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中文摘要

首先我們探討如何運用微中子混合角資訊及微中子望遠鏡預期精度重建天文微中子之源頭味比例。之後我們探討如何分類天文微中子之味變換機制。有別傳統方法，我們提出新的味轉換矩陣，使得味變換機制之理論分類大為簡化。

English Abstract

We first discuss how well one can reconstruct the flavor ratios of astrophysical neutrinos at the source, given achievable efficiencies of neutrino telescopes in flavor discriminations and expected understandings of neutrino mixing parameters in the future. We then discuss how to probe flavor transition mechanisms of propagating astrophysical neutrinos. In this regard, we propose a model independent parameterization for neutrino flavor transitions. We illustrate how one can determine parameters of this parameterization by neutrino telescope measurements.

一、前言

We report on results of a three-year research on ultra-high energy cosmic rays and related high energy neutrinos. In Section II, we state the motivation for such an investigation. In Section III, we discuss existing works on this subject and our approach to the problem. In Section IV, we outline our research method. Our results are summarized in Section V. We also summarize results of other relevant works in this section.

二、研究目的

Almost all previous studies treat astrophysical neutrinos as the beam source for extracting neutrino mixing parameters. To have a better determination of neutrino mixing parameters, for instance the atmospheric mixing angle θ_{23} and the CP phase δ, a combined analysis of terrestrially measured neutrino flavor ratios from different astrophysical sources, such as the pion source and the muon-damped source, has been considered [1,2]. A natural question to ask is how well one can determine the neutrino flavor ratio at the astrophysical source. The answer to this question depends on our knowledge of neutrino mixing parameters and the achievable accuracies in measuring the neutrino flavor ratio on the Earth such as $R \equiv \phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$. In this work, we answer this question with a statistical analysis.

Besides probing the neutrino flavor ratio at the astrophysical source, it is also important to understand the flavor transition mechanisms of propagating astrophysical neutrinos. This investigation relies heavily on our understanding of astrophysical neutrino sources through more conventional astronomy. Recently, a systematic study on possible neutrino flavor ratios from cosmic accelerators listed on the Hillas plot was initiated [3]. The neutrino flavor ratio at the source depends on the spectrum index of injecting protons, the size of the acceleration region, and the magnetic field strength at the source. In some regions of the above-mentioned parameters, the neutrino flavor ratios are energy dependent while in some other parameter regions they could behave as those of a pion source or those of a muon-damped source, which are both energy independent. Taking the astrophysical neutrino sources as either pion source or muon-damped source, we discuss how to probe the flavor transition mechanisms of astrophysical neutrinos from measuring the previously mentioned neutrino flavor ratio parameters *R* and *S* with terrestrial neutrino telescopes. To effectively classify possible flavor transition models of astrophysical neutrinos, we propose a new parametrization for the transition probability matrix, which is related to the conventional parametrization by a similarity transformation.

三、文獻探討

To reconstruct the neutrino-flavor ratio at the source with a statistical analysis, we employ the following best-fit values and 1 σ ranges of neutrino mixing parameters [4]

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

for the major part of our analysis. In the above parameter set, the best-fit value of θ_{23} is smaller than π/4. There exist proposals to probe $\sin 2\theta_{23}$ by future atmospheric neutrino experiments [5, 6] and long baseline neutrino experiments [7]. We therefore include in our analysis the hypothetical scenario that $(\sin 2\theta_{23})_{\text{best-fit}}=0.55$ with an error identical to the one associated with $(\sin 2\theta_{23})_{\text{best-fit}}=0.45$. Finally we also consider a θ_{13} range suggested in Ref. [8] where

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

by a global analysis. For future neutrino-telescope measurements, we consider the accuracy in the measurement of *R* at 10% for the pion source and the muon-damped source. We take the simplification that *ΔS/S* is related to *ΔR/R* via [1]

$$\left(\frac{\Delta S_i}{S_i}\right) = \frac{1+S_i}{\sqrt{S_i}}\sqrt{\frac{R_i}{1+R_i}}\left(\frac{\Delta R_i}{R_i}\right)$$

with *i* denoting either the pion source or the muon-damped source.

To probe the flavor transition mechanism of astrophysical neutrinos, the authors of Ref. [9] considered typical astrophysical sources and applied the flavor transition probability matrix *P* derived from the standard neutrino oscillation model or flavor transition models involving new physics for obtaining possible flavor ratios to be measured by terrestrial neutrino telescopes. It was pointed out that there are some flavor transition models which can produce rather distinctive neutrino flavor ratios on the Earth compared to those produced by the standard neutrino oscillation model, even with uncertainties of neutrino mixing parameters taken into account. Hence these flavor transition models can be tested on the basis of their flavor ratio predictions for astrophysical neutrinos arriving on the Earth. In our approach, we test the fundamental structure of a given flavor transition model, namely the Q matrix of the model, which is related to the conventional P matrix by a similarity transformation. We shall describe this transformation later. We note that the matrix elements of Q can be determined by performing fittings to the flavor-ratio measurements in the neutrino telescopes. The obtained ranges for these matrix elements can be used as the basis for testing any flavor transition model.

四、研究方法

For statistical analysis, we construct

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

with $i=\pi$, μ and $s_{jk}^2 \equiv sin^2\theta_{jk}$. In $R_{i;\mathrm{th}}$ and $S_{i;\mathrm{th}}$, the variables s_{jk}^2 can vary between 0 and 1 while $\cos\delta$ can vary between -1 and 1. In our analysis, we scan all possible neutrino flavor ratios at the source that give rise to a specific χ_i^2 value. Since we take $R_{i;\mathrm{exp}}$ and $S_{i;\mathrm{exp}}$ as those generated by input true values of initial neutrino flavor ratios and neutrino mixing parameters, we have $(\chi_i^2)_{\mathrm{min}}=0$ occurring at the above input true values of parameters. Hence the boundaries for 1σ and 3σ ranges of initial neutrino flavor ratios are given by $\chi_i^2 = 2.3$ and $\chi_i^2 = 11.8$ respectively.

To derive the Q matrix representation, we note that the neutrino flavor composition at the source can be written as $\Phi_0=V_1+aV_2+bV_3$ with $V_1=(1,1,1)^T$, $V_2=(0,-1,1)^T$ and $V_3=(2,-1,-1)^T$. The ranges for a and b are $-1/3+b\leq a\leq 1/3-b$ and $-1/6 \leq b\leq 1/3$. Following the same parametrization, we write the neutrino flux reaching to the Earth as $\Phi=\kappa V_1+ \rho V_2+\lambda V_3$. It is easy to show that

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

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

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

In other words, Q is related to P by a similarity transformation where columns of the transformation matrix $\mathbf{A}$ correspond to vectors V_1, V_2, and V_3, respectively. The conservation of total neutrino flux during propagations corresponds to $\kappa=1/3$. In general flavor transition models, κ could be less than 1/3 as a consequence of (ordinary) neutrino decaying into invisible states or oscillating into sterile neutrinos. The coefficients κ, ρ and λ are related to neutrino fluxes on the Earth via

$$\rho = (\phi_\tau - \phi_\mu)/2, \qquad \lambda = \phi_e/3 - (\phi_\mu + \phi_\tau)/6.$$

It is then clear that, for fixed a and b, the first row of matrix Q determines the normalization for the total neutrino flux reaching to the Earth, the second row of Q determines the breaking of ν_μ-ν_τ symmetry in the arrival neutrino flux, and the third row of Q determines the flux difference $\phi_e-(\phi_\mu+\phi_\tau)/2$.

五、結果與討論

The details on the reconstruction of astrophysical neutrino flavor ratio at the source can be found in [10,11]. Summarizing Ref. [10], we have found that, by just measuring R alone from either an input pion source or an input muon-damped source with a precision $\Delta R/R$ = 10%, the reconstructed 3σ range for the initial neutrino flavor ratio is almost as large as the entire physical range for the above ratio. However, by simultaneous measurements of R and S, the pion source and the muon-damped source can be distinguished at the 3σ level for $(\sin 2\theta_{13})_{\text{best-fit}}=0$, $\Delta R_i/R_i$ = 10% with $i=\pi, \mu$ and a $\Delta S_i/S_i$ related to the former by the Poisson statistics. With $(\sin 2\theta_{13})_{\text{best-fit}} > 0$ as suggested in Ref. [8], the CP phase δ is seen to affect the reconstructed range for the neutrino flavor ratio at the source. We have also performed a statistical analysis with the errors of θ_{23} and θ_{12} both reduced to a half and the limit of θ_{13} improved to $\sin^2\theta_{13} < 0.0025$. We found that the improvement on the reconstructed 3σ range for the initial neutrino flavor ratio is negligible although the improvement on the 1σ range is noticeable. In summary, we have demonstrated that it is challenging to reconstruct the neutrino flavor ratio at the astrophysical source, requiring at least a decade of data taking in a neutrino telescope such as IceCube for distinguishing between the pion source and the muon-damped source. We stress that the large uncertainty in the flavor ratios of astrophysical neutrinos should be taken into account as one uses these neutrinos as a beam source to extract the neutrino mixing parameters. In Ref. [11], we pointed out that the new set of neutrino flux ratio parameters

$R' \equiv \phi(\nu_e)/(\phi(\nu_\mu)+\phi(\nu_\tau))$ and $S' \equiv \phi(\nu_\mu)/\phi(\nu_\tau)$ are more appropriate for neutrino energies higher than 33 PeV. In such an energy range, both muon and tau leptons behave like tracks while the electron has a shower signature. It turns out the measurement of R' is already useful for distinguishing between pion source and the muon-damped source. The further measurement of S' does not help in this respect due to the ν_μ-ν_τ symmetry.

In the Q matrix formulation of neutrino flavor transition, we have found great simplifications in classifying possible flavor transition models. First, for flux-conserving models, one always has κ=1/3 in the Q matrix parametrization, irrespective of the initial flavor composition characterized by parameters a and b. This implies Q_{11}=1 and Q_{12}=Q_{13}=0. Second, for those models which do not seriously break the ν_μ-ν_τ symmetry, the second and third rows of P are almost identical. This implies $(Q_{21},Q_{22},Q_{23})\approx(0,0,0)$ and $(Q_{12},Q_{22},Q_{32})^T=(0,0,0)^T$. We have seen that the first and second rows of Q as well as the matrix element Q_{32} are already constrained in a simple way by assuming the conservation of total neutrino flux and the validity of approximate ν_μ-ν_τ symmetry. Hence, under these two assumptions, one can simply use the values for Q_{31} and Q_{33} to classify flavor transition models. This is the most important advantage of Q matrix parametrization. The details on probing Q_{31} and Q_{33} with neutrino telescope measurements are discussed in our recent paper [12].

六、計畫成果自評

The result in Ref. [10] has been orally presented in ***International Europhysics Conference on High Energy Physics*** held at Krakow, Poland in 2009. The series of results, Ref. [10,11,12], will be presented in an invited talk of the symposium ***Flavor Physics in the LHC Era*** to be held in Singapore in Nov. 2010. We are working on a paper addressing the application of Q matrix parametrization [13]. In 2009, we also published a paper in Physical Review Letter [14] on the plasma wakefield acceleration of ultra high energy cosmic rays. This result was reported by a staff writer in ***Physics Today online.***

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