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Atmospheric neutrinos: Status and prospects

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Abstract

We present an overview of the current status of neutrino oscillation studies at atmospheric neutrino experiments. While the current data gives some tantalising hints regarding the neutrino mass hierarchy, octant of θ_{23} and δ_{CP}, the hints are not statistically significant. We summarise the sensitivity to these sub-dominant three-generation effects from the next-generation proposed atmospheric neutrino experiments. We next present the prospects of new physics searches such as non-standard interactions, sterile neutrinos and CPT violation studies at these experiments.

1. Introduction

In 1996, data from atmospheric neutrinos at the Super-Kamiokande (SK) experiment confirmed neutrino flavor oscillations beyond any doubt [1]. This established the existence of neutrino masses and mixing, and was hailed as the first unambiguous evidence of physics beyond the Standard Model (SM) of elementary particles. Finally, the year 2015 witnessed the awarding of Nobel Prize to Professor Takaaki Kajita for leading the SK collaboration to this remarkable discovery of flavor oscillation of atmospheric neutrinos. Professor Kajita shared the Nobel Prize

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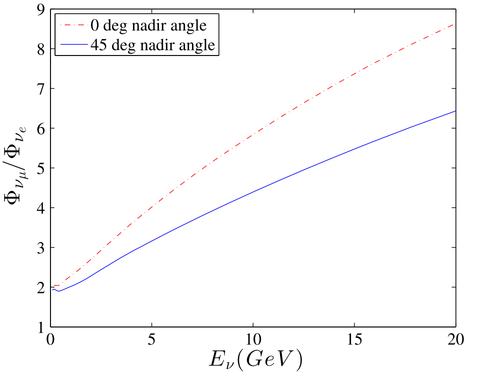

Fig. 1. Ratio of $\Phi_{\nu_\mu}/\Phi_{\nu_e}$ fluxes as a function of neutrino energy for two nadir angles of 0° and 45°.

with Professor Art McDonald of the Sudbury Neutrino Observatory, who was given the award for unambiguously establishing flavor oscillations of the solar neutrinos [2].

Atmospheric neutrinos are produced when cosmic ray particles collide with the nuclei in the earth's atmosphere, producing pions and kaons which subsequently decay into neutrinos.

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu),$$
$$\mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)\,.$$

We can see that these sets of decay channels would give the flux ratio of muon to electron neutrinos of about 2. The exact value of the atmospheric neutrino fluxes depend on a lot of issues and are calculated numerically for a given geographical location on earth [3]. We show in Fig. 1 this ratio as a function of neutrino energy for two neutrino trajectories. The red (broken) line is for nadir angle of 0° (zenith angle 180°) and blue (solid) line is for nadir angle of 45° (zenith angle 135°). We note that this ratio is larger for more vertically travelling neutrinos and increases with increasing energy. The reason for the former is that the depth of the atmosphere is less for vertical trajectories compared to horizontal trajectories, giving vertically travelling particles lesser time to decay. The reason for the increase of this ratio with energy is that the higher energy particles take longer to decay making the decay process complete and leading to fewer electron type neutrinos and antineutrinos.

Atmospheric neutrinos were originally of interest to the high energy physics community mainly because they constituted the most significant background to proton decay experiments. Indeed, the first observation of atmospheric neutrinos was reported in 1965 at the Kolar Gold Field experiment in India [4] and almost simultaneously by an experiment led by Fred Reines in South Africa [5], both of which were looking for proton decay. A discrepancy between the predicted atmospheric neutrino fluxes and that observed in detectors was reported first by the Kamiokande II [6] experiment which was set-up to look for proton decay. This anomaly was resolved in terms of flavor oscillations by the SK experiment which established the existence of neutrino masses and mixing.

There are proposals to build bigger and better detectors in the future, some of which would be detecting atmospheric neutrinos. Amongst the most promising next-generation atmospheric neutrinos detectors are the Hyper-Kamiokande (HK) [7], which will be a megaton-class water Cherenkov detector with fiducial volume roughly 20 times that of SK. The ICAL detector at the India-based Neutrino Observatory (INO) [8] is proposed to be a 50 kton magnetised iron