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Probing Flavor Transition Mechanisms of Astrophysical Neutrinos

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The determination of neutrino flavor transition mechanism by neutrino telescopes is presented. We first propose a model-independent parametrization for flavor transitions (such as standard three-flavor oscillations, neutrino decays or others) of astrophysical neutrinos propagating from their sources to the Earth. We demonstrate how one can constrain parameters of the above parametrization by performing flavor identifications in neutrino telescopes. Given the anticipated flavor discrimination capability in the future radio-wave based neutrino telescope, we work out the corresponding allowed ranges for flavor transition parameters. The possibility of distinguishing neutrino decay models from the standard three-flavor oscillations in the future neutrino telescope as mentioned is discussed.

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PoS(EPS-HEP2011)047

1. The Parametrization of Flavor Transition Mechanisms

The effect of neutrino flavor transition processes occurring between the astrophysical source and the Earth is represented by the matrix P such that

$$\Phi = P\Phi_0, \tag{1.1}$$

where $\Phi = (\phi(\nu_e),\ \phi(\nu_\mu),\ \phi(\nu_\tau))^T$ is the flux of neutrinos reaching to the Earth, while $\Phi_0 = (\phi_0(\nu_e),\ \phi_0(\nu_\mu),\ \phi_0(\nu_\tau))^T$ is the flux of neutrinos at the astrophysical source. We note that our convention implies $P_{\alpha\beta} \equiv P(\nu_\beta \to \nu_\alpha)$. It is convenient to parametrize the initial flux of neutrinos by [1]

$$\Phi_0 = \frac{1}{3}\mathbf{V}_1 + a\mathbf{V}_2 + b\mathbf{V}_3, \tag{1.2}$$

where $\mathbf{V}_1 = (1,1,1)^T$, $\mathbf{V}_2 = (0,-1,1)^T$, and $\mathbf{V}_3 = (2,-1,-1)^T$. In this parametrization, we have taken the normalization $\phi_0(\nu_e)+\phi_0(\nu_\mu)+\phi_0(\nu_\tau) = 1$. The ranges for a and b are $-1/3+b \le a \le 1/3-b$ and $-1/6 \le b \le 1/3$ such that the condition $0 \le \phi_0(\nu_\alpha) \le 1$ holds for each neutrino flavor α. For the well known pion source with $\Phi_0 = (1/3,2/3,0)^T$ and the muon-damped source with $\Phi_0 = (0,1,0)^T$ [2], one has $(a,b) = (-1/3,0)$ and $(a,b) = (-1/2,-1/6)$, respectively. Under the same basis, the neutrino flux reaching to the Earth can be written as

$$\Phi = \kappa\mathbf{V}_1 + \rho\mathbf{V}_2 + \lambda\mathbf{V}_3. \tag{1.3}$$

It is easy to show that

$$\begin{pmatrix} \kappa \\ \rho \\ \lambda \end{pmatrix} = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix} \begin{pmatrix} 1/3 \\ a \\ b \end{pmatrix}, \tag{1.4}$$

where $Q = \mathbf{A}^{-1}P\mathbf{A}$ with

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 2 \\ 1 & -1 & -1 \\ 1 & 1 & -1 \end{pmatrix}. \tag{1.5}$$

The parameters κ, ρ and λ are related to the flux of each neutrino flavor by

$$\phi(\nu_e) = \kappa + 2\lambda,\ \phi(\nu_\mu) = \kappa - \rho - \lambda,\ \phi(\nu_\tau) = \kappa + \rho - \lambda, \tag{1.6}$$

with the normalization $\phi(\nu_e)+\phi(\nu_\mu)+\phi_(\nu_\tau) = 3\kappa$. Since we have chosen the normalization $\phi_0(\nu_e)+\phi_0(\nu_\mu)+\phi_0(\nu_\tau) = 1$ for the neutrino flux at the source, the conservation of total neutrino flux during propagations corresponds to $\kappa = 1/3$. It is helpful to rewrite Eq. (1.6) as

$$\rho = \left(\phi(\nu_\tau)-\phi(\nu_\mu)\right)/2,\ \lambda = \phi(\nu_e)/3 - \left(\phi(\nu_\mu)+\phi(\nu_\tau)\right)/6. \tag{1.7}$$

It is clear from Eqs. (1.4) and (1.7) that the first row of matrix Q determines the normalization of the total neutrino flux reaching to the Earth, the second row of Q determines the breaking of $\nu_\mu - \nu_\tau$ symmetry [3, 4] in the arrival neutrino flux, and the third row of Q determines the flux difference $\phi(\nu_e) - (\phi(\nu_\mu)+\phi(\nu_\tau))/2$.

PoS(EPS-HEP2011)047

The flux conservation condition $\kappa = 1/3$ requires $Q_{11} = 1$ and $Q_{12} = Q_{13} = 0$, since the coefficients a and b are arbitrary. Furthermore, in the exact $\nu_\mu - \nu_\tau$ symmetry limit, one can show that [5] $Q_{21} = Q_{22} = Q_{23} = Q_{32} = 0$. Therefore, under these two conditions, there are only two free parameters, Q_{31} and Q_{33}, for classifying all possible neutrino flavor transition models. For three-flavor neutrino oscillations in the tribimaximal limit of mixing angles, i.e., $\sin^2\theta_{12} = 1/3$, $\sin^2\theta_{23} = 1/2$, and $\sin^2\theta_{13} = 0$, we have [5]

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/3 \end{pmatrix}. \tag{1.8}$$

We note that the $\nu_\mu - \nu_\tau$ symmetry is broken by recent measurements of θ_{13} angle in T2K [6] and Double Chooz [7] experiments. With θ_{12} and θ_{23} unchanged and θ_{13} taken as the T2K best-fit value $\sin^2 2\theta_{13} = 0.11$ at the CP phase $\delta = 0$ for the normal mass hierarchy, we arrive at

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.025 & -0.075 \\ 0 & -0.025 & 0.30 \end{pmatrix}. \tag{1.9}$$

We note that the second row of Q is non-vanishing, and so is the element Q_{32}. In this work, we shall confine our discussions in the $\nu_\mu - \nu_\tau$ symmetry limit.

Since we are interested in distinguishing neutrino decay models from the three-flavor neutrino oscillations by neutrino telescopes, it is desirable to calculate Q matrices corresponding to various neutrino decay models. The simplest case of neutrino decays is that both the heaviest and the middle mass eigenstates decay to the lightest mass eigenstate. In this case, one can show that [5]

$$Q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ D & 0 & 0 \end{pmatrix}, \tag{1.10}$$

with $D = 1/2$ for the normal mass hierarchy and $D = -1/2$ for the inverted mass hierarchy.

2. Probing the flavor transition parameters Q_{31} and Q_{33}

It has been shown [8] that the event ratio of muon tracks to showers in IceCube can be used to determine the flavor ratio of neutrino fluxes. In fact, the flux ratio $R = \phi(\nu_\mu)/(\phi(\nu_e) + \phi(\nu_\tau))$ can be extracted [9]. In an appropriate energy window, one can also identify ν_τ so that the flux ratio $S = \phi(\nu_e)/\phi(\nu_\tau)$ can be measured [10]. To probe Q_{31} and Q_{33}, a precise knowledge of neutrino flavor ratio at the astrophysical source is required [11]. The results of probing these parameters via astrophysical sources are given in Ref. [5].

We note that the cosmogenic neutrino flux [12] resulting from GZK interactions is a pion source for its main spectrum, i.e., $(a, b) = (-1/3, 0)$ for the cosmogenic neutrino flux. Eqs. (1.4) and (1.7) then imply

$$\phi(\nu_e) - \left(\phi(\nu_\mu) + \phi(\nu_\tau)\right)/2 = Q_{31}. \tag{2.1}$$

Clearly Q_{31} can be probed by measuring the flux ratio $R' = \phi(\nu_e)/\left(\phi(\nu_\mu) + \phi(\nu_\tau)\right)$. Such a flavor discrimination could be achieved in the radio-wave based neutrino telescope due to LPM

PoS(EPS-HEP2011)047

effect [13]. It has been shown that the newly proposed Askaryan Radio Array [14] can detect roughly 50 cosmogenic neutrino events in 3 years for baseline flux models, such as the model proposed in the second paper of Ref. [12]. With the three-flavor neutrino oscillation as the input true model, Fig. 1 shows the allowed 1σ and 3σ ranges of the parameter Q_{31} for a 20% accuracy on R' measurement. It is seen that such an accuracy on R' is sufficient to rule out the simplest type of neutrino decay models at 3σ.

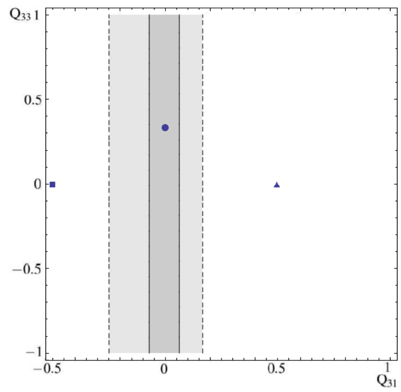

Figure 1: The 1σ and 3σ allowed ranges of Q_{31} for a 20% accuracy on R' measurement. The circle denotes the input true model while the triangle and the square denote the simplest neutrino decay model in normal and inverted mass hierarchies, respectively.

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