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（超高能宇宙射線及其對應微中子之關聯性研究）

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中文摘要

未來微中子天文望遠鏡若能達到 10%量測精度，亦即測量 $R\equiv\phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ 與 $S\equiv\phi(\nu_e)/\phi(\nu_\tau)$到百分之十精度，我們可以區分$\pi$介子源與渺子源到 3 個標準差。如果單測量 R 則難以區分上述高能微中子源。我們也討論輕子 CP 相位對重建天文微中子源的影響。

English Abstract

We discuss the reconstruction of neutrino flavor ratios at astrophysical sources from future neutrino-telescope measurements, given the knowledge of neutrino mixing angles obtained from terrestrial experiments. With a statistical analysis, we demonstrated that the pion source and the muon damped source can be distinguished from each other at the 3σ level provided the accuracies in the measurement of $R\equiv\phi(\nu_\mu)/(\phi(\nu_e)+\phi(\nu_\tau))$ and $S\equiv\phi(\nu_e)/\phi(\nu_\tau)$ can both reach about 10%. On the other hand, the above two sources are very difficult to distinguish by merely measuring R alone. We also discuss the effect of leptonic CP phase on such a flavor-ratio reconstruction.

一、 前言

This is the second mid-term report for a three-year project on the correlation research of ultra-high energy cosmic ray and corresponding neutrino. 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 shall answer this question with a statistical analysis.

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 1σ ranges of neutrino mixing parameters

[3]

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

for the major part of our analysis. In the above parameter set, the best-fit value of θ_{23} is smaller than $\pi/4$. There exist proposals to probe $\sin^2\theta_{23}$ by future atmospheric neutrino experiments [4, 5] and long baseline neutrino experiments [6]. 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. [7] 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 $\Delta S/S$ is related to $\Delta R/R$ 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 the pion source and the muon-damped source respectively.

四、研究方法

For statistical analysis, we construct

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

with $i=\pi,\ \mu$ and $s^2_{jk}\equiv \sin^2\theta_{jk}$. In $R_{i;\text{th}}$ and $S_{i;\text{th}}$, the variables s^2_{jk} 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 $R_{i;\text{exp}}$ and $S_{i;\text{exp}}$ as those generated by input true values of initial neutrino flavor ratios and neutrino mixing parameters, we have $(\chi_i^2)_{\min}=0$ 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 $\Delta\chi_i^2 = 2.3$ and $\Delta\chi_i^2 = 11.8$ respectively.

五、結果與討論

The details of our result can be found in our recent preprint [8]. In summary, 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. Furthermore, with the muon-damped source as the true source, the astrophysical hidden sources can be ruled out at the 3σ level. With $(\sin^2\theta_{13})_{\text{best-fit}} > 0$ as suggested in Ref. [7], 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.

六、計畫成果自評

We have a paper posted on the archive [8] and to be submitted to Physical Review D. This paper was presented in the 8^{th} International Workshop on Particle Physics Phenomenology held in Tainan, Taiwan. In this year, we also published a paper in Physical Review Letter [9] on the plasma wakefield acceleration of ultra high energy cosmic rays and completing a work on the detection of tau neutrinos through radio wave band of geo-synchrotron radiation produced by electromagnetic showers [10].

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