Search for point sources of neutrinos with KGF underground muon detectors (*)

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Summary. — The proton decay detectors operated underground in the Kolar Gold Fields in India during 1980-1993 have recorded a large number of muon events. Out of these, 243 large zenith angle events were selected as being due to muons arising from neutrino interactions in the surrounding rock. This selection was based on the different zenith angular distributions of the atmospheric and neutrino-induced muons. These selected events are analysed here to look for powerful point sources of neutrinos.

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1. – Introduction

Active Galactic Nuclei (AGN) have been considered as possible sources of very high-energy ($\sim 10^{15}$ eV) neutrinos and the possibility of detection of these neutrinos has been discussed by Stecker *et al.* [1, 2] and others [3]. For the detection of neutrinos the target material has to be large and in this context large underground or underwater experiments offer the best choice. In the case of deep underground experiments, the normal cosmic-ray muon background is low and the muons produced in the surrounding rock by the neutrinos form the signal.

The Proton Decay Detectors operated during 1980-1993 deep underground in Kolar Gold Fields (KGF), India have recorded a large number of muon events and in this paper we report on the analysis of 243 single muon tracks due to neutrino interactions in the surrounding rock. We have already presented the analysis of 188 such events [4],

(*) The authors of this paper have agreed to not receive the proofs for correction.

but now we have included the results from the Phase III detector as well as the recent results from Phase I and Phase II detectors.

2. – Detectors

The KGF nucleon decay experiment consisted of 3 detectors; of these Phase I was operated at the depth of 2.3 km ($7000\ \mathrm{hg/cm^2}$) and Phase II and Phase III detectors at the depth of 2.0 km ($6045\ \mathrm{hg/cm^2}$). These detectors are of fine grain calorimetric type with iron absorbers in between proportional counter layers which were arranged in orthogonal geometry to find the spatial direction of tracks. Some relevant details of these detectors are given in table I. Phase III detector was similar to the other two except that it had no absorber other than at the top. More details about these detectors can be found in [5-7].

The basic trigger is a 5-fold coincidence of any five layers out of any 11 consecutive layers. In order to record very large angle tracks, an additional trigger of a two-layer coincidence with at least three nearby counters per layer was used. With these triggers, the detectors cover almost all the directions in space except for a narrow region between zenith angles 88.5° and 91.5° when the track crosses only one layer and remains undetected.

3. – Analysis

The zenith angular distributions of all the single track muon events are shown in figs. 1 and 2 for the depths $7000\ \mathrm{hg/cm^2}$ and $6045\ \mathrm{hg/cm^2}$, respectively. There are two peaks, one around 20° and another near 85° in both figures. The first peak is due to the atmospheric muons whose intensity underground falls off rapidly near 60° and the second peak is due to the neutrino-induced muons from the surrounding rock which increases as the zenith angle increases. Thus, by restricting the zenith angular region to 60°-90°-120° and 65°-90°-115° for Phase I and Phase II and III detectors, respectively, one can select events due to neutrino interactions alone. A total of 243 neutrino events (78, 126, 39 from Phase I, II and III, respectively) have been selected. In this selection, we have rejected single tracks with large scatter inside the detector, path length inside the detector $< 2\,\mathrm{m}$ or ambiguity in the angle measurement.

The angular resolution for the arrival direction of the neutrino depends on 1) the angular resolution of the muon track in the detector which is estimated as 0.7° taking into account the path length and individual ionizations in the proportional counters 2) the difference in the directions of the incoming neutrino and the outgoing muon

TABLE I. – *Detector characteristic.*

	Phase I	Phase II	Phase III
No. of proportional counter layers	34	60	20
Size	$6\times 4\ \mathrm{m^2}$	$6\times 6\ \mathrm{m^2}$	$6\times 6\ \mathrm{m^2}$
Absorber between layers	1/2″ Fe	1/4″ Fe	No absorber
Minimum energy of muon to cross detector vertically	1.0 GeV	1.3 GeV	0.4 GeV

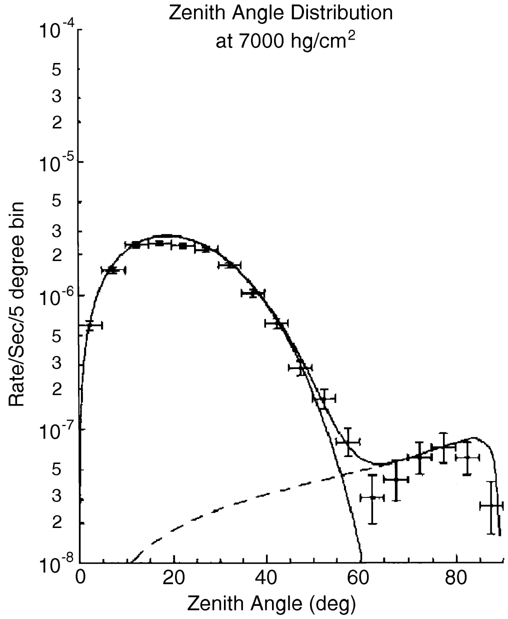

Fig. 1. – Phase I zenith angle distribution.

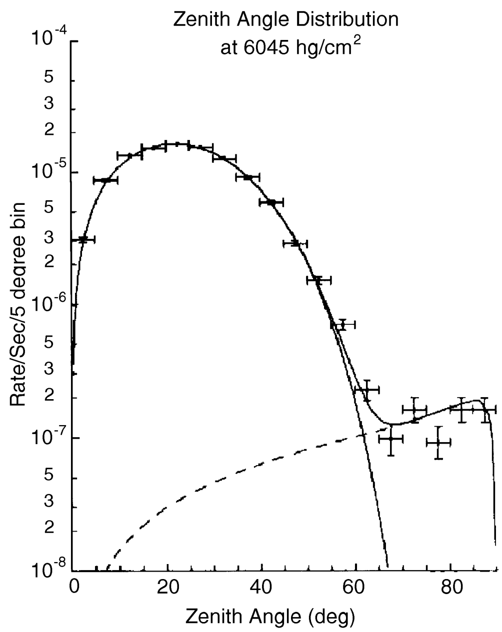

Fig. 2. – Phase II zenith angle distribution.

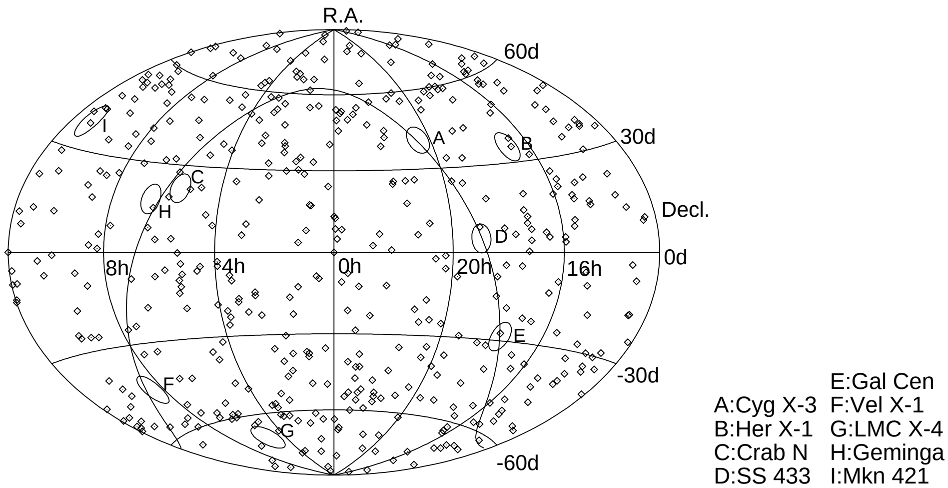

Fig. 3. – The arrival direction of the 243 large zenith angle events in equatorial coordinates.

at the interaction vertex in the rock and 3) the multiple-Coulomb scattering of the muon in the rock before it enters the detector. Assuming a differential energy spectrum of the form $E^{-2.1}$ for the neutrinos and a cut-off energy of 10^{16} eV, it was estimated that on average there is a difference of $\sim 2°$ or more between the arrival direction of neutrino and the muon angle recorded in the detector due to the latter two causes alone. Thus, a conservative value 2.8° has been assumed for the angular resolution of the neutrino arrival direction.

The arrival direction of all the 243 selected events in equatorial coordinates are shown in fig. 3. Since the upward- and downward-going muons cannot be distinguished due to the slow response of the proportional counters, each event is plotted as two points, one at (δ, α) and another at $(-\delta, \alpha + 180°)$ in this figure.

We have considered several possible point sources of high-energy neutrinos as shown in table II. By finding the number of neutrinos coming from the direction of the

TABLE II. – *Muon flux, neutrino flux and luminosity at these sources.*

Source	Exposure (cm^2 s)	No. of events	Back-ground	Upper limit (90% c.l.)		
				μ flux (/cm^2 s)	ν flux (/cm^2 s)	ν luminosity (/erg s)
Cyg X-3	5.35×10^{13}	0	0.95	4.3×10^{-14}	7.1×10^{-6}	1.7×10^{39}
Her X-1	4.19×10^{13}	2	0.94	10.1×10^{-14}	17.4×10^{-6}	7.3×10^{38}
Crab Nebula	3.94×10^{13}	0	0.66	5.8×10^{-14}	9.7×10^{-6}	6.5×10^{37}
SS 433	3.45×10^{13}	1	0.88	9.3×10^{-14}	15.4×10^{-6}	2.3×10^{38}
Galactic center	4.30×10^{13}	1	0.70	8.1×10^{-14}	13.5×10^{-6}	2.3×10^{39}
Vel X-1	6.06×10^{13}	0	0.97	3.8×10^{-14}	6.3×10^{-6}	2.0×10^{37}
LMC X-4	8.54×10^{13}	1	1.27	3.8×10^{-14}	6.2×10^{-6}	2.6×10^{40}
Geminga	3.78×10^{13}	1	0.55	9.3×10^{-14}	15.4×10^{-6}	2.6×10^{35}
Mkn421	5.07×10^{13}	4	0.92	13.8×10^{-14}	22.9×10^{-6}	5.9×10^{47}

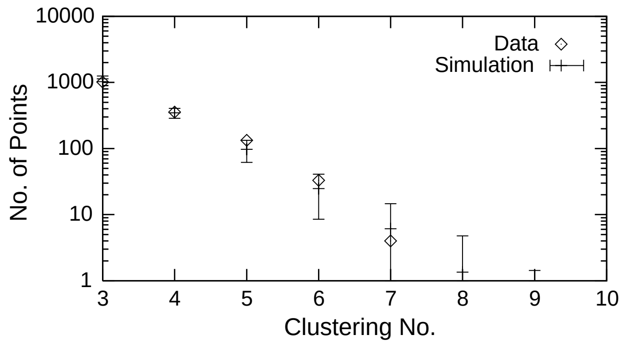

Fig. 4. – Monte Carlo simulation to find probability.

source within a cone of half-angle 5° (considering the angular resolution of 2.8°), we have obtained 90% confidence level upper limits on the ν-luminosity by the method explained in our previous paper [4]. These cones corresponding to different sources are marked in fig. 3 also. As can be seen from table II and fig. 3 only around the active galaxy Mkn421 which has a BL Lac. type AGN and from which the Whipple Group has detected high-energy γ-rays [8], we have seen 4 events within the cone. The chance probability for this to happen with an estimated background of 0.92 events within a cone in this direction assuming a Poisson distribution is only 0.011. But still this cannot indicate a possible ν-emission from Mkn421 since a detailed Monte Carlo simulation of chance clustering of events agrees with observation as explained below.

4. – Simulation and discussion

A Monte Carlo simulation was carried out to find the number of cases with certain number of events inside the cone of half-angle 5° around a fixed solid angle (equivalent to $1^\circ \times 1^\circ$ at the equator) in a given direction in space. In this simulation due weightage was given to the time of exposure in each celestial direction and the perpendicular area presented by the detector to that direction. The results of the simulation (diamond points) and observation (with errors) are shown as a function of number of events inside the cone (fig. 4). As can be seen from this figure, the observation and expectation match and hence the clustering of 4 events in the direction of Mkn421 has been rejected as pure chance. Also it must be noted that since the sense of direction of muon is not available in this experiment, some events out of these 4 may be just pure artifact.

Kamiokande II has reported [9] a clustering of 3 events around $\delta = 19^\circ$ and $\alpha = 353^\circ$. We have seen no clustering in this direction.

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REFERENCES

[1] Stecker F. W. *et al.*, *Phys. Rev. Lett.*, **66** (1991) 2697.
[2] Stecker F. W. *et al.*, *Phys. Rev. Lett.*, **69** (1992) 2738 (E).
[3] Several Authors, *High Energy Neutrino Astrophysics*, edited by J. G. Learned *et al.* (World Scientific, Singapore) 1992.
[4] Adarkar H. *et al.*, *Astrophys J.*, **380** (1991) 235.
[5] Adarkar H. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **284** (1989) 422.
[6] Adarkar H. *et al.*, *Indian J. Pure Appl. Phys.*, **27** (1989) 679.
[7] Adarkar H. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **308** (1989) 679.
[8] Punch M. *et al.*, *Nature*, **358** (1992) 477.
[9] Hirata K. *et al*, *Phys. Rev. D*, **39** (1989) 1481.