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行政院國家科學委員會補助專題研究計畫成果報告

（微中子天文物理之研究）

計畫類別：x 個別型計畫　　□ 整合型計畫
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執行單位：國立交通大學物理所

一、中文摘要

我們探討微中子及 tau 輕子在地球中之傳播行為。從微中子與核子之散射截面積，我們計算出各類入射微中子淺穿過地球後導致之 tau 輕子流量

在 GeV 到 TeV 能量之間, 我們指出 Tau 微中子天文學的良機. 經過微中子振盪分析, 我們發現以上能量範圍內, 大氣背景 tau 微中子流量遠小於大氣背景 muon 微中子流量. 此背景值差異導致銀河系 tau 微中子遠比銀河系 muon 微中子容易觀測.

我們也探討微中子在地球裏的物資振盪效應，以此決定θ_{13} 及θ_{23}. 最後我們也參與量測大氣螢光效率，本量測使用史丹福加速器中心的 28.5GeV 的電子束。

關鍵詞：微中子振盪、Tau 微中子、螢光

Abstract

We study the propagation of high- energy neutrinos and tau leptons inside the Earth. Given AGN, GRB and GZK incident neutrino fluxes, we calculate the resulting tau neutrino fluxes resulting from neutrino-nucleon scattering as the incident neutrinos skim a part of the Earth.

We point out the opportunity of tau neutrino astronomy for neutrino energies roughly between 10 and 100 GeV's. We demonstrate that, with neutrino oscillation effects taken into account, the atmospheric tau neutrino flux are highly suppressed compared to its muon neutrino counterpart. The flavor dependence in the background atmospheric neutrino flux leads to drastically different prospects between the observations of astrophysical muon neutrinos and those of astrophysical tau neutrinos. We illustrate this point by discussing the viability of observing tau neutrinos from the galactic-plane, produced by cosmic ray-matter scattering.

We also study the matter-enhanced neutrino oscillations inside the Earth. We discuss how a very long baseline neutrino oscillation experiment may determine the neutrino mixing angle θ_{13} and θ_{23}. Finally we participate in measuring the air fluorescence spectra using the SLAC 28.5 GeV electron beam.

Keywords: Neutrino Oscillation, Tau Neutrino, Fluorescence

二、緣由與目的

The detection of high-energy neutrinos (E> 10^5 GeV) is crucial to identify the extreme energy sources in the Universe, and possibly to unveil the puzzle of cosmic rays with energy above the GZK cutoff [1]. These proposed scientific aims are well beyond the scope of the conventional high energy gamma-ray astronomy. Because of the expected small flux of the high-energy neutrinos, large scale detectors (> 1 km^2) seem to be needed to obtain the first evidence.

There are two different strategies to detect the footprints of high-energy neutrinos. The first strategy is implemented by installing detectors in a large volume of ice or water where most of the scatterings between the candidate neutrinos and nucleons occur essentially inside the detector, whereas the second strategy aims at detecting the air showers caused by the charged leptons produced by the neutrino-nucleon scatterings taking place inside the Earth or in the air, far away from the instrumented volume of the detector. The latter strategy thus includes the possibility of detection of quasi horizontal incident neutrinos which are also referred to as the Earth-skimming neutrinos. These neutrinos are considered to interact below the horizon of an Earth based surface detector. The second strategy is proposed only recently [2]. The Pierre Auger observatory group has simulated the anticipated detection of the air showers from the decays of tau leptons [3]. The tau air-shower event rates resulting from the Earth-skimming tau neutrinos for different high-energy neutrino telescopes are given in [4]. A Monte-Carlo study of tau air-shower event rate was also reported not long ago [5]. We note that Ref. [4] does not consider the tau-lepton energy distribution in the ν_τ-nucleon scattering, and only the incident tau neutrinos with energies greater than 10^8 GeV are considered. For Ref. [5], we note that only the sum of tau air shower event rates arising from different directions is given. Hence some of the events may be due to tau-leptons/neutrinos traversing a large distance. As a result, it is not possible to identify the source of tau-neutrino flux even with the observation of tau-lepton induced air-shower.

In this work, we shall focus on the high energy Earth-skimming neutrinos and shall calculate the energy spectrum of their induced tau leptons, taking into account the inelasticity of neutrino-nucleon scatterings and the tau-lepton energy loss in detail. Our work differs from Ref. [5] by our emphasis on the Earth-skimming neutrinos. We shall present our results in the form of outgoing tau-lepton spectra for different distances inside the rock, instead of integrating the energy spectra. As will be demonstrated, such spectra are insensitive to the distances traversed by the Earth-skimming ν_τ and τ. They are essentially determined by the tau-lepton range. Because of this characteristic feature, our results are useful for setting up simulations with specifically chosen air-shower content detection strategy, such as detection of the Cherenkov radiation or the air fluorescence.

For the second project, we observe that the studies on atmospheric and solar neutrino oscillations render useful information on the neutrino mass-square differences and mixing angles among different flavors [6, 7]. Both types of neutrinos come from sites with well known matter contents and densities. This is essential for one to extract neutrino mass and mixing parameters. The natural extension of such studies is to detect neutrinos from other astrophysical sites. Given our current understanding on the neutrino properties, the observation of astrophysical neutrinos provide complementary information on the specific astrophysical site to that obtained from conventional astrophysical means. In this regard, we discuss the viability of seeing the galactic-plane through detecting galactic neutrinos in the energy regime of Super-Kamiokande detector or its extension, i.e. from GeV to TeV energy scales. **Such detections shall open a new avenue for the neutrino astronomy.** To understand the background issue in the detection of astrophysical tau neutrinos, it is important to perform a careful calculation on the atmospheric tau neutrino flux.

Concerning the third project, it is well known that the oscillation $\nu_\mu \rightarrow \nu_e$, for example, is enhanced (suppressed) by the matter effect for $\Delta m_{31}^2 > 0$ ($\Delta m_{31}^2 < 0$). The matter effect to the anti-neutrino oscillation is just the opposite. In this work, we shall concentrate on the muon neutrino survival probability $P(\nu_\mu \rightarrow \nu_\mu)$. It has been pointed out [8] that $P(\nu_\mu \rightarrow \nu_\mu)$ also receives large matter effects in a very long baseline, due to the interplay of large matter effects to $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu \rightarrow \nu_\tau)$.The large matter effect to $P(\nu_\mu \rightarrow \nu_\mu)$ implies that this probability is sensitive to the mixing angle θ_{13} and θ_{23}. Therefore a measurement of $P(\nu_\mu \rightarrow \nu_\mu)$ in the vicinity of a specific energy generally determines a curve in the θ_{13} -θ_{23} plane. In reality, the measurement should determine a band in the θ_{13} -θ_{23} plane taking into account the experimental error. We have observed that $P(\nu_\mu \rightarrow \nu_\mu)$ near its local minimum is sensitive to θ_{23}. On the other hand, it is sensitive to θ_{13} near its local maximum. Therefore, measuring $P(\nu_\mu \rightarrow \nu_\mu)$ both in the vicinity of its local minimum and local maximum could determine simultaneously θ_{13} and θ_{23}.

Finally, we have participated in an SLAC-based experiment FLASH from the beginning of 2003. This experiment is initiated to provide more understanding on the discrepancies between HiRes and AGASA experiments [9]. We investigate the atmospheric fluorescence efficiency, adopted in the analysis of HiRes experiment, using the SLAC 28.5 GeV electron beam. The goal of this experiment is to achieve a better than 10% accuracy for the fluorescence measurement. With such accuracy, it is sufficient to shed some light on the discrepancy between HiRes and AGASA cosmic ray spectra. The justifications for using SLAC electron beam to study the physics of UHECR are the following: (a) an extensive air shower produced by a hadron at relevant cosmic ray energies is a superposition of electromagnetic sub-showers. The atmospheric fluorescence energy measurement is dominated by the luminosity of the shower at its maximum development. SLAC primary electron beams interacting in thick targets produce similar secondary electron energy distributions. (b) Important N_2 fluorescence transitions are not accessible by proton excitation. Electron beams are required to study all the relevant transitions. (c) SLAC has beams with a beam bunch energy equivalent to 10^{20} eV (28.5 GeV $\times 10^9$ particles/bunch). Each bunch will produce a superposition of electromagnetic showers in a thick target. The energy distribution of electrons in the resulting shower, as it exits the target into a controlled atmosphere, is calculable and known to be similar to that expected in an UHE shower near shower maximum. The first part of FLASH experiment was completed in September 2003, and the result will be soon. The second and third runs of FLASH experiment were completed in June and July 2004 respectively. These two runs of experiments have the SLAC 28.5 GeV electron beam colliding into a variable thick target radiator and measure the fluorescence yield as a function of shower depth. The objective of this measurement is to establish the proportionality of the fluorescence yield to the shower charge particle energy depositions. In these two runs, Taiwan team contributed in building a monitor for shower’s lateral profile. The measurements of shower lateral profiles are important for verifying various shower simulation packages. These packages are used in the process of reconstructing the primary cosmic ray energy. The data from shower lateral profile monitor has been analyzed.

三、結果與討論

For the first project, we study the major channel for producing the tau lepton flux, i.e., by the charged-current weak interaction process $\nu_\tau N \rightarrow \tau + X$. We computed tau lepton fluxes resulting from three kinds of incident high energy neutrino fluxes, the GZK [10], GRB [11] and AGN [12] neutrino fluxes. For the AGN case, the outgoing tau lepton flux is found to be suppressed by five orders of magnitude compared to the incoming neutrino fluxes for an energy around 10^6 GeV, and is insensitive to the distance (up to 500 km) the tau neutrino (lepton) traverses inside the earth. This reflects the fact the tau lepton flux is mainly determined by the tau lepton range. We also observe this property for tau-lepton fluxes in the GRB case. In the GZK case, the tau lepton flux for a 500-km traveling distance is however suppressed compared to the tau flux for a traveling distance less than 100 km. This is understood by the fact that GZK neutrinos carry much higher energies than those of AGN neutrinos. As the neutrino-nucleon interaction cross section grows with the energy, the flux of the GZK neutrinos attenuates as they traverse the earth. This attenuation in turn decreases the outgoing tau-lepton flux. Our results are very useful to set up simulations for the event rate of high-energy tau leptons induced by the incident Earth-skimming high-energy neutrinos. We also find that, for the GZK case where the incident neutrino spectrum is rather flat, there exists a suppression of ocean-skimming-neutrino induced tau lepton flux as compared to the rock-skimming case. This observation is very crucial for determining the spectrum index of the incident high energy neutrino flux. This part of work is published in [13].

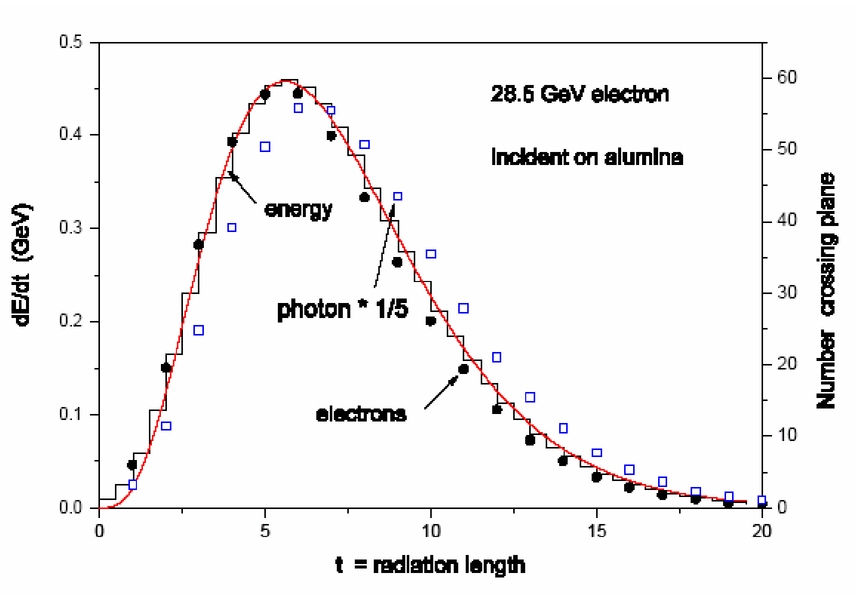
For the second project, we found drastically different drastically different prospects between the observations of astrophysical muon neutrinos and those of astrophysical tau neutrinos, due to much smaller background atmospheric tau neutrino flux compared to the muon neutrino case. Specifically the galactic-plane tau neutrino flux dominates over the atmospheric tau neutrino flux for neutrino energy beyond 10 GeV. Hence the galactic plane can in principle be seen through tau neutrinos with energy greater than 10 GeV. In a sharp contrast, the galactic muon neutrino flux does not dominate over its atmospheric counterpart until the energy of 10^6 GeV. For neutrino energy greater than 10^6 GeV, the galactic-plane muon neutrino flux is already too suppressed to be observed, despite its dominance over atmospheric background! To establish the above difference between tau neutrino and muon neutrino astronomy, we make use of the atmospheric neutrino mixing parameters $\sin^2(2\theta) = 1$, $1.3\cdot10^{-3} < \delta m^2/\mathrm{eV}^2 < 3\cdot10^{-3}$. In the detailed calculations of atmospheric tau neutrino flux, we found that the atmospheric tau neutrino flux at the horizontal direction is two orders of magnitude larger than the corresponding downward flux for neutrino energies between 1 and 10 GeV. On the other hand, the fluxes with zenith angles between 0 and 90 degrees merge for neutrino energies greater than 700 GeV, provided that the intrinsic atmospheric tau neutrino flux is calculated with perturbative QCD. Should one adopt a non-perturbative model for the intrinsic tau neutrino flux, the resulting tau neutrino fluxes on Earth at different zenith angles would merge at energies lower than 700 GeV. We have observed that the upward atmospheric tau neutrino fluxes show oscillatory behaviors. For the averaged flux with $-1<\cos(\text{zenith angle})< -0.4$, the atmospheric tau neutrino flux is found to be comparable to the atmospheric muon neutrino flux for $E_\nu< 40$ GeV. The comparison of this flux with the horizontal atmospheric tau neutrino flux is also interesting. Two fluxes are in fact comparable for $E_\nu< 10$ GeV. This shows that the $\nu_\mu \rightarrow \nu_\tau$ oscillation is already quite significant in the horizontal direction for such an energy range. Nevertheless, the upward atmospheric ν_τ flux takes over from $E_\nu > 10$ GeV until $E_\nu \cong 3$ TeV where two fluxes merge again. This part of works are published in [14,15].

In the third project, we have first analyzed the correlation of $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\nu_\mu \rightarrow \nu_e)$, which allows to determine the mixing angles θ_{13} and θ_{23} simultaneously. We take a baseline length of the order 10000 km for illustration. The signatures of matter effects are identified. The earlier version of this work appeared in [16]. We are currently revising this work, emphasizing the measurement of $P(\nu_\mu \rightarrow \nu_\mu)$ alone. With the measurement extending to a wide energy range, the above probability can be both sensitive to both θ_{13} and θ_{23}.

Finally, in the FLASH thin target experiment, we have observed fluorescence directly from the 28.5 GeV electron beam colliding into a thin air chamber. With the SLAC beam intensity, we observed approximately 10^2 to 10^4 photoelectrons per pulse. We studied the total fluorescence yield Y and the differential spectrum $dY/d\lambda$. To achieve for spectral resolution, narrow band optical filters are used. The team from Taiwan, including NTU and NCTU, has contributed to this experiment by making a beam-spot monitor, which is based upon the principle of optical transition radiation. Such a monitor was proven very useful to reduce some backgrounds in this experiment. The thin target paper is under preparation, with some calibrations to be completed.

The thick target run aims at clarifying the following issues: (1) is the fluorescence yield produced by a shower directly proportional to the energy deposition of the charged particles in the air, (dE/dx)? (2) What are the contributions of low-energy (below ~1 MeV) shower particles, to the fluorescence light yield? (3) Can existing shower models (e.g. EGS, GEANT, CORSIKA) therefore reliably predict the fluorescence yield in air?

The thick target paper has been submitted [17] for publication. The main result in this paper can be illustrated with the following plot:



The closed circle and open square stand for the electron number and photon number (*1/5) respectively. The red curve is the fitting for the energy deposition. The energy deposition is seen to be roughly proportional to the charged particle distributions. This is a simulation result. However, in [17], it is demonstrated that such a proportional relation indeed holds where the energy deposition is given by the measurement of fluorescence yields while the charged particle distribution is determined by the ion chamber measurement.

四、計畫成果自評

Our work on Earth-skimming tau neutrinos and tau leptons has been well received. Besides being cited 17 times so far, it is very useful for experimentalists to estimate their Earth-skimming event rates. This work was presented in ISMD 04 held in Sonoma University in July 2004 (see the conference report). Our work on the tau neutrino astronomy in GeV to TeV energy range will be very important once the neutrino flavor identification in this range becomes effective. We have done a very careful work on calculating the atmospheric tau neutrino flux for all possible zenith angles. This result provides a good estimation on the background to the search of astrophysical tau neutrinos. Furthermore, the measurement of atmospheric tau neutrino flux is by itself very interesting and rewarding as well.

The work on the very long baseline neutrino oscillations begins with a very nice observation. Namely $P(\nu_\mu \rightarrow \nu_\mu)$ could be sensitive to both θ_{13} and θ_{23}, as long as the measurement can be done in a wide enough energy range. The detailed analysis on this is yet to be carried out.

Finally, the measurement on the fluorescence yield has a very important implication on the cosmic ray energy determination. While we have not completed the thin target analysis, the thick target result is satisfactory, namely the fluorescence yield is shown to be proportional to the charged particle distributions. Furthermore, the lateral profile we have measured using the scintillator screen and CCD camera agrees with the existing shower simulation.

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