Mixed high energy neutrinos from cosmos

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Production of the expected high energy neutrino flux with energy greater than tens of thousands of GeV in some astrophysical sites such as the galactic plane as well as the centers of some distant galaxies is reviewed. The expected changes in these neutrino fluxes because of neutrino oscillations during their propagation to us are described. Observational signatures for these neutrino fluxes with and without neutrino oscillations are discussed.

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I. GENERAL INTRODUCTION

In the standard model of the electro weak interactions, the lepton masses and the values of other parameters such as weak mixing angle, couplings, etc. are arbitrary and are therefore determined by experiments. These parameters are independent of each other and can not be determined uniquely, while the neutrino is taken to be massless because of maximal parity violation. The masslessness of the neutrino however does not follow from any other theoretical ground unlike the local gauge invariance for the photon

In order to search for physics beyond the standard model of particle physics, light neutrino masses are incorporated in the extensions of the standard model. Empirically, one places finite non-vanishing upper bounds on measurable neutrino masses. Presently, there is some indirect empirical evidence for the masslessness of the neutrino

Massive neutrinos quite likely mix. The mixing of quarks is an established fact and because of quark-lepton symmetry, it is natural to assume that leptons exhibit mixing as well. An additional argument, in this sense, is provided by grand unification models, in which quarks and leptons are described in a unified manner.

Mixing means that \( \nu_e, \nu_\mu \) and \( \nu_\tau \), i.e., the states created in weak interactions, are different from the states \( \nu_1, \nu_2 \) and \( \nu_3 \) that have definite masses. The neutrinos \( \nu_e, \nu_\mu \) and \( \nu_\tau \) are orthogonal combinations of \( \nu_1, \nu_2 \) and \( \nu_3 \) with different phases between them. In addition, the sterile neutrinos may mix with these neutrinos.

Neutrino mixing has, as its consequence, neutrino oscillations, i.e., the process of periodic (complete or partial) conversion of neutrinos of one type into another, for instance, \( \nu_e \rightarrow \nu_\mu \rightarrow \nu_e \rightarrow \ldots \). The components \( \nu_i \) of a mixed neutrino have different masses and hence different phase velocities. It follows that the phase difference caused by the mass difference between the \( \nu_i \) vary monotonically during the propagation. This phase change manifests itself as neutrino oscillations.

If neutrino oscillations do occur in vacuum, matter can enhance their depth (probability amplitude) up to a maximal value. That is, a monotonic change of density may lead to resonant conversions between various neutrino flavors. This follows from the fact that when neutrinos propagate through a monotonically changing density medium, \( \nu_e \) and \( \nu_\mu \) (\( \nu_\tau \)) feel different potentials, because \( \nu_e \) scatters off electrons via both neutral and charged currents, whereas \( \nu_\mu \) (\( \nu_\tau \))
scatters off electrons only via the neutral current. This induces a coherent effect in which maximal conversion of $\nu_e$ into $\nu_\mu$ take place (even for a rather small intrinsic mixing angle in the vacuum), when the phase difference arising from the potential difference between the two neutrinos cancel the phase caused by the mass difference in the vacuum.

During nearly past half a century, the empirical search for neutrinos has spanned roughly six orders of magnitude in neutrino energy $E$, from $\sim 10^{-3}$ GeV up to $\sim 10^3$ GeV. The lower energy edge corresponds to the Solar neutrinos, whereas the upper energy edge corresponds to the Atmospheric neutrinos. A detailed early description of the Solar neutrino search can be found in [6], whereas for recent status, see, for instance [7]. The aspects of neutrino production in Atmosphere of earth related to neutrino oscillation studies are recently reviewed in [8]. The intermediate energy range corresponds to terrestrial neutrinos such as from reactors (and accelerators) and the Supernova neutrinos. Thus, obviously either going in energy range below these values or above are the available frontiers. For a general introduction of the possibility of having neutrinos with energy $> 10^3$ GeV, see [9]. The upper energy edge for these high energy neutrinos is limited only by the concerned experiments. More detailed general discussions in the context of high energy neutrinos can be found in [10, 11]. Despite the availability of the somewhat detailed discussion of progress cited in the last reference, the field of high energy neutrino astrophysics is still passing through its initial stage of development.

Main terrestrial empirical highlights include the early discovery of the $\bar{\nu}_e$, the existence of three light stable neutrinos flavors $\nu_e$, $\nu_\mu$ and $\nu_\tau$ as well as the recent (tentative) evidence for the $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillations. The extra-terrestrial highlights include the observation of Solar neutrinos and the $\nu_e \rightarrow \nu_\mu, \nu_\tau$ oscillations for these neutrinos, the same from Atmosphere of earth with Atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations. The confirmation of role of neutrinos in dynamics of supernova core collapse via SN 1987A also needs to be mentioned here [12].

The above highlighted empirical search has thus already given us quite useful insight into neutrino intrinsic properties such as mass and mixing. Massive neutrinos and their associated properties such as Dirac or Majorana character of their mass, their mixings (and magnetic moments) can have important consequences in astrophysics. In this review, I shall discuss some of the selected consequences and the constraints implied by these consequences on neutrino properties as well as the insight that one may gain about the nature of the astrophysical (or/and cosmological) sites and the interactions that produce these high energy neutrinos. The explanation of observed Solar $\nu_e$ deficit relative to its production value in the core of the Sun, via $\nu_e \rightarrow \nu_\mu, \nu_\tau$ conversion occurring inside the Sun is an impressive example in this context [13].

The general plan of this mainly pedagogical review is as follows. In Section IIA and IIB, the presently envisaged motivations and absolute levels of the expected high energy neutrino flux from some representative examples of cosmos around us such as our galactic plane are presented. This includes also the one arising from the interaction of ultra high energy cosmic ray flux ($E \geq 10^9$ GeV) with the matter and radiation inside the sources (such as center of our and other galaxies) of as well as during propagation of ultra high energy cosmic ray flux to us. In Section IIC, the
effects of neutrino flavor mixing for high energy neutrino flux are discussed, whereas in Sect. IID, main high energy neutrino interactions relevant for possible future observations are described along with a discussion of possibility of neutrino flavor identification. Section III gives the summary and conclusions.

II. HIGH ENERGY NEUTRINOS FROM COSMOS

A. Introduction

Neutrinos with $E > 10^3$ GeV are expected to mainly arise from the interaction of ultra high energy cosmic rays considered to be protons ($p$) here with the matter ($p$) and/or radiation ($\gamma$) present in cosmos. Examples of the astrophysical sites where these interaction may occur include the galactic plane, other sites within our galaxy as well as distant sites such as centers of nearby active galaxies (AGNs) and sites for gamma ray bursts (GRBs). Searching for high energy neutrinos thus can in turn also constrain the particle identity of ultra high energy cosmic rays.

As mentioned in the general introduction, here plan is to briefly review the present motivations of study of these high energy neutrinos. Though, so far there is no observation of neutrinos with energy greater than few thousand GeV, whose origin can not be associated with the Atmosphere of earth, nevertheless, somewhat optimistically speaking, given the current status of high energy neutrino detector developments and the absolute levels of predicted high energy neutrino fluxes, it is expected that possibly the first evidence of high energy neutrinos may appear within this decade.

A main motivation of high energy neutrino search is the quest of the microscopic understanding of the nature and origin of observed ultra high energy cosmic rays, namely the presently open questions such as whether they are protons, photons, neutrinos, heavy nuclei such as iron nuclei or some other particles suggested beyond the standard model of particle physics, and where and how they are produced or accelerated. A positive observation of high energy neutrinos can raise the possibility of simultaneous explanation of observed high energy photons ($E_{\gamma} \approx 10^3$ GeV) and ultra high energy cosmic rays as a result of hadron acceleration and interaction in the presently expanding universe.

Neutrinos with energy $> 10^3$ GeV can act as probes of the ultra high energy phenomena observed in the Universe. Unlike photons and charged particles such as protons and heavy nuclei, which can be absorbed or deflected by dust, other intervening matter or magnetic fields, neutrinos can more easily reach the earth because of their weak interactions with matter particles. It is therefore hoped that such neutrinos can provide information about the astrophysical (or/and cosmological) sources that will be complementary to inferences based on visual observations.

A better understanding of the interactions involved in neutrino production and a more accurate estimate of resulting neutrino fluxes could entail important consequences. Among these are insights into intrinsic properties of neutrinos such as mass and mixing [14], and the possible role of gravity on neutrino propagation in astrophysical environments [15]. However, it all depends on the existence of a sizable high energy neutrino flux. Assuming an existence of a sizable high energy neutrino flux, several of the other neutrino intrinsic properties as well as the useful information
about the source producing these neutrinos can be obtained, at least in principle. These include testing neutrino decay hypothesis, constraints on neutrino magnetic moment, quantum gravity effects on neutrino propagation, tests of possible violation of equivalence principle by neutrinos, as well as information on different properties of relic neutrinos. Also possibly enhancement in neutrino nucleon interaction cross section because of various new physics effects may be constrained. An early attempt to constrain the neutrino nucleon interaction cross section is discussed in.

The relevant average physical picture in AGNs is as follows. Some galaxies (~ 1%) have quite bright centers. The photon luminosity of these galaxies typically reach \((10^{44} - 10^{48})\) erg s\(^{-1}\). These galaxies are typically several Mpc away from us (where 1 pc \(\sim 3 \cdot 10^{18}\) cm). In general, AGNs refer to these bright and compact central regions, which may extend up to several pc in the center. These central compact regions have the remarkable property of being much more luminous than the rest of the entire galaxy. It is hypothesized that the existence of a super massive black hole with mass, \(m_{\text{BH}} \sim (10^6 - 10^{10}) m_\odot\), where \(m_\odot \sim 2 \cdot 10^{33}\) g, may explain the observed brightness as this super massive black hole captures the matter around it through accretion. This super massive black hole is presently hypothesized to be formed by the collapse of a cluster of stars. Some AGNs give off a jet of matter that stream out from the central compact region in a transverse plane and produce hot spots when the jet strikes the surrounding matter at its other ends. During and after accretion, the (Fermi) accelerated ultra high energy protons may collide with other protons and/or with the ambient photons in the vicinity of an AGN or/and in the associated jets/hot spots to produce unstable hadrons (such as \(\Delta\)). These unstable hadrons decay mainly into neutral and charged pions. The neutral pions further decay dominantly into photons and thus may explain a large fraction of the observed brightness, whereas the charged pions mainly decay into neutrinos. AGNs, therefore, have been targeted as one likely source of high energy neutrinos. Currently, the photohadronically \((p\gamma)\) produced diffuse flux of high energy neutrinos originating from AGNs dominate over the flux from other sources above the relevant Atmospheric neutrino background typically for \(E \geq 10^6\) GeV. For further reading on astrophysical super massive black holes, see.

Recently, fireballs are suggested as a possible production scenario for gamma ray bursts as well as high energy neutrino bursts at the site. Though, the origin of these gamma ray burst fireballs is not yet understood, the observations suggest that generically a very compact source of linear scale \(\sim 10^7\) cm through internal or/and external shock propagation produces these gamma ray bursts (as well as burst of high energy neutrinos) mainly in \(p\gamma\) interactions. Typically, this compact source is hypothesized to be formed possibly due to merging of binary neutron stars or due to collapse of a super massive star. Thus, fireballs have also been suggested as a probable scenario for the observed gamma ray bursts, and they too are expected to emit neutrinos with energies in excess of thousands of GeV, possibly above the Atmospheric neutrino background. For a recent review, see.

A nearby and more certain source of high energy neutrinos is our galactic plane. The incoming ultra high energy cosmic ray protons interact with the ionized hydrogen clouds there and can produce high energy neutrinos in \(pp\) interactions. Present estimates indicate that the diffuse galactic plane muon neutrino flux can dominate over the
TABLE I: Comparison of the cross sections and average fraction of incident high energy carried by neutrinos for the three high energy neutrino production interactions discussed in the text at $\sqrt{s} \sim 1.2$ GeV.

| Interaction          | $\sigma$(mb) | Average fraction of incident high energy carried by neutrinos |
|----------------------|--------------|-------------------------------------------------------------|
| $p\gamma \rightarrow N\pi^{\pm}$ | $\leq 5 \cdot 10^{-1}$ | $E_{\nu}/E_p \leq 5\%$ |
| $pp \rightarrow N\pi^{\pm}$       | $\sim 3 \cdot 10^{1}$  | $E_{\nu}/E_p \leq 5\%$ |
| $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$ | $< 10^{-3}$ | $E_{\nu}/E_{\gamma} \leq 30\%$ |

Atmospheric one for $E > 10^5$ GeV. Other sources within the galaxy such as galactic micro quasars may also produce high energy muon neutrino flux around this energy.

**B. Expected neutrino production**

Several types of interactions and the resulting unstable particles can in principle give rise to high energy neutrino flux in cosmos. For definiteness, here I shall consider only $p(\gamma, p)$ interactions to illustrate some examples of presently envisaged main source interactions and to classify the expected high energy neutrino production sites accordingly.

A presently favorable astrophysical (or bottom up) scenario for high energy neutrino production is that the observed ultra high energy cosmic rays beyond GZK cutoff (see later) are dominantly protons and that the observed high energy photon flux can be associated with these. On the other hand, an unfavorable scenario is that the ultra energy cosmic rays are dominantly other than protons and that the observed high energy photon flux has purely electromagnetic origin. In the latter case, there will still be neutrino flux but at a rather suppressed level (such as in $\gamma\gamma$ interactions) as compared to the former case. The latter possibility is recently discussed in some detail in [28].

The main interactions responsible for the production of these high energy neutrinos include the $p\gamma$ and $pp$ interactions (see Table II for some characteristics). For the behavior of these cross sections as a function of center-of-mass energy $\sqrt{s}$ in the range of interest, see [29]. There is formation of $\Delta$ resonance in $p\gamma$ interactions, at $\sqrt{s} \sim m_\Delta \sim 1.2$ GeV, where $s \simeq m_p^2 + 4E_pE_\gamma$, that mainly decay into electron and muon neutrinos. Two behaviors of the $p\gamma$ cross section, near $\sqrt{s} \sim 1.2$ GeV make it an important channel for high energy neutrino production, the relatively large width of the $\Delta$ resonance, $\Gamma_\Delta/m_\Delta \sim 10^{-2}$, and the almost constant behavior of the cross section for $\sqrt{s} > m_\Delta + \Gamma_\Delta$. Under the assumption of all other similar conditions, it is the interaction cross section that determines the absolute level of high energy neutrino production.

For illustrative purpose, Fig. 1 displays a simple classification flow chart for presently envisaged sources of high energy neutrinos. It includes the possibility of high energy neutrino production from cosmic relics, referred to as $X$ [30]. Briefly, these relics are considered to be formed in the early epochs of the universe such as during inflation epoch. The large amount of energy trapped in these relics may be released in the form of grand unification scale gauge bosons which in turn decay/annihilate into standard model particles including neutrinos. The direct channel $X \rightarrow \nu\bar{\nu}$ is also possible [31]. These relics need not be far away from us. In fact, some of the models suggest that they may be a part of our galactic dark matter halo implying at a distance of $\leq 10$ kpc. If these $X$’s can be the
Typically, an acceleration mechanism for cosmic ray protons is required with a power law flux spectrum, \( F_p(E) \propto E^{-\varsigma} \) with \( \varsigma \sim 2 \). In general, astrophysical source(s) should be at a distance of \( \leq 50 \) Mpc.

Astrophysical or Bottom Up

\[ p(\gamma, p) \rightarrow \pi^\pm \rightarrow \mu^\pm \rightarrow \nu \]

Interaction, Decay or/and Annihilation

Cosmological or Top Down

\[ X \rightarrow q\bar{q} \rightarrow \pi^\pm \rightarrow \mu^\pm \rightarrow \nu \]

Here, no acceleration mechanism is required for cosmic ray protons. If the cosmo relic \( X \)'s can be a dominant source for ultra high energy cosmic rays (UHECR), then it requires that \( m_X c^2 \geq E_{\text{UHECR}}^{\text{max}} \).

\[ \bar{X}X \rightarrow q\bar{q} \rightarrow \pi^\pm \rightarrow \mu^\pm \rightarrow \nu \]

**FIG. 1:** A simple classification flow chart for presently envisaged main sources of high energy neutrinos. Only non tau neutrino production is illustrated.

dominant sources of observed ultra high energy cosmic rays then this in turn severely constrain their number density \( n_X \), life time \( \tau_X \), mass \( m_X \), and thus determine the resulting high energy neutrino flux spectrum shape and absolute level. This possibility is referred to as the cosmological (or top down) scenario for expected high energy neutrino production. The distance restrictions do not necessarily always apply for this kind of sources. Currently, the
ultra high energy cosmic rays with energy $E_{\text{UHECR}}^{\text{max}}$ up to $\sim 3 \times 10^{11}$ GeV are observed \[33\]. The cosmological sources however require physics beyond standard model to work \[34\].

Depending on the details of the astrophysical or cosmological model for high energy neutrino production scenario, either the observed photon flux or proton flux or both are used to determine the absolute level of the expected neutrinos flux. From the cosmos, presently high energy photons and ultra high energy cosmic rays (considered to be protons here) are observed in the relevant context. Their observed level of flux determines the absolute flux level of neutrinos as high energy neutrinos are secondary in nature in the sense that they are not matter particles and are not a significant fraction of the matter density associated with a specific known astrophysical or/and cosmological source. On the other hand, neutrinos are stable and neutral and therefore for this precise reason will carry useful information about the source.

Supposing protons can escape the extra galactic astrophysical sources and can be a dominant fraction of the observed ultra high energy cosmic ray flux, the resulting high energy (muon) neutrino flux mainly in $p\gamma$ and $pp$ interactions either arising from inside the source or during propagation has to be less than this. It can be typically $\leq 10^{-8}$ GeV/cm$^2$·s·sr$^{-1}$ for $10^5 < E/\text{GeV} < 10^{12}$ \[35\]. This bound further tightens by a factor of 1/2 once the neutrino flavor oscillation effects are taken into account (see later).

Consider now briefly the $p\gamma \rightarrow \Delta \rightarrow p\pi$ ($N = p$) interactions occurring during the propagation of ultra high energy cosmic rays either inside an astrophysical source or between the source and the earth in the presence of a dense photon background. This is to serve as an illustrative example for having an order of magnitude idea of the expected $E$. The threshold energy for protons interacting with photons at an angle $\phi$ to form $\Delta$ resonance, is

$$E_{\text{th}}^p = \frac{(m_p + m_\pi)^2 - m_p^2}{2E_\gamma (1 - \cos \phi)},$$

which in case of head on interactions further simplifies to

$$E_{\text{th}}^p \approx \frac{m_p m_\pi}{2E_\gamma}.$$ (2)

For $E_p < E_{\text{th}}^p$, the interaction $p\gamma \rightarrow pe^+e^-$ dominates the energy loss for protons. If $E_\gamma = E_{\gamma}^{\text{CMB}} \sim 2.7$ K then $E_{\text{th}}^p \sim 10^{11}$ GeV. The $p\gamma$ interaction length can be defined as

$$\lambda \sim 1/n_\gamma \sigma_{p\gamma \rightarrow p\pi}.$$ (3)

For instance, if $n_\gamma = n_\gamma^{\text{CMB}} \sim 410$ cm$^{-3}$ for $E_\gamma = E_{\gamma}^{\text{CMB}}$ then $\lambda < 6$ Mpc, where $\sigma_{p\gamma \rightarrow p\pi}$ is given in Table I.

The propagation of ultra high energy proton flux, $F_p$, can be studied in the presence of photon background in distance $r$, by solving the following equation

$$\frac{dF_p(E, r)}{dr} = -\frac{1}{\lambda(E)} F_p(E, r).$$ (4)

The negative sign indicates the decrease in the ultra high energy proton flux because of interaction described by $\lambda$. This results in an exponential cut off in $p$ flux spectrum for $r \geq 50$ Mpc. In case of ubiquitous cmb photon background,
it is commonly referred to as Greisen Zatsepin Kuzmin (GZK) cut off. It occurs at $E_p^{th} \sim 10^{11}$ GeV, according to Eq. (2). The resulting GZK (muon) neutrino flux spectrum peaks at $\sim 10^9$ GeV by sharing roughly $(1/4) \cdot (1/5)$ of the $E_p^{th}$.

The matter density in interstellar medium as well as in several of the astrophysical sites such as the galactic plane, the AGNs and the GRBs, is rather small (relative to that in Atmosphere of earth). Therefore, a rather simple formula can be used to estimate the integral high energy neutrino flux spectrum in $p\gamma$ and/or $pp$, in units of $(\text{cm}^2 \cdot \text{s} \cdot \text{sr})^{-1}$, in a specific individual astrophysical site

$$F_\nu^0(E) = \int_{E_{max}}^{E} dE F_p(E) g(E) \frac{d\sigma(p(\gamma,p)\rightarrow \nu Y)}{dE}.$$  

(5)

Here $F_p(E)$ parameterizes the high energy proton flux. The function $g(E) \equiv r/\lambda(E)$ gives the number of $p(\gamma,p)$ interactions within the distance $r$. The $dn/dE \equiv \sigma^{-1}d\sigma/dE$ is the neutrino energy distribution in above interactions. The implicit assumption here is that the unstable hadrons and leptons produced in above interactions decay before they interact owing to the fact that the matter density in the distance $r$ is assumed to be rather small. Also, the effects of possible red shift evolution and magnetic field of the astrophysical sources are neglected for simplicity.

There is yet another possible class of astrophysical sources of high energy neutrinos that are essentially neither constrained by observed high energy photon nor by ultra high energy cosmic ray flux. It is so because in this class of sources, the matter density is considered to be too large so that neither of the above leave the source. These sources are therefore commonly referred to as hidden sources or neutrinos only sources. The high energy neutrino production occurs in same $pp$ (or $p\gamma$) interactions here also. These can only be constrained by the high energy neutrino flux (non) observations.

The above discussion is restricted to non tau neutrino production only. In the $\pi^\pm \rightarrow \mu^\pm \rightarrow \nu$ decay situation, the relative ratio of resulting electron and muon neutrino flux is $1:2$ respectively. The astrophysical tau neutrino flux is produced in decays of $D_S^\pm$. For $\sqrt{s} \sim m_\Delta$, it is known that $\sigma[p(\gamma,p)\rightarrow D_S^\pm Y]/\sigma[p(\gamma,p)\rightarrow \pi^\pm Y] \leq O(10^{-3} - 10^{-4})$.

The high energy tau neutrino flux is thus rather suppressed at the production sites and can therefore be taken as approximately zero, resulting in $1:2:0$. For a recent review on astrophysical tau neutrinos, see, whereas for cosmological tau neutrinos, see, for instance.

C. Oscillations during propagation: Effects of neutrino mixing

In view of recent growing evidence of neutrino flavor oscillations, I shall here elaborate the relative changes expected in the high energy neutrino flux because of neutrino flavor oscillations.

There are at least two aspects of neutrino propagation effects that need somewhat careful considerations in study of neutrino mixing effects for high energy neutrinos. These are: the neutrino interactions with the background particles inside the (astrophysical) source of neutrinos as well as between the source and the earth. The present knowledge of matter density, $\rho$ inside the known sources as well as between these sources and the earth imply that
it is rather quite small (as compared to that in Sun). As a result, the level crossing (or resonance) condition, namely $G_F p/m_N \sim \Delta m^2/2E$, for matter enhanced neutrino flavor oscillations is not satisfied. Level crossing is a necessary condition for occurrence of matter enhanced neutrino flavor oscillations. Therefore, there are essentially no matter effects on pure vacuum flavor oscillations. Note that this is in contrast to the situation in Sun and Super novae. Furthermore, the neutrino nucleon and neutrino electron inelastic interaction effects are also small enough to influence the mixed neutrino propagation even at ultra high energy in a significantly observable manner. This is also because of rather small matter density. Therefore, I elaborate here only effects of neutrino flavor mixing in vacuum (with no matter interactions)\(^1\).

Note from the previous subsection that the high energy neutrinos are produced in the following relative ratios

$$P(\nu_\alpha \rightarrow \nu_\beta; L) \equiv P_{\alpha \beta} = \delta_{\alpha \beta} - \sum_{j \neq k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k} (1 - e^{-i \Delta m^2_{jk} L/2E}).$$

\(^1\) If i) $0.1 \leq \sin^2 2\theta \leq 0.95$, ii) $E \geq 10^{19}$ GeV (essentially irrespective of $\Delta m^2$ values), iii) the red shift $z \geq 3$ at production, and iv) $\xi \geq 1$, where $\xi \equiv (n_\nu - n_{\bar{\nu}})/n_{\gamma}$, then a deviation from pure vacuum flavor oscillations can be of the order of few percent, when high energy neutrinos scatter over the very low energy relic neutrinos during their propagation to us in the interstellar medium.\(^2\)
In the far distance approximation, namely, in the limit \( L \to \infty \), one obtains

\[
P(\nu_\alpha \to \nu_\beta; L \to \infty) \simeq \delta_{\alpha\beta} - \sum_{j \neq k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k},
\]

\[
\simeq \frac{3}{\sum_{j=1}^{3} |U_{\alpha j}|^2 |U_{\alpha j}|^2}.
\]

(11)

Because of the assumed averaging over the rapidly oscillating phase \( l_{osc} \ll L \), where \( l_{osc} = 2E/\Delta m_{23}^2 \), the last two expressions are independent of \( E \) and \( \Delta m^2 \). Under this assumption, the oscillation probability can be written as a symmetric matrix \( P \) such that

\[
P = \begin{pmatrix}
P_{ee} & P_{e\mu} & P_{e\tau} \\
P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\
P_{e\tau} & P_{\mu\tau} & P_{\tau\tau}
\end{pmatrix}.
\]

(12)

For vanishing \( \delta_{13} \) and \( \theta_{13} \), using Eq. (11), it is straightforward to obtain

\[
P_{e\mu} \simeq 2c_{12}^2 s_{12}^2 c_{23}^2, \quad P_{e\tau} \simeq 2s_{12}^2 s_{23}^2 c_{23}, \quad \text{and} \quad P_{\mu\tau} \simeq c_{23}^2 s_{23}^2 (1 + c_{12}^4 + s_{12}^4).
\]

(13)

Using above Eq., a simple form for \( P \) matrix can be obtained in the case of bi maximal mixing as

\[
P = \begin{pmatrix}
5/8 & 3/16 & 3/16 \\
3/16 & 13/32 & 13/32 \\
3/16 & 13/32 & 13/32
\end{pmatrix},
\]

(14)

as presently in the context of three (active) neutrino flavors, the Solar electron neutrino deficit can be explained with \( (\Delta m^2, \sin^2 2\theta) \) as \( (10^{-5} \text{eV}^2, \sim 1) \) via \( \nu_e \to \nu_\mu \) or \( \nu_e \) oscillations. The Atmospheric muon neutrino deficit can be explained with \( (10^{-3} \text{eV}^2, \sim 1) \) via \( \nu_\mu \to \nu_\tau \) oscillations. The above \( P \) matrix satisfies the following unitarity conditions:

\[
1 - P_{ee} = P_{e\mu} + P_{e\tau}, \quad 1 - P_{\mu\mu} = P_{e\mu} + P_{\mu\tau}, \quad \text{and} \quad 1 - P_{\tau\tau} = P_{e\tau} + P_{\mu\tau}.
\]

(15)

Namely, the disappearance of a certain neutrino flavor is equal to the appearance of this flavor into other (active) neutrino flavors. High energy neutrino flux arriving at the earth can then be estimated using

\[
F_{\nu_\alpha} = \sum_{\beta} P_{\alpha\beta} F_{\nu_\beta}^0,
\]

(16)

where \( P_{\alpha\beta} \) is given by Eq. (11). Note that in case of initial relative flux ratios as \( 1 : 2 : 0 \) [see Eq. (6)], one always get

\[
F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} = 1 : 1 : 1,
\]

(17)

under the assumption of averaging irrespective of any specific flavor oscillation solution for Solar neutrino problem 46. A considerable enhancement in \( F_{\nu_\tau} \) relative to \( F_{\nu_\tau}^0 \) because of neutrino oscillations is evident. A somewhat detailed numerical study that takes into account the effects of non vanishing \( \delta_{13} \) and \( \theta_{13} \) indicates that the deviation \( \epsilon \),
from these final relative ratios is not more than few percent (namely, $|\epsilon| \leq 0.1$ in $1 \pm |\epsilon|$)\cite{14}. There could, in principle, be several intrinsic neutrino properties that may lead to deviations from $1 : 1 : 1$ final relative ratios other than $|\epsilon|$ as well as an energy dependence, such as neutrino spin flavor conversions\cite{47}. Some astrophysical/cosmological reasons at the source can also possibly contribute to $\epsilon$.

Measuring the three flavor ratios (and in particular deviations from $1 : 1 : 1$) may entail several important consequences such as $\nu_\tau$ flavor appearance (which has not yet achieved in terrestrial experiments because of flavor oscillations), the insight into the production mechanism (whether through $\pi^\pm$ or not) and about its astrophysical or cosmological origin\cite{48}. In the above simplified discussion, the expression for $P$ neither depends on $\Delta m^2$ nor on $E$. However, in some situations, this need not be the case. In that case, one need to use complete expression for $P$ given by Eq. (10) and possibly have to average over the red shift distribution of astrophysical sources, $f(z)$. This gives the effect of evolution of the sources with respect to $z$. The $P$ can then be calculated using Eq. (10) with $E \rightarrow (1 + z)E$ in following formula

$$P_{\alpha\beta}(E) = \frac{\int_{0}^{z_{\text{max}}} P_{\alpha\beta}(E,z) f(z) dz}{\int_{0}^{z_{\text{max}}} f(z) dz}.$$ \hspace{1cm} (18)

The $f(z)$ can be found in\cite{42}.

D. Prospects for possible future observations

I shall here describe the basic essential factors such as the neutrino nucleon/electron interaction cross section and the range of the associated charged leptons typically in the energy range $10^{3} \div 10^{7}$ that determine the (limited) near future prospects for observations of high energy neutrinos. The current and near future status of the dedicated high energy neutrino detectors is given in\cite{49}.

Briefly, the present detectors based on Cherenkov radiation measurement, in ice or water are the Antarctic Muon and Neutrino Detector Array (AMANDA) and its proposed extension, the Ice Cube, the lake Baikal detector and the Astronomy with a Neutrino Telescope and Abyss environmental RESearch (ANTARES) detector array. The hybrid detectors based on particle and radiation measurement such as Pierre Auger Observatory may also detect high energy neutrinos\cite{50}. Detectors based on alternative detection techniques such as radio wave detection are also in operation, such as Radio Ice Cherenkov Experiment (RICE). This detector is based on Askaryan effect\cite{51}. This effect is briefly defined as follows: In an electromagnetic shower generated in deep inelastic neutrino nucleon interaction, the electrons and photons in the shower generate an excess of $\sim 10 - 20\%$ electrons in the shower because of the electron and photon interactions with the medium in which the shower develops. This in turn generate coherent radio wave pulse (in addition to other type of radiation), if the wavelength of this radio emission is greater than the size of the shower. The search for alternative high energy neutrino detection medium other than air, water and/or ice, such as rock salt has also been attempted for radio wave emission\cite{52}. It might also be possible to detect the acoustic pulses generated by deep inelastic neutrino nucleon interactions near or inside the detector. An attempt in this direction is through
Sea Acoustic Detection of Cosmic Objects (SADCO) detector array. Other modern proposals include space based detectors such as Orbiting Wide Angle Light collector (OWL/Air Watch) and Extreme Universe Space Observatory (EUSO).

Among all these, somewhat stringent upper bounds on (diffuse) high energy neutrino flux are reported by AMANDA and Baikal detectors. From AMANDA (B10), now it is typically \( \leq 8.4 \times 10^{-7} \text{GeV}(\text{cm}^2 \cdot \text{s} \cdot \text{sr})^{-1} \) in the energy range \( 6 \cdot 10^3 < E/\text{GeV} < 10^6 \) \[53\]. The effective area for AMANDA detector is \( \sim 10^{-2} \text{km}^2 \) for a \( 10^4 \text{ GeV} \) muon neutrino. This upper bound is based on non observations of upward going high energy muon neutrinos (with \( \sim E^{-2} \) energy spectrum index) after subtracting the relevant Atmospheric muon neutrino background. The next generation of high energy neutrino detectors are considered to have an effective area of \( \sim 1 \text{ km}^2 \).

The high energy neutrino observation can be achieved in the following two main interactions: the deep inelastic neutrino nucleon and neutrino electron interactions. The deep inelastic neutrino nucleon interaction can proceed via \( Z \) or \( W^\pm \) exchange. The former is called neutral current (NC) interaction, whereas the later is called charged current (CC) interaction. The CC interactions \( (\nu_eN \rightarrow \alpha Y) \) are most relevant for prospective high energy neutrino observations. The showers, the charged particles and the associated radiation emission such as Cherenkov radiation from these interactions are the measurable quantities. The CC deep inelastic neutrino nucleon cross section \( \sigma_{\nu_eN}^{CC}(E) \) over nucleons with mass \( m_N \), can be written as a function of the incoming neutrino energy \( E \) as:

\[
\sigma_{\nu_eN}^{CC}(E) = \frac{2G_F^2 m_N E}{\pi} \int dx \int dy \left( \frac{m_W^2}{Q^2 + m_W^2} \right)^2 \cdot x \cdot \left\{ \left[ 1 - \frac{m^2_N x^2 y^2}{Q^2} \right] \left[ f_d(x, Q^2) + f_s(x, Q^2) + f_b(x, Q^2) \right] + \left( 1 - y \right)^2 - \frac{m^2_N x^2 y^2}{Q^2} \right\} \left[ f_u(x, Q^2) + f_d(x, Q^2) + f_s(x, Q^2) \right].
\]

The integration limit for \( x \) and \( y \) can be taken between 0 and 1. This expression can be straightforwardly obtained using \( s = 2m_N E \) in \[20\]. Here \( f_q(x, Q^2) \) are the parton distribution functions. The \( f_q(x, Q^2) \)'s may be evaluated at \( Q^2 = m_Z^2 \) for small \( x \) \( (x \leq 10^{-4} \pm 5) \). The \(-Q^2\) is the invariant momentum transfer between the incoming neutrino and outgoing charged lepton. In above Eq., \( y \equiv (E - E')/E \) is the inelasticity in the neutrino nucleon interactions. It gives the fraction of \( E \) lost in a single neutrino nucleon interaction in the lab frame. The \( x \equiv Q^2/2m_N(E - E') \) is the fraction of the nucleon’s momentum carried by the struck quark. The charged lepton mass is ignored here in comparison with \( m_N \). The \( \sigma_{\nu_eN}^{CC}(E) \) for anti neutrinos can be obtained using Eq. \[19\] with appropriate changes.

The neutrino electron interaction cross section on the other hand has a resonant character for \( s = 2m_e E_{\bar{\nu}_e} \):

\[
\sigma(\bar{\nu}_e e \rightarrow W^- \rightarrow \text{hadrons}) = \frac{\Gamma_W(\text{hadrons})}{\Gamma_W(e^+\nu)} \cdot \frac{G_F^2 s}{3\pi} \cdot \left[ \frac{m_W^4}{(s - m_W^2)^2 + \Gamma_W^2 m_W^2} \right],
\]

where \( \Gamma_W \)'s can be found in \[20\]. The above resonant interaction select the anti electron neutrino flavor as well as the energy, namely \( E_{\bar{\nu}_e} = m_W^2/(2m_e) \sim 6.3 \cdot 10^6 \text{ GeV} \). This interaction may, in principle, be used to calibrate the high energy neutrino energy provided it can possibly be discriminated from neutrino nucleon interaction in a detector. The
FIG. 2: Examples of high energy $\bar{\nu}_e$ interaction cross section over two different target particles as a function of $E_{\bar{\nu}_e}$ (GeV). The minimum value of $E_{\bar{\nu}_e}$ corresponds to $(m_W + \Gamma_W)^2/2m_e$.

$\sigma(\bar{\nu}_e e^- \rightarrow W^- \rightarrow \text{hadrons})$ has a slight enhancement because of hard photon emission in the final state for $\sqrt{s} \geq \Gamma_W$. It is given by

$$\sigma(\bar{\nu}_e e^- \rightarrow W^- \gamma) = \frac{\sqrt{2} \alpha G_F}{3u^2(u-1)} \left[ 3(u^2 + 1) \ln \left\{ \frac{(u-1)m_W^2}{m_e^2} \right\} - (5u^2 - 4u + 5) \right], \quad (21)$$

where $u = s/m_W^2$. In Fig. 2 the three cross sections are plotted for illustration. The $\sigma_{CC}^{\nu_e N}(E)$ is calculated using Eq. (19) with CTEQ(5M) parton distribution functions generated by Coordinated Theoretical and Experimental Project on QCD Phenomenology and Tests of the Standard Model [54].

The high energy neutrino flux arrives at an earth based detector in three general directions in equal proportion. The downward going neutrinos do not cross any significant earth cord before reaching the (under ground) detector. The (quasi) horizontal and upward going neutrinos cross the earth with increasing cord length respectively before reaching the detector.

1. Downward going

The event rate for downward going high energy neutrinos in CC deep inelastic interactions is given by

$$\text{Rate} = A \int_{E_{\nu_e}^{\min}}^{E_{\nu_e}^{\max}} dE_{\nu_e} P_{\nu_e \rightarrow \alpha}(E_{\nu_e}, E_{\nu_e}^{\min}) F_{\nu_e}, \quad (22)$$

here $A$ is the area of the high energy neutrino detector. The $F_{\nu_e}$ can be obtained using Eq. (16). In the above equation

$$P_{\nu_e \rightarrow \alpha}(E_{\nu_e}, E_{\nu_e}^{\min}) = N_A \int_0^{1-E_{\nu_e}^{\min}/E_{\nu_e}} dy R_{\alpha}(E_{\nu_e}, E_{\nu_e}^{\min}) \frac{d\sigma_{CC}^{\nu_e N}(E_{\nu_e}, y)}{dy}. \quad (23)$$
FIG. 3: Left panel: Expected downward going $e$–like, $\mu$–like and $\tau$–like event rate produced by AGN neutrinos as a function of minimum energy of the corresponding charged lepton in a large (proposed) km$^3$ volume ice or water neutrino detector. Three flavor neutrino mixing is assumed. Right panel: Approximate representative event topologies for the three neutrino flavors in a km$^3$ volume water or ice neutrino detector for the order of magnitude energy interval shown in left panel.

The $d\sigma/dy$ can be obtained using Eq. (19). The $N_A$ is the Avogadro’s constant. Various $R$’s are given in Table II. Note that for $\tau$ lepton, it is the decay length that is considered as its range with $E_{\tau}^{\text{min}} \sim 2 \cdot 10^6$ GeV and $E_{\tau}^{\text{max}} \sim 2 \cdot 10^7$ GeV as the value of $D$ is chosen as $10^5$ cm for illustration here [57]. Also note that $R_e \equiv R_e(E)$ only.

Detailed estimates of the high energy neutrino event rates are done mainly numerically [58]. These estimates are model dependent. The event rates of downward high energy neutrinos typically vary between $\sim O(10^1)$ and $\sim O(10^2)$ in units of (yr sr)$^{-1}$ for the proposed km$^3$ volume ice or water neutrino detector. The left panel of Fig. 3 displays the three downward going event rates along with examples of approximate event topologies for AGN neutrinos [59].

In this AGN model, the $pp$ interactions inside the core of the AGN are considered to play an important role. The $e$–like event rate is obtained by rescaling the $\mu$–like event rate. The indicated order of magnitude energy interval is relevant for proposed km$^3$ volume high energy neutrino detectors for possible neutrino flavor identification.

The downward going high energy neutrinos of different flavors interact with the medium (free nucleons) of the detector, deep inelastically mainly through CC interactions. The three flavors on the average give rise to different event topologies based on these interactions and the behavior of the associated charged lepton. For instance, for

| Lepton Flavor | $R$(cmwe) |
|---------------|------------|
| $e$           | $40 \left[ (1 - \langle y(E) \rangle) \frac{E}{6 \cdot 10^7 \text{GeV}} \right]$ |
| $\mu$         | $\frac{1}{2} \ln \left( \frac{a + b E_{\mu}}{a + b E_{\mu}^{\text{min}}} \right)$, $a = 2 \cdot 10^{-3}$ GeV/cmwe, $b = 3.9 \cdot 10^{-6}$ /cmwe |
| $\tau$        | $D = \frac{E(1 - y)\tau}{10^5}$, $D = 10^5$ cm |

TABLE II: The three charged lepton ranges discussed in the text.
$10^6 \leq E/\text{GeV} \leq 10^7$, in proposed km$^3$ volume ice or water neutrino detectors, typically the downward going high energy electron neutrinos produce a single shower, the muon neutrinos produce muon like tracks passing through the detector (along with a single shower), whereas the tau neutrinos produce two hadronic showers connected by tau (muon like) track and is such that the amplitude of the second shower is essentially a factor of two larger as compared to the first. Here, amplitude refers to maximum number of charged particles per unit length (see right panel of Fig. 3).  

2. **Upward going**

For upward going high energy neutrinos, a shadow factor $S(E)$ is included in the integral given by Eq. (23). The shadow factor $S(E)$ takes into account the effects of absorption by earth. The absorption of upward going high energy neutrinos by earth is **neutrino flavor dependent**. For $E \geq 10^6$ GeV, the upward going tau neutrinos may reach the surface of the earth in a relatively small number by lowering their energy so that $E < 10^6$ GeV, whereas the upward going electron and muon neutrinos are almost completely absorbed by the earth. For further details, see [56].

3. **Quasi Horizontal**

It might become possible to observe the (air) showers produced by charged leptons produced in neutrino nucleon interactions occurring near the surface of earth. Here a cord of earth essentially equal to just one neutrino nucleon interaction length is considered to be traversed by high energy neutrinos before reaching the detector. This situation is in **contrast** to upward going high energy neutrinos which are basically completely absorbed by the earth because of multiple interactions [62].

For a recent discussion on prospects for observations of near horizontal high energy (tau) neutrinos, see [63], whereas for ultra high energy neutrinos, see [64]. The emerging tau lepton spectra induced by quasi horizontal (or earth skimming) neutrinos, using Monte Carlo simulation techniques are calculated in some detail in [65].

### III. SUMMARY AND CONCLUSIONS

Detailed study of high energy neutrino fluxes from different astrophysical sites such as the galactic plane, as well as other more far away anticipated astrophysical and cosmological sites will provide valuable information about the neutrino intrinsic properties and the site itself. Given the current status of absolute level of expected high energy neutrinos, the detectors with area $> (0.1 - 1) \text{ km}^2$ seems to be needed to obtain the first evidence.

For more distant and energetic sources, the prospective high energy neutrino observation will provide clues for a solution of the long standing problem of origin of observed ultra high energy cosmic rays. The (non) observation of high energy neutrinos will also help to better model the underlying physics of the far away astrophysical and cosmological...
sites. In this context, present motivations for their searches are reviewed, with a description of their possible connection with ultra high energy cosmic rays. Some presently envisaged main high energy neutrino production mechanisms are summarized via a simple classification flow chart. Three flavor neutrino oscillation description is reviewed and its implications for the three relative ratios of high energy neutrinos are given. Furthermore, the essentials of prospective observations of high energy neutrinos are briefly described including the possible relevant observational signatures.

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