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Determining the Flavor Ratio of Astrophysical Neutrinos

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We discuss the reconstruction of neutrino flavor ratios at astrophysical sources through the future neutrino-telescope measurements. We demonstrate that the accuracies in the measurements of $R \equiv \phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$ should both be better than 10% in order to distinguish between the pion source and the muon-damped source at the 3σ level.

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1. Introduction

Most of the astrophysical neutrinos are believed to be produced by decays of charged pions and subsequent decays of muons. This leads to the neutrino flux ratio $\phi_0(\nu_e):\phi_0(\nu_\mu):\phi_0(\nu_\tau)=1:2:0$ at the astrophysical source where $\phi_0(\nu_\alpha)$ is the sum of ν_α and $\bar{\nu}_\alpha$ flux. Such a flux ratio results from an implicit assumption that the muon decays into neutrinos before it loses a significant fraction of its energy. However, in some source the muon quickly loses its energy by interacting with strong magnetic fields or with matter [1, 2, 3]. Consequently this type of source has a neutrino flavor ratio $\phi_0(\nu_e):\phi_0(\nu_\mu):\phi_0(\nu_\tau)=0:1:0$, which is referred to as the muon-damped source. The third type of source emits neutrons resulting from the photo disassociation of nuclei. As neutrons propagate to the Earth, $\bar{\nu}_e$ are produced from neutron β decays [4], leading to a neutrino flavor ratio $\phi_0(\nu_e):\phi_0(\nu_\mu):\phi_0(\nu_\tau)=1:0:0$. There exist numerous works which take astrophysical neutrinos as the beam source for extracting neutrino mixing parameters. To have a better determination of certain neutrino mixing parameter, for instance the atmospheric mixing angle θ_{23} or the CP phase δ, a combined analysis on the terrestrially measured flavor ratios of astrophysical neutrinos coming from different sources, such as the pion source and the muon-damped source, has been considered [5, 6]. A natural question to ask is then how well one can distinguish these neutrino sources. The answer to this question depends on our knowledge of neutrino mixing parameters and the achievable accuracies in measuring the neutrino flavor ratios on the Earth such as $R\equiv\phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ and $S\equiv\phi(\nu_e)/\phi(\nu_\tau)$. We shall try to answer this question in this report.

2. Statistical Analysis

To reconstruct the neutrino flavor ratio at the source with a statistical analysis, we employ the following best-fit values and 1σ ranges of neutrino mixing angles [7]

$$\sin^2\theta_{12}=0.32^{+0.02}_{-0.02},\ \sin^2\theta_{23}=0.45^{+0.09}_{-0.06},\ \sin^2\theta_{13}<0.019. \tag{2.1}$$

The statistical analysis is then performed with the following formula

$$\chi^2=\left(\frac{R_{\rm th}-R_{\rm exp}}{\sigma_{R_{\rm exp}}}\right)^2+\left(\frac{S_{\rm th}-S_{\rm exp}}{\sigma_{S_{\rm exp}}}\right)^2+\sum_{jk=12,23,13}\left(\frac{s^2_{jk}-(s_{jk})^2_{\rm best\,fit}}{\sigma_{s^2_{jk}}}\right)^2 \tag{2.2}$$

with $\sigma_{R_{\rm exp}}=(\Delta R/R)R_{\rm exp}$, $\sigma_{S_{\rm exp}}=(\Delta S/S)S_{\rm exp}$, $s^2_{jk}\equiv\sin^2\theta_{jk}$ and $\sigma_{s^2_{jk}}$ the 1σ range for s^2_{jk}. Here $R_{\rm th}$ and $S_{\rm th}$ are theoretical predicted values for R and S respectively while $R_{\rm exp}$ and $S_{\rm exp}$ are experimentally measured values. The values for $R_{\rm exp}$ and $S_{\rm exp}$ are generated from input true values of neutrino flavor ratios at the source and input true values of neutrino mixing parameters as given by Eq. (2.1). We assumes that both ΔR and ΔS are dominated by the statistical errors. In this case, they are related to each other by [5]

$$\left(\frac{\Delta S}{S}\right)=\frac{1+S}{\sqrt{S}}\sqrt{\frac{R}{1+R}}\left(\frac{\Delta R}{R}\right). \tag{2.3}$$

Let us take the accuracy for measuring R to be $\Delta R/R=10\%$. The value for $\Delta S/S$ can be calculated from Eq. (2.3). The reconstruction of neutrino flavor ratio with the above given $\Delta R/R$

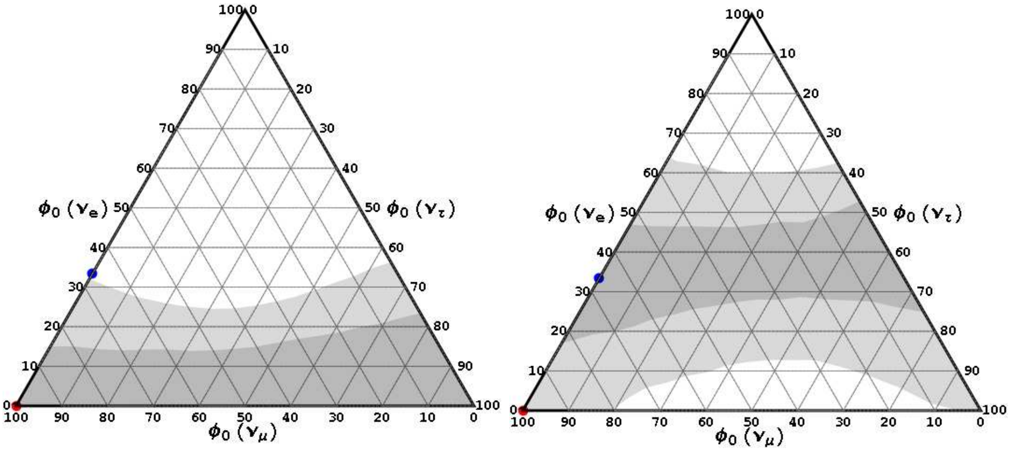

Figure 1: The reconstructed ranges for the neutrino flavor ratios with $\Delta R/R = 10\%$ and $\Delta S/S$ related to the former by Eq. (2.3). Gray and light gray areas denote the reconstructed 1σ and 3σ ranges respectively. The left panel is the result for an input muon-damped source (red point) while the right panel is that for an input pion source (blue point).

and $\Delta S/S$ is shown in Fig. 1. For an input muon-damped source, the pion source can be ruled out at the 3σ level as shown in the left panel of the figure. However, the converse is not true as depicted in the right panel of the figure. To rule out the muon-damped source in this case, one has to reduce $\Delta R/R$ to 6% and reduce $\Delta S/S$ accordingly by Eq. (2.3). Alternatively, one can achieve the same by reducing errors of $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ by 30% and improving the bound on θ_{13} to $\sin^2\theta_{13} < 0.0025$. Finally we have also considered a θ_{13} range suggested by Ref. [8] where

$$\sin^2\theta_{13} = 0.016 \pm 0.010(1\,\sigma) \tag{2.4}$$

by a global analysis. Since the best-fit value for θ_{13} is now non-vanishing, the reconstructed neutrino flavor ratio depends on the CP phase. The details of such a study is presented in Ref. [9].

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