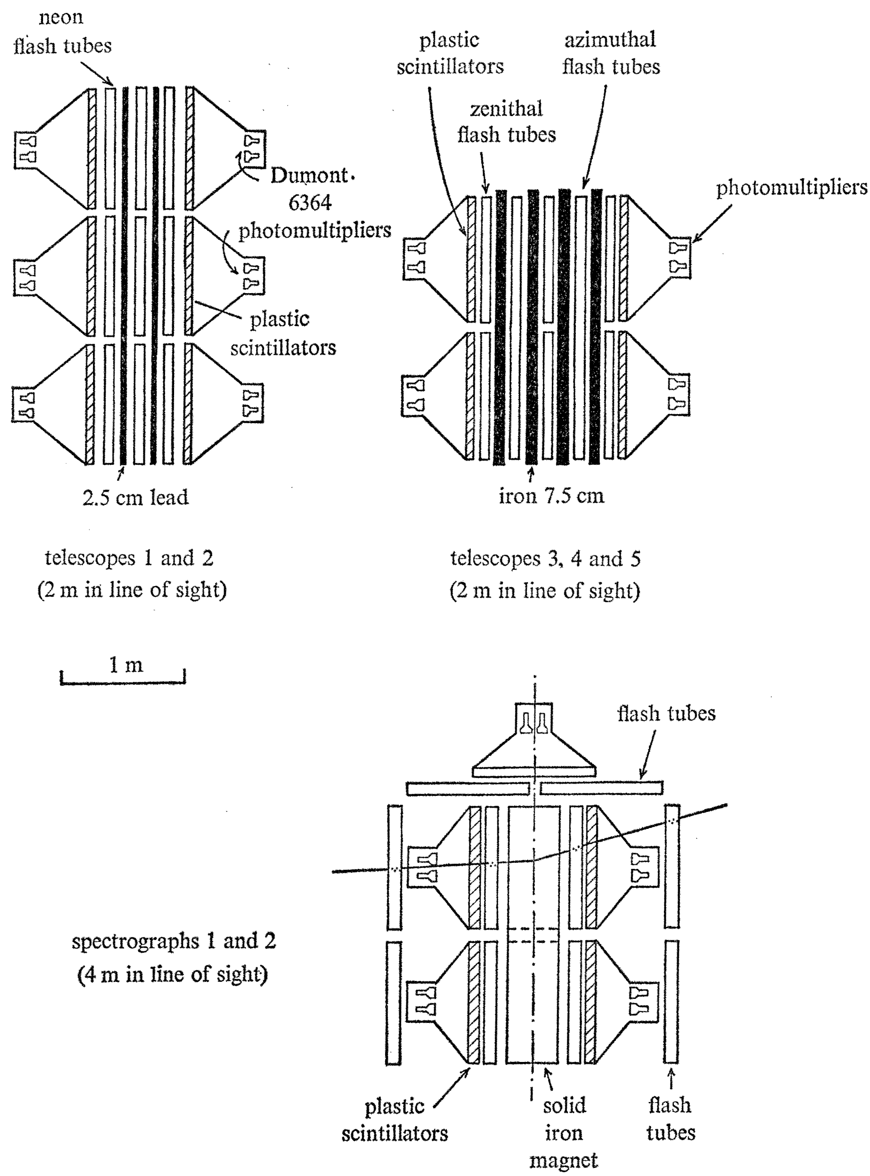


FIGURE 2. The detectors at K.G.F.

system. In many cases secondaries were generated in the absorber, and by studying these the sense of direction of the incident particle could be obtained. Figure 2 shows diagrammatically the three types of detectors.

2.3. *Triggering*

In the case of telescopes 1 and 2, and in telescopes 3, 4 and 5 until the beginning of 1968, the basic trigger was provided by a fourfold coincidence between pulses from a pair of photomultipliers viewing 1 m^2 area of one wall and a similar pair on the other wall. From the beginning of 1968, the basic trigger in telescopes 3, 4 and 5 was provided by a twofold coincidence between pulses from the photomultipliers viewing any 1 m^2 area of scintillator in either wall of the detector; this is referred to as 'one side triggering' (o.s.t). Although with o.s.t. the accidental coincidence rate was very high, it was employed in view of the following three clear advantages: it made possible the recording of low energy events in which the particles involved were unable to penetrate the whole of the telescope; with this trigger, neutrino interactions that occurred inside the detector could be recorded; and finally the aperture of the telescope was enhanced.

2.4. *Magnet spectrographs—further details*

Since a full description of the magnetic spectrographs has not been given earlier, some additional details are presented here.

An electromagnet of the solid-iron type, of total thickness 40 cm, was placed between the vertical scintillator walls. The magnet was operated at its maximum field of 14 kG. Columns of flash-tubes were placed on both sides of the vertical walls of plastic scintillators. Additionally, a (1 m × 4 m) layer of plastic scintillator, and below it a (2 m × 4 m) box of flash-tubes were employed above the magnet; the top scintillator, in conjunction with the side scintillators, could provide a trigger, and thus enable the recording of a comparatively high rate of atmospheric muons incident at angles close to the zenith. This was valuable as it provided the necessary checks on the efficient operation of the spectrographs.

The maximum detectable momentum of the spectrographs for large angle particles which traversed four trays of flash-tubes was estimated to be *ca.* 30 GeV/*c*; but for particles at oblique angles which passed through only three trays of tubes it was much less, typically *ca.* 8 GeV/*c*. The aperture of each of the spectrographs was *ca.* 35 m^2 sr for isotropically arriving radiation.

2.5. *Operational details*

Whenever a trigger was provided by the scintillators (a fourfold coincidence or o.s.t.), the photomultiplier pulses were recorded on oscilloscopes. About 30 μs after the trigger, a high voltage pulse was applied to the electrodes of the flash tube arrays; this time delay ensured that there was no interference with the oscilloscope recording (no loss of detection efficiency resulted from the time delay). The flash tubes were photographed, in several cases via a mirror system, as also were the cathode-ray oscilloscopes. The data from the experiment were thus finally recorded on film, the camera lenses being continuously open.

Key voltages, rates and pulse profiles were monitored and frequent checks on the flash-tubes were made by pulsing in the presence of a strong radioactive source. The detectors were also triggered at intervals of $4\frac{1}{2}$ h during operation to minimize fogging by accumulated stray light and to give further checks on operation.

In the case of telescopes 1 and 2, and spectrographs 1 and 2, a knowledge of which particular scintillator was traversed enabled the azimuthal angle to be defined in a very approximate manner; in the case of the other telescopes the azimuthal angles were measured accurately through the azimuthal tubes.

3. Basic data

3.1. *Period of operation*

Telescopes 1 and 2 were commissioned in early 1965. This was followed by the commissioning of telescopes 3, 4 and 5 in March 1966; telescopes 3, 4 and 5 were placed on o.s.t. early in 1968. The two magnet spectrographs were in operation from June 1967. All the detectors were operated until June 1969, when the neutrino project was terminated. The actual operating times for the various detectors are given in the first row of table 1.

Table 1. Division of events and exposure times

	tels. 1, 2	tels. 3, 4, 5	o.s.t.	specs. 1, 2
exposure time/h	49047	17560	26196	24813
number of atmospheric muons	42	2	76†	82
number of neutrino-induced events ($\phi \geqslant 50°$)	7	2	5	2
aperture × time appropriate to neutrino-induced events/m^2 s sr ($\phi \geqslant 50°$)	2.10×10^9	0.37×10^9	0.85×10^9	1.39×10^9

† Includes particles passing through only one tray of flash-tubes.

3.2. *Features of events recorded*

From the flash tube photographs it was possible to distinguish the following features of the detected events;

(*a*) Inclination of the particle trajectory, from which the projected zenith angle (p.z.a.) could be obtained in the case of telescopes 1 and 2 and the spectrographs and spatial zenith angle (s.z.a.) in the case of telescopes 3, 4 and 5.

(*b*) Penetration of local absorbers, from which it was possible to distinguish between electrons and (μ, π).

(*c*) Degree of accompaniment by electromageic component.

(*d*) Sense of direction of the incident particle in those cases in which secondaries of reasonably high energy were generated in the absorber.

3.3. *Distinction between atmospheric muons and neutrino-induced muons*

At the depth of operation the vertical intensity of muons is about $10^{-6}\,m^{-2}\,s^{-1}\,sr^{-1}$, which is a factor of 10^{-8} down on the intensity at ground level; this provides an indication of the extent to which the flux of atmospheric muons has been attenuated in the over-burden above the detectors. Further, the intensity of atmospheric muons falls off very rapidly with increasing zenith angle, θ; the angular distribution being approximately described by $I(\theta, h) = I(0, h) \sec\theta \exp\{-9(\sec\theta - 1)\}$ at the present depth, h, of observation. The neutrinos, on the other hand, arrive fairly isotropically, with some excess towards the horizontal direction. As a result, small zenith angles are mainly populated by atmospheric muons and large angles by neutrino-induced events.

A spatial angle of 50° was adopted as the boundary beyond which it could be safely assumed that the events were due to neutrinos; and events with angles above this value are given in table 2. It will be noted that the spatial angles are not well determined in those detectors without azimuthal tubes (telescopes 1 and 2 and the spectrographs); very approximate azimuthal angles are, however, available in these cases from a knowledge of the individual scintillators traversed. This criterion of spatial angle was used only to set the boundary; for comparison with theory, those events with projected zenith angles greater than 50° have been used (table 1).

Table 2. Description of individual neutrino-induced events

	projected z.a.	penetration	event no.
(A) telescopes 1 to 5 (2-side trigger)	75°	> 6 cm Pb	3
Single muons	60° (spatial 72°)	> 45 cm Fe	30
	73° (spatial 74°)	> 32 cm Fe	36
	51.5°	> 7 cm Pb	20
multiple events			
2 diverging particles	96°, 99°	> 6 cm Pb, > 3 cm Pb	4
2 diverging particles	85°	> 6 cm Pb, > 7 cm Pb	74
3 diverging particles	96°, 335°, 48°	> 6 cm Pb, ?, interaction	29
pen. part. + cascade	85°	> 5 cm Pb	43
2 pen. particles + 2 associated particles	51°, 57°, 60°, 10°	> 8 cm Pb, > 8 cm Pb, < 3 cm Pb, ?	48
(B) telescopes 3 to 5 (o.s.t.)			
single muons			
prod. small sh. (figure 4)	94°	> 35 cm Fe	016
single muon	54° (spatial 60°)	> 42 cm Fe	093
prod. small shower	55° ± 5° (sp. 81 ± 5°)	> 35 cm Fe	073
multiple events			
dense shower	at 98 ± 10° inside detector	≳ 10 cm Fe, cascade energy > 2.5 GeV	061
3 diverging particles	at 125 ± 30° inside detector	one particle penetrates at least 50 cm Fe	070

(C) Spectrographs	projected z.a.	spatial z.a. range	momentum	sign	
†Downward muon losing energy (figure 5)	48°	48° to 54°	~ 2 GeV/c	+	S23
probably upward muon, k.o. electron (figure 6)	121°	121° to 117°	≳ 4 GeV/c	probably +	S40
downward muon, losing energy	83°	83° to 86°	1 to 2 GeV/c	+	S71
†single muon	46°	46° to 69°	> 4 GeV/c	?	S103

† Outside acceptance and not used in rate calculations—see text.

3.4. *Description of individual neutrino events*

Details relating to all events that have been attributed to neutrino interactions are given in table 2. Photographs and diagrams of some of the earlier events have already been published by Achar *et al.* (1965*b*, *c*) and Menon *et al.* (1967); and here, in figures 3 to 6 are given some of the more recent cases.

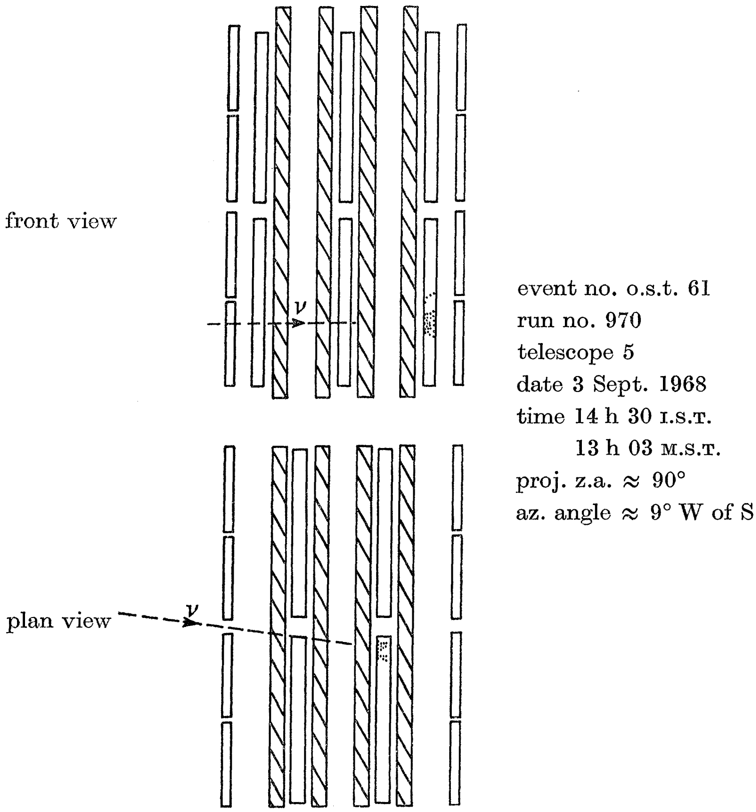


FIGURE 3. A neutrino interaction occurring inside a detector (o.s.t.).

There are two events (S 23 and S 103), observed in the magnet spectrographs, which do not definitely satisfy the condition that the spatial zenith angle be greater than 50° but are, nevertheless, probably due to neutrinos. In event S 23, the projected zenith angle is between 48° and 54° (and thus possibly below 50°) and the trajectory is due to a slow muon whose curvature in the magnet is so great that it is very likely to be neutrino-induced; atmospheric muons at this depth have a mean energy of several hundred GeV and the probability of observing such a low energy muon is very small. The other event, S 103, which has a momentum beyond the m.d.m. of the spectrograph; has a zenith angle in the range 46 to 69° and is thus, again, possibly below 50°. Both events are given in table 2 but not used in the calculations.

Despite the fact that the number of events is small (16 with projected angles above 50°), a number of interesting observations can be drawn:

(i) Upward moving events have been seen and this is a sure indication of neutrino origin. Six events correspond to upward moving particles and five to downward

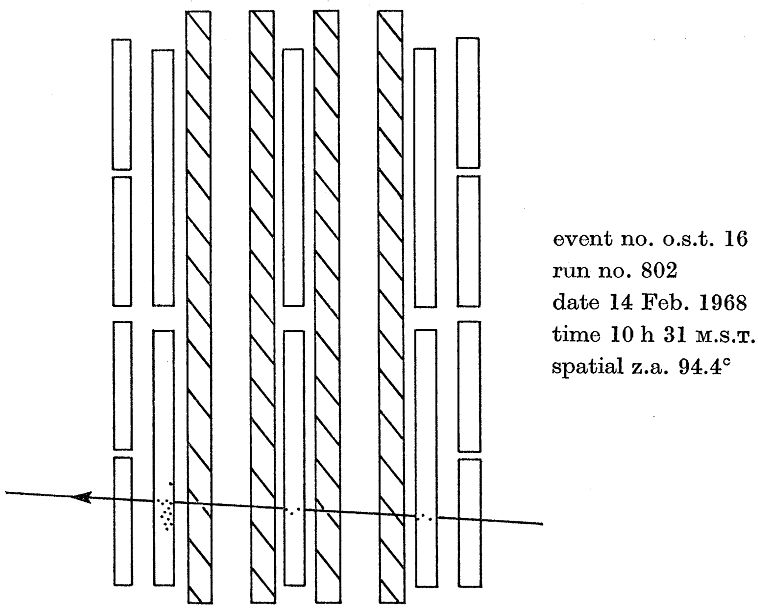


FIGURE 4. An example of an upward moving neutrino-induced muon (o.s.t.).

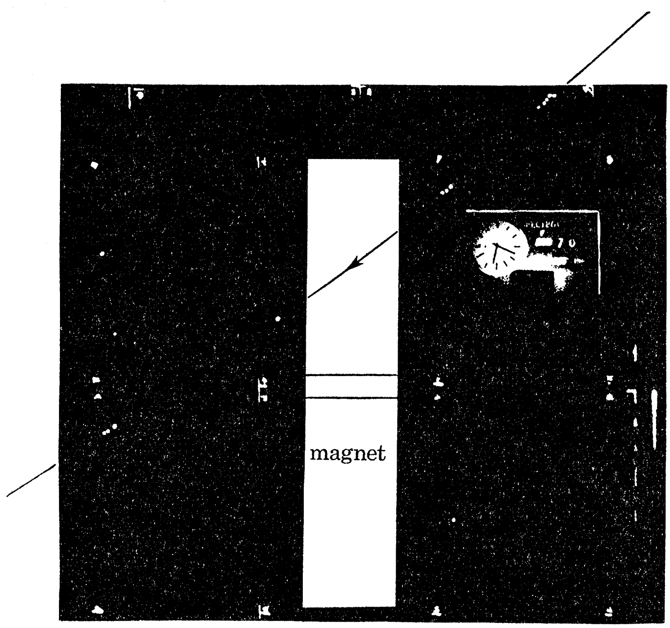


FIGURE 5. A slow downward-moving muon (event S 23, see table 2).

moving particles; there are five cases in which the direction of motion is unknown; and there is event S 23 (downward moving), already discussed in the previous paragraph.

(ii) Two of the events observed in the o.s.t. run involved neutrinos which interacted inside the apparatus; in both cases the neutrinos were upward moving.

(iii) Penetration of a considerable thickness of absorber by some of the particles indicates that there is a high probability that they were muons.

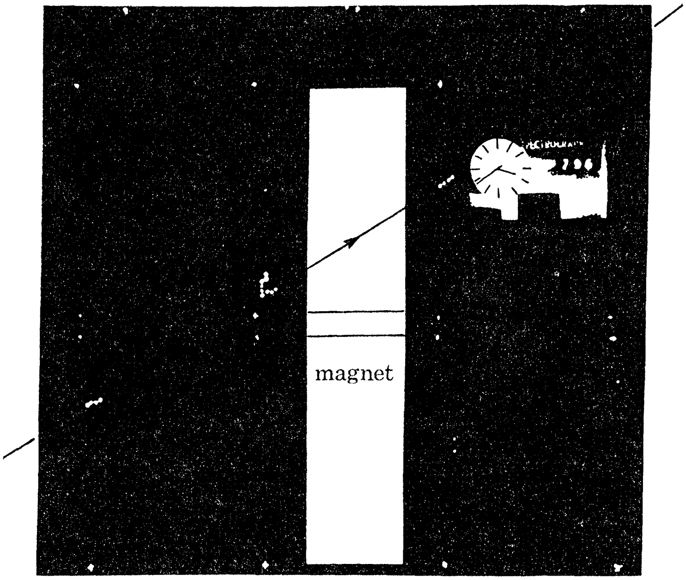


FIGURE 6. A neutrino-induced muon, probably moving upwards (event S 40, see table 2).

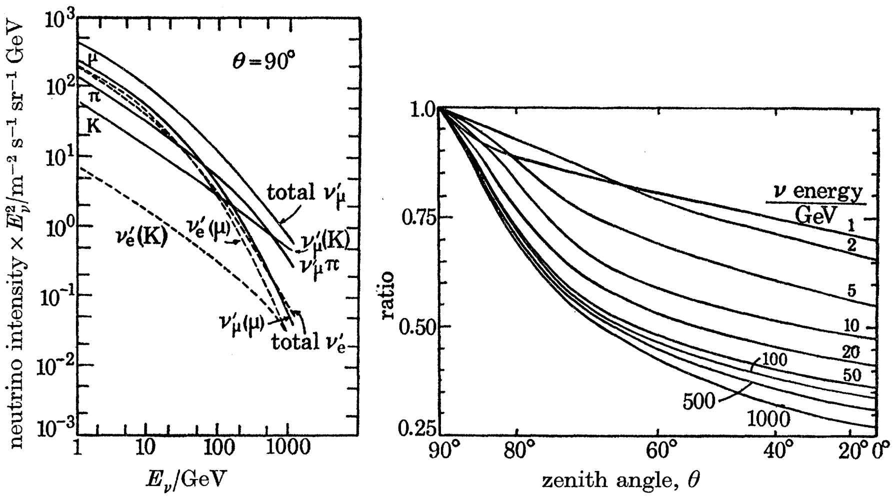
(iv) The spectrograph measurements suggest that the mean energy of the detected muons is low (less than a few tens of GeV). This result is consistent with that based on the analysis carried out by Menon *et al.* (1967), on part of the data, which showed that the frequency of production of electromagnetic showers by the neutrino-induced muons is much lower than that for atmospheric muons; in that paper the effective mean energy of the neutrino-induced muons was estimated to be below *ca.* 30 GeV and the best estimate was plotted at a value of 3 GeV.

3.5. *Intensity of detected events*

In addition to the exposure times and numbers of detected particles, table 1 gives the product of aperture and time for the neutrino-induced events. The neutrino intensity is not expected to be isotropic but is a function of zenith angle (§ 4.1 and figure 7*b*); it is larger at large zenith angles and this enhancement becomes greater with increasing neutrino energy. In obtaining the apertures necessary for the comparison of observed and expected numbers of events the variation of predicted neutrino-induced muon rate (§ 4.1 and figure 8) has been folded in with the appropriate geometrical acceptances in such a way as to give the effective apertures in the horizontal direction. In the case of o.s.t. allowance has also been made for the loss of efficiency of the scintillators at large zenith angles occasioned by the need to operate the photomultipliers at a rather low voltage to ensure that the rate due to background radioacitivity was not excessive.

The figures given in table 1 are from the angular variation shown in figure 8 for the case '$\sigma_{in} \propto E_\nu$ to 10 GeV then constant' (denoted by 'case 1'). If it transpires that this form of cross-section is not correct then the resulting muon intensity will be somewhat different. From the data of table 1 the horizontal intensity of ν-induced muons is

$$I_{\mu\nu}(\theta = 90^\circ) = (3.5 \pm 0.9)\, 10^{-9}\, \mathrm{m^{-2}\, s^{-1}\, sr^{-1}}.$$



(*a*) contributions from various decays

(*b*) intensity relative to that at 90°, as a function of energy

FIGURE 7. Energy spectra of neutrinos produced in the atmosphere, after Osborne *et al.* (1965) (ν'_μ denotes $\nu_\mu + \bar{\nu}_\mu$ and ν'_e denotes $\nu_e + \bar{\nu}_e$; in (*a*) the letter in brackets after the type of neutrino indicates the parent particle).

One may also quote an overall average intensity for spatial angles larger than 50°:

$$I_{\mu\nu}(\theta > 50^\circ) = (2.6 \pm 0.7)\, 10^{-9}\, \mathrm{m^{-2}\, s^{-1}\, sr^{-1}}.$$

This is found by dividing the number of events by the product of running time and the simple geometrical apertures of the telescopes; it is thus equivalent to postulating an isotropic flux of neutrinos. Clearly it is of value only for comparing with data from other experiments having very similar geometry.

4. Comparison between the expected and observed rates of neutrino interactions

If the large angle events are assumed to be due to the secondaries of neutrino interactions, which is the most reasonable assumption, then some conclusions can be drawn about the form of the neutrino-nucleon cross-section at high energies by comparing the observed numbers of events with expectation for different types of neutrino interactions and corresponding cross sections. A necessity is the energy spectrum of ν_μ and $\bar{\nu}_\mu$ and some discussion of this quantity is desirable.

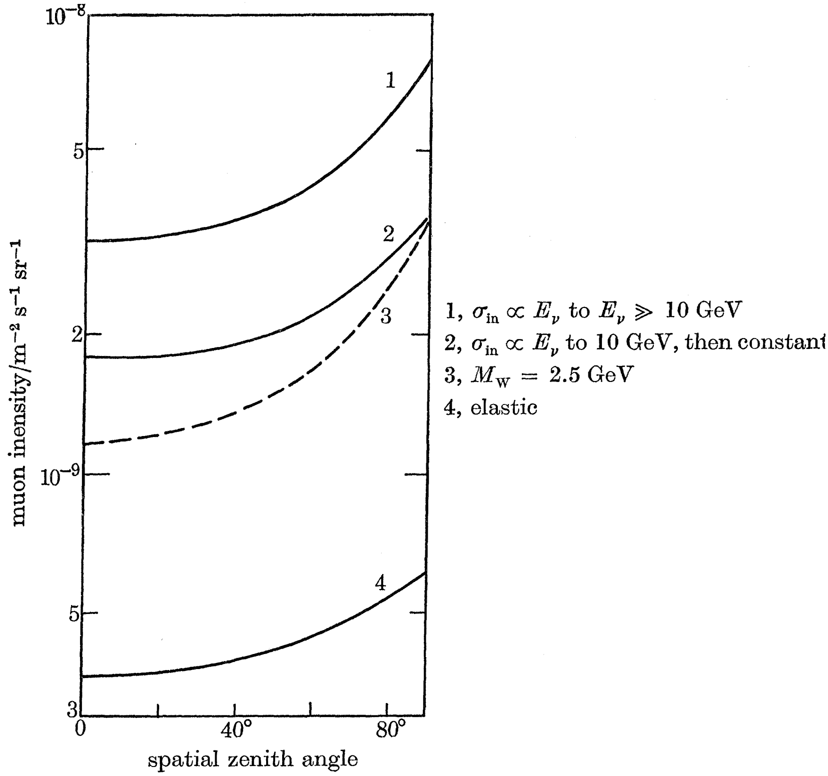


FIGURE 8. The predicted angular variation of the neutrino-induced muon intensity.

4.1. *The energy spectrum of neutrinos*

In the absence of unexpectedly large fluxes of extra-terrestrial neutrinos the vast majority of those detected underground will have come from the various decays of the secondary cosmic ray component in the atmosphere, notably from the decays

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \pi^- \to \mu^- + \bar{\nu}_\mu,$$
$$K^+_{\mu 2} \to \mu^+ + \nu_\mu, \quad K^-_{\mu 2} \to \mu^- + \bar{\nu}_\mu,$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu, \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu.$$

A variety of cosmic-ray data are used in calculating the expected spectra, notably the sea level muon spectrum as a function of angle and the muon charge ratio, these measurements being used to determine the production spectra of the pions, kaons and muons in the atmosphere. Calculations have been reported by a number of authors, the most comprehensive being those of Cowsik *et al.* (1963, 1966) and Osborne *et al.* (1965). The results of the latter authors for the important case of horizontally arriving particles are shown in figure 7*a*. The relative contributions to the neutrino intensity from the various decays are indicated; it is seen that in the important region of energy 1 to 100 GeV a significant fraction of the neutrinos come from μ-decay. The variation with zenith angle of the total neutrino intensity is shown in figure 7*b*.

It has been assumed in these calculations that the majority of the particles generated in the high energy nucleon-air nucleus collisions are pions; to be specific the ratio of kaons to pions (of the same energy) has been assumed to be 20 %. This assumption is not very well founded but fortunately the neutrino spectrum is not very sensitive to small changes in the K/π ratio; for example, at $E_\nu = 50$ GeV an uncertainty of ± 20 % in the K/π ratio would cause an error in the neutrino intensity of ± 10 % in the horizontal direction and *ca.* ± 30 % in the vertical direction (see Osborne *et al.* 1965). Large changes in the K/π ratio will of course, affect the spectrum significantly.

4.2. *Neutrino interation mechanisms*

4.2.1. *Processes*

Neutrinos interact through both elastic and inelastic processes:

(i) Elastic $\nu_\mu + N \rightarrow N' + \mu$

(ii) Inelastic $\nu_\mu + N \rightarrow N' + \mu + \pi$'s etc.,

and, if the intermediate boson, W, exists:

$$\nu_\mu + N \rightarrow N + \mu + W \quad \text{(incoherent production)},$$

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

and also $\bar{\nu}_e + e^- \rightarrow W^-$ (Glashow resonance).

As can be seen, muons are generated in all of these interactions (and a further muon can arise in the leptonic decay of the W); and all of these can, in principle, contribute to the flux of detected muons. Furthermore, the pions from inelastic interactions should be detectable.

4.2.2. *Information from accelerator experiments*

From the experiments carried out at the high energy accelerators (Argonne, Brookhaven and C.E.R.N.) information is available concerning the types of neutrino interactions, and the corresponding cross-sections, up to energies of *ca.* 10 GeV. In previous reports, we have used the accelerator data that was then available. For the present analysis, we have adopted the latest C.E.R.N. data (Budagov *et al.* 1969) shown in table 3. It should be emphasized that the interactions studied in the accelerator experiments are primarily based on ν_μ beams; $\bar{\nu}_\mu$ – interactions have not yet been examined, except in the case of the elastic process.

In the elastic cross-section, differences are predicted below *ca.* 1 GeV but both cross-sections reach the same asyptotic limit a little above 1 GeV, which is well within the energy range accessible in the current accelerator experiments. Experimental observations with regard to the elastic interaction of ν and $\bar{\nu}$ are in good agreement with theoretical predictions.

In the case of inelastic interactions, there have been suggestions (Gross & Llewellyn-Smith 1969) that the cross section for $\bar{\nu}-\mathrm{N}$ may be, on the average, one-third of that of $\nu-\mathrm{N}$ at high energies. However, coupled with the smaller cross-section is the prediction that the fraction of energy taken by the muon (f) should be greater; and the net result is that the muon yeilds from the sum of ν_μ and $\bar{\nu}_\mu$ interactions will only be about 30 % less than that calculated for the adopted case of $\sigma_\nu = \sigma_{\bar{\nu}}$ with $f_\nu = f_{\bar{\nu}}$. Bjorken & Paschos (1970) have shown that a difference in ν and $\bar{\nu}$ total cross-sections is characteristic of the parton-models that have been discussed in connexion with electroproduction results from SLAC in the deep inelastic continuum. They estimate that $\sigma_{\bar{\nu}}$, total $\lesssim (0.7 \pm 0.1)\,\sigma_{\nu\,\mathrm{total}}$ when the cross-sections are averaged over neutron and proton targets.

TABLE 3. CHARACTERISTICS OF ν_μ INTERACTIONS FROM THE C.E.R.N. MEASUREMENTS FOR $1 \lesssim E \lesssim 10$ GeV

interaction	cross-section	mean fraction of energy taken by muon, f
elastic	$(0.6 \pm 0.2)\ 10^{-38}\ \mathrm{cm}^2$ per n – p pair	0.95 ± 0.05
inelastic ($N^*_{\frac{3}{2}\frac{3}{2}}$ production only)	$(1.13 \pm 0.28)\ 10^{-38}\ \mathrm{cm}^2$/proton	0.75
all processes (elastic + inelastic)	$(0.8 \pm 0.2)\ E_\nu\ 10^{-38}\ \mathrm{cm}^2$/nucleon	0.54 ± 0.06

4.2.3. *The situation at neturino energies above* 10 GeV

From the accelerator experiments we know that the inelastic cross-section rises linearly with the neutrino energy up to an energy approaching 10 GeV. What happens beyond has been the subject of speculation. Lee (1961) has shown that the cross-section for $\nu-\mathrm{N}$ collisons at high energies, which might have been expected to rise linearly with E_ν, will instead be of the form $\sigma(E_\nu) \propto E_\nu^{\frac{1}{2}}$ in view of strong interaction effects. More recently however, Bjorken & Paschos (1970) have suggested that the cross-section for $\nu-\mathrm{N}$ collisions may rise linearly to very high neutrino energies, a suggestion that comes from the new experimental data on electron–proton scattering, involving high q^2- and high energy transfers to the hadron system, which indicates a point-like structure for the nucleon.

For our calculations relating to the expected number of events in the present experiment a variety of assumptions have been made about the form of the inelastic cross-sections above 10 GeV. If there is no intermediate boson it is simply assumed that the inelastic cross-section continues to rise linearly with neutrino energy up to a particular cutoff energy. Above this energy the cross-section remains constant and the muon takes practically all of the neutrino energy. In figure 10 the predicted numbers of events are given for cutoff energies at 10 and 100 GeV, and for the case of no cutoff. Allowance has been made for the uncertainties in the predicted numbers by taking into account the errors in the machine data (table 3), amounting to ± 27 % and the uncertainty, ± 10 % in the energy spectrum of neutrinos in the important energy region.

If the intermediate boson exists there will be contributions to the total rate both from the elastic and inelastic processes and from the production of the boson in the Coulomb field of the nucleus. In this case the predictions of scale invariance (Bjorken & Paschos 1970), are followed, i.e. that the inelastic cross-section rises

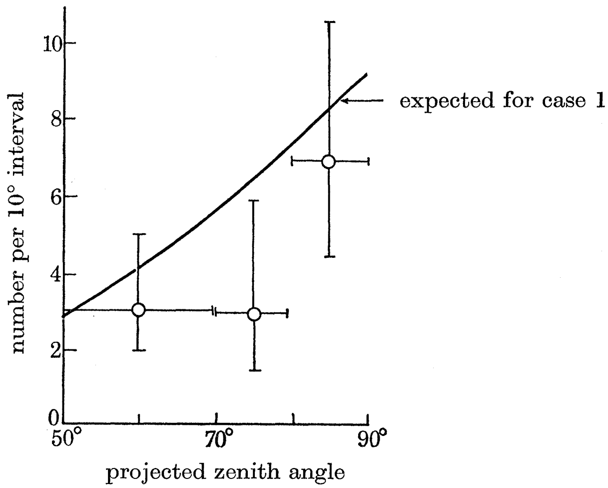


FIGURE 9. A comparison of the measured angular distribution of neutrino-induced events with prediction.

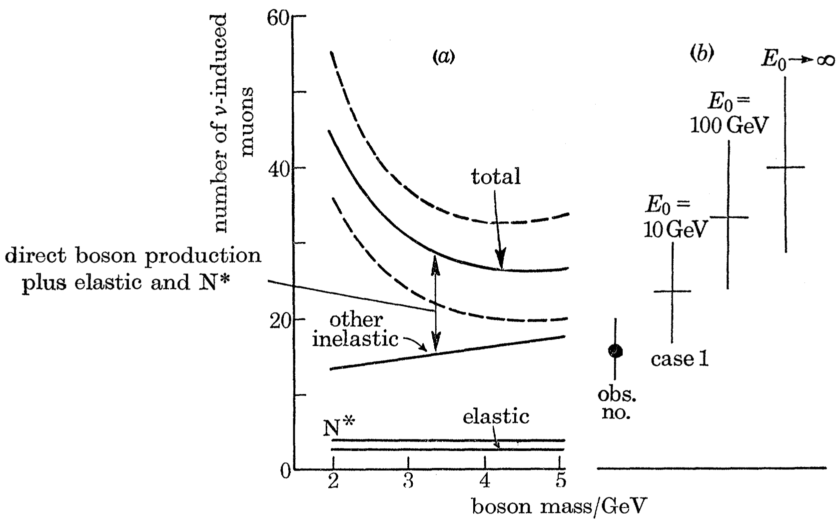


FIGURE 10. Comparison of the observed number of neutrino-induced events with expectation for the various interaction processes and for a number of assumptions. Uncertainties, to the extent of ± standard deviation are shown on the total expected numbers. The cosmic ray neutrino spectrum adopted is that given in figure 7.

linearly up to $E_\nu \approx M_W^2/2M_P$; for higher energies the boson causes a reduction in the rate of increase of the cross-section because of the propagator term $(1+q^2/M_W^2)^{-2}$ and at very high energies, $E_\nu \gg M_W^2/2M_P$, the total inelastic cross-section will be given by $\sigma_{tot} \propto \ln(2M_P E_\nu/M_W^2)$. The result is that the predicted number of muons from inelastic interactions increases with boson mass. It should be emphasized, however, that a reduction in the rate of growth of the cross-section for neutrino interactions at a particular energy does not necessarily imply the existence of the intermediate boson of a corresponding mass.

In predicting the number of muons from intermediate boson production some changes have been made in the numerical values we had used earlier (Menon *et al.* 1967). The cross-section continues to be the same in that they come from the work of Wu *et al.* (as quoted by Burns *et al.* 1965), and of Von Gehlen (1963), but an allowance has been made for an uncertainty of ± 20 % on the values. M. Veltman (1969, private communication) has calculated the fraction of neutrino energy retained by the prompt muon, for a boson mass of 1.8 GeV, for neutrinos of energy 100 to 1000 GeV interacting with copper nuclei. For $E_\nu = 100$, 400 and 1000 GeV the average values for $f(= E_\mu/E_\nu)$ are 0.13, 0.17 and 0.21 respectively. In the light of these calculations we have taken the fraction applicable here to be 0.14 ± 0.05. This is greater than the threshold values taken by Menon *et al.* (1967), but still well below the asymptotic value ($f \approx 0.6$) as derived from the expression of Lee (1961), which clearly is not applicable for the energy range of importance in the present investigation. In calculating the number of muons from the decay of the boson a range of values of the leptonic branching ratio from 0.5 to 0.9 has been used compared to the previously assumed value of 0.8. As before it is assumed that the boson has no anomalous magnetic moment. In figure 10 the predicted number of events is given for values of boson mass 2 to 5 GeV. The number of muons from boson production falls with increasing mass and is barely significant compared to the inelastic contribution above $M_W = 4$ GeV. The total number passes through a broad minimum between $M_W = 4$ and 5 GeV.

4.3. *Comparison with observations*

Figure 10 gives a summary of the expected numbers of neutrino induced muons for the different assumptions concerning the cross-sections, the individual contributions of the various interaction processes being shown.

Also shown in figure 10 is the observed number of events; a comparison with the expected number of events brings out the striking fact that the uncertainties on the latter numbers are bigger than the statistical error on the former. This affects the conclusions that can be drawn.

If the boson does not exist, this comparison appears to suggest that the inelastic cross-section reaches its limiting values not much above 10 GeV. However, if one wishes to set an upper limit to the cutoff energy at a 95 % confidence level, it is found that it is just possible to obtain agreement with the predicted number for the case of no cutoff.

If the boson exists then one can say with 95 % confidence that its mass is greater than 3 GeV. The best value for the boson mass is 4.5 GeV, but with this mass the predicted number is still 1.3 standard deviations bigger than the observed number. The predicted numbers have been calculated using a neutrino spectrum obtained from the sea level muon spectrum assuming that the K/π ratio is 20 %; this is the most probable value. If one assumes, however, that muons and neutrinos, of energies relevant to our experiment, come from pion decay only then the predicted numbers will be reduced, typically by 18 %. The lower limit on the boson mass will be correspondingly reduced to 2.5 GeV. Finally, the smaller cross section predicted for $\bar{\nu}$ interactions would also lead to a lower limit of 2.5 GeV for the mass of the W-boson.

4.3.2. *Neutrino-induced multi-track events*

In this experiment we have observed a comparatively high frequency of multiple-track neutrino-induced events, i.e. five such in a total of 11 events; we discount the o.s.t. data for which the efficiency for the detection of multi-track events is not well known. This high frequency, 45 ± 20 %, is somewhat hard to understand on a conventional basis, since a straightforward estimate shows that only 10 % of the detected events should show pionic accompaniment with the muon for case 1. Phenomenologically it can of course be proposed that the fraction of energy, f, falls with increasing energy above 10 GeV, and that there is also a continuously increasing inelastic cross-section. Such a situation can be envisaged in the case of production of W-bosons of reasonably large mass, where the value of f as given by Veltman (1969) is small ($f \approx 0.14$) and the cross-section rises steadily up to very high energies. In the case of point interactions, however, it is difficult to understand (Bjorken 1970) how f can decrease gradually or have such a small value.

An intriguing feature of the multi-track events is that their points of origin lie very close to the detector. Events 4 and 43, with two and three penetrating particles respectively, originated inside the rock at a depth between about 0 and 4 m. The other three events, nos. 29, 48 and 74, had their points of origin very close to the detector system, lying close to the rock surface, or in the structural elements of the detector or even in the air or in the detector elements themselves. (Incidentially, events no. 70 of o.s.t., in which the interaction was due to an upward moving neutrino, also had its point of origin just at the rock surface or in the air). We believe that this aspect may be quite significant.

4.3.3. *Angular distribution*

Figure 9 shows the experimental data on the angular distribution of neutrino-induced muons plotted for rather large cells of angle; projected angles have been used for this analysis and the data from all the detectors have been added; the expected numbers were derived for the various acceptances of the respective detectors. It can be seen that there is rough agreement in the shapes of the observed and expected distributions, indicating that the interpretation of the detected events in terms of neutrino interactions is largely correct, although the data are not sufficiently precise to enable a distinction to be made between different forms of cross-sections.

4.3.4. *Charge ratio of neutrino-induced muons*

In view of the presumed sources of the neutrinos in the various decays in the atmosphere a negative excess is expected among the neutrino-induced muons, the actual magnitude of the excess depending on the zenith angle of incidence and the exact composition of the parents of neutrinos. To be specific, for a K/π ratio of 0.2, for neutrinos of energy $\sim$ 100 GeV, and at a zenith angle 90°, the charge ratio μ^-/μ^+ is expected to be $\sim$ 1.7. These considerations are valid only for the case in which the cross-section for neutrinos and antineutrinos are equal. However, if one allows for the possibility mentioned earlier regarding inelastic cross-sections for νN and $\bar{\nu}$N interactions, i.e. in the limiting case $\sigma_{\text{inel}}(\bar{\nu}\text{N}) = \frac{1}{3}\sigma_{\text{inel}}(\bar{\nu}\text{N})$, the negative excess would be amplified accordingly. Unfortunately, the sample of events at our disposal (two positive, one probably positive and one uncertain) is too small to draw any definite conclusion about this aspect.

4.4. *Comparison with the Case–Wits–Irvine experiment*

Groups from the Case Institute of Technology, University of Witswatersrand and the University of California (Irvine), have jointly carried out an experiment deep underground at *ca.* 3200 m in the E.R.P. Mines near Johannesburg in South Africa. Their aim, like ours, was to detect muons generated in the interaction of cosmic ray neutrinos in the rock surrounding their apparatus. They have employed two vertical walls, of total area $\approx$ 100 m^2, of liquid scintillator separated by *ca.* 1.8 m. They did not employ visual detectors or absorbers in their detector assembly.

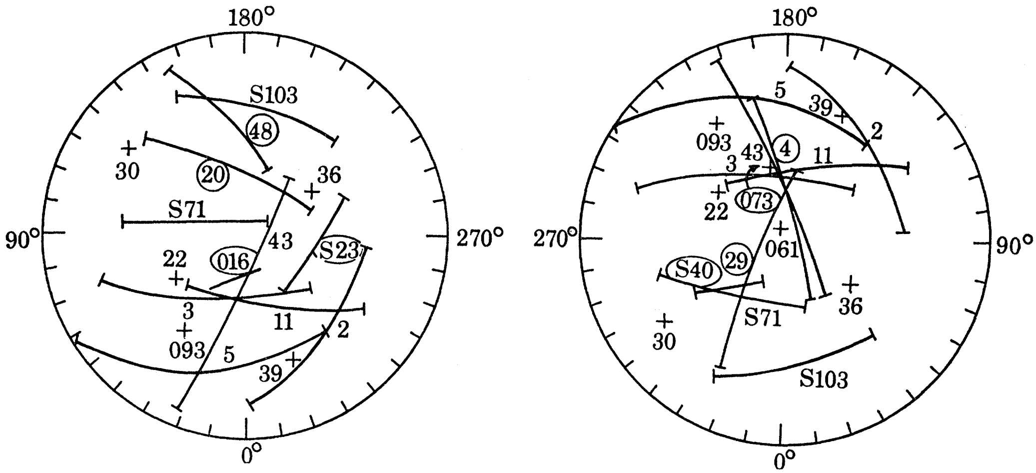
From their measurements, Crouch *et al.* (1970) have given the intensity of neutrino-induced muons as $(3.7 \pm 0.6)\ 10^{-9}\ \text{m}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ assuming an isotropic distribution. If the distribution were isotropic the value would be directly comparable with our own value of $(2.6 \pm 0.7)\ 10^{-9}\ \text{m}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ quoted in § 3.5. As it is, with the angular distribution of neutrinos peaked towards the horizontal direction and the differing angular acceptances of the detectors at the two locations a small difference in the intensities would be expected, our own intensity being the smaller.

It is satisfying that these two experiments performed by two different groups on events with rather rare occurrence have yielded results that are consistent to the extent indicated.

5. Celestial coordinates of the detected events

Although the flux of extraterrestrial neutrinos in the GeV region is expected to be very small compared with that of atmospheric neutrinos, it is obvious that it cannot be ruled out *a priori* that some of the detected neutrinos arise from cosmic sources. In so far as the muons appear to have energies of the order of a few GeV they will have preserved the initiating neutrino directions to within a few degrees and the celestial coordinates of the muons will thus represent possible coordinates of their parent neutrinos.

The celestial coordinates of events with projected zenith angles greater than 45° are plotted in figure 11. Events in telescopes 1 and 2 and in the spectrographs give arcs rather than points because of the large uncertainty in aximuth; whereas in the case of events in telescopes 3, 4 and 5, the spatial angles are defined with a precision of $\pm 1°$. Where the sense of direction of the muon is known, i.e. if a knock-on shower is produced or if the muon arises from an observed inelastic interaction, then the arc can be plotted in the relevant celestial hemisphere. These events are shown ringed in figure 11. For many events, however, the sense of direction is not known and an arc must be plotted in each hemisphere.



(*a*) Northern Celestial Hemisphere (*b*) Southern Celestial Hemisphere

FIGURE 11. Celestial coordinates of the neutrino-induced events. (*a*) refers to the predicted contributions for the case where the intermediate boson exists and (*b*) gives the predictions for the case of no boson; E_0 is the neutrino energy at which the linear rise in the inelastic cross-section terminates.

In the Southern Hemisphere four of the arcs intersect in a rather small circle of confusion—an occurrence which has a chance probability of 10^{-3}. However, an examination of the 15 likely cosmic ray sources in this hemisphere (strong radio sources and pulsars), shows that none is in the vicinity. Turning to the Northern hemisphere, three of the arcs which cross in the other hemisphere are reflected because of uncertainty in the sense of direction, and there is thus an equivalent small area of intersection there. 3C 10 (Tycho Brahe's Supernova) is within 1 or 2° of this intersection, but with the inherent uncertainties in locations it is difficult to place confidence in a grouping of this type. Further, we see no evidence for any such grouping in regions populated by other brighter supernovae. It is therefore most likely that the grouping near 3C 10 is due merely to chance. It is hoped that future experiments will examine this aspect of cosmic ray neutrino studies carefully.

6. Conclusions

From our experiment we can draw the following conclusions:

(1) A number of unambiguous cases have been recorded of cosmic ray neutrino-induced muons. Clear cases have been seen of upward moving neutrino-induced muons and of neutrino interactions within the detector assembly itself.

(2) The observed rate of neutrino-induced events is consistent within the errors with that expected on the basis of the estimated flux of cosmic ray neutrinos and their cross-section for interaction; concerning the latter there are several uncertainties (in the extrapolation from accelerator energies to higher energies and in estimating the fraction of energy given by the neutrino to the muon). It is of interest that uncertainties in the expected numbers are at present larger than uncertainties in the observed numbers.

To be more specific about the form of the inelastic cross-section, the observed rate is consistent with the assumption that the cross-section rises linearly up to energies of the order of 10 GeV, in agreement with the accelerator results, and saturates thereafter. The present results do not, however, definitely preclude the possibility that the cross-section rises linearly up to very high energies.

(3) If the W-boson exists, its mass must be larger than 3 GeV.

(4) An important aspect of the present observations is that, among the events recorded, there is an unexpectedly large fraction of neutrino-induced multi-track events; this aspect needs further careful consideration.

(5) It is satisfying that two different experiments (at Kolar and in South Africa) have yielded results which are consistent with one another within statistical accuracy.

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