Effects of conversions for high energy neutrinos originating from cosmological gamma-ray burst fireballs

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We study neutrino conversions in the recently envisaged source of high energy ($E \gtrsim 10^6$ GeV) neutrinos, that is, in the vicinity of cosmological gamma-ray burst fireballs (GRB). We consider mainly the possibility of neutrino conversions due to an interplay of neutrino transition magnetic moment, $\mu$, and the violation of equivalence principle (VEP), parameterized by $\Delta f$, in a reasonable strength of magnetic field in the vicinity of the GRB. We point out that for $\Delta f \sim 10^{-25}(\delta m^2/1\text{eV}^2)$, a resonant spin-flavour precession between $\bar{\nu}_\mu$ and $\nu_\tau$ may occur in the vicinity of GRB for $\mu \sim 10^{-12} \mu_B$ ($\mu_B$ is Bohr magneton), thus enhancing the expected high energy $\nu_\tau$ flux from GRBs.

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I. INTRODUCTION

Recently, cosmological fireballs are suggested as a possible production site for gamma-ray bursts as well as the high energy ($E \gtrsim 10^6$ GeV) neutrinos [1]. Although, the origin of these cosmological gamma-ray burst fireballs (GRB) is not yet well-understood, the observations [2] 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 the (burst of) high energy neutrinos. Typically, this compact source is hypothesized to be formed possibly due to the merging of binary neutron stars or due to collapse of a supermassive star.

The main source of high energy tau neutrinos in GRBs is the production and decay of $D^+_S$. The production of $D^+_S$ may be through $p\gamma$ and/or through $pp$ collisions. In [3], the $\nu_e$ and $\nu_\mu$ flux is estimated in $pp$ collisions, whereas in [4], the $\nu_e$ and $\nu_\mu$ flux is estimated in $p\gamma$ collisions for GRBs. In $pp$ collisions, the flux of $\nu_\tau$ may be obtained through the main process of $p+p \rightarrow D^+_S + X$. The $D^+_S$ decays into $\tau^+$ lepton and $\nu_\tau$ with a branching ratio of $\sim 3\%$. This $\tau^+$ lepton further decays into $\nu_\tau$. The cross-section for $D^+_S$ production, which is main source of $\nu_\tau$’s, is 1-2 orders of magnitude lower than that of $D^+$ and/or $D^-$ which
subsequently produces $\nu_e$ and $\nu_\mu$. The branching ratio for $\nu_e$ and/or $\nu_\mu$ production is higher up to an order of magnitude than for $\nu_\tau$ production (through $D_S^\pm$). These imply that the $\nu_\tau$ flux in $pp$ collisions is suppressed up to 3-4 orders of magnitude relative to corresponding $\nu_e$ and/or $\nu_\mu$ fluxes. In $p\gamma$ collisions, the main process for the production of $\nu_\tau$ may be $p+\gamma \rightarrow D_S^+ + \Lambda^0 + \bar{D}^0$ with similar relevant branching ratios and corresponding cross-section values. Here the corresponding main source for $\nu_e$ and $\nu_\mu$ production is $p+\gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$. Therefore, in $p\gamma$ collisions, the $\nu_\tau$ flux is also suppressed up to 3-4 orders of magnitude relative to $\nu_e$ and/or $\nu_\mu$ flux. Thus, in both type of collisions, including the relevant kinematics, the $\nu_\tau$ flux is estimated to be rather small relative to $\nu_e$ and/or $\nu_\mu$ fluxes from GRBs, typically being, $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) \lesssim (10^{-4} - 10^{-5})$.

In this brief report, we consider the possibility of obtaining higher $\nu_\tau$ neutrino flux, that is, $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) \gg 10^{-4}$, from GRBs through neutrino conversions as compared to no conversion situation. In particular, we obtain the range of neutrino mixing parameters resulting from an interplay of possible violation of the equivalence principle (VEP) parameterized by $\Delta f$ and the magnetic field in the vicinity of GRBs yielding $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) \gg 10^{-4}$. The possibility of VEP arises from the realization that different flavours of neutrinos may couple differently to gravity.

The present study is particularly useful as the new ice/water Čerenkov light neutrino telescopes namely AMANDA and Baikal (also the NESTOR and ANTARES) will have energy, angle and flavour resolution for high energy neutrinos originating at cosmological distances. Recently, there are several discussions concerning the signatures of a possible neutrino burst from GRBs correlated in time and angle. In particular, there is a suggestion of measuring $\nu_\tau$ flux from cosmologically distant sources through a double bang event or through a small pile up of upgoing $\mu$-like events near $(10^4 - 10^5)$ GeV.

The plan of this brief report is as follows. In Sect. II, we briefly describe the matter density and magnetic field in the vicinity of GRBs. In Sect. III, we discuss in some detail, the range of neutrino mixing parameters that may give rise to relatively large precession/conversion probabilities resulting from an interplay of VEP and the magnetic field in the vicinity of GRBs for vanishing gravity and vacuum mixing angles. In the same Sect., we briefly discuss the relevant neutrino mixing parameter range for non-vanishing gravity and vacuum mixing angles with vanishing neutrino magnetic moment. In Sect. IV, we give estimates of separable but contained double bang event rates induced by high energy $\nu_\tau$’s originating from GRBs without/with conversions for illustrative purposes and finally in Sect. V, we summarize our results.
II. THE MATTER DENSITY AND THE MAGNETIC FIELD IN THE VICINITY OF GRB

According to [1], the high energy neutrino production may take place in the vicinity of \( r_p \sim \Gamma^2 c \Delta t \). Here \( \Gamma \) is the Lorentz factor (typically \( \Gamma \sim 300 \)) and \( \Delta t \) is the observed GRB variability time scale (typically \( \Delta t \sim 1 \) ms). Thus, the fireball matter density is \( \rho \sim 10^{-13} \) g cm\(^{-3} \) in the vicinity of \( r_p \) [1]. In these models, the typical distance traversed by neutrinos may be taken as, \( \Delta r \lesssim (10^{-4} - 1) \) pc, in the vicinity of GRB, where 1 pc \( \sim 3 \times 10^{18} \) cm. These imply that average effective width of matter traversed by neutrinos originating from GRB is \( l_{GRB} \sim \rho \times \Delta r \sim 10^4 \) g cm\(^{-2} \). In the presence of matter, the relevant effective width of matter needed for appreciable spin-flavour conversions is \( l_m \sim \sqrt{2} \pi m_N / G_F \sim 2 \times 10^9 \) g cm\(^{-2} \). Thus, \( l_{GRB} \ll l_m \), and hence no matter effects are expected due to coherent forward scattering of neutrinos off the background for high energy neutrinos originating from GRBs.

Taking the observed duration of the typical gamma-ray burst as, \( \Delta t \lesssim 1 \) ms, we obtain the mass of the source as, \( M_{GRB} \lesssim \Delta t / G_N \), where \( G_N \) is the gravitational constant. Let us mention here that for the relatively shorter observed duration of gamma-ray burst from a typical GRB, \( \Delta t \sim 0.2 \) ms, implying \( M_{GRB} \sim 40 M_\odot \) (where \( M_\odot \sim 2 \times 10^{33} \) g is solar mass). We use \( M_{GRB} \sim 2 \times 10^2 M_\odot \) in our estimates.

The magnetic field in the vicinity of a GRB is obtained by considering the equipartition arguments [1]. We use the following profile of magnetic field, \( B_{GRB} \), for \( r > r_p \) [11]

\[
B_{GRB}(r) \simeq B_0 \left( \frac{r_p}{r} \right)^2, \tag{1}
\]

where, \( B_0 \sim L^{1/2} c^{-1/2} (r_p \Gamma)^{-1} \) with \( L \) being the total wind luminosity (typically \( L \sim 10^{51} \) erg s\(^{-1} \)).

III. NEUTRINO CONVERSIONS IN GRB

Consider a system of two mixed neutrinos \( \bar{\nu}_\mu \) and \( \nu_\tau \) for simplicity. The difference of diagonal elements of the \( 2 \times 2 \) effective Hamiltonian describing the dynamics of the mixed system of these oscillating neutrinos in the basis \( \psi^T = (\bar{\nu}_\mu, \nu_\tau) \) for vanishing vacuum and gravity mixing angles is [12]

\[
\Delta H = V_G - \delta, \tag{2}
\]

whereas, each of the off diagonal elements is \( \mu B \) (\( \mu \) is neutrino magnetic moment). In Eq. (2), \( \delta = \delta m^2 / 2E \), where \( \delta m^2 = m^2(\nu_\tau) - m^2(\bar{\nu}_\mu) > 0 \) and \( E \) being the neutrino energy. Here \( V_G \) is the effective potential felt by the neutrinos at a distance \( r \) from a gravitational source of mass \( M \) due to VEP and is given by [3]
where $\Delta f = f_3 - f_2$ is a measure of the degree of VEP and $\phi(r) = G_N M r^{-1}$ is the gravitational potential in the Keplerian approximation. In Eq. (3), $f_3 G_N$ and $f_2 G_N$ are respectively the gravitational couplings of $\nu_\tau$ and $\bar{\nu}_\mu$, such that $f_2 \neq f_3$. There are three relevant $\phi(r)$’s that need to be considered \cite{1}. The effect of $\phi(r)$ due to supercluster named Great Attractor with $\phi_{SC}(r)$ in the vicinity of GRB; $\phi(r)$ due to GRB itself, which is, $\phi_{GRB}(r)$, in the vicinity of GRB and the galactic gravitational potential, which is, $\phi_G(r)$. Therefore, we use, $\phi(r) \equiv \phi_{SC}(r) + \phi_{GRB}(r) + \phi_G(r)$. However, $\phi_G(r) \ll \phi_{SC}(r), \phi_{GRB}(r)$ in the vicinity of GRB. Thus, $\phi(r) \simeq \phi_{SC}(r) + \phi_{GRB}(r)$. If the neutrino production region $r_p$ is $\lesssim 10^{13}$ cm then at $\sim r_p$, we have $\phi_{GRB}(r) > \phi_{SC}(r)$. At $r \sim 6 \times 10^{13}$ cm, $\phi_{GRB}(r) \sim \phi_{SC}(r)$ and for $r \gtrsim 10^{14}$ cm, $\phi_{GRB}(r) < \phi_{SC}(r)$. If the supercluster is a fake object then $\phi(r) \simeq \phi_{GRB}(r)$. Here we assume the smallness of the effect of $\phi(r)$ due to an active galactic nucleus (AGN), if any, nearby to GRB.

The possibility of vanishing gravity and vacuum mixing angle in Eq. (2) allows us to identify the range of $\Delta f$ relevant for the neutrino magnetic moment effects only. Latter in this Sect., we briefly comment on the ranges of relevant neutrino mixing parameters for non-vanishing gravity and vacuum mixing angles with vanishing neutrino magnetic moment.

The case of $\bar{\nu}_e \rightarrow \nu_\tau$ can be studied by replacing $\bar{\nu}_\mu$ with $\bar{\nu}_e$ along with corresponding changes in $V_G$ and $\delta m^2$. Let us here mention that initial flux of $\bar{\nu}_e$ may be smaller than that of $\nu_\mu$ by a factor of less than 2 \cite{1}, thus also possibly enhancing the expected $\nu_\tau$ flux from GRBs through $\bar{\nu}_e \rightarrow \nu_\tau$. However, we have checked that observationally this possibility leads to quite similar results in terms of event rates and are therefore not discussed here further. We now intend to study in some detail, the various possibilities arising from relative comparison between $\delta$ and $V_G$ in Eq. (2).

Let us first ignore the effects of VEP ($\Delta f = 0$). For constant $B$, the spin-flavour precession probability $P(\bar{\nu}_\mu \rightarrow \nu_\tau)$ is obtained using Eq. (2) as

$$P(\bar{\nu}_\mu \rightarrow \nu_\tau) = \left[ \frac{(2\mu B)^2}{(2\mu B)^2 + \delta^2} \right] \sin^2 \left( \sqrt{(2\mu B)^2 + \delta^2} \cdot \frac{\Delta r}{2} \right). \quad (4)$$

We take $\mu \sim 10^{-12} \mu_B$ or less, where $\mu_B$ is Bohr magneton, which is less than the stringent astrophysical upper bound on $\mu$ based on cooling of red giants \cite{13}. We here consider the transition magnetic moment, allowing the possibility of simultaneously changing the neutrino flavour as well as the helicity. Thus, the precessed $\nu_\tau$ is an active neutrino and interacts weakly. If $\mu$ is of Dirac type, then the precession leads to disappearance/nonobservation of $\nu_\tau$ as the precessed $\nu_\tau$ is now a sterile one. In Eq. (4), $\Delta r$ is the width of the region with $B$. Note that if $\delta \ll 2\mu B$, then, for $E \sim 2 \times 10^6$ GeV and using Eq. (1), we obtain $\delta m^2 \ll 5 \times 10^{-8}$ eV$^2$. We take, $\delta m^2 \sim 10^{-9}$ eV$^2$, as an example and consequently we obtain from Eq. (4) an energy independent large ($P > 1/2$) spin-flavour precession probability for
$\mu \sim 10^{-13}\mu_B$ with $10^{-4} \lesssim \Delta r/\text{pc} \lesssim 1$. Let us mention here that the typical relevant energy span for high energy neutrinos originating from the considered class of GRBs is an order of magnitude, that is, $2 \times 10^6 \lesssim E/\text{GeV} \lesssim 2 \times 10^7$ (see Sect. IV). Thus, for $\mu$ of the order of $10^{-13}\mu_B$, the $\nu_\tau$ flux may be higher than the expected one from GRBs in the absence of spin-flavour precessions, that is, $(\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu) > 10^{-3}$ due to neutrino spin-flavour precession effects. Since the neutrino spin-flavour precession effect is essentially determined by the product $\mu B$ so one may rescale $\mu$ and $B$ to obtain the same results. For $\delta \simeq 2\mu_B$ and $\delta \gg 2\mu_B$, we obtain from Eq. (4), an energy dependent $P$ such that $P < 1/2$.

With non-vanishing $\Delta f$ ($\Delta f \neq 0$), a resonant character in neutrino spin-flavour precession can be obtained for a range of values of relevant neutrino mixing parameters $\delta$ Two conditions are essential to obtain a resonant character in neutrino spin-flavour precession: the level crossing and the adiabaticity condition. The level crossing condition is obtained by taking $\Delta H = 0$ and is given by:

$$\delta m^2 \sim \left(\frac{|\Delta f|}{10^{-25}}\right)\text{eV}^2. \quad (5)$$

The other essential condition, namely, the adiabaticity in the resonance reads:

$$\kappa = \frac{2(2\mu B)^2}{|dV_G/dr|}. \quad (6)$$

Note that here $\kappa$ depends explicitly on $E$ through $V_G$ unlike the case of ordinary neutrino spin-flip induced by the matter effects. A resonant character in neutrino spin-flavour precession is obtained if $\kappa \gtrsim 1$ such that Eq. (5) is satisfied. We notice that, $B_{\text{ad}}/B_{\text{GRB}} \lesssim 1$ for $\mu \sim 10^{-12}\mu_B$. Here $B_{\text{ad}}$ is obtained by setting $\kappa \sim 1$ in Eq. (6). The general expression for relevant neutrino spin-flavour conversion probability is given by $P(\bar{\nu}_\mu \rightarrow \nu_\tau) = 1/2 - \left(\frac{1}{2} - P_{\text{LZ}}\right)\cos 2\theta_B, \quad (7)$

where $P_{\text{LZ}} = \exp(-\frac{\pi}{2}\kappa)$ and $\tan 2\theta_B = (2\mu B)/\Delta H$ is being evaluated at the high energy neutrino production site in the vicinity of GRB. In Fig. 2, we plot $P(\bar{\nu}_\mu \rightarrow \nu_\tau)$, given by Eq. (7), as a function of neutrino energy $E$ (GeV) for different $\Delta f$ as well as $\delta m^2$ values. Note that the resonant spin-flavour precession probability is $> 1/2$ for a relatively large range of $\delta m^2$ (and $\Delta f$ values). The expected spectrum $F(\nu_\tau + \bar{\nu}_\tau)$ of the high energy tau neutrinos originating from GRBs due to spin-flavour conversions is calculated as $\text{[	extsuperscript{1}]\text{[	extsuperscript{2}]}}$.

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\textsuperscript{1}From above discussion, it follows that $E$ dependent/independent spin-flavour precession may also be obtained for nonzero $\Delta f$, however, given the current status of the high energy neutrino detection, for simplicity, we ignore these possibilities which tend to overlap with this case for a certain range of relevant neutrino mixing parameters; for details of these possibilities in the context of AGN, see $\text{[	extsuperscript{3}]\text{[	extsuperscript{4}]}}$.\textsuperscript{2}
\[ F(\nu_\tau + \bar{\nu}_\tau) = [1 - P(\bar{\nu}_\mu \to \nu_\tau)]F^0(\nu_\tau + \bar{\nu}_\tau) + P(\bar{\nu}_\mu \to \nu_\tau)F^0(\nu_\mu + \bar{\nu}_\mu), \tag{8} \]

where \(F^0\)’s are the neutrino flux spectrums originating from GRBs. In Fig. 3, we plot the expected \(\nu_\tau\) spectrum obtained by neutrino spin-flavour precessions and conversions (induced by an interplay of VEP and the magnetic field in GRBs). We use the GRB spectrum for \((\nu_\mu + \bar{\nu}_\mu)\), i.e., \(F^0(\nu_\mu + \bar{\nu}_\mu)\) from [1] and \(F^0(\nu_\tau + \bar{\nu}_\tau)\) from [4] and multiply these by respective \(P(\bar{\nu}_\mu \to \nu_\tau)\) given by Eq. (8) to obtain \(F(\nu_\tau + \bar{\nu}_\tau)\) due to resonant spin-flavour precession (lower curve in Fig. 2). The upper curve in Fig. 2 is obtained by multiplying \(P\) given by Eq. (4) for small \(\delta m^2\).

Let us now consider briefly the effects of nonvanishing gravity mixing angle \(\theta_G\) and non-vanishing vacuum mixing angle \(\theta\) for vanishing neutrino magnetic moment. If \(\theta_G = 0\) and \(\theta \neq 0\), then taking the distance between a typical GRB and our galaxy as, \(L \sim 1000\) Mpc, the vacuum flavour oscillations may occur between \(\nu_\mu\) and \(\nu_\tau\) for \(\delta m^2 \sim 10^{-3}\)eV\(^2\) with maximal vacuum flavour mixing between \(\nu_\mu\) and \(\nu_\tau\). These values of neutrino mixings have been suggested as a possible explanation of recent superkamiokande data concerning the deficit of atmospheric muon neutrinos [14]. The corresponding expression for flavour oscillations in vacuum is

\[ P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{\delta m^2}{4E}L \right). \tag{9} \]

Note that here the resulting \(P\) is \(\sim 1/2\) due to the fact that \(4E/\delta m^2 \ll L\). For \(\theta_G \neq 0\) and \(\theta = 0\), in the case of massless or degenerate neutrinos, the corresponding vacuum flavour oscillation analog for \(\nu_e \to \nu_\tau\) is obtained through \(\theta \to \theta_G\) and \(\frac{\delta m^2}{4E} \to V_G\). For maximal \(\theta_G\), the sensitivity of \(\Delta f\) may be estimated by equating the argument of second sin factor equal to \(\pi/2\) in the corresponding expression for \(P\) [14]. This implies \(\Delta f \sim 10^{-41}\) with \(\phi(r) \simeq \phi_{SC}(r)\). Note that this value of \(\Delta f\) is of the same order of magnitude as that expected for neutrinos originating from AGNs [14]. In contrast to neutrino spin-flavour precession effects given by Eq. (4) resulting in \(P > 1/2\), the vacuum flavour oscillations give \(P \sim 1/2\), thus, allowing the possibility of isolating the mechanism of oscillation since the high energy neutrino telescopes may attempt to measure \((\nu_\tau + \bar{\nu}_\tau)/(\nu_\mu + \bar{\nu}_\mu)\). Further, with the improved information on either \(\Delta f\) and/or \(\mu\), one may be able to distinguish between the situations of resonant and nonresonant spin-flavour precession induced by an interplay of VEP and \(\mu\) in \(B_{GRB}\). Concerning possibilities of resonant flavour conversion, a resonant or/and nonresonant flavour conversion between \(\nu_e\) and \(\nu_\tau\) in the vicinity of a GRB is also possible due to an interplay of vanishing/nonvanishing vacuum and gravity mixing angles [14]. For instance, with \(\theta \to 0\), a resonant flavour conversion between \(\nu_e\) and \(\nu_\tau\) may be obtained if \(\sin^2 2\theta_G \gg 0.25\). Here the relevant level crossing may occur at \(r \sim 0.1\) pc with \(\delta m^2 \sim 10^{-6}\) eV\(^2\).
IV. SIGNATURES OF HIGH ENERGY $\nu_\tau$ IN NEUTRINO TELESCOPES

The km$^2$ scale high energy neutrino telescopes may be able to obtain first examples of high energy $\nu_\tau$, through double bangs, originating from GRBs correlated in time and direction with corresponding gamma-ray burst [9]. The first bang occurs due to charged current interaction of high energy tau neutrinos near/inside the neutrino telescope producing the tau lepton and the second bang occurs due to hadronic decay of this tau lepton. Following [17], we present in Table I, the expected contained but separable double bang event rates for downgoing $\nu_\tau$ in 1 km$^2$ size water Čerenkov high energy neutrino telescopes for illustrative purposes. To calculate the event rates, we use Martin Roberts Stirling (MRS 96 R1) parton distributions [18] and present event rates in units of yr$^{-1}$ sr$^{-1}$. We have checked that other recent parton distributions give quite similar event rates and are therefore not depicted here. From Table I, we notice that the event rates for neutrino spin-flavour precession are up to $\sim$ 4 orders of magnitude higher than that for typical intrinsic (no oscillations) tau neutrino flux.

The condition of containedness is obtained by requiring that the separation between the two bangs is less than the typical $\sim$ km size of the neutrino telescope. It is obtained by equating the range of tau neutrino induced tau leptons with the size of detector implying $E < \sim 2 \times 10^7$ GeV. The condition of separableness is obtained by demanding the separation between the two bangs is larger than the typical spread of the bangs such that the amplitude of the second bang is essentially 2 times the first bang. This leads to $E > \sim 2 \times 10^6$ GeV [9].

V. RESULTS AND DISCUSSION

We have studied in some detail the effects of neutrino spin-flavour conversions due to an interplay of the effect of possible VEP and the magnetic field in GRBs and have obtained the relevant range of neutrino mixing parameters for appreciable neutrino conversion probabilities. We have also briefly commented on the corresponding range of neutrino mixing parameters for vanishing neutrino magnetic moment.

The matter density in the vicinity of GRB is quite small (upto 4-5 orders of magnitude)
to induce any resonant flavour/spin-flavour neutrino conversion due to normal matter effects. We have pointed out that a resonant character in the neutrino spin-flavour conversions may nevertheless be obtained due to possible VEP. The corresponding degree of VEP may be \( \sim (10^{-35} - 10^{-25}) \) depending on \( \delta m^2 \) value.

The double bang event rate for intrinsic (no oscillations/conversions) high energy tau neutrinos originating from GRBs turns out to be small as compared to that due to precession/conversion effects up to a factor of \( \sim 10^{-4} \). Thus, the high energy neutrino telescopes may provide useful upper bounds on intrinsic properties of neutrinos such as mass, mixing and magnetic moment, etc.. The relevant tau neutrino energy range for detection in 1 km\(^2\) neutrino telescopes may be \( 2 \times 10^6 \lesssim E/\text{GeV} \lesssim 2 \times 10^7 \) through characteristic contained but separable double bang events.

Observationally, the high energy \( \nu_\tau \) burst from a GRB may possibly be correlated to the corresponding gamma-ray burst/highest energy cosmic rays (if both have common origin) in time and in direction thus raising the possibility of its detection even if there is relatively large background flux of high energy tau neutrinos from AGNs also from oscillations. If the range of neutrino mixing parameters pointed out in this study is realized terrestially/extraterrestrially then a relatively large \( \nu_\tau \) flux from GRBs is expected as compared to no oscillation/conversion scenario.

Since the high energy neutrino telescopes may measure the ratio of the sum of tau and antitau neutrinos and the muon and antimuon neutrinos, so in principle, any change in the expected relatively small (upto 4 orders of magnitude) ratio may be attributed to spin-flavour precession/conversion effects as the \( \nu_\mu \rightarrow \nu_s \) channel may alternatively be a possible explanation of recent superkamiokande results concerning the deficit of atmospheric muon neutrinos.

The flavour/spin-flavour conversions may occur possibly through several mechanisms. We have discussed in some detail mainly the spin-flavour precession/conversion situation induced by a nonzero neutrino magnetic moment and by a relatively small violation of equivalence principle as an example to point out the possibility of obtaining higher tau neutrino fluxes as compared to no oscillations/conversions scenarios from gamma-ray burst fireballs.

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TABLE I. Event rate (yr$^{-1}$sr$^{-1}$) for high energy tau neutrino induced contained but separable double bangs in various energy bins using MRS 96 parton distributions.

| Energy Interval       | Rate (yr$^{-1}$sr$^{-1}$) | no osc | spin-flavour precession | vac osc |
|----------------------|----------------------------|--------|-------------------------|---------|
| $2 \times 10^6 \leq E$/GeV $\leq 5 \times 10^6$ | $10^{-5}$ | $1 \times 10^{-1}$ | $0.5 \times 10^{-1}$ |
| $5 \times 10^6 \leq E$/GeV $\leq 7 \times 10^6$ | $2 \times 10^{-6}$ | $2 \times 10^{-2}$ | $10^{-2}$ |
| $7 \times 10^6 \leq E$/GeV $\leq 1 \times 10^7$ | $2 \times 10^{-6}$ | $2 \times 10^{-2}$ | $10^{-2}$ |
| $1 \times 10^7 \leq E$/GeV $\leq 2 \times 10^7$ | $2 \times 10^{-6}$ | $2 \times 10^{-2}$ | $10^{-2}$ |
FIG. 1. $P(\nu_\mu \rightarrow \nu_\tau)$ using Eq. (7) as a function of $E$ (GeV) for different $\delta m^2$ and $\Delta f$ values.
FIG. 2. Expected $\nu_{\tau}$ flux spectrum due to different spin-flavour conversion mechanisms.