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Probing pseudo-Dirac neutrino through detection of neutrino-induced muons from gamma ray burst neutrinos

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Abstract. The possibility to verify the pseudo-Dirac nature of neutrinos is investigated here via the detection of ultra-high energy neutrinos from distant cosmological objects like γ-ray bursts (GRBs). The very long baseline and the energy range from $\sim$TeV to $\sim$EeV for such neutrinos invoke the likelihood to probe very small pseudo-Dirac splittings. The expected secondary muons from such neutrinos that can be detected by a kilometer scale detector such as ICECUBE is calculated and compared with the same in the case of mass-flavour oscillations and for no oscillation cases. The calculated muon yields indicate that to probe such small pseudo-Dirac splittings one needs to look for a nearby GRB (red shift $z \sim 0.03$ or less) whereas for a distant GRB ($z \sim 1$) the flux will be much depleted and such phenomenon cannot be distinguished. Also calculated are the muon-to-shower ratios.

Keywords. Ultra-high energy neutrinos; pseudo-Dirac neutrinos; neutrino oscillation.

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1. Introduction

Evidence has been obtained from the satellite-borne observations, the existence of the gamma ray bursts (GRB) from extra galactic (or galactic) sources characterised by sudden intense flashes of γ-rays. The GRBs can produce very high energy ($\gtrsim 10^{16}$ eV) cosmic rays. Although the mechanism of such GRBs are not fully understood, various model calculations suggest that neutrinos of that energy range are also produced in GRBs and should be detected by very large detectors like a kilometer cube water Cherenkov detector (e.g. ICECUBE at south pole). Because of their astronomically long baseline ($\gtrsim$ Megaparsec or Mpc) these ultra-high energy (UHE) neutrinos may open up a new window in very small mass square difference (Δm^2) regime and may throw more insight to neutrino physics. A viable way to detect such UHE neutrinos is to look for upward going secondary muons produced by the charged current (CC) interaction of such UHE ν_μ with the terrestrial rock. Already installed AMANDA in the south pole and the future ICECUBE [1] detector, are able to detect such secondary muons. Both are water Cherenkov detectors and use south pole ice as the detector material.

The possibility that the UHE neutrinos from a distant GRB can probe very low Δm^2 region much below the solar or atmospheric neutrino regime, can be utilised in investigating the proposed pseudo-Dirac nature of the neutrinos [2,3] through its detection in large (~km^2) detectors [4] like ICECUBE. In the pseudo-Dirac scenario, each active neutrino is split into two almost degenerate components of active and sterile part. This can be theoretically realised from the generic mass matrix in $[\nu_{\rm L}, (\nu_{\rm R})^C]$ basis which can be written as (for one generation)

$$\begin{pmatrix} m_{\rm L} & m_{\rm D} \\ m_{\rm D} & m_{\rm R} \end{pmatrix},$$

where the tiny Majorana mass terms $m_{\rm L}$ and $m_{\rm R}$ ($m_{\rm L}, m_{\rm R} \ll m_{\rm D}$) are introduced to slightly lift the degeneracy of Dirac mass $m_{\rm D}$. Thus the Dirac neutrino is split into a pair of almost degenerate Majorana neutrinos with nearly maximum mixing angle given by $\tan 2\theta = 2m_{\rm D}/(m_{\rm R} - m_{\rm L})$. In this scenario, therefore, each of the three neutrino species is split up into a pair of neutrinos with very tiny mass square difference $\Delta m^2 = 2m_{\rm D}(m_{\rm L} + m_{\rm R})$. For three-generation scenario, therefore each of the three types of neutrinos has this pseudo-Dirac splitting of very small mass square difference.

The purpose of this work is to demonstrate the possibility of probing the pseudo-Dirac nature by studying the neutrino oscillation effects through the detection yield of neutrino-induced muons in a large (km^2) neutrino detector such as ICECUBE. For this purpose, the expected muon signal induced by neutrinos from a GRB at Mpc distance is calculated by separately folding (i) the flavour oscillation effects and (ii) the oscillation effects in pseudo-Dirac scenario to the GRB neutrino flux.

2. GRB flux, neutrino oscillations and number of secondary muons

The GRB neutrino flux is estimated by considering the relativistic fireball model [5]. In the relativistic expanding fireball model of GRB, protons (also electrons, positrons and photons) produced in the magnetic field of the rotating accretion disc around a possible black hole are accelerated perpendicular to the accretion disc at almost the speed of light forming a jet which is referred to as fireball. The burst is supposed to be the dissipation of kinetic energy of this relativistic expanding fireball. These very highly energetic protons in the jet then interact with the photons and produce pions (cosmological beam dump) through the process of Δ resonance. (The pions are also produced through the *pp* process.) These pions then decay to yield ν_μ and ν_e in the approximate proportion of $2:1$.

The neutrino flux from a GRB depends on several GRB parameters. Firstly, the Lorentz boost factor Γ is required for the transformation from the fireball blob to observer's frame of reference. As the shocked protons in the blob photoproduce pions, the photon break energy (as the photon spectrum is considered broken) and the photon luminosity L_γ (generally ~10^{53} erg/s) are important parameters for determining the neutrino spectrum.

With all these, the neutrino spectrum from a GRB can be parametrised as [6,7]

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = A \times \min(1, E_\nu/E_\nu^b) \times \frac{1}{E_\nu^2}. \tag{1}$$

In the above, E_ν is the neutrino energy, N_ν is the number of neutrinos and

$$\begin{aligned} E_\nu^b &\simeq 10^6 \frac{\Gamma_{2.5}^2}{E_{\gamma,\mathrm{MeV}}^b} \mathrm{GeV} \\ \Gamma_{2.5} &= \Gamma/10^{2.5} \\ A &= \frac{E_{\mathrm{GRB}}}{1 + \ln(E_{\nu\mathrm{max}}/E_\nu^b)}, \end{aligned} \tag{2}$$

where $E_{\nu\mathrm{max}}$ is the cut-off energy for the GRB neutrinos and E_{GRB} is the total energy that a GRB emits. Now, the observed energy E_ν^{obs} of a neutrino with the actual energy E_ν coming from a GRB at a red-shift distance z is given by the relation $E_\nu^{\mathrm{obs}} = E_\nu/(1+z)$ and similarly, the maximum observable neutrino energy $E_{\nu\mathrm{max}}^{\mathrm{obs}} = E_{\nu\mathrm{max}}/(1+z)$. The co-moving distance d of a GRB at red-shift z is given by

$$\mathrm{d}(z) = \frac{c}{H} \int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_\Lambda + \Omega_\mathrm{M}(1+z')^3}}, \tag{3}$$

where Ω_M is the matter density (both luminous and dark) and Ω_Λ is the dark energy density respectively in units of critical density of the universe and c, H are the velocity of light in vacuum and Hubble constant respectively. In the present calculation $c = 3 \times 10^5$ km/s and $H = 72$ km/s/Mpc (1 Mpc $= 3.086 \times 10^{19}$ km). Therefore, the neutrinos from a single GRB that can be observed on Earth per unit Energy per unit area of the Earth is given by

$$\frac{\mathrm{d}N_\nu^{\mathrm{obs}}}{\mathrm{d}E_\nu^{\mathrm{obs}}} = \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \frac{1}{4\pi d^2(z)} (1+z). \tag{4}$$

Here, as is evident from the above, the total flux per unit area per unit energy from a single GRB is being considered rather than the flux per unit time.

The production process of UHE neutrinos suggests that the neutrino flavours are produced in the ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Considering the maximal mixing between ν_μ and ν_τ (as indicated by the atmospheric neutrino data) and the element U_{e3} of the mass-flavour mixing matrix to be zero, the flavour ratio on reaching the Earth, for neutrino mass-flavour oscillation, becomes $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ irrespective of the solar mixing angle. Needless to say, because of the astronomical baseline ($L \sim$ Mpc), the acquired relative phases of the propagating neutrino mass eigenstates are averaged out ($\Delta m^2 L/E \gg 1$) and the UHE neutrinos from a GRB reaching the Earth are incoherent mixture of mass eigenstates. Therefore, the probability for measuring a particular flavour β by a terrestrial neutrino telescope, if only flavour oscillation is considered, is $P_\beta = 1/3$.

On the other hand, in pseudo-Dirac scenario, we have each of the three mass eigenstates ν_1, ν_2 and ν_3 to be nearly degenerate pairs and thus one obtains a total of six mass eigenstates. Kobayashi and Lim [3] worked out the mixing in such scenario and calculated the oscillation probability. Following [3] and Beacom *et al* [4] the probability P_β to detect a flavour β by a neutrino telescope for pseudo-Dirac neutrinos is

$$P_\beta = \sum_\alpha w_\alpha \sum_{j=1}^{3} |U_{\alpha j}|^2 |U_{\beta j}|^2 \left[1 - \sin^2 \left(\frac{\Delta m_j^2 L}{4E} \right) \right] , \tag{5}$$

where $m_j (j = 1, 3)$ denotes the mass eigenstates for the three types of neutrinos, Δm_j^2 is the mass square difference due to pseudo-Dirac splitting of the mass eigenstate ν_j. α, β, ... denote the flavour index and $U_{\alpha j}$ is the CKM matrix for three generation mass to flavour mixing. w_α is the relative flux of each of the neutrino flavours (α) at the production point ($\sum_\alpha w_\alpha = 1$).

The total number of secondary muons induced by GRB neutrinos at a detector of unit area is given by (following [6,8,9])

$$S = \int_{E_{\rm thr}}^{E_{\nu {\rm max}}^{\rm obs}} {\rm d}E_\nu^{\rm obs} \frac{{\rm d}N_\nu^{\rm obs}}{{\rm d}E_\nu^{\rm obs}} P_{\rm surv}(E_\nu^{\rm obs}, \theta_z) P_\mu(E_\nu^{\rm obs}, E_{\rm thr}). \tag{6}$$

In the above, $P_{\rm surv}$ is the probability that a neutrino reaches the detector without being absorbed by the Earth. This is a function of the neutrino–nucleon interaction length in the Earth and the effective path length $X(\theta_z)$ (g cm^{-2}) for incident neutrino zenith angle θ_z ($\theta_z = 0$ for vertically downward entry with respect to the detector). The interaction length $L_{\rm int}$ is given by

$$L_{\rm int} = \frac{1}{\sigma^{\rm tot}(E_\nu^{\rm obs}) N_A} \tag{7}$$

and

$$P_{\rm surv}(E_\nu^{\rm obs}, \theta_z) = \exp[-X(\theta_z)/L_{\rm int}] = \exp[-X(\theta_z)\sigma^{\rm tot} N_A], \tag{8}$$

where $N_{\rm A} (= 6.022 \times 10^{23} {\rm g}^{-1})$ is the Avogadro number and $\sigma^{\rm tot} (= \sigma^{\rm CC} + \sigma^{\rm NC})$ is the total cross-section. The effective path length $X(\theta_z)$ is calculated as

$$X(\theta_z) = \int \rho(r(\theta_z, \ell)) {\rm d}\ell. \tag{9}$$

In eq. (9), $\rho(r(\theta_z, \ell))$ is the matter density inside the Earth at a distance r from the centre of the Earth for neutrino path length ℓ entering into the Earth with a zenith angle θ_z. The quantity $P_\mu(E_\nu^{\rm obs}, E_{\rm thr})$ in eq. (6) is the probability that a secondary muon is produced by CC interaction of ν_μ and reach the detector above the threshold energy $E_{\rm thr}$. This is then a function of $\nu_\mu N$ (N represents nucleon)–CC interaction cross-section $\sigma^{\rm CC}$ and the range of the muon inside the rock.

$$P_\mu(E_\nu^{\rm obs}, E_{\rm thr}) = N_{\rm A} \sigma^{\rm CC} \langle R(E_\nu^{\rm obs}; E_{\rm thr}) \rangle. \tag{10}$$

In the above $\langle R(E_\nu^{\rm obs}; E_{\rm thr}) \rangle$ is the average muon range given by

$$\langle R(E_\nu^{\rm obs}; E_{\rm thr})\rangle = \frac{1}{\sigma^{\rm CC}} \times \int_0^{1-E_{\rm thr}/E_\nu} {\rm d}y R(E_\nu^{\rm obs}(1-y), E_{\rm thr}) \frac{{\rm d}\sigma^{\rm CC}(E_\nu^{\rm obs}, y)}{{\rm d}y}, \tag{11}$$

where $y = (E_\nu^{\rm obs} - E_\mu)/E_\nu^{\rm obs}$ is the fraction of energy loss by a neutrino of energy $E_\nu^{\rm obs}$ in the charged current production of a secondary muon of energy E_μ. Needless to say that a muon thus produced from a neutrino with energy E_ν can have the detectable energy range between $E_{\rm thr}$ and E_ν. The range $R(E_\mu, E_{\rm thr})$ for a muon of energy E_μ is given as

$$R(E_\mu, E_{\rm thr}) = \int_{E_{\rm thr}}^{E_\mu} \frac{{\rm d}E_\mu}{\langle {\rm d}E_\mu/{\rm d}X\rangle} \simeq \frac{1}{\beta} \ln\left(\frac{\alpha + \beta E_\mu}{\alpha + \beta E_{\rm thr}}\right). \tag{12}$$

The average lepton energy loss with energy E_μ per unit distance travelled is given by [8]

$$\left\langle \frac{{\rm d}E_\mu}{{\rm d}X} \right\rangle = -\alpha - \beta E_\mu. \tag{13}$$

The values of α and β used in the present calculations are

$$\begin{aligned} \alpha &= \{2.033 + 0.077 \ln[E_\mu({\rm GeV})]\} \times 10^{-3}\ {\rm GeV\ cm^2\ g^{-1}} \\ \beta &= \{2.033 + 0.077 \ln[E_\mu({\rm GeV})]\} \times 10^{-6}\ {\rm cm^2\ g^{-1}} \end{aligned} \tag{14}$$

for $E_\mu \lesssim 10^6$ GeV [10] and

$$\begin{aligned} \alpha &= 2.033 \times 10^{-3}\ {\rm GeV\ cm^2\ g^{-1}} \\ \beta &= 3.9 \times 10^{-6}\ {\rm cm^2\ g^{-1}} \end{aligned} \tag{15}$$

otherwise [11].

3. Calculations and results

The GRB neutrino flux is calculated for a GRB with energy $E_{\rm GRB} = 10^{53}$ erg. The neutrino break energy E_ν^b is calculated following eq. (2) with the Lorentz factor $\Gamma = 50.12$ and corresponding photon break energy $E_{\gamma,{\rm MeV}}^b = 0.794$. These values are obtained from Guetta *et al* [12] from their fireball model framework calculations. These values are tabulated in ref. [6]. The calculation is performed for several values of red-shift (z). In this calculation all length units are taken in km.

The probability P_β in eq. (5) is computed with solar mixing angle $\theta_\odot = 32.31°$, the atmospheric mixing angle $\theta_{\rm atm} = 45.0°$ and 1–3 mixing angle $\theta_{13} = 0$. Also, the representative pseudo-Dirac splittings are considered as $\Delta m_j^2 = 10^{-12}$ eV^2 for each of the three species. Note that, in this case, P_β for mass-flavour oscillation is 1/3. GRB neutrino flux with red-shift z, per square kilometer on Earth per unit energy (GeV) for a zenith angle θ_z, is obtained using eqs (1)–(4) and then multiplied by the probability P_β.

The secondary muon yield at a kilometer scale detector such as ICECUBE is calculated using eqs (6)–(15). The Earth matter density in eq. (9) is taken from ref. [9] using the preliminary Earth reference model (PREM). The interaction cross-sections – both charged current and total – used in these equations are taken from the tabulated values (and the analytical form) given in ref. [13]. In the present calculations $E^{\rm obs}_{\nu{\rm max}} = 10^{11}$ GeV and threshold energy $E_{\rm thr} = 1$ TeV are considered.

Figure 1 shows the total yield of secondary muons induced by UHE neutrinos from GRBs of different red-shift values ranging from 0.02 to 3.8, for three cases, namely (i) no neutrino oscillation, (ii) mass-flavour oscillation and (iii) the psedo-Dirac oscillation. The zenith angle is taken to be $\theta_z = 180°$ (vertically upwards neutrino, i.e. muons coming from vertically below the detector). Figure 2 is same as figure 1 but for $\theta_z = 100.9°$. The pseudo-Dirac case distinctly differs from flavour oscillation and no oscillation scenarios. In the present case considered here, the secondary muon events for pseudo-Dirac oscillation is almost half the yield from the expected events if the UHE neutrinos suffer only mass-flavour oscillation and same is around six times less in case there is no oscillation.

We have also repeated the calculation with the isotropic flux resulting from the summation of sources as given by Gandhi *et al*

$$\mathcal{F}(E_\nu) = \frac{{\rm d}N_{\nu_\mu+\bar{\nu}_\mu}}{{\rm d}E_\nu} = \mathcal{N}\left(\frac{E_\nu}{1\ {\rm GeV}}\right)^{-n} {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}\ {\rm GeV}^{-1}. \tag{16}$$

In the above,

$$\mathcal{N} = 4.0\times 10^{-13},\quad n=1,\quad \text{for } E_\nu < 10^5\ \text{GeV},$$

$$\mathcal{N} = 4.0\times 10^{-8},\quad n=2,\quad \text{for } E_\nu > 10^5\ \text{GeV},$$

Thus,

$$\begin{aligned}\frac{{\rm d}N_{\nu_\mu}}{{\rm d}E_\nu} &= \phi_{\bar{\nu}_\mu} = \frac{{\rm d}N_{\bar{\nu}_\mu}}{{\rm d}E_\nu} = \phi_{\bar{\nu}_\mu} = 0.5\mathcal{F}(E_\nu)\\ \frac{{\rm d}N_{\nu_e}}{{\rm d}E_\nu} &= \phi_{\nu_e} = \frac{{\rm d}N_{\bar{\nu}_e}}{{\rm d}E_\nu} = \phi_{\bar{\nu}_e} = 0.25\mathcal{F}(E_\nu).\end{aligned} \tag{17}$$

The total number of secondary muons (from the charged current interaction of ν_μ only) at a kilometer scale detector for such flux are obtained as (i) 4.3 per year for pseudo-Dirac oscillation, (ii) $\sim$9 per year for mass-flavour oscillation and (iii) $\sim$18 per year for an average distance of the GRBs $\sim$ 100 Mpc. These numbers can be compared with the single GRB case at $z = 0.03 \simeq 100$ Mpc and at a zenith angle $\theta_z = 100.9°$. The secondary muon yields at ICECUBE-type detector are 22 for pseudo-Dirac case, 44.65 for mass-flavour oscillation case and 77.5 for no oscillation case. Similar calculations for single GRB case at $z = 1.0$, yield the expected number of muons as 0.016 for pseudo-Dirac case, 0.03 for mass-flavour oscillation case and 0.06 for no oscillation case. Therefore, for the case of single GRB event at a very long distance ($z \sim 1$), the neutrino flux will be much reduced and it is not possible to distinguish the single GRB effect from the isotropic GRB neutrino flux and consequently it will be very difficult to obtain any signature of pseudo-Dirac nature. But for a GRB occurring much nearer, the secondary muon

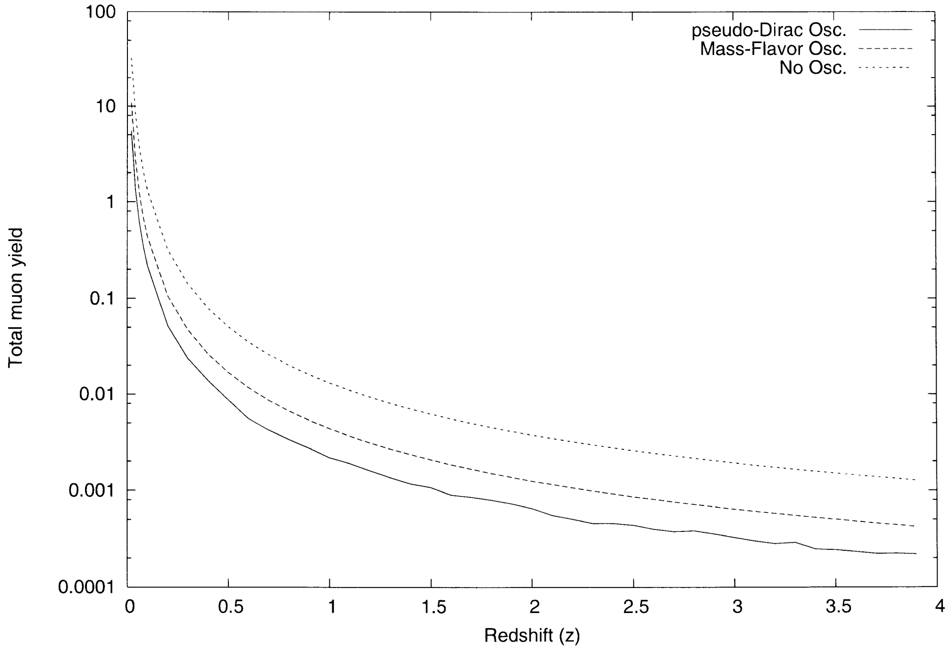

Figure 1. The comparison of total secondary muon yields in cases of (i) pseudo-Dirac oscillation, (ii) mass-flavour oscillation and (iii) no oscillation for ultra-high energy neutrinos from GRBs at different z-shift (z) distance. The zenith angle θ_z is 180°. See text for other GRB parameters considered.

yield is considerably higher than the ones from the isotropic flux and thus raises the hope of being distinguished from the isotropic flux. Also, the muon yield for ordinary mass-flavour oscillation is almost double the yield for the case of pseudo-Dirac. This, along with the high muon yield from the neutrinos from a single GRB occurring comparatively nearer is encouraging for determining the pseudo-Dirac nature, if any, for the neutrinos.

In order to consider the signature of other neutrino flavours in the detector, we have also studied the neutrino signature from the shower events produced at the detector (kilometer scale) by neutral current interactions of all neutrino flavours as also the electromagnetic shower produced by the charged current interactions of ν_e. For charged current interaction of ν_τ we have not considered the so-called 'double bang' events or 'lollipop' events as they are very difficult to detect and they are possibly significant in a narrow energy window. Instead, we consider here the decay channel of tau lepton [14] obtained from charged current interactions of ν_τ, where muons are produced following the interaction, $\nu_\tau \to \tau \to \bar{\nu}_\mu \mu \nu_\tau$. These muons can then be detected as muon tracks [15] in the kilometer-scale detector. Therefore, the number of muons from tracks are now obtained as the sum of the muon tracks from ν_μ (charged current interactions) and the same obtained from ν_τ as discussed. The event rate for the shower case is given by

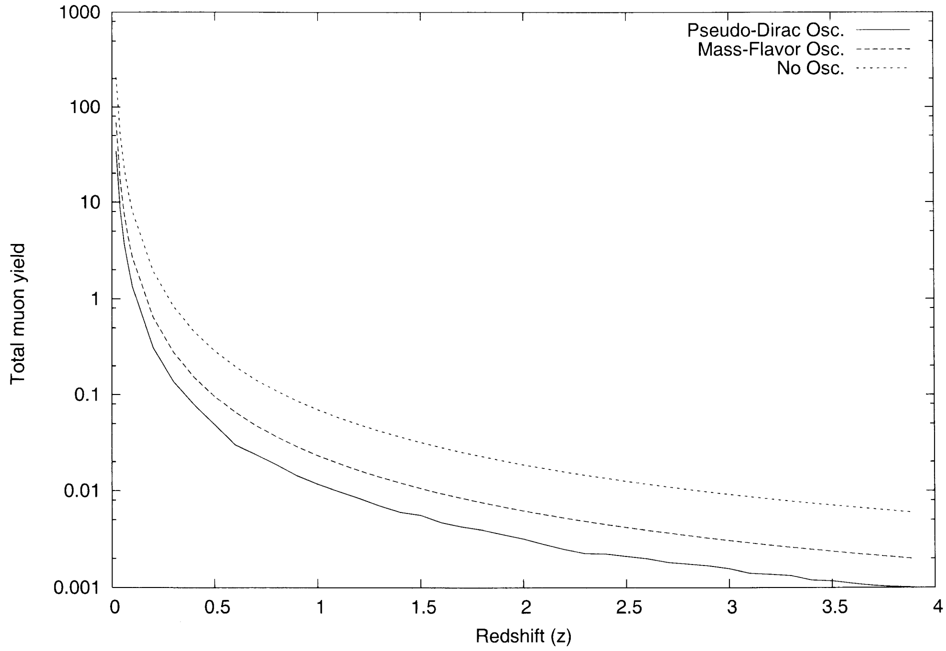

Figure 2. Same as figure 1 but for $\theta_z = 100.9°$.

$$N_{\text{sh}} = \int \mathrm{d}E_\nu \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} P_{\text{surv}}(E_\nu) \times \int \frac{1}{\sigma^j} \frac{\mathrm{d}\sigma^j}{\mathrm{d}y} P_{\text{int}}(E_\nu, y). \tag{18}$$

In the above, $\sigma^j = \sigma^{\text{CC}}$ (for electromagnetic shower from ν_e charged current interactions) or σ^{NC} as the case may be. In the above, P_{int} is the probability that a shower produced by the neutrino interactions will be detected and is given by

$$P_{\text{sh}} = \rho N_{\text{A}} \sigma^j L, \tag{19}$$

where ρ is the density of the detector material and L is the length of the detector ($L = 1$ km for ICECUBE).

We have calculated the ratio (R) of total muon track events and shower events for the three scenarios, namely, pseudo-Dirac oscillation, mass-flavour oscillation and no oscillation. In the case of a single GRB at $z = 0.03$ and $\theta_z = 100.9°$ these ratios are 2.55, 3.23 and 5.61 respectively for the three scenarios. For the isotropic flux, these ratios are found to be 2.95, 3.72 and 6.45 respectively. The results are summarised in table 1.

4. Conclusion

In this report, the possibility of probing pseudo-Dirac neutrino through ultra-high energy neutrinos from distant GRBs is considered. The difference of the muon

Table 1. The expected muon yields and muon-to-shower ratios for three different oscillation scenarios for GRBs with two red-shifts $z = 0.03$ and 1.0.

	Muon yield			Muon-to-shower ratio		
Red-shift (z)	Pseudo-Dirac	Mass-flavour Osc.	No Osc.	Pseudo-Dirac	Mass-flavour Osc.	No Osc.
0.03	22	44.65	77.5	2.55	3.23	5.61
1.0	0.018	0.03	0.06	2.43	3.00	5.21

yields for three cases, namely, pseudo-Dirac oscillations, flavour oscillations and no oscillation are demonstrated for GRBs with different z-shift values in the case of a kilometer-scale detector such as ICECUBE. The results for neutrino from a single GRB and neutrinos from all the GRBs producing a total isotropic flux are separately considered. It is found that for a single GRB at a low red-shift the muon yield is considerably higher than that obtained from the sum total isotropic flux from other GRBs and the muon yield for pseudo-Dirac case is almost twice that for mass-flavour oscillations. This is an encouraging indication for the possibility of identifying such signatures. If the detector size is increased, this possibility will be certainly improved. The shower produced by different neutrino flavours are also investigated and muon-to-shower ratios are calculated for various cases discussed above. In this case, we find that the difference is not significant enough both in terms of neutrino fluxes (single GRB and isotropic flux) and the nature of neutrino oscillations (pseudo-Dirac and mass-flavour) to make any effective comment. Of course, the uncertainty in initial GRB neutrino fluxes and the background at the detector may suppress the effects caused by possible pseudo-Dirac nature. Predicting more accurate GRB neutrino flux and precision measurements of neutrino-induced muons (as also showers induced by UHE neutrinos) at such detectors or preferebly larger detector may throw more insight in detecting the pseudo-Dirac nature, if exists, in neutrinos.

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