Proposal to look for an up/down asymmetry in atmospheric neutrinos beyond Multi-GeV region with existing experimental data

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We discuss a possible test of neutrino oscillation hypothesis by proposing the combined analysis of high energy atmospheric neutrino induced muon events that have been detected around horizontal direction in the Kolar Gold Field (KGF) underground site and below the horizontal direction by many large detectors such as Super-Kamiokande and MACRO. Up/down asymmetry obtained using contained events recorded by detectors at Kamioka site probes low energy region of atmospheric neutrino whereas, the suggested method probes high energy neutrinos. It mainly depends on the observations and it is free of uncertainties in neutrino flux, interaction cross section etc. In this paper we demonstrate that the method is sensitive to a region of oscillation parameter space that explains all the features of atmospheric neutrino data in the Super-Kamiokande detector; the limiting factor being the statistical strength of the KGF observations. This method provides the only way to study the up/down asymmetry beyond Multi-GeV region which is yet to be measured experimentally.
I. MOTIVATION

Evidence for oscillation of atmospheric neutrino has been seen in Super-Kamiokande detector (SK) \[1\]. For a successful interpretation of the data, a neutrino squared mass difference in the range:

$$\Delta m^2 = 10^{-3} \text{ to } 10^{-2} \text{ eV}^2$$

and a nearly maximal mixing angle $\theta$ are suggested. The interpretation in terms of dominant $\nu_\mu \leftrightarrow \nu_\tau$ oscillation channel is favored (even if it is not possible at present to exclude the oscillations into a sterile neutrino). Results from earlier experiments on atmospheric neutrino anomaly such as Kamiokande \[2\], IMB \[3\], Frejus \[4\], NUSEX \[5\] as well as recent results from MACRO \[6\] and Soudan-2 \[7\] are consistent with the results from Super-Kamiokande detector. The shape of zenith angle distribution of events recorded at Baksan experiment \[8\] is not in good agreement with the expectation. Also, the agreement does not improve much by invoking neutrino oscillation scenario.

Different tests of these observations are essential in the perspective of passing from “evidence” to “discovery”. Furthermore, new tests should address the problem of precise evaluation of the parameters of oscillation. Long baselines between the points of neutrino production and detection with controlled artificial neutrino beams will permit crucial tests, especially if sufficiently large values of $L/E$ will be amenable. In this connection, new results from Super-Kamiokande, MACRO and Soudan-2 \[8\] \[11\] will be important to optimize the strategy of search (characteristics of the neutrino flux, design of the detectors, etc.) and also to interpret the result. At the same time, the new neutrino detectors will be able to study in more detail the natural (and cost free) atmospheric neutrinos flux.

At Super-Kamiokande detector, one of the most important observations is certainly the up/down asymmetry in $\nu_\mu$-induced muon flux. The significance of this result is well beyond the level that could be attributed to the systematic effects coming from geomagnetic effect, detector response etc. The most favored interpretation is in terms of flavour oscillations of neutrinos. However, the asymmetry has only been observed in $\nu_\mu$-induced muons with Sub-GeV and Multi-GeV energy range by studying events with neutrino interactions inside the detector identified as fully or partially contained (FC or PC) events. The events of this type are mostly due to low energy neutrino interactions in the GeV range.

It is very important to extend the search of an up/down asymmetry beyond the Multi-GeV region, in order to test the interpretation in terms of neutrino oscillations more directly, and to further constrain the allowed parameter space. This can be accomplished by using the $\nu_\mu$-induced muons in the surrounding rock. The advantage of using this data sample is the increase in the effective detector mass and interaction cross section with the neutrino energy, which compensates for the loss in steeply falling energy spectrum of neutrinos, roughly as a power law (Section [11]). Because of this, the average energy of neutrino for these events is large compared to FC or PC events. However, in order to study the up/down asymmetry, $A_{U/D}$, beyond the Multi-GeV energy region, it is necessary to obtain the upward and downward going $\nu_\mu$-induced muon fluxes. In the present study we formulate a proposal to achieve this goal by mean of existing data.

II. UP/DOWN ASYMMETRY

Many large detectors like Super-Kamiokande and MACRO have recorded large numbers of $\nu_\mu$-induced muons produced in the surrounding rock and passing (or stopping) through the detectors. However, due to shallow depth of operation of these detectors, cosmic muon flux dominates over the $\nu_\mu$-induced muon flux in downward direction (except for certain directions in azimuthal angle, where the mountain is thicker and the shield more efficient); hence, detectors cannot distinguish these events from each other. The upward $\nu_\mu$-induced muon flux can be measured accurately, but this is insufficient to study the up/down asymmetry mentioned above. However, detectors operated at deep underground Kolar Gold Fields (KGF) \[9\] mines can provide the lacking information. Due to large depth of operation and flat terrain; beyond a certain zenith angle, the flux of cosmic muons is very small as compared to that of $\nu_\mu$-induced muons in the surrounding rock. Being gaseous detectors, they cannot distinguish between the particles moving in the upward and downward directions. Therefore, KGF detectors measure the sum of upward and downward induced muon fluxes in a given zenithal direction. Hence, by combining data from KGF with those from SK and MACRO, it is possible to obtain the upward and downward fluxes. Such an analysis permits the study of the up/down asymmetry beyond the Multi-GeV region.

Some of the essential features of these detectors are summarized in Table \[10\]. It is important to observe that the energy thresholds for muons in these detectors are different. To get the asymmetry mentioned above, it is necessary to have the same cut on visible energy of muon in all the detectors. If the energy threshold for KGF detectors is increased, then there can be a substantial loss of statistics. Hence, it is necessary to match the energy threshold of other detectors with that of KGF. Incidentally, this would also lead to further enhancement in the statistics of SK and MACRO detectors.

The extraction of the asymmetry parameter requires the results on $\nu_\mu$-induced muon flux obtained by the
| Detector | Location | Min. Depth | $E_{\text{min}}^\mu$ | Ref. |
|----------|----------|------------|------------------|-----|
| Super Kamiokande | Japan | 2700 | 1.6 | [10] |
| KGF | Grand Sasso, Italy | 3150 | 1.0 | [10] |
| Phase-1 | KGF | 7000 | 0.6 | [10] |
| Phase-2 | KGF | 6045 | 0.5 | [10] |

TABLE I. Features of SK, MACRO and KGF detectors.

SK/MACRO and KGF Collaborations. At present, these results are available from the SK experiment for upward through going and stopping muons [6]. MACRO has published the same for through going muons [1]. The KGF experiment has published the event rate of $\nu_\mu$-induced muons in rock for one part of the existing data set; but, in order to obtain the flux, informations on the angular acceptance, and the efficiencies of trigger and detection are also necessary. Since the available information is not sufficient to extract the proposed asymmetry parameter directly from the published experimental data, we have evaluated the sensitivity reach of the proposal based on certain assumptions. Each of the assumptions mentioned below, corresponds to a specific step in the experimental analysis.

- We assume that it is possible to get the $\nu_\mu$-induced muon flux at the same muon energy threshold ($E_\mu > 0.5$ GeV), and the same (zenith) angular interval from all the detectors.

- SK and MACRO detectors have recorded a large number of upward going $\nu_\mu$-induced muon events that are produced in the surrounding rock. Moreover, SK and MACRO being ongoing experiments, will collect more data. Whereas, KGF experiment has been stopped in 1992 and is estimated to have recorded about 250 events (Section IV) of similar kind arriving in upward as well as downward directions in a zenith angle cone of $55^\circ < \Theta < 125^\circ$. Hence, statistical error on downward flux will be relatively much higher as compared to that on upward flux. This is due to the fact that the error on downward flux, which is determined by combining KGF and SK/MACRO data, mainly depends on the statistical strength of the KGF data. Because of this, we neglect the errors on the experimentally determined upward flux, and treat it as true upward $\nu_\mu$-induced muon flux in our estimate of the sensitivity.

- Phase-2 detector at KGF site has observed about 23,000 cosmic muons [10]. Similarly, in Phase-1 detector also a large number of cosmic muons have been recorded. These observations are in excellent agreement with the predictions of Miyake’s empirical relation [1] up to $\Theta < 55^\circ$ for Phase-1 and $\Theta < 60^\circ$ for Phase-2 detectors. Beyond zenith angle of 60$^\circ$ for Phase-1 detector ($65^\circ$ for Phase-2 detector) the rate of cosmic muons is negligible as compared to the $\nu_\mu$-induced rate. However, in the preceding bin, i.e., $55^\circ < \Theta < 60^\circ$ they are estimated to be comparable (cosmic muon rate is estimated to be about 30% of total rate [12]). In order to increase the angular acceptance, we shall assume that it is possible to determine the $\nu_\mu$-induced muon flux from data in this bin, by subtracting cosmic muon flux obtained using Miyake’s relation from observed flux in the same bin (and similarly for Phase-2 detector in the angular bin of $60^\circ < \Theta < 65^\circ$).

- Since the aperture area for KGF detector is not available, we have assumed it to be equal for all bins due to nearly cubic geometry of the detector.

- Systematic effects arising due to different detection techniques, geomagnetic locations, composition of the surrounding rock etc. are not considered in estimating the sensitivity of the proposed method.

With these assumptions, the sensitivity of the proposal to oscillation parameters is obtained by the following steps:

1. The $\nu_\mu$-induced muon flux, $\mathcal{F}_\mu(\Delta m^2, \theta, \Theta_i)$, is evaluated for each zenith angle bin of 5$^\circ$ in the range of $55^\circ < \Theta < 125^\circ$ as a function of two flavour oscillation parameters (for $\nu_\mu \leftrightarrow \nu_\tau$ oscillation) using the available information on neutrino cross section, $\nu_\mu$-flux, range of muons etc. as described in the next section.

2. The exposure factor for KGF setup (for preselected oscillation parameters) is obtained by normalising total flux to the observed number of events as:

$$\mathcal{E} = \frac{N_{KGF}}{\sum_{i=11}^{24} \mathcal{F}_\mu(\Delta m^2, \theta, \Theta_i)}$$

where $\Theta_i = 5^\circ \times i + 2.5^\circ$. The total number of events observed at KGF detectors with the suggested cuts is estimated to be $N_{KGF} \approx 250$ (Section IV).

3. Using this factor, we calculate the expected number of events, $N_{KGF}(\Theta_i)$, in each angular bin for the KGF (up+down) setup. The same exposure factor $\mathcal{E}$ is used to determine $N_{U/P}(\Theta_i)$, the number of upward events in the KGF data set:

$$N_{KGF}(\Theta_i) = \mathcal{E} \times [\mathcal{F}_\mu(\Theta_i) + \mathcal{F}_\mu(180^\circ - \Theta_i)],$$

$$N_{U/P}(\Theta_i) = \mathcal{E} \times \mathcal{F}_\mu(\Theta_i)$$

(2)
To obtain $N_{UP}$ experimentally, the number of SK/MACRO events have to be rescaled to their exposure factors, and then multiplied by the KGF exposure factor. However, since the statistics of the SK/MACRO detectors are quite high as compared to that of KGF, the estimated number of upward going events can be treated as a true number. The sensitivity of the method is controlled then by the statistical fluctuations of $N_{KGF}$. Using Eqs. (6), the total number of events with exclusion of the horizontal bin ($85^\circ < \Theta < 95^\circ$), can be obtained. We denote them as $N_{KGF}$ and $N_{UP}$, for KGF and SK/MACRO setup respectively.

4. Now we can evaluate the asymmetry between the upward and downward fluxes as:

$$A_{U/D}^\mu = \frac{N_{UP}}{N_{KGF} - N_{UP}}$$

5. Finally, the sensitivity to the oscillation parameters is expressed as the significance of deviation of the asymmetry from unity.

We emphasize once again that the sensitivity has been evaluated only on the basis of statistical strength of the data. Possible systematic effects, if any, that could arise while combining the results from different detectors have to be taken into account while performing the comparison.

III. $\nu_\mu$-INDUCED MUON FLUX

The estimation is based on the current knowledge of neutrino flux, its interaction cross section and muon energy loss in matter. The $\nu_\mu$-induced muon flux in each angular bin can be written as:

$$dF_\mu(\Delta m^2, \theta, E_\nu, \Theta) = dF_{\nu_\mu}(\Delta m^2, \theta, E_\nu, \Theta) \times Y_{[\nu_\mu \rightarrow \nu_\mu]}(E_\nu)$$

where we assumed that the $\nu_{\mu}$-induced muon maintains the original neutrino direction; an analogue formula holds for the $\nu_{\tau}$-induced muon flux.

The function $Y_{[\nu_\mu \rightarrow \nu_\mu]}$ is the muon yield per neutrino. The yield increases with energy of neutrino and depends on minimum visible energy of muon required by the detector ($E_{min}$). The yield is calculated by considering the inclusive cross section for muon production $\sigma_{[\nu_\mu \rightarrow \nu_\mu]}$, times the number of target nucleons per cm$^2$ giving rise to sufficiently energetic muon above the threshold energy $E_{min}$ (0.5 GeV in the present calculation):

$$Y_{[\nu_\mu \rightarrow \nu_\mu]}(E_\nu) = \int_{E_{min}}^{E_\nu} dE_\nu \frac{d\sigma_{[\nu_\mu \rightarrow \nu_\mu]}}{dE_\mu}(E_\nu, E_\mu) \times N_A [R(E_\mu) - R(E_{min})]$$

$N_A$ is the Avogadro number and $R(E_\mu)$ is the range of muons in the rock. We used neutrino flux from [3]. For the cross section, we followed the prescriptions of [4], splitting (according to the hadronic invariant mass $W$) the quasi-elastic [5], the delta-resonance [6] and the deep-inelastic (GRV94 form factors [7]) contributions to the charged current reaction. For the range $R(E_\mu)$ we used the results illustrated in [5].

For non-zero neutrino oscillation parameters, the $\nu_\mu$ flux will get suppressed as:

$$dF_{\nu_\mu}(\Delta m^2, \theta, E_\nu, \Theta) = dF_{\nu_\mu}^0(E_\nu, \Theta) \times P_{[\nu_\mu \rightarrow \nu_\mu]}(\Delta m^2, \theta, E_\nu, L_\nu)$$

The survival probability $P_{[\nu_\mu \rightarrow \nu_\mu]}$ for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is given by

$$P_{[\nu_\mu \rightarrow \nu_\mu]}(\Delta m^2, \theta, E_\nu, L_\nu) = 1 - \sin^2(2\theta) \sin^2 \left( 1.27 \frac{\Delta m^2 [eV^2] \times L_\nu [km]}{E_\nu [GeV]} \right)$$

where $\theta$ is the flavour mixing angle, $\Delta m^2$ the square-mass difference, $L_\nu$ is the distance travelled by neutrino between its production and interaction point. The distance travelled by neutrino, in turn, depends on the zenith angle:

$$L_\nu = \sqrt{(R_{\oplus} + H_p)^2 - (R_{\oplus} - H_d)^2 \sin^2 \Theta - (R_{\oplus} - H_d) \cos \Theta}$$

$R_{\oplus}$ denotes the radius of Earth, $H_p$ the height of neutrino production in the atmosphere, $H_d$ the depth of operation.

The estimated $\nu_\mu$-induced muon flux $F_\mu(\Delta m^2, \theta, \Theta_i)$ is obtained in each angular bin by integrating Eq. (6) over the allowed range of zenith angle ($\Theta - 2.5^\circ < \Theta < \Theta + 2.5^\circ$) and neutrino energy ($E_\nu > E_{min}$). Fig. 1 shows the normalised integral flux of $\nu_\mu$-induced muons as a function of neutrino energy arriving in a nearly horizontal direction $\Theta = 87.5^\circ \pm 2.5^\circ$. As can be seen from the figure; (a) Neutrinos with energies up to 10 GeV are estimated to contribute only to 22% of total events (the same becomes 12 % at the SK muon energy threshold). In presence of oscillations, which mostly affect the lowest energy neutrinos, this fraction will diminish further. (b) Half of the observed events are expected to be originating from neutrinos of energy $E_\nu > 50$ GeV (for SK muon energy threshold, the median is estimated to be at $\sim 75$ GeV). This clearly illustrates that the proposed asymmetry samples more energetic neutrinos than those in Sub and Multi-GeV data sets. It also indicates the necessity of comparing data from different detectors at the same muon energy threshold as stated in section II.
The statistical strength of KGF data is the crucial factor which controls the significance of a possible deviation of the observable $A^\mu_{U/D}$ from unity, and consequently the sensitivity to the parameters of neutrino oscillations. The number of events recorded by KGF detectors in part of their data sample is 213 \cite{10}. Using this and the total running time of Phase-2 detector \cite{9}, we estimate the total number to be 225 events. The same path length criteria was applied to Phase-1 and Phase-2 detectors, which led to higher muon energy threshold for Phase-1 detector (Table \ref{table1}). In order to match the energy threshold with that of Phase-2 detector, it is necessary to reduce the path length cut by about 20\%, which in turn will enhance the aperture, and hence the number of events in the Phase-1 detector. In addition to this, there will be a further enhancement due to an increase in the angular acceptance by an additional 5\%. Therefore, in total we estimate about $N_{KGF} \approx 250$ events from the two detectors in KGF site within the zenith angle range of $55^\circ < \Theta < 125^\circ$.

The error on up/down asymmetry is obtained by propagating the statistical error on KGF observations as:

$$\Delta A^\mu_{U/D} = A^\mu_{U/D} \frac{\sqrt{N'_{KGF}}}{N_{KGF} - N'_{UP}}$$ (9)

Fig. 2 shows the plot of the asymmetry $A^\mu_{U/D}$ as function $\Delta m^2$ (at maximal mixing). As it can be seen from the plot, the asymmetry approaches unity at small or large values of $\Delta m^2$. At small values, neither upward going nor downward going neutrinos get oscillated significantly and hence asymmetry will be close to unity due to negligible oscillation. For very large values of $\Delta m^2$, oscillation length is quite small as compared to the distance travelled by neutrino arriving in the zenith angle range of $55^\circ < \Theta < 125^\circ$. Hence the oscillation probability asymptotically approaches to half (at maximal mixing) for upward as well as downward directions, making again asymmetry closer to unity. This implies that the parameter $A^\mu_{U/D}$ cannot distinguish between extreme values of $\Delta m^2$.

Average distance travelled by neutrino in upward direction in zenith angle region of $95^\circ < \Theta < 125^\circ$ is \(\sim 3000 \text{ km}\), and the median energy of neutrino is \(\sim 50 \text{ GeV}\) (Fig. 3). Neutrino oscillations (see Eq. (7)) at these typical values are maximal for $\Delta m^2 \approx 2 \cdot 10^{-2} \text{ eV}$. This value is consistent with the best sensitivity point \(\sim 2 \cdot 10^{-2} \text{ eV}\).

\begin{figure}[h]
\centering
\includegraphics{fig1.png}
\caption{Parent neutrino energy distribution for induced muons with $E_\nu > 0.5 \text{ GeV}$ arriving at nearly horizontal direction ($\Theta = 87.5^\circ \pm 2.5^\circ$).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics{fig2.png}
\caption{Up/down Asymmetry beyond Multi-GeV Region, assuming maximal mixing angle.}
\end{figure}

\footnote{The SK analysis of East-West effect proves that the theoretical expectations are well met by experimental data \cite{12}.} The significance of a deviation of $A^\mu_{U/D}$ from unity can
be obtained from the estimated value of $A_{U/D}^\nu$, and error on it (see Eqs. (11)). This is translated to a probability, by equating it to the integral of Gaussian probability distribution below the estimated significance. We obtain the sensitivity regions in $(\Delta m^2, \sin^2 2\theta)$ parameters space, which corresponds to a chance probability of < 5% (and < 1%) to have the estimated value of the asymmetry as a result of a statistical fluctuation. These regions are shown in Fig. 3. It can be seen that the proposed method is sensitive to $\Delta m^2$ in the range of $10^{-3}$ eV$^2$ to 1 eV$^2$ at maximal mixing. This more or less completely spans the region of oscillation parameters obtained by SK detector to explain their full data sample.

Sensitivity of the proposed method is derived on the assumption that experimental data from all the detectors will be available at same visible energy threshold. We show now that, even releasing this assumption, the conclusions would not change significantly. Using the formalism described in Section III we estimated that $U_{P_{KGF}} = 1.22 \times U_{P_{SK}}$ and $U_{P_{KGF}} = 1.13 \times U_{P_{MACRO}}$, where $U_{P_{KGF}}, U_{P_{SK}}$ and $U_{P_{MACRO}}$ denote the upward going $\nu_e$-induced muon flux at corresponding energy threshold of these detectors in the angular region of interest. If we are able to control the error on $(U_{P_{KGF}}/U_{P_{SK}} - 1)$ at the level of 17%, or the error on $(U_{P_{KGF}}/U_{P_{MACRO}} - 1)$ at the level of 28%, then an uncertainty of $\sim 3\%$ would be introduced in the expected number of upward going events $N^e_{UP}$, which was assumed to be the true number of events in our sensitivity calculations. Since this uncertainty is small as compared to statistical error on KGF data; it would not affect the sensitivity region significantly. It seems to be quite possible to reach the desired control on the uncertainty. This is because we only need to get the ratio of neutrino induced muon flux at different muon energy threshold, wherein most of the uncertainties on neutrino flux, interaction cross section etc. tends to get cancelled out while considering ratios. In this respect, it is to be noted that ratio of number of stopping to through-going muons is predicted to an accuracy of 13% at SK; the uncertainty being dominated by the spectrum of primary cosmic rays.

V. SUMMARY AND DISCUSSIONS

Neutrino oscillation signatures are studied in SK detector by several methods, namely; a) ratio of electron-like to muon-like events using contained data sample, b) up/down asymmetry of contained muon events, c) shape of zenith angle distribution of upward going passing through muons and d) the ratio of stopping to through going upward muons. It is to be noted that oscillation parameters are better constrained by the contained event data samples, which corresponds to neutrinos of relatively low energy. However, these data may not be able to improve the constraints further, once the systematic errors start dominating over statistical errors. Therefore, it is necessary to make more effective use of the data sample that probes the high energy neutrino spectrum.

We have shown that it is possible to obtain the up/down asymmetry $A_{U/D}^\nu$, beyond the Multi-GeV energy region using the currently available data from KGF, SK and MACRO experiments. This is a direct measurement as it does not require any a priori knowledge of neutrino flux, its zenith angle distribution, interaction cross section etc. (the intrinsic asymmetry of the flux due to geomagnetic effects only affects the low energy neutrinos, which, however, give a rather small contribution to the neutrino parent spectrum shown in Section IV). We have demonstrated that this measurement is sensitive to the allowed region of neutrino oscillation parameter space suggested by the recent results from SK Collaboration [1]. We have not attempted an accurate study of systematics. However, we checked that the inclusion of geomagnetic effects does not lead to a significant change in the sensitivity region.

The best fit value obtained by Super-Kamiokande Collaboration [2] using Sub and Multi-GeV data is $\Delta m^2 = 3.5 \times 10^{-3}$ eV$^2$, and maximal mixing; as can be seen from Fig. 3, these parameters lie within the sensitive region of the proposed method.

In conclusion, the proposed asymmetry parameter, $A_{U/D}^\nu$, entails high energy neutrinos and it could be obtained using currently available data from different experiments. The analysis of this parameter permits an independent test of neutrino flavour conversion, having sensitivity to the range of neutrino oscillation parameters suggested by Super-Kamiokande experiments.
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