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Neutrino Detectors of the Future: A comparison table

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1 Introduction

This report summarizes the relevant information about neutrino detectors being constructed or being planned for the future, including their physics potential and timescale over which they aim to achieve their physics goals.

The solar and atmospheric neutrino anomalies can be elegantly explained in terms of oscillations among the three active neutrino flavours. The neutrino oscillation hypothesis received further boost from the results of the long baseline experiments KamLAND, with reactor $\bar{\nu}_e$s as the source, and K2K, which used accelerator ν_μs as the source.

The three neutrino flavours ν_e, ν_μ and ν_τ mix to form three mass eigenstates ν_i with masses m_i $(i = 1, 2, 3)$. The mixing matrix, called the PMNS matrix, can be parametrised in terms of three mixing angles, $\theta_{12}, \theta_{13}, \theta_{23}$ and a CP violating phase $\delta_{\rm CP}$, as in the case of the CKM matrix of the quark sector. Neutrino oscillations depend only on *mass-squared differences* and hence it is not possible to measure the scale of neutrino masses in neutrino oscillation experiments. Tritium beta decay and neutrinoless double beta decay experiments can provide information on the neutrino mass scale. However the mass-squared differences $\Delta m^2_{32} = m^2_3 - m^2_2$ and $\Delta m^2_{21} = m^2_2 - m^2_1$, along with the mixing angles and the CP violating phase $\delta_{\rm CP}$, can be measured in long baseline neutrino oscillation experiments.

A physically well motivated form of PMNS matrix is [1]

$$U = U_{23}(\theta_{23}) U_{\rm CP}(\delta_{\rm CP}) U_{13}(\theta_{13}) U_{12}(\theta_{12}), \tag{1}$$

where

$$U_{23}(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \tag{2}$$

and

$$U_{\rm CP}(\delta_{\rm CP}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_{\rm CP}} & 0 \\ 0 & 0 & e^{-i\delta_{\rm CP}} \end{pmatrix}. \tag{3}$$

The matrices U_{13} and U_{12} can be written in analogy to U_{23}. The results of the CHOOZ experiment, in combination with the analysis of atmospheric neutrino anomaly, place a stringent bound [2, 3]

$$\sin^2 2\theta_{13} \leq 0.2. \tag{4}$$

In the limit of small θ_{13}, it can be shown that

$$\Delta m^2_{32} \simeq \Delta_{\rm atm} \quad \text{and} \quad \theta_{23} \simeq \theta_{\rm atm} \tag{5}$$

$$\Delta m^2_{21} \simeq \Delta_{\rm sol} \quad \text{and} \quad \theta_{12} \simeq \theta_{\rm sol}, \tag{6}$$

where $\Delta_{\rm atm}$ and $\theta_{\rm atm}$ are the mass-squared difference and mixing angle needed to resolve the atmospheric neutrino anomaly, *under the assumption that only two flavours are involved in the oscillations*. $\Delta_{\rm sol}$ and $\theta_{\rm sol}$ are also defined in a similar manner.

Presently Δ_{21} has been measured to significant precision by the KamLAND experiment but the accuracy on θ_{12}, from both KamLAND and solar neutrino experiments, is limited [4]

$$\Delta m_{21}^2 = (8.3 \pm 0.5) \times 10^{-5}\ \text{eV}^2,\ 27^\circ \leq \theta_{12} \leq 41^\circ. \tag{7}$$

Furthur improvement in our knowledge of θ_{12} will require precision solar neutrino experiments. Analysis of atmospheric neutrino anomaly gives the bounds [5]

$$\Delta m_{32}^2 = (1.5 - 3.4) \times 10^{-3}\ \text{eV}^2,\ 36^\circ \leq \theta_{12} \leq 54^\circ. \tag{8}$$

The goals of long baseline experiments are

1. Verifying the oscillation hypothesis directly by observing the energy dependence of the neutrino survival probability,
2. Improving the precision of Δm_{32}^2 and θ_{23} and
3. Obtaining, if possible, proof for non-zero values of θ_{13} and δ_{CP}. If not, then seek to improve the bounds on them.

2 Sources

Below we give brief descriptions of the types of neutrino sources already available and/or being considered.

1. *Atmospheric*: Atmospheric neutrinos consist of $\nu_\mu, \bar{\nu}_\mu, \nu_e$ and $\bar{\nu}_e$ with fairly well understood fluxes. These neutrinos are produced in the decays of muon, pions and kaons produced in the interactions of cosmic rays with atmospheric nuclei. We expect the total number of muon-type neutrinos to be twice as large as the total number of electron-type neutrinos. The energies of these neutrinos can range from 100 MeV to 100 GeV, though the flux falls steeply as $E^{-2.7}$ for energies above 1 GeV.
2. *Conventional Beams*: Conventional beams are essentially beams of ν_μ with small (less than 1 %) contamination of other flavours. The ν_e contamination of the beam limits the experiment's ability to observe ν_e appearance and hence to measure θ_{13}. To produce conventional neutrino beams, a beam of high energy protons is directed to a target, the resulting positively charged pions are collected, focussed and allowed to decay in a long decay pipe. After this decay, a reasonably collimated muon neutrino beam is obtained. A muon anti-neutrino beam can be obtained by collecting negatively charged mesons rather than positively charged mesons. Fluxes of neutrino beams are parametrized in terms of number of protons on target (POT) per year. Conventional beams have POT of about 10^{20} per year.
3. *Superbeam*: Superbeams are technology upgraded versions of conventional beams. Neutrinos in superbeams are generated by the using the "off-axis technology" to produce a narrow band beam, *i.e.*, the energy spectrum has a sharp peak. However, the proton fluxes are expected to higher by a factor of 10 to 50. The source power for superbeams is $\simeq 10^{21}$ POT per year.

4. *Neutrino Factories*: These are based on muon storage rings where it will be possible to capture roughly 10^{20} muons (of either sign) per year. A muon storage ring has a racing track design with long, parallel, straight sections connected at the end by semi-circular sections. Beams of high energy accelerated muons (E $\sim$ 20 to 50 GeV) circulate in the storage ring and can be made to decay in the straight sections. These decays produce a well collimated and intense neutrino beam. The composition and spectra of intense neutrino beams will be determined by the charge, momentum and polarization of the stored muons. The beam consists of ν_μ and $\bar{\nu}_e$ if the ring contains μ^-, and it consists of $\bar{\nu}_\mu$ and ν_e if the ring contains μ^+.

3 Detector types

Below we give a brief description of the types of detectors and their main properties.

1. *Water Cerenkov Detector*: Highly purified water is used as the detecting element. High energy charged particles passing through the water produce Cerenkov light which is detected by Photo Multiplier Tubes (PMTs) surrounding the water. Based on the patter of Cerenkov light emission, these detectors can identify both electrons/positrons and muons/antimuons. Energy reconstruction of very high energy ($E_\nu \geq 5$ GeV) is difficult because of a large number of particles in the hadron shower produced in the deep inelastic scattering, many of which will be below their Cerenkov threshold. There is no magnetic field with these detectors and hence the charge of a particle can not be identified.

2. *Liquid Argon Detector*: Liquid Argon is used as the detecting medium. The tracks produced by charged particles are identified in the liquid and based on the pattern of tracks the particle is identified. The detector has good calorimetry along with excellent particle identification capability. There is no magnetic field hence it is not possible to distinguish between particles and corresponding anti-particles.

3. *Iron Calorimeter*: Iron Calorimeters consist of iron (steel) modules interspersed with sensitive elements in which charged particles deposit energy. These detectors can not be used to detect electron-type neutrinos and hence are capable of observing only ν_μ and $\bar{\nu}_\mu$. A magnetic field, however, can be added, in which case distinction between the produced μ^- and μ^+ is possible.

4. *Emulsion Detector*: In this detector emulsion films (50 μm thick) are employed to observe the trajectories of τ and its decay products. These films are interleavened with 1 mm thick lead plates to provide a large (1.8 ktons) target mass. In addition to the emulsion films, the detector also contains a magnetic spectrometer which measures the charge and the momentum of muons going through it.

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General features of future detectors

Expt.	Detector (mass)	Source	L (Km)	$< E_\nu >$ (GeV)	Location
MINOS [6, 7]	Iron Calorimeter (5.4 Kt)	Atmospheric Conventional Beam	15-13000 735	1-100 3, $\sim$8, $\sim$11	Soudan, **US**
ICARUS [6, 8]	Liquid Argon TPC (2.35 Kt)	Conventional Beam	732	17	LNGS, **Europe**
OPERA [6, 9]	Emulsion Cloud Chamber (1.65 Kt)	Conventional Beam	732	17	LNGS, **Europe**
T2K [10]	Water Cerenkov (50 Kt)	Superbeam (Off-axis)	295	0.76	Kamioka, **Japan**
NOνA [11]	Liquid Scintillator (50 Kt)	Superbeam (Off-axis)	812	2.22	**US**
D-CHOOZ [12]	Liquid Scintillator (11.3 t)	Reactor	1.05	0.004	France
SK-III [13]	Water Cerenkov (50 Kt)	Atmospheric Superbeam	15-13000 295	1-100 0.76	**Japan**
UNO [14]	Water Cerenkov (1 Mt)	Atmospheric Superbeam	15-13000 $\sim$2500	1-100 $\sim$0.5-7	**US**
Hyper-K [15]	Water Cerenkov (1 Mt)	Atmospheric Superbeam	15-13000 295	1-100 4.0	**Japan**
INO [16, 17]	Iron Calorimeter (50 - 100 Kt)	Atmospheric Superbeam/NF	15-13000 TBD	1-100 TBD	**India**

TBD $\rightarrow$ To be decided.

Table 1: *Detector type, neutrino source, baseline (L), average energy ($< E_\nu >$) and location of the future experiments planned in next 10-15 years.*

Physics Potential and Timescale of future detectors

Expt.	Channel	Physics Potential	Data taking/ Partial results*
MINOS [6, 7]	$\nu_\mu \to \nu_{\mu,e}$	**Atm:** Compare ν_μ and $\bar{\nu}_\mu$ osc. : CPT test **Beam:** $\lvert\Delta m^2_{32}\rvert \sim 12\%$, $\sin^2\theta_{23} \sim 38\%$ precision** Improve $\sin^2 2\theta_{13} \sim$ factor of 2 over CHOOZ	Started/2007 2005/2007 2005/2007
ICARUS [6, 8]	$\nu_\mu \to \nu_{e,\mu,\tau}$	**Beam:** τ, e appearance, proton decay $\lvert\Delta m^2_{32}\rvert$, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ precision as in MINOS **Possible Atmospheric ν, Supernova ν**	2005/2009 2005/2009 2005/?
OPERA [6, 9]	$\nu_\mu \to \nu_{e,\mu,\tau}$	**Beam:** τ, e appearance, proton decay $\lvert\Delta m^2_{32}\rvert$, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ precision as in MINOS	2006/2010 2006/2010
T2K [10]	$\nu_\mu \to \nu_{e,\mu}$	**Beam:** e appearance $\lvert\Delta m^2_{32}\rvert \sim 6\%$, $\sin^2\theta_{23} \sim 22\%$ precision** Improve $\sin^2 2\theta_{13} \sim$ factor of 6 over CHOOZ CP Violation, Proton decay (phase II)	2009/2014 2009/2014 2009/2014 2017/2018
NOνA [11]	$\nu_\mu \to \nu_{e,\mu}$	**Beam:** e appearance Improve $\sin^2 2\theta_{13} \sim$ factor of 6 over CHOOZ Sign Δm^2_{32}, CP Violation $\nu_\mu \to \nu_\mu$ disappearance : CPT test, θ_{23} Search for sterile ν	2011/2012 2011/2012 2011/2017 2011/2012 2011/2012
D-CHOOZ [12]	$\bar{\nu}_e \to \bar{\nu}_e$	**Beam:** $\sin^2 2\theta_{13} < 0.03$, at 90% CL Improve $\sin^2 2\theta_{13} \sim$ factor of 4 over CHOOZ	2007/2010 2007/2010
SK-III [13]	$\nu_\mu \to \nu_{e,\mu}$	**Atm:** $\lvert\Delta m^2_{32}\rvert \sim 10\%$, $\sin^2\theta_{23} \sim 20\%$ precision** Improve $\sin^2 2\theta_{13} \sim$ factor of 2.3 over CHOOZ**	2006/2016 2006/2016
UNO [14]	$\nu_\mu \to \nu_{e,\mu,\tau}$	**Atm:** Possible τ appearance, L/E dip **Beam:** Sign Δm^2_{32}, $\sin^2\theta_{13}$ to below 0.005 $\nu_\mu \to \nu_e$ appearance : $\Delta m^2_{21}, \theta_{12}$ **Proton decay, Supernova ν**	2017/2018 2017/2018 2017/2018 2017/?
Hyper-K [15]	$\nu_\mu \to \nu_{e,\mu,\tau}$	**Atm:** Possible τ appearance, L/E dip **Beam:** $\sin^2\theta_{13}$ sensitivity below 10^{-3} Sign Δm^2_{32}, δ_{CP} **Proton decay, Supernova ν**	2017/2018 2017/2018 2017/2018 2017/?
INO [16, 17]	$\nu_\mu \to \nu_\mu$	**Atm:** L/E dip, CPT test Sign Δm^2_{32} $\lvert\Delta m^2_{32}\rvert$, $\sin^2\theta_{23}$ precision as in MINOS **Beam:** $\lvert\Delta m^2_{32}\rvert$, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ precision, δ_{CP}	2008/2011 (50 Kt) 2008/2015 (100 Kt) 2008/2012 (100 Kt) TBD/+1 Year

$*$ → **Estimated** $**$ → **Precision at 3σ (total spread around central value)**
TBD → To be decided.

Table 2: *Physics potential and timescale estimated for the various neutrino experiments planned in next 10-15 years.*