CHAPTER 1

Introduction

Neutrinos belong to the family of elementary particles. They do not have electric charge and they are the lightest known particles of matter. Their masses have never been directly measured yet, but from the experiments studying tritium beta decays it is known that electron neutrinos are a few orders of magnitude lighter than electrons [1]. Similarly to the situation with other elementary particles, gravitational interactions can be neglected. Therefore, neutrinos effectively interact with surrounding world only via the weak interactions. There are three known neutrino flavours: electron neutrino ν_e, muon neutrino ν_μ and tau neutrino ν_τ. The difference between them becomes apparent when they take part in the charged-current weak interactions: electron neutrinos are produced together with electrons, muon neutrinos together with muons and tau neutrinos together with taus.

Neutrinos can change their identity during propagation in space. Thus, for example electron neutrinos produced in the thermonuclear fusion reactions in the Sun can transform on their way to the Earth into ν_μ or ν_τ and possibly again into ν_e. This phenomenon is called neutrino oscillations. Discovery of neutrino oscillations at the turn of the 21st century [3–5] was one of the turning points in particle physics. This fact was acknowledged in the year 2015 when physicists Takaaki Kajita and Arthur B. McDonald were awarded the Nobel Prize in Physics for their leading role in "the discovery of neutrino oscillations, which shows that neutrinos have mass" [6]. Since the discovery, a number of experiments have studied neutrino interactions from natural and artificial sources. Disappearance of muon and electron neutrinos in accordance with the three-flavour neutrino oscillation theory was observed in various experiments. The reduced flux of $\nu_\mu/\overline{\nu}_\mu$ was measured in experiments studying atmospheric neutrinos [3, 7–10] and accelerator neutrinos [11–16]. Disappearance of $\overline{\nu}_e$ was observed with neutrinos from reactors [17–20] and disappearance of ν_e with neutrinos from the Sun [21–26]. Furthermore, the T2K (Tokai to Kamioka) experiment observed first appearance of electron neutrinos [27] and the OPERA experiment presented 5σ evidence [30] of appearance of tau neutrinos, both in the accelerator originated beam of muon neutrinos.

Production of tau neutrinos in the neutrino oscillations is one of the least known areas of neutrino physics because searching for this process is extremely difficult. The only way to discover interaction of ν_τ is by detecting a tau lepton produced in the charged-current interaction of ν_τ in a detector. Tau lepton, however, is an unstable particle with the very short lifetime: $t = (290.3 \pm 0.5) \times 10^{-15}$ s [1]. Therefore, in most detectors it is only possible to observe products of decay of the tau lepton – not the τ itself. Additionally, there are several different channels of τ decay. As decay channels are very different from each other, it is not feasible to formulate a single selection procedure for all channels.

Tau lepton is a heavy particle, with mass above 1.7 GeV. This leads to the high threshold energy about 3.5 GeV needed to produce τ particle in the simplest interaction of ν_τ. Consequently,

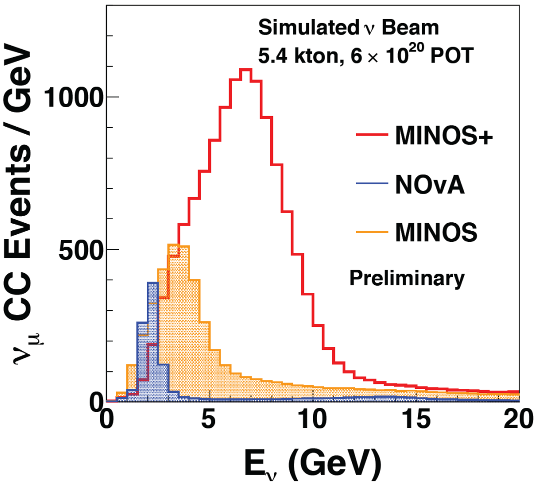

Figure 1.1. NuMI neutrino fluxes as seen by the on-axis experiments MINOS and MINOS+ and off-axis experiment NOvA.

high enough neutrino energies are required to observe this process. Such neutrinos can be found in the spectrum of neutrinos produced in the atmosphere of the Earth and can be produced in accelerators. Most of current accelerator neutrino experiments however, have beam energy too low to study τ appearance. The exception is the MINOS+ experiment with mean beam energy about 6.5 GeV (Fig. 1.1). It is located on the NuMI beam axis, while other accelerator experiments currently analysing data, T2K [31] and NOvA [32], are situated off the beam axis. Neutrino energy distributions in these off-axis experiments have maximum close to the oscillation maximum and most of the flux in the regions where cross section for charged-current interactions of ν_τ is very small (Figs. 1.1 and 1.2).

OPERA (Oscillation Project with Emulsion-tRacking Apparatus), the only experiment that presented evidence of appearance of ν_τ with a significance larger than 5σ, used the beam of mean energy about 17 GeV. This experiment was exposed to the CNGS neutrino beam from CERN to the Gran Sasso Laboratory in the years 2008–2012. The main goal of the OPERA experiment was to show the evidence of appearance of tau neutrinos produced due to the oscillations of accelerator muon neutrinos, on the long, 730 km way from the source to the detector. Thanks to the unique spacial resolution of nuclear emulsion it was possible to select tau lepton and its decay products.

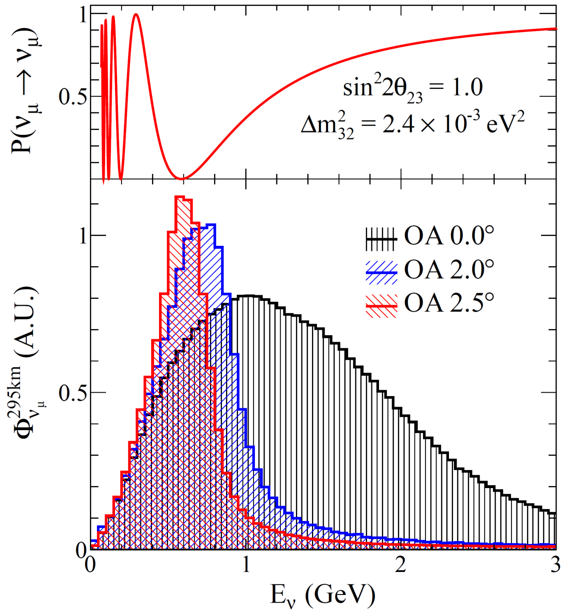

Figure 1.2. Bottom: Neutrino fluxes as produced by the Japan Proton Accelerator Research Complex (J-PARC) seen at different angles from the neutrino beam axis. T2K experiment is located 2.5° off the beam axis. Top: Muon neutrino survival probability at the T2K location ($L = 295$ km). Image from [34].

The OPERA collaboration found 5 events that are consistent with the hypothesis of three-flavour $\nu_\mu \to \nu_\tau$ oscillations [30]. The expected background in this model is (0.25 ± 0.05), while the expected signal is (2.64 ± 0.53).

The three-flavour model of neutrino mixing provides a very good description of most of the world's neutrino data, with a prominent exception of the result from the Liquid Scintillator Neutrino Detector (LSND) [33] experiment. LSND observed an excess of $\overline{\nu}_e$ events in the beam of $\overline{\nu}_\mu$ that could be explained by oscillations involving new type of neutrinos, called sterile. These non-standard neutrinos do not take part in the weak interactions as described by the Standard Model (SM) of fundamental particles and their interactions [129]. Therefore, experiments cannot search for interactions of sterile neutrinos; what they can do, is to search for the modifications of the oscillation model resulting from the sterile neutrinos mixing with known, active neutrinos. Sterile neutrinos can possibly interact through Yukawa couplings with the Higgs boson or take part in the interactions involving the physics beyond the SM.

In the SM active neutrinos are massless. However, the observed phenomenon of neutrino oscillations is the proof that neutrinos are massive particles. Therefore, the Standard Model has to be extended to introduce neutrino mass generation mechanism. The simplest extension is the introduction of the right-handed neutrino fields that would be sterile because in the SM only left-handed particles take part in the weak interactions. The Dirac[1] neutrino mass generation would be then similar to the generation of masses of charged fermions. As all fundamental fermions except neutrinos can be both left- and right-handed, the existence of right-handed neutrinos would restore the symmetry between quarks and leptons. It is also possible that neutrinos are Majorana[2] particles and the construction of corresponding mass term in the Lagrangian could involve a Higgs triplet state or two Higgs doublets.

Theoretically, there is neither bound on the number of sterile neutrinos nor on their mass scales. As a result, there are several possibilities considered: very light sterile neutrinos with masses smaller than 0.1 eV [38–40, 58], sterile neutrinos at the keV scale [46], heavy sterile neutrinos up to the electroweak scale and above [47, 48], and neutrinos at the eV scale. The possible neutrino oscillations involving three active states and one or more eV-scale sterile neutrinos is currently a hot topic in the physics of elementary particles [35, 36, 43, 44, 49] as they could explain the anomalies observed in short-baseline accelerator neutrino experiments LSND and MiniBooNE as well as in the gallium and reactor experiments. Various experiments search or plan to search for sterile neutrinos in various channels [55–76, 170–173] and set limits on oscillation parameters in models with sterile neutrinos. Some parameters of the models that include sterile neutrinos are already severely constrained. The weakest limits are set on the parameters θ_{34} and $\theta_{\mu\tau}$ related to the mixing of ν_τ with sterile states. Constraints of these parameters can be obtained from the study of data related to the neutral-current, mediated by Z boson, NC interactions or in the experiments searching for the anomalous ν_τ appearance. The MINOS+ experiment with high-statistics of data collected in the Near Detector and beam energy big enough to produce tau leptons is in the unique position to search for the appearance of ν_τ due to the presence of sterile neutrinos and to constrain $\theta_{\mu\tau}$.

Presence of one eV-scale neutrino with large value of θ_{34} can have important implications on physics potential of the future long-baseline experiments [169]. In Deep Underground Neutrino Experiment (DUNE) [174, 175] mixing angle θ_{34} (and associated phase δ_{34} violating symmetry CP)[3] can influence ν_e appearance and ν_μ disappearance via matter effects. If θ_{34} is large, close to its

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[1] Dirac neutrinos would acquire mass, similarly to charged leptons and quarks, by interacting with Higgs field. Dirac neutrino is a different particle from antineutrino.

[2] Majorana neutrino is its own antiparticle.

[3] CP symmetry is the combination of C (charge conjugation) symmetry and P (parity). C-symmetry transforms a particle into the corresponding antiparticle, while P-symmetry is the symmetry that inverts the space coordinates.

current upper limit, DUNE can probe CP-violation induced by δ_{34}. Moreover, with large θ_{34} the sensitivity of DUNE to determine mass ordering (hierarchy) can decrease from 5σ to 4σ.

In this monography it is reviewed what has been learned from the studies of standard and non-standard oscillations involving tau neutrinos. The analysis techniques developed to study ν_τ interactions and experimental results are presented with special emphasis on techniques developed by the author of monography for MINOS and MINOS+. The described MINOS and MINOS+ sterile neutrino analyses of charged-current (with W-boson exchange), CC ν_μ and neutral-current (with Z-boson exchange), NC interactions not only lead to the strong constraints of the LSND result, but also set constraints on θ_{34} parameter. The search for the anomalous appearance of ν_τ in the MINOS+ and future experiments can give access to the weakly known area of the mixing of ν_τ with sterile states via constraints on the angle $\theta_{\mu\tau}$ and thus provide unique information about sterile neutrinos.

The author of the monography has been working in neutrino physics field and has been the member of MINOS and MINOS+ collaborations since the year 2003; in the years 2003–2007 was affiliated to the University of Oxford and in the year 2008 introduced Faculty of Physics of the University of Warsaw to the MINOS collaboration. Since then, the author has been the representative of the University of Warsaw in the MINOS and later in the MINOS+ experiment. The author participated in the construction of the MINOS Near Detector in the year 2004 and for all years of MINOS and MINOS+ running was actively participating in the data taking. In the year 2013 created remote control room (Remote Operation Centre, ROC) in Warsaw and was periodically a shifter controlling the Near and Far detector data taking from Warsaw. The author formulated the idea to search for sterile-tau mixing in the MINOS+ Near Detector and is the leading person working on ν_τ physics in the MINOS+ experiment. The author developed analysis methods dedicated for the tau appearance search: the new, three-dimensional method of reconstruction of neutrino interactions in the MINOS (and MINOS+) Near and Far detectors and application of the Hough transform method to reconstruct very short tracks (both described in Section 4.4); selection of ν_τ interactions in the MINOS detectors, including the application of kNN multivariate method to this problem (Section 4.5) and has developed the procedure to find the sensitivity of an experiment and set the limits in the plane $(\sin^2 2\theta_{\mu\tau}, \Delta m^2_{41})$ (Section 5.6). Finally, the author discusses the prospects of future experiments for search of tau-sterile mixing.