Proc Indian Natn Sci Acad, **70, A,** No.1, January 2004, pp.11–25
© Printed in India.

PERSPECTIVES OF EXPERIMENTAL NEUTRINO PHYSICS IN INDIA

V S NARASIMHAM
Tata Institute of Fundamental Research Mumbai 400 005 (India)

(Received 10 February 2003; Accepted 30 June 2003)

A description of the early work on experimental observation and study of cosmic ray neutrinos in India is sketched here. This includes experiments to measure the variation of intensity of cosmic ray muons down to great depths underground, the first detectors for neutrino detection, and the consolidation of neutrino data using large scale proton decay experiments. Also included is a brief description of special (Kolar) events recorded in the KGF detectors, that defy explanation on the basis of normal muon or neutrino interactions. Results from the neutrino experiments conducted in other laboratories around the same time period as well as those recorded in all the first-generation proton decay experiments will be reviewed briefly.

Key Words: Cosmic Rays; Kolar Gold Fields; Underground Experiments; Neutrino Detectors; Atmospheric Neutrinos; Kolar Events; Proton Decay

1 Introduction

Primary Cosmic Radiation (PCR), the only source of high energy elementary particles until the advent of accelerators in the early 1960s, was the subject of intense study at a number of laboratories around the world including those in India, and in particular at the Tata Institute of Fundamental Research, Mumbai (TIFR). The detection media used were nuclear emulsions flown at balloon altitudes (at Hyderabad) and triggered cloud chambers operated at mountain altitudes (at Ooty), to study the composition of primary cosmic rays and secondary hadron interactions respectively. This was closely followed by extensive air shower (EAS) studies using a network of scintillation detectors arranged in an array at both sea-level and at mountain altitudes.

This led to the study of hadron collisions at ultra high energies which are not available from accelerator beams, by a detailed simulation and comparison with the EAS data on electrons, muons and hadrons. A different path was taken in the study of cosmic ray muons in the early 1950s. The Kolar Gold Fields (KGF) provided an ideal environment to study muons at different depths underground and thereby allowed the study of their energy spectrum and angular distributions up to very high energies, much beyond what was possible with magnet spectrometers operated at sea level.

It has long been recognized that the secondary cosmic radiation is a rich source of neutrinos with a wide range of energies. This was based on the understanding that cosmic ray secondaries comprise high energy pions and muons and their decays in the Earth's atmosphere provide a copious source of neutrinos. The first suggestion that cosmic ray neutrinos could be detected by experiments operated deep underground was made in 1960 by Markov and his collaborators. An estimate of fluxes was made by Greisen[1], and detailed calculations on fluxes and angular distributions were first made by Zatsepin and Kuzmin[2] with pions and muons as the source of neutrinos. Some of these authors talked of installations of area 300 m^2 or 10 m^3 in volume but felt that some idea of cross-section was necessary and one should await the results of the then planned accelerator experiments.

It was only from the accelerator experiment of Danby et al.[3] at Brookhaven, that one became aware of the distinction between the muon and electron neutrinos and of the large cross-section for ν-N interactions at a few GeV. Detailed estimates of fluxes of muon and electron neutrinos and anti-neutrinos from all possible decay modes of kaons, in addition to those from pions and muons, were made by Osborne et al.[4] and Cowsik et al.[5]

At the Kolar Gold Mines, a detailed mapping of

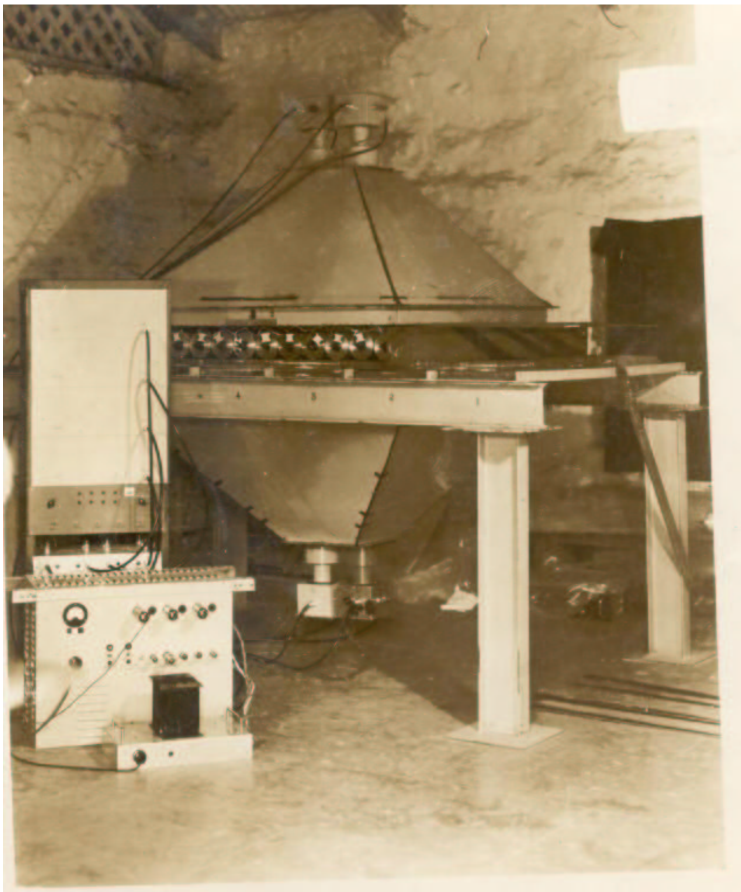


Fig. 1 The scintillator-lead-GM counter telescope used at great depths in KGF mines. A coincidence of pulses from PMTs viewing the two scintillators and the sandwiched GM counter array provided the signal with negligible background.

Table I
Summary of muon measurements by MNR experiment in KGF mines.

Depth from surface in meters	Depth from the top of the atmosphere (mwe)	Time of observation: Hrs. Mins.	Number of counts observed	Counting rate in counts/hr
270	810	60 - 20	10,152	168.3 ± 1.7
800	1812	100 - 28	1,029	10.23 ± 0.32
1130	3410	211 - 45	142	0.67 ± 0.056
1415	4280	944 - 06	127	0.132 ± 0.012
2110	6380	2992 - 40	18	$(6.0\pm 1.4)\times 10^{-3}$
2760	8400	2880 - 00	none	$< 3.47 \times 10^{-3}$

cosmic ray muons as a function of depth and angle was undertaken since 1960 in a series of experiments by Miyake, Narasimham and Ramanamurty up to $\sim$ 3 km below ground. It was clear that the muon fluxes attenuate rapidly with depth and are so low at the great depth of 8400 hg/cm^2, that no count was recorded for 2 months in detectors of area 3 sq. meters. This paved the way for a realistic estimate of the muon background for a possible neutrino detector using the advantage of great depths for unambiguous detection of events from neutrino interactions (see Menon et al.[6]). This was indeed the starting point for the neutrino experiments conducted in KGF, India, and in the ERPM mines in South Africa during 1965.

2 Cosmic Ray Muons

A brief description of the muon experiments at KGF will be useful to understand how the neutrino experiments evolved in a natural manner.

The KGF mines are situated at 870 m above sea level at a latitude of 12°54′N near Bangalore, South India; it has a flat surface topography (±40m) over a 3 km × 3 km area around the main shaft of the Champion reef mine. The mines have an extended network of tunnels underground permitting observations at a series of depths down to 3 km, i.e., 8400 hg/cm^2 of Kolar rock. The Kolar rock has special characteristics in terms of density (3.02 g/cm^3), and chemical composition i.e. $\langle Z/A \rangle = 0.495$ and $\langle Z^2/A \rangle = 6.4$ when compared to the so-called standard rock (0.5, 5.5 respectively). The first experiments on depth variation of muon fluxes at KGF were conducted by Sreekantan et al.[7] up to depths of 900 hg/cm^2. At KGF, 1 hg/cm^2 is equivalent to approximately 30 cm of rock thickness.

A new series of TIFR experiments was started in 1961 by Miyake, Narasimham and Ramanamurty[8](MNR) covering depths ranging from 816 to 8400 hg/cm^2. They employed a scintillation counter-lead telescope of area 1.62 m^2 in a 4-fold coincidence mode of photomultipliers (PMT's) and added another similar unit (with an extra layer of GM counters) to increase the rate of collection of muons at depths of 6380 and 8400 g/cm^2. A picture of the detector is shown in Fig. 1. Table I provides some details of the data collected in these experiments (Miyake et al.[10]). The counting rates were converted to actual fluxes by taking account of the aperture and the angular distribution of muons at each depth of observation. The angular distribution was known only for the very shallow depths at that time and one had to infer it for great depths from the Depth vs Intensity relation of muons.

The angular distributions of muons were measured at KGF by a TIFR–Durham University experiment (Achar et al.[9]) using neon flash tubes (glass tubes of 1 cm diameter, 2 m long, filled with spectroscopic neon and sealed) as visual track detectors; they had a resolution of approximately 10° in the projected zenith angle of the tracks. The angular distribution was measured at depths of 816, 1812 and 4100 hg/cm^2 and found to be consistent with those derived indirectly from depth-intensity variation. See Fig. 2. This was indeed the starting point to use a visual detector at KGF in the study of cosmic rays at great depths. Neon flash tube arrays were used in all experiments conducted at KGF subsequently, until proportional counters in large numbers were employed in the massive proton decay experiments during 1980.

While the angular distribution could be expressed as $I(\theta) = I(0) \cos^n \theta$ for shallow depths, the exponential depletion of flux at great depths is more accurately expressed as $I(h, \theta) = I(h, 0) \sec \theta \exp[-n(\sec \theta - 1)]$. At the depth of 7000 hg/cm^2 , the exponent $n = 9 \pm 0.5$, a fact that is crucial in the identification of neutrino events to be discussed in the next section.

3 Neutrino Experiments at KGF

The no-count observation of the experiment of Miyake et al.[10] at the depth of 8400 hg/cm^2 led to the conclusion that the atmospheric muon intensity has been attenuated to such an extent that one could search for rare processes like the interaction of high energy neutrinos of the cosmic ray beam. However, with the measured cross-section up to 10 GeV and the estimated fluxes of all neutrinos, it was clear that at least a few kilotons of target would be required to record a few neutrino interactions per year. On the other hand, one could detect the muons produced in the charged current neutrino interactions in the surrounding rock by using modest detector arrays of large area. The target material available in such a case depends upon the range of the muon inside the rock, which is proportional to the muon (neutrino) energy. Furthermore, one could suppress the residual atmospheric muon background by utilizing the widely different features of the angular distributions. While atmospheric muons have a steep distribution with a peak in the vertical direction, the neutrino-induced muons have a nearly isotropic distribution but with an energy-dependent excess in the horizontal direction. This feature was exploited in designing the detector arrays as horizontal telescopes, which provided maximum sensitivity for detection of neutrino events.

Very little was known at this time from the accelerator experiments about neutrino interactions at energies beyond a few GeV and the success of cosmic ray experiments indeed depended heavily on the predictions on the cross-section at higher energies and the details of interactions. The neutrino-interactions studied at accelerators (ANL, BNL and CERN) in the early 1960s were based primarily upon ν_μ beams; $\overline{\nu}_\mu$ interactions were not studied as also the ν_e and $\overline{\nu}_e$ processes. The ν_μ cross-sections measured at CERN upto 10 GeV and the mean fraction, f, of muon energy in charged current processes can be summarized as follows[13]:

- *Elastic:* $(0.6 \pm 0.2) \times 10^{-38}$ cm^2 per n-p pair, $f = 0.95 \pm 0.05$.

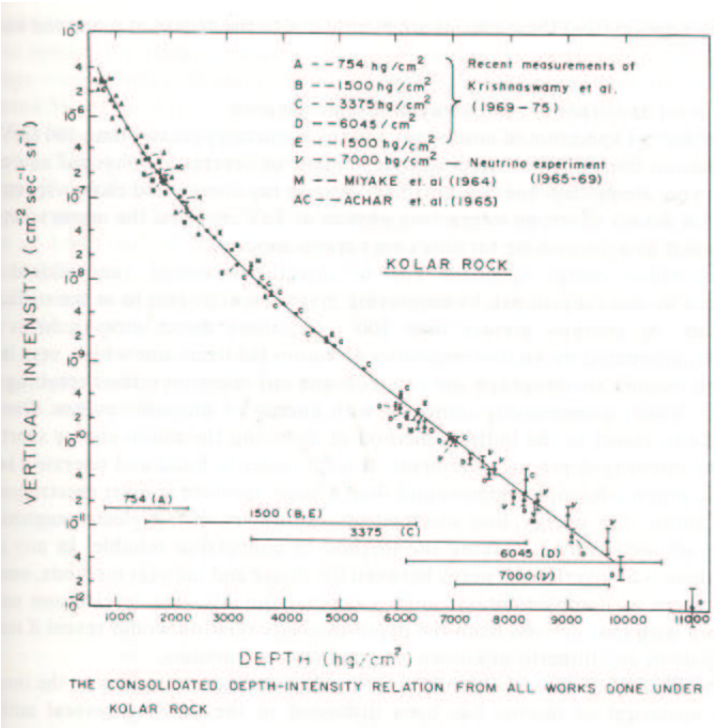


Fig. 2 Depth vs. Intensity plot from all experiments conducted at KGF until 1970. Many points in this plot were extracted from angular distributions assuming that only pions and kaons are the parents of muons.

- *Inelastic* ($N^*_{3/2\ 3/2}$ production): $(1.13 \pm 0.28) \times 10^{-38}$cm^2 per proton, $f = 0.75$.

- *All (elastic + inelastic):* $(0.8 \pm 0.2) \times E_\nu \times 10^{-38}$ cm^2 per nucleon, $f = 0.54 \pm 0.06$.

The atmospheric neutrino fluxes—muon and electron types and their anti-particles—had been estimated in detail by this time using specific interaction models (Cowsik et al.[5]) or working back from the observed energy spectrum of muons to the production spectra of pions and kaons in the collisions of cosmic rays in the Earth's atmosphere[4]. The fluxes and their angular distributions as a function of energy, as estimated by Osborne et al., are shown in Fig. 3.

The principle of detection of neutrino events was to a) deploy detectors at great depths underground, b) maximize the exposure and suppress the residual atmospheric muon component by employing horizontal telescopes or of a rail-geometry, and c) search for muons generated by neutrino interactions in surrounding rock, at large zenith angles, using visual detectors. The target mass is provided by the rock and its weight depends on the range of a muon produced in neutrino-interactions; this in turn depended on the muon energy whose fraction, f, in the interaction is related to the processes at play, as given above.

The rate of neutrino interactions inside the rock can be expressed as follows:

$$I^i(\theta)d\theta = \int_{\text{th}} F^i(E_\nu, \theta)\mathrm{d}E_\nu \mathrm{d}\theta \times \sigma(E_\nu) \times R^i[E/f_i] \times N_{\text{Av}} \times \rho \ ,$$

where θ is the zenith angle of neutrinos; i is the flavour index–$\nu_e, \nu_\mu, \overline{\nu}_e, or \overline{\nu}_\mu$; σ is the cross-section; f is the fraction of energy transferred to leptons; R is the range of muons in g per cm^2 ; N_{AV} is the Avagadro number and ρ is the density of rock. The lower limit 'th' is the trigger level for each of the detectors.

KGF Neutrino Detectors

The neutrino experiment at KGF was conducted by groups from TIFR, India, Durham University, UK, and Osaka City University, Japan, using techniques perfected over the years for the muon experiments described in Section 2, i.e., basic trigger with scintillation counters and Neon Flash Tubes (NFT) for tracking detectors. Seven detectors were deployed in a long tunnel at the depth of 2.3 km in the Heathcote shaft of Champion reef mines, in three batches spread over

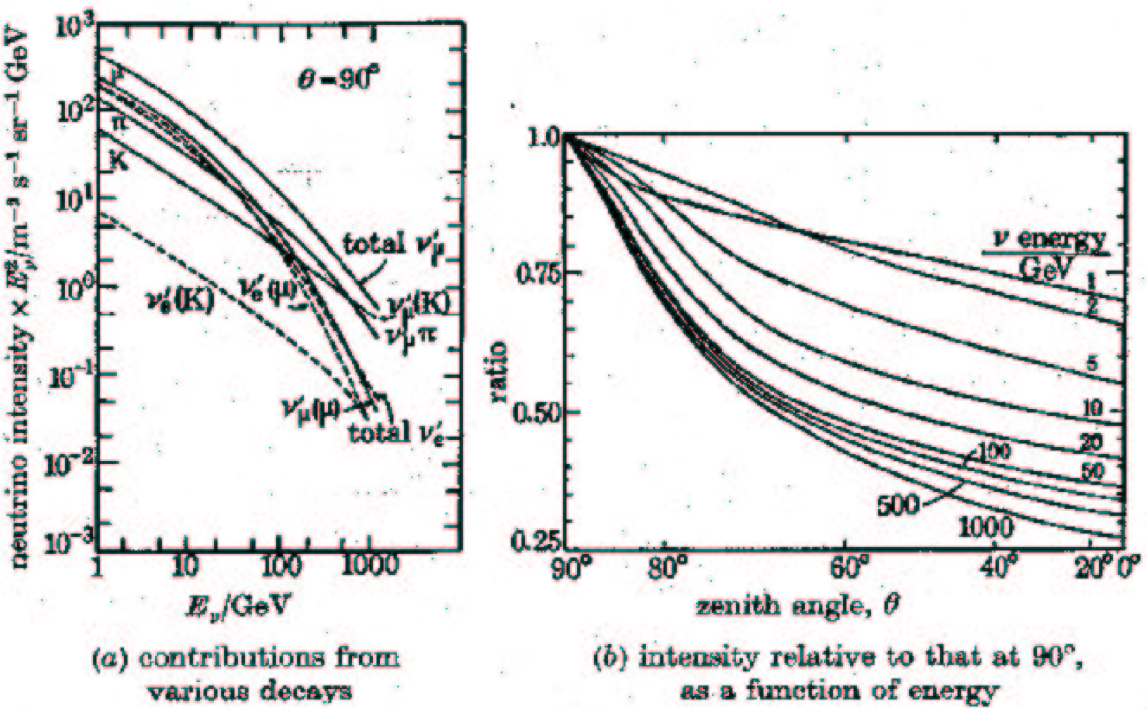


Fig. 3 Energy spectra of neutrinos produced in the atmosphere, after Osborne et al.[4] (ν'_μ denotes $\nu_\mu + \bar{\nu}_\mu$ and ν'_e denotes $\nu_e + \bar{\nu}_e$; in (a) the letter in brackets after the type of neutrino indicates the parent particle).

2 years, starting from the end of 1964. All of them had vertical walls of scintillators as trigger, NFT as tracker and absorber walls of lead (Telescopes 1,2), iron (Telescopes 3,4,5) or magnetized iron (Spectrographs 6,7), as shown in Fig. 4. This geometry provided maximum aperture for near horizontal tracks, where the atmospheric muon background is negligible.

A schematic of the three types of detectors is shown in Fig. 4. By April 1965, the first telescopes (Tels. 1 & 2) were operational and the first ever clear neutrino events were recorded in them in May 1965. The scintillator walls were of area 2m $\times$ 3m (Tels. 1,2), 2m $\times$ 2m (Tels. 3,4,5) and 2m $\times$ 4m in the spectrographs. Each 1m square area was viewed by 2 PMTs whose pulses were measured over a dynamic range of $\sim$ 20 with on-line oscilloscopes and which were also used to generate the trigger. Between these walls of scintillators, the NFT trays (4 staggered layers in each) and absorbers walls were sandwiched as shown in Fig. 4. The absorbers were two walls of 2.5 cm thick lead in Tels. 1 & 2, four iron walls of 7.5 cm thickness in Tels. 3,4 & 5 and 40 cm thick magnetized iron in the spectrographs 1 & 2. These provided different thresholds (100 MeV for Tels. 1 & 2 and larger for the rest of the detectors) and distinction between the electromagnetic component and muons/hadrons traversing these detectors. The visual tracking detectors were built into modules of area 1m $\times$ 2m with 4 staggered layers of 2 cm dia, 2m long NFT's, and were pulsed with high voltage on trigger from scintillators. These allowed measurement of spatial angles in Tels 3,4 & 5 due to orthogonally placed NFT arrays, but only projected angles in Tels. 1 & 2 and the two spectrographs, with an overall accuracy of $\sim 1°$.

The primary trigger was by a 4-fold coincidence of PMT pulses on opposite walls of the detectors. With a minimum threshold of $\sim$ 100 MeV, there was essentially no background from radioactivity—the signal comprised entirely of cosmic ray muons and a tiny number of neutrino-induced events. A detailed description of the detectors, trigger and analysis of neutrino data was given by Narasimham[11].

Identification of Neutrino-Induced Events and Results

As discussed in section 2, the atmospheric muons have a very steep angular distribution at this depth and their flux falls to negligible levels at large zenith an-

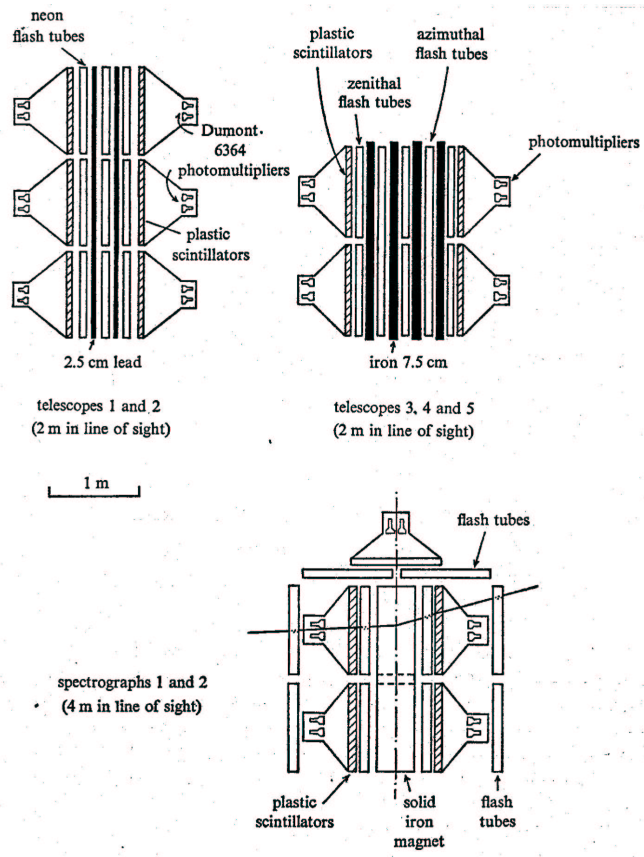


Fig. 4 Neutrino detectors at the depth of 2.3 km at KGF

gles. On the other hand, the neutrinos arrive fairly isotropically at these depths. As a result, a cut on the zenith angle of muons ($\geq 50°$) provided an efficient filter for neutrino events. In some cases, upward going muons/events could be easily identified by their shower profile in the detector and these are undeniably due to upward going neutrinos.

A total of 220 events were recorded in these detectors; of these, 18 were identified as products of neutrino interactions. The remainder, with zenith angles $< 50°$, were attributed to atmospheric muons. The number of events in each category and exposures are given in Table II.

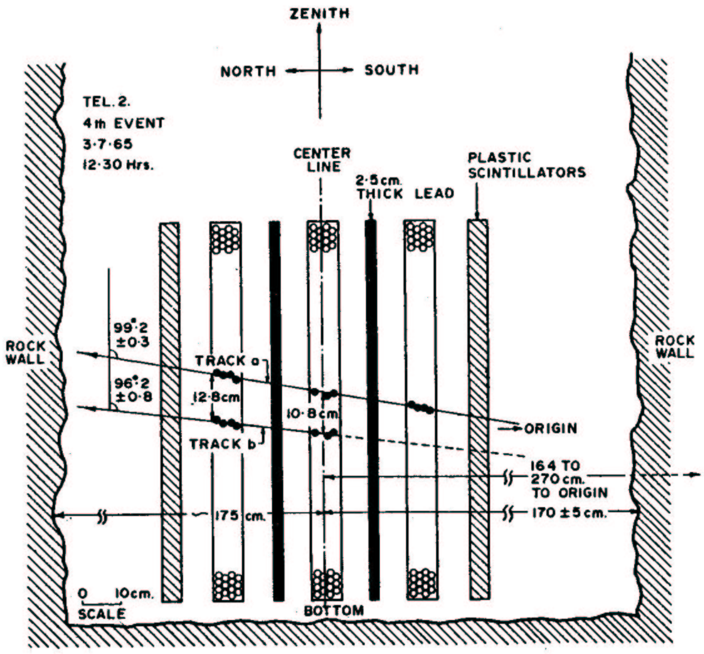
The first neutrino event recorded underground was in early 1965 (Achar et al.[12]). The first clear inelastic neutrino event was Event 4 in Telescope 2 with two well-defined tracks emerging from the rock in an upward direction, see Fig. 5. Based on the prevailing knowledge at that time, it was considered as a candidate for W-boson production, with one track due to charged current interaction of a muon neutrino in rock and the second one due to a muon from decay of an associated W-boson i.e., $\nu + N \to N' + \mu + W$, with $W \to \mu + \nu$. From these data, the horizontal intensity of ν-induced muons with energy loss > 100 MeV was estimated as $I_\mu(\theta = 90°) = (3.5 \pm 0.9) \times 10^{-13}/\text{cm}^2$/sec/st.

A detailed comparison with the estimated number of events for different scenarios on the growth of cross-section with energy, W-boson production etc., was made, using the available accelerator based data[13] and the theoretical extrapolations; this is shown in Fig. 6. Krishnaswamy et al.[14] had then concluded that the mass of the W-boson should be at least 3 GeV at 90% confidence level—much before the advent of high energy neutrino beams and the eventual discovery of W and Z bosons at the CERN p-$\overline{p}$ collider. One should also mention the use of magnetic spectrographs for the first time in these studies. Each of the two spectrographs had a magnetic field of 1.4 Tesla and an MDM of $\sim$30 GeV/c for the best configuration of tracks; but for typical tracks it was $\sim$10 GeV/c. In a total aperture $\times$ time of $1.4 \times 109/\text{m}^2$/sec/st, only 4 neutrino-events were recorded. The muons in these events had momenta $\leq$ 4GeV/c except one which was close to the MDM. The signs of charges were 3 posi-

Table II

Division of events and exposure times. (OST was a special trigger using PMTs on any one side-wall of counters, to increase the event rates.)

Detector ⟶	Telescopes 1 & 2	Telescopes 3,4 & 5	OST	Spectrographs 1 & 2
Run time (years)	5.6	2.0	2.99	2.83
No. of atmospheric muons	42	2	76	82
No. of ν-induced muons	7	2	5	2
Aperture × time ($\theta > 50°$) ($/m^2/sec/st$)	2.1×10^9	0.37×10^9	0.85×10^9	1.39×10^9



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

Fig. 5 An expanded view of a section of Telescope 2 in which an inelastic collision in rock of an upward-moving neutrino was recorded. The black dots are the fired NFTs.

tive and one undecided. We will compare these results with predictions, in section 4.2, where the Utah results on the energy spectrum of ν-induced muons are presented.

Events With Unusual Features (Kolar Events)

In the neutrino experiments at 7000 hg/cm^2, as well as those conducted later at 3375 hg/cm^2 and the proton decay experiments in the KGF mines, it was noticed (Krishnaswamy et al.[15]) that some multi-track events (6 in total) had unusual features which could not be explained away by any known processes of muons or neutrinos. They are characterized by the following features:

1. The event consisted of two or more tracks, with at least one of them a muon or a pion as seen from their penetrating power without showering.
2. All tracks of the event seemed to originate from a vertex located either in air or thin detector materials, based on an extrapolation of projected angles of tracks.
3. The tracks had a large opening angle ($\sim 45°$) between them and
4. their rate was depth-independent and was a fraction of neutrino events.

A few examples of such events recorded in the neutrino detectors at 2.3 km depth are shown in Fig. 7. The first event had 3 tracks, out of which there is at

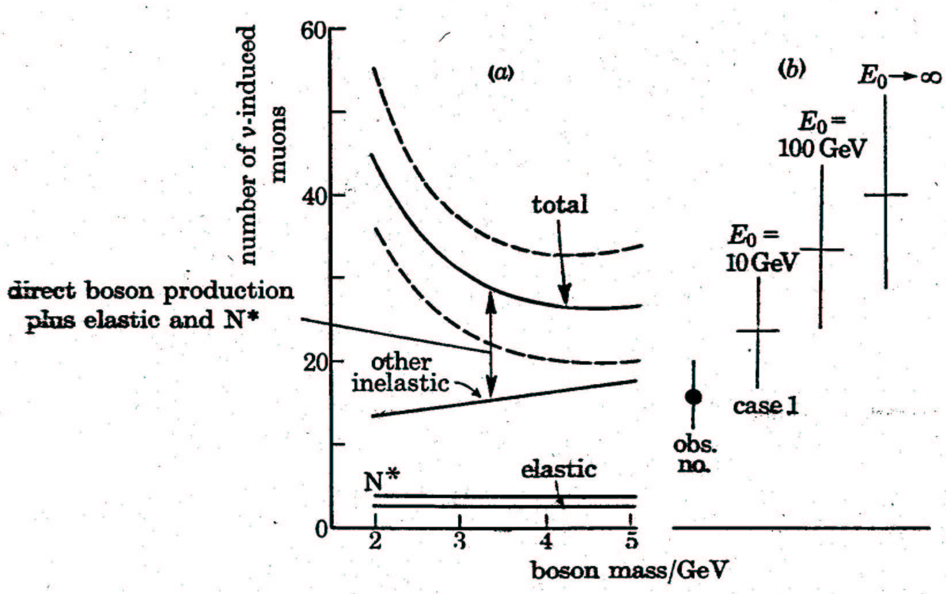


Fig. 6 Comparison of the observed number of neutrino events with estimates based on various interaction processes. E_0 is the neutrino energy at which the cross-section was assumed to level off. The errors shown are of 1σ value.

least one penetrating track (μ/π) traversing lead absorbers without showering. When extrapolated, they meet in air at a distance of 45 cms from the nearest rock wall. The second one had 3 penetrating tracks with a large opening angle. The third one has only 2 tracks, either due to μ or π at an opening angle of $\sim 63°$. In the proton decay experiments at KGF there were similar examples. One of them consisted of an upward-going muon ($>$ 1 GeV) at an angle of 62° , a down-going shower at a median angle of 51° with visible energy of $>$ 2 GeV and with the vertex close to the edge of the rock wall. It was suggested that most of these events could be due to new particles of mass of a few GeV with an unusually long life-time of $\sim 10^{-9}$ sec. and produced at a rate of the same order of magnitude as that of the atmospheric neutrino interactions. Searches were made at the ν- experiments at CERN[16] and at Fermilab[17] but they led to negative results with bounds on cross-sections (and masses) to produce neutral, long-lived particles in neutrino interactions.

A number of theoretical attempts were made[18, 19, 20] to understand the production processes and see if they could fit into the prevailing schemes of particles and their interactions. The Kolar events have so far remained an enigmatic puzzle and they need to be studied with specially designed detectors that can address their special characteristics.

4 Contemporary Neutrino Experiments

In this section we describe some of the other neutrino experiments that were contemporary to the KGF neutrino experiments.

Experiments in South African Mines

Around the same time as the KGF neutrino-experiments, groups from Case Institute of Technology, University of California (Irvine) and University of Witswatersrand had set up an experiment in the E.R.P. Mines in South Africa at a depth of 3200 m. The principle of detection of ν-events was essentially the same as in the KGF experiment i.e., to look for interaction products from surrounding rock. Their detector (see Fig. 8) arranged in a rail geometry comprised 2 walls of liquid scintillation tanks of total area 160 m^2. Each tank had dimensions of 500 cm $\times$ 56 cm $\times$ 13 cm and was viewed by PMTs from both sides. This gave a position measurement ($\pm$ 15 cm) along the length of the tank and when combined with the location of the hit tanks in the 3-tier bays, gave an angular resolution of $\pm$ 10°. In the first experiment, started in 1965 with 54 tanks, there was neither an absorber nor a tracking detector and the detection depended on the

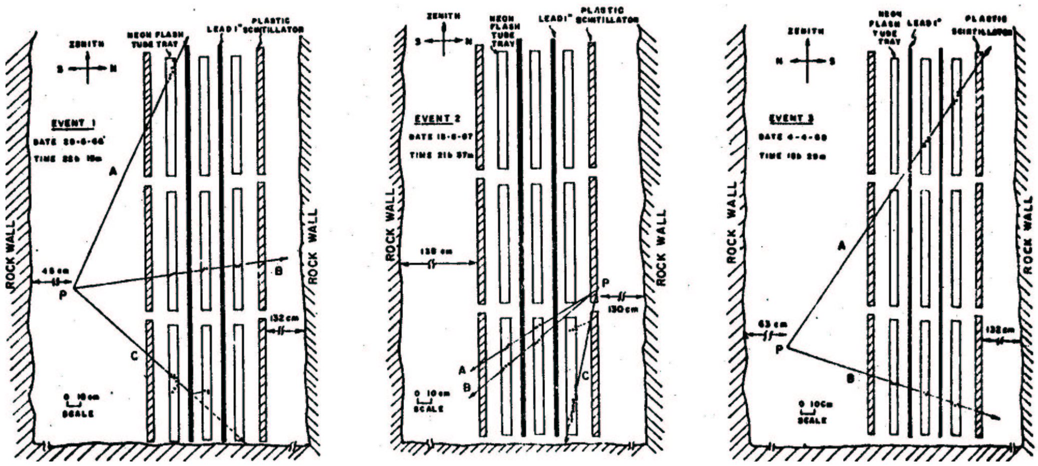


Fig. 7 Multi-track (Kolar) events recorded in KGF neutrino-detectors.

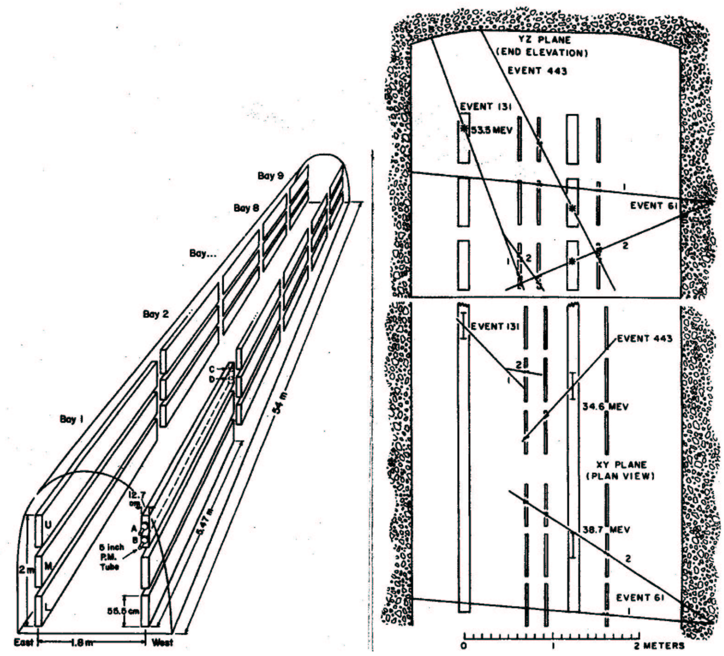


Fig. 8 On the left is shown the detector array in ERP mines with only scintillator tanks in a rail geometry. On the right are shown particle trajectories for 3 types of events in yz and xy views in the final detector assembly including a tracker.

great depth, the energy deposit, and the crude zenith angle of tracks as measured from the well-separated bays of scintillators.

The first detector recorded about 35 neutrino events from which the flux of ν-induced muons was determined as $(3.5 \pm 0.7)10^{-13}/\text{cm}^2$/sec/st, assuming an isotropic angular distribution. Subsequently, it was shifted to a new site, 50m deeper, where the detector was expanded to include neon flash tubes as tracking detectors. About 50,000 of them were used in an orthogonal geometry straddling the scintillator tanks, to get an angular resolution of 0.5°. Some representative events are shown in Fig. 8 where the hits in the flash tubes can also be seen. Event 131 is probably an atmospheric muon at $\theta = 34 \pm 5^\circ$; event 61 is neutrino-induced and has two tracks at 68° and 84° with vertex at the edge of rock; event 443 has a single track at 41° and is a border line case between these two types of processes. The angular distribution of all events recorded in this experiment[21] is shown in Fig. 9, where one notices the clear separation between atmospheric muons and neutrino-induced events. The data were

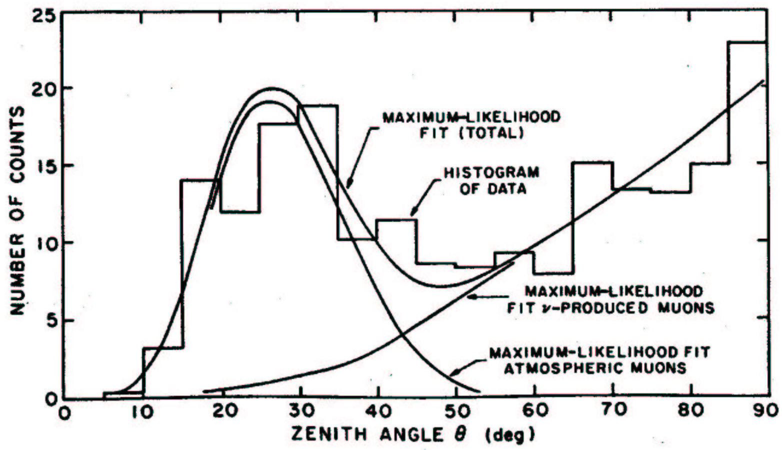


Fig. 9 Zenith angle distribution of events in the ERPM experiment, South Africa.

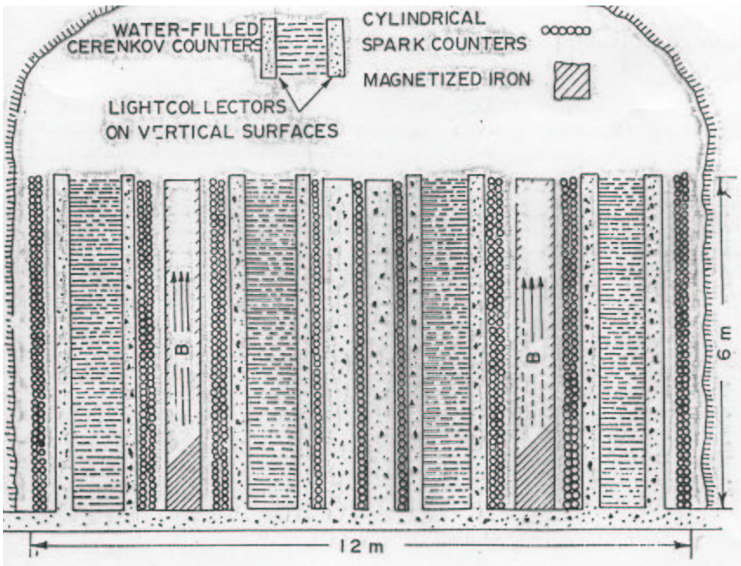


Fig. 10 The neutrino detector in Utah salt mines.

fitted by a curve giving the vertical intensity of muons vs vertical depth, *h*, as

$$I_{\nu_\mu}(h_0) = A\exp(-h_0/\gamma) + I^{\nu}_{\nu_\mu} ,$$

where $A = (2.26 \pm 0.16) \times 10^{-6}/\mathrm{cm}^2/sec/st$, and $\gamma = (7.58 \pm 0.09) \times 10^4$ g.cm^{-2} and the flux of ν-induced muons, $I^{nu}_{\nu\mu} = (2.23 \pm 0.20) \times 10^{-13}/\mathrm{cm}^2/sec/st$. The ν-induced muon flux from this measurement is consistent with that of its Phase 1 result mentioned above; it is also in general agreement with the fluxes reported from the KGF experiment.

The Neutrino Experiment in the Utah Salt Mine

A 2 kton detector was employed by the University of Utah group in a salt mine under the Utah mountains with a vertical overburden of 1500 hg/cm^2 . Due to the shallow depth of the location, only up-going particles could be unambiguously identified with neutrino interactions. The detector, shown in Fig. 10, had fast timing from water Cerenkov detectors for trigger as well as to get the sense of motion of particles, cylindrical spark counters for tracking, and magnetised iron to measure momenta upto ∼100 GeV/c.

While it had collected lot of data on the atmospheric muons in terms of angular distribution, charge ratio as a function of energy, and multiplicity distribution of muons, only a few neutrino events with measurement of muon momenta were reported from this detector [22]. The energy spectrum thus obtained is shown in Fig. 11, where the KGF data is also plotted. The conclusion was that the spectrum is con-

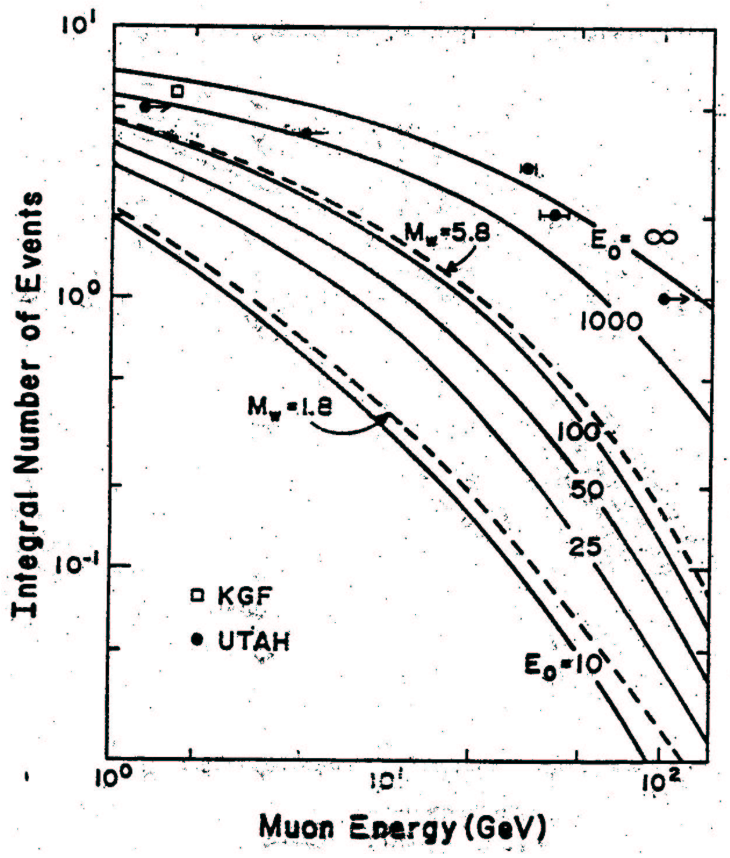


Fig. 11 The energy spectrum of neutrino-induced muons, measured by the Utah and KGF experiments.

sistent with a linear growth of neutrino cross-section upto high energies and that the W-boson mass has to be large.

The BAXAN Neutrino Detector

This detector had a large array of liquid scintillator tanks at a vertical depth of 300 m in the Elbrus mountain of Baxan valley, Russia. With about 3000 tanks (330 tons of liquid) arranged in 4 well-separated layers and fast timing, it was designed to identify the up-moving ν-induced muons (threshold of 2 GeV) from the overwhelming down-moving atmospheric muon flux. Based on 19 up-moving muons in the angular range of $\pm 50^\circ$ around the vertical direction, they obtained the vertical flux of $(1.92 \pm 0.44) \times 10^{-13}$ /cm^2/sec/st. This was in close agreement with their estimates on the neutrino-induced muon fluxes which led Boliev et al.[23] to set an upper limit of 6×10^{-3} eV^2 on Δm^2 at maximum mixing angle in the 2-neutrino oscillation scenario.

In summary, neutrino events were detected unambiguously amidst the large cosmic ray background using different techniques and the observed rate of interactions in rock was consistent with the estimates based on the atmospheric neutrino fluxes and the cross-sections measured at the accelerators, as of 1971.

5 Neutrinos as Background to Proton Decay Experiments

The Grand Unified Theories (GUT), proposed during the mid 1970s, invariably led to the prediction of non-conservation of baryon number as the only consequence that could be tested at the laboratory level. In particular, it was predicted that proton decay or bound nucleon decay could occur with a mean life of $10^{30} - 10^{34}$ years and into a variety of decay channels depending on the details of the GUT models. The experiments conducted deep underground until then, either to study atmospheric muons at KGF[6], or neutrino interactions in the ERPM[24] and KGF mines[25], were used to set lower limits of about 10^{30} years on the lifetime of bound nucleons. But these were counting type experiments of limited mass and were never designed to search for nucleon decay events that would have special decay characteristics and they had no ability to discriminate against the background from low energy neutrino events.

Dedicated proton decay experiments were therefore planned in late 1970s to extend the reach and to distinguish the possible decay signal from the background. With total visible energy in such decays being less than 1 GeV, it was the low energy neutrino component that posed a formidable background. This led to a variety of detector designs, such as fine grain calorimeters, tracking detectors and water Cerenkov detectors to discriminate against such background. It is but natural that these experiments also collected rich data on atmospheric neutrinos from confined events of low energy to through-going muons produced in interactions in the surrounding rock.

The first experiment of this type was started at KGF in 1980 at the depth of 2.3 km with 140 tons of steel plates and proportional counters followed by another 340 ton expanded version at the depth of 2 km. This was followed by a fine grain tracker with Irocchi tubes at a depth of 1.5 km under Mt Blanc, an NFT tracking detector in the Frejus tunnel at a depth of 1.6 km, a massive water Cerenkov detector by Irvine-Michigan-Brookhaven (IMB) groups in Cleveland salt mines at a depth of 600 m and a water Cerenkov detector using large PMTs at a depth of 1 km in the Kamioka mines.

Neutrino Results from KGF Nucleon Decay Experiments

The first (Phase 1) detector was set up at a depth of 2.3 km, close to the site of the earlier neutrino experiment. The main detector modules were sealed proportional counters of cross-section 10 cm $\times$ 10 cm and 4m (6m) length, which provided tracking and also ionization measurement of particles[26]. They were arranged in a 140 ton array of 34 horizontal layers with $1/2''$ thick iron absorbers between them as shown in Fig. 12.

The zenith angles of penetrating tracks were measured to better than 1° and the energy loss $\mathrm{d}E/\mathrm{d}x$ of particles and penetration of absorbers were used to distinguish electrons from muons/pions. Another detector (Phase 2) of similar design but with a total weight of 340 tons and comprising 60 horizontal layers of proportional counters in a cubical detector of side 6m, was set up a few years later at a depth of 2 km in the same mines[27]. In addition to neutrino interactions in the surrounding rock, one has also neutrino events produced within the detector material (iron) acting as target. The latter category comprises the fully confined events as well as partially confined events with vertex inside the detector. Since the timing response of the counters was not adequate to measure the sense of direction, only the muons traversing the detector at large angles ($> 55°$ in Phase 1 and $> 60°$ in Phase 2 detectors) could be unambiguously identified as due to ν_μ interactions in rock.

A detailed evaluation of the early data from the KGF detector was made by Krishnaswamy et al.[27]; this involved a study of various processes of neutrino interaction leading to confined events with energy up to a few GeV, through-going muons due to high energy neutrinos (mean energy $\sim$ 50 GeV) and the intermediate energy events classified as partially confined ones. We present here only the category of through-going muons. The total numbers of such events recorded in these experiments, conducted over 10 years[29] are shown in Table III and their angular distributions in Fig. 13.

Table III

Details of KGF data on neutrinos during 1980–90. The number of neutrino-induced muons includes includes up-going muons while the background is mostly from the first bin after the cut-off angle.

Experiment	Live Time (Years)	No. of ν-induced muons	Background (atm. muons)
Phase I	8.41	139 ($55° - 125°$)	11.3
Phase II	5.53	182 ($60° - 120°$)	17.8
Total		321	29.1 ± 2.3

One notices in this plot a clear separation of the two types of events i.e., atmospheric and neutrino-induced. The number of the observed neutrino events with separate cuts on zenith angles for Phase 1 & 2 detectors were consistent with predicted values within the statistical accuracies of data and the uncertainties in fluxes and cross-sections [17,30].

The Phase 1 & 2 detectors had recorded $\sim$ 100 confined events, out of which $\sim$ 84 had visible energy larger than 200 MeV, in a total exposure of 1.65 kton years. These included single tracks (μ, π), showers (e,π^0) and inelastic events with multi-track configuration. These were analysed in terms of ν-interactions as well as possible decay of bound nucleons in the iron absorber and also in the detector material. An early analysis of the Phase 1 data was given by Krishnaswamy et al.[27]. While there were candidate events that are consistent with nucleon decay in this final sample, they are by no means unambiguous or conclusive to be ruled out as rare ν-interactions. These data were therefore used to set stringent lower limits

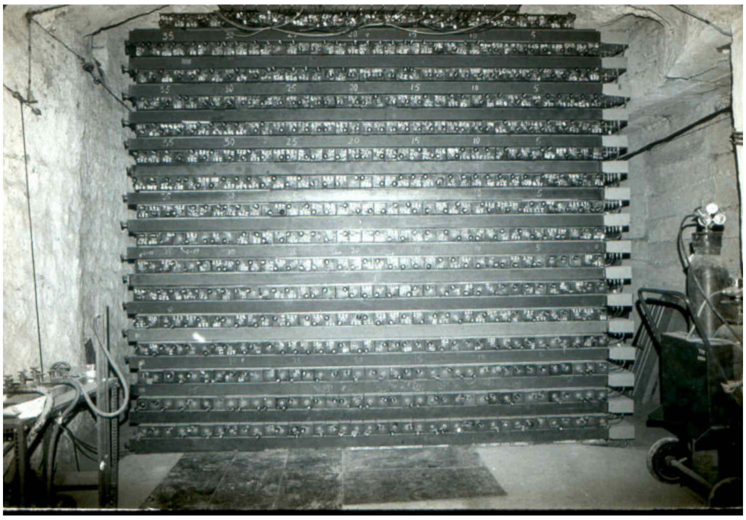


Fig. 12 Front view of Phase 1 Nucleon decay detector at 2.3 km depth in KGF. Each square section seen here is of a proportional counter giving a grid size of 10 cm × 10 cm.

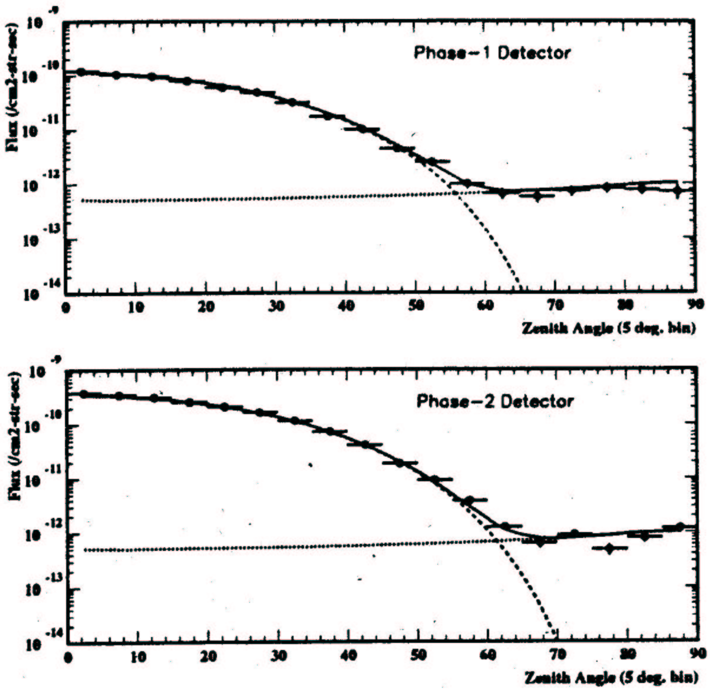


Fig. 13 Angular distribution of through-going muons in KGF detectors.

on the life-time of bound nucleons that could decay into a variety of channels predicted by grand unified theories.

Neutrino Data from Other Proton Decay Experiments

As mentioned earlier, two types of detectors were employed to search for proton decay:

1. Fully activated water Cerenkov detectors by Irvine-Michigan-Brookhaven collaboration[31] in Cleveland salt mines in USA, Harvard-Pennsylvania-Wisconsin[32] under Utah mountains in USA, and Kamiokande[33] collaborations in a mine in Japan.

2. Tracking calorimeters with iron absorbers by Nusex in Mt Blanc tunnel[34]; Frejus experiment[35] in a tunnel in France and Soudan II experiment

Table IV
A compendium of results from the proton decay detectors of the 1980s. Here ST stands for (muon like) single tracks; SH for e-like showers, and R is as defined in the text. A comparison with calculations from a Monte Carlo (MC) simulation is also shown.

Experiment	Exposure (kton year)	ν_μ data (ST)	ν_μ M.C (ST)	ν_e data (SH)	ν_e M.C (SH)	R ratio of ratios
			Contained events only			
IMB1	3.80	104	136	297	265	0.68 ± 0.08
Kamioka-ring	7.70	234	356.8	248	227.6	0.60 ± 0.06
Kamioka-decay		182	277.5	300	313.9	0.69 ± 0.06
IMB-3 ring	7.70	182	268	325	257.3	0.54 ± 0.05
IMB-3 decay		208	261.5	402	348.5	0.64 ± 0.07
Frejus contained	2.00	94	100	89	82	0.87 ± 0.13
Soudan 2	1.01	33.5	42.1	35.3	28.7	0.64 ± 0.19
NUSEX	0.5	32	36.8	18	20.5	0.99 ± 0.29
			Including the uncontained events			
Kamioka Multi-GeV						0.59 ± 0.08
Frejus-Total						0.96 ± 0.18

in a mine in Minnesota, USA[36].

The largest among these were at IMB (with 9 ktons of water under 1600 hg/cm^2) and Kamiokande (with 3 ktons of water under 2700 hg/cm^2) whereas the Frejus experiment had 800 tons of steel and a fine-grain flash chamber tracker at 4400 hg/cm^2 and the Nusex experiment employed 160 tons of steel plates with Irocchi tube tracking. Since they were operated at different depths underground, different strategies were needed to suppress cosmic ray background. While only strong lower limits could be set on proton decay life-time from these experiments, the wealth of data on atmospheric neutrinos allowed a detailed study of fluxes of electron and muon neutrinos. A summary of the neutrino data obtained from these experiments is shown in Table IV.A strong evidence from the large water detectors on the depletion of ν-induced muons, as exemplified by the ratio $R = (N_\mu/N_e)_{data}/(N_\mu/N_e)_{MC}$ has been a clear signal for neutrino oscillations. These were confirmed by the statistically significant results on angular distributions of ν-induced muons and electrons in the new 50 kton Super-Kamiokande detector as well as the Soudan 2 tracking detector.

Summary

In this short historical review of the beginnings of atmospheric neutrino physics, we have attempted to show the gradual progress of the experimental field step from the first detection of atmospheric muon neutrinos to the currently exciting phase of neutrino oscillation phenomena. Looking back at the vantage point of the mid 1960s with the no-count observation at 3 km depth pointing us to neutrino experiments at KGF, the field has grown to an unrecognizable state where it has provided, presumably, the first glimpse of signals beyond the Standard Model.

References

1 K Greisen Proc Int Conf on Instrumentation for High Energy Physics (Berkeley) *Inter-Science Publ* 1960 p 209

2 Z A Zatsepin and V A Kuzmin *Sov Phys JETP* **14** (1962) 1294

3 G Danby *et al Phys Rev Lett* **9** (1962) 36

4 J L Osborne *Proc Phys Soc* **86** (1965) 93

5 R Cowsik *et al Proc Ind Acad Sci* **53** (1966) 217

6 M G K Menon *et al Nuovo Cim* **30** (1963) 1208; *Phys Lett* **5** (1963) 272

7 B V Sreekantan *et al Proc Ind Acad Sci* **43** (1956) 113

8 S Miyake, V S Narasimham, P V Ramana Murty *Nuovo Cim* **32** (1963) 1505; *ibid* **32** (1963) 1524

9 C V Achar *et al Proc Phys Soc* **86** (1965) 1305

10 S Miyake *J Phys Japan* **18** (1963) 1093

11 V S Narasimham Ph.D thesis Univ. of Bombay 1967

12 C V Achar *et al Phys Lett* **18** (1965) 196; **19** (1965) 78

13 I Budagov *et al Phys Lett* B **30** (1969) 364

14 M R K Krishnaswamy *et al Proc Roy Soc Lond* A **323** (1971) 489

15 M R K Krishnaswamy *et al Phys Lett* B **57** (1975) 105; *Pramana* **5** (1975) 59

16 H Faissner *et al Phys Lett* B **60** (1976) 401

17 A C Benvenuti *et al Phys Rev Lett* **32** (1974) 125; *ibid* (1974) 1454; *Phys Rev Lett* **35** (1975) 1486

18 A de Rujula *et al Phys Rev Lett* **35** (1975) 628

19 J C Pati and A Salam Preprint ICTP/75/73 1975

20 G Rajasekaran and K V L Sarma *Pramana* **5** (1975) 78

21 M F Crouch *et al Phys Rev* D **18** (1978) 2239

22 H E Bergeson *et al Phys Rev Lett* **31** (1973) 66

23 M M Boliev *et al Sov J Nucl Phys* **34** (1981) 787

24 F Reines and M F Crouch *Phys Rev Lett* **32** (1974) 438

25 R Cowsik and V S Narasimham *Phys Rev* D **22** (1980) 2204

26 M R K Krishnaswamy *et al Phys Lett* B **106** (1981) 339

27 M R K Krishnaswamy *et al Pramana* **19** (1982) 525; *Proc of ICOBAN* Bombay (1982) p115

28 M R K Krishnaswamy *et al Proc of ICOBAN* Park city (1984)

29 S R Dugad *et al* 2001 (TIFR internal note- unpublished)

30 J G H De Groot *et al Z Phys* C **1** (1979) 143

31 R M Bionta *et al Phys Rev Lett* **51** (1983) 27

32 E Aprille-Gibboni *et al Proc of ICOBAN* Park city (1984) p3

33 M Koshiba *et al Proc of ICOBAN* Park city (1984) p69

34 G Battistoni *et al Phys Lett* B **115** (1982) 461

35 R Berloutaud *Proc of ICOBAN* Park city (1984) p247

36 K Ruddick *Proc of ICOBAN* Park city (1984) p252

37 M V Markov *Proc Int Conf on High Energy Physics* Rochester (1960) p579

38 F Reines *et al Phys Rev Lett* **15** (1965) 429