NEUTRINO PHYSICS AND REQUIREMENTS TO ACCELERATORS

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Abstract

Tremendous progresses have been seen on neutrino physics in the past twenty years. The discovery of the neutrino oscillation in 1998 leads to the firm establishment of a theoretical model with 6 free parameters. In 2012, the last unknown neutrino mixing angle, θ_{13}, is discovered to be non-zero. Together with other two known angles, θ_{12} and θ_{23}, the picture is completed. In this talk, I will review latest results of the neutrino oscillation, and describe future plans for remaining oscillation parameters: mass hierarchy and CP phase, together with ideas to search for sterile neutrinos. In particular, requirements to accelerators for the measurement of CP phase are discussed.

INTRODUCTION

Neutrinos, as three out of twelve the most elementary particles, play vital roles not only in the particle physics, but also in astrophysics and cosmology. Since they are extremely abundant, the evolution of the universe is strongly influence by their mass. Neutrinos can be emitted by galaxies, supernovae, the sun, the earth, and man-made sources such as nuclear reactors, accelerators, even the human body. They only interact weakly with matter, hence are very difficult to be detected and not well known.

Studies of the neutrino physics are mainly focused on three categories: 1) fundamental properties such as the mass and the magnetic moment; 2) oscillation properties and search for sterile neutrinos; 3) high energy neutrino astronomy. In this talk I will only discuss the category 2).

Oscillation is a fundamental property of neutrinos, since it is related to the neutrino mass and may generate leptonic CP violation to explain the matter-antimatter asymmetry of the universe. For two-flavor oscillation in vacuum, the oscillation probability is expressed as:

$$P(\nu_1 \to \nu_2) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E),$$

where $\sin^2 2\theta$ denotes the oscillation amplitude and $\Delta m^2 L/E$ represents the oscillation frequency. For 3 generations of neutrinos, the theoretical description becomes the following:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathbf{V}_{e1} & \mathbf{V}_{e2} & \mathbf{V}_{e3} \\ \mathbf{V}_{\mu 1} & \mathbf{V}_{\mu 2} & \mathbf{V}_{\mu 3} \\ \mathbf{V}_{\tau 1} & \mathbf{V}_{\tau 2} & \mathbf{V}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The mixing matrix V can be written as[1,2],

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathbf{c_{23}} & \mathbf{s_{23}} \\ 0 & -\mathbf{s_{23}} & \mathbf{c_{23}} \end{pmatrix} \begin{pmatrix} \mathbf{c_{13}} & 0 & \mathbf{s_{13}} \\ 0 & \mathbf{e^{-i\delta}} & 0 \\ -\mathbf{s_{13}} & 0 & \mathbf{c_{13}} \end{pmatrix} \begin{pmatrix} \mathbf{c_{12}} & \mathbf{s_{12}} & 0 \\ -\mathbf{s_{12}} & \mathbf{c_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$, (i,j=1,2,3).

There are 6 independent parameters in this matrix. Among them, θ_{12}, ΔM^2_{12}, θ_{23}, $|\Delta M^2_{23}|$ are known for more than 10 years, θ_{13} is known since last year, while the sign of ΔM^2_{23} (also called mass hierarchy) and the CP phase δ are to be determined.

KNOWN PARAMETERS

There have been quite some progresses on the precision of the known parameters very recently, while a major step is the discovery of non-zero θ_{13} in 2012.

Solar Neutrinos: θ_{12} and ΔM^2_{12}

The first evidence of neutrino oscillation appeared in 60's-80's when R. Davis found the solar neutrino deficit with respect to the solar model[1]. The issue was finally settled in 2001 when SNO found that the disappeared solar ν_e actually become ν_μ and ν_τ[3]. KamLAND in 2002 confirm the solar neutrino oscillation and measured θ_{12} & ΔM^2_{12} unambiguously by using reactor neutrinos[4]. Over the last 10 years there had been a lot of improvements on the precision of θ_{12} & ΔM^2_{12}. The latest one is from KamLAND this year[5] by using the information during the reactor-off period after the earth quake and the nuclear accident in Fukushima. The combined fit together with other solar experiments is shown in Figure 1 and best values are:

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$
$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

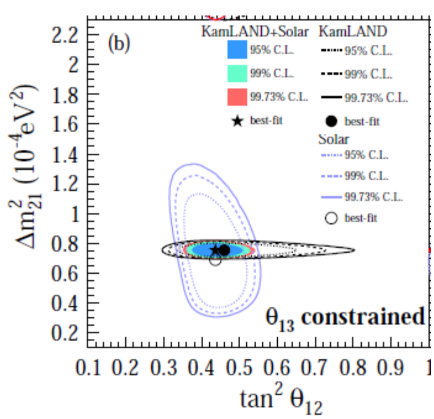

Figure 1: The latest measurement of θ_{12} & ΔM^2_{12} by the KamLAND Experiment[5].

Currently major issues related to the solar neutrinos are solar-itself related, and a future experiment which can significantly improve the precision of θ_{12} & ΔM^2_{12} is called "Daya Bay II", which will be discussed later.

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Atmospheric Neutrinos: θ_{23} and ΔM^2_{23}

The first evidence of the atmospheric neutrino oscillation was observed in 80's by Kamiokande and IMB[1]. In 1998, Superkamiokande observed atmospheric ν_μ disappearance as a function of L/E[6], strongly suggests that neutrinos do oscillate. Such a major discovery was confirm by accelerator experiments including K2K, Minos and T2K, and later by the ν_τ appearance experiment OPERA[1]. Minos reported this year the latest result which combined results from all the experiments as shown in Figure 2[7]. The best values are

$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$
$$|\Delta m^2| = (2.41^{+0.09}_{-0.10}) \times 10^{-3}\,\mathrm{eV}^2$$

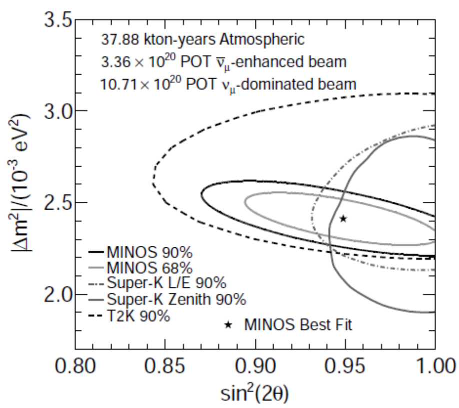

Figure 2: Latest results from the Minos experiment: a better determination of θ_{23} & $|\Delta M^2_{23}|$[7].

Please note that only the absolute value of $|\Delta M^2_{23}|$ is measured, its unknown sign(also called mass hierarchy) is a major target of future experiments. Another issue is whether θ_{23} is maximized, namely whether $\theta_{23}= 45^o$. It can be addressed by future accelerator-based experiments, such as Nova and HyperK, which can improve the precision of θ_{23} & $|\Delta M^2_{23}|$ significantly, hopefully at a level close to 1%.

Reactor Neutrinos: θ_{13} and ΔM^2_{13}

Here, ΔM^2_{13} is not an independent parameter, rather $\Delta M^2_{13}=\Delta M^2_{32}+\Delta M^2_{21}$. In the case of the normal hierarchy, $|\Delta M^2_{13}|=|\Delta M^2_{32}|+|\Delta M^2_{21}|$ while for the inverted hierarchy, $|\Delta M^2_{13}|=|\Delta M^2_{32}|-|\Delta M^2_{21}|$.

The major progress since the establishment of the neutrino oscillation in 1998 is the discovery of a non-zero θ_{13} in 2012. In fact, hints of non-zero θ_{13} appeared in 2011 when T2K reported the appearance of 6 events over an estimated background of 1.6 events, corresponding to a statistical significance of 2.5σ[8]. Soon after, the Minos and Double Chooz experiment both reported results with a statistical significance of 1.7 σ[9, 10].

The Daya Bay experiment is designed to search for non-zero θ_{13} with a sensitivity to $\sin^2 2\theta_{13}$ up to 0.01 at 90% Confidence Level(CL). The experiment is arranged as shown in Figure 3, where two near detectors are for the reactor monitoring while one far detector is for the deficit measurement[11].

Figure 3: the Daya Bay experiment layout.

In each hall, two(near site) or four(far site) neutrino detector modules are submerged in the water pool for shielding backgrounds, with RPC gaseous detector at the top to track cosmic-muons.

After 55 days of data taking, a deficit of neutrino events at the far site is clearly seen, as shown in Figure 4[12]. A detailed oscillation analysis results a determination of the oscillation amplitude:

$$\mathrm{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst}).$$

The statistical significance is 5.2σ, corresponding to a probability of 10^{-7} for θ_{13} being zero.

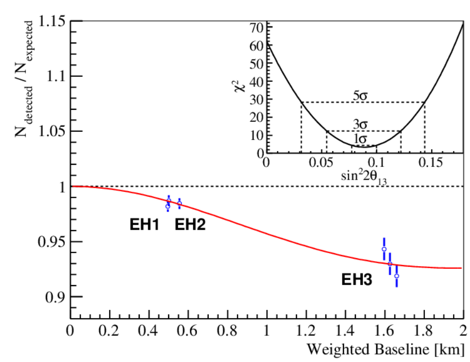

Figure 4: The neutrino deficit at the far site(EH3) seen by the Daya Bay experiment[12].

Soon after, RENO[13], Double Chooz[14] and T2K[15] confirmed this result by their measurements with a statistical significance of 4.9σ, 3.1σ and 3.1σ, respectively.

These experiments will continue to take data and improve the precision. In fact, the Daya Bay experiment already reached the statistical significance of 7.7σ [16], and in 3-5 years from now, $\mathrm{Sin}^2 2\theta_{13}$ will be determined to a precision of about 4%. At this moment, there are now proposals planning to improve further this precision.

SEARCH FOR UNKNOWNS

The future unknowns are mainly the neutrino mass hierarchy, the CP phase and whether there exist sterile neutrinos. They can be studied mainly by reactor, atmospheric and accelerator neutrinos.

Mass Hierarchy by Reactor Neutrinos

Reactor neutrinos can be used to determine the mass hierarchy[17]. The Daya Bay II experiment plans to use two reactor complexes in the south of China with a total thermal power of 36 GW[18]. The baseline is about 55 km, right at the oscillation maximum of θ_{12}, as shown in Figure 5. The detector is a 20 kt liquid scintillator with a light yield better than 1200 PE/MeV, technically very challenging. With 6 years of data taking, this experiment can determine the mass hierarchy at 4σ level, independent of the CP phase.

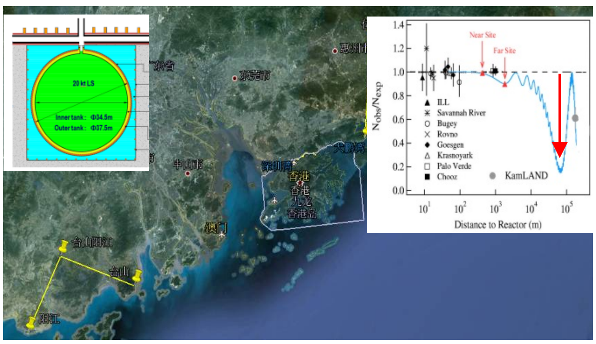

Figure 5: The experimental plan using reactor neutrinos for the mass hierarchy.

This experiment can also measure precisely the mixing parameters of θ_{12}, ΔM^2_{12} and ΔM^2_{23} to be better than 1%, a precision hard to be overtaken.

Mass Hierarchy & CP Phase by Accelerators

Atmospheric neutrino experiments, such as PINGU, INO[19] and HyperK[19,20], can also measure the neutrino mass hierarchy, with a sensitivity strongly depending on the CP phase. HyperK is a huge water Cerenkov detector with a total mass of 1 Mt. Figure 6 shows its sensitivity to mass hierarchy and CP phase, respectively.

HyperK(& T2HK) is also a target of the accelerator neutrino beam from J-PARC. The sensitivity from the neutrino beam is far better than that of atmospheric neutrinos, as seen in Figure 6.

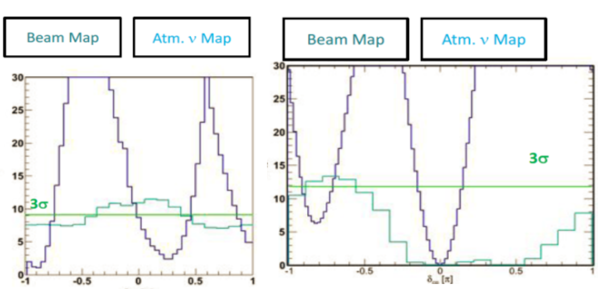

Figure 6: Sensitivity of HyperK to the mass hierarchy and CP phase, using atmospheric neutrinos and accelerator neutrino beams[20].

In fact, there are several experimental proposals to use neutrino beams generated by pion decays which are produced by protons bombarding a target, as listed in Table 1.

Table 1: Future accelerator neutrino experiments[20-23]

Exp.s	Beam power (MW)	Base -line (km)	Detector	Start time
Nova	0.7	810	14 kt Fe Calor.	2015
HyperK	0.75	295	560 kt water	2022
LBNE	0.7→2.3	1300	10kt→35Kt LAr TPC	2022
LBNO	0.75→2.0	2300	20 kt LAr TPC +35 kt Fe Calor.	?

Their sensitivities to the mass hierarchy are generally better than that of HyperK, thanks to their longer baselines, while for the CP phase, HyperK is the best due to its massive detector.

Long baseline neutrino experiments usually require a very powerful proton accelerator and a sophisticated target to be able to handle the enormous heat generated by the proton beam. The longer the baseline, the higher the power needed, as shown in Table 1. Many labs have a long range plan to increase the beam power gradually, and a phased R&D program.

As an example, CERN plans to have following neutrino beams: 1) use the 400 GeV proton beam extracted from SPS towards Finland with a power of 0.75 MW; 2) build a new proton beam towards Fréjus with a power of ~2MW.

A proposal to use the beam as the phase 0, before the far detector in Finland being built, is to move partially the ICARUS and OPERA detector at Gran Sasso for a very short baseline neutrino experiment, NESSIE+ICARUS, to search for sterile neutrinos[24].

Search for Sterile Neutrinos

Sterile neutrinos may exist and oscillate with their active partners, ν_e & ν_μ & ν_τ. Theoretically there are many good reasons to have them in various extensions of the Standard Model. There are also several experimental "hints" to support the idea. On the other hand, attempts to accommodate all the "hints" by a global fit seem not successful[25]. New results on the cosmological bounds from PLANC also do not support the existence of KeV neutrinos in the universe, although there are always ways out if needed. The only solution is experimental tests.

There are now tens of proposals to search for sterile neutrinos. They fall into three categories: 1) put a strong radioactive source in or near an existing liquid scintillator detector, such as KamLAND and Borexino; 2) put a detector right next (~ a few meters) to a reactor; 3) put a detector close to the accelerator beam target (~ hundreds of meters).

Experimentalists are actually trying to use this opportunity to develop technologies for the future long baseline experiments. One example is NESSIE+ICARUS at CERN using the beam from SPS, as we mentioned before[24]. NESSIE is a magnetized Iron calorimeter while ICARUS is a LAr TPC. There are two detectors, one at 300 m, and the other one at 1600m.

Another example is IsoDAR and DAEdALUS based on pion-decay-at-rest[26]. Using several superconducting Cyclotrons with a power of ~MW at ~3 locations, muon neutrinos at different baselines can be produced and the oscillation with a L/E dependence can measure the CP phase δ. As the first phase, IsoDAR uses the injector is to generate 60 MeV protons with a power of 0.6 MW towards a ^{9}Be target in the detector volume (D2O). The produced neutrons can then interact with ^{7}Li foil in the detector to generate ^{8}Li which will then decay to produce electron anti-neutrinos.

Another idea, often called nuSTORM, is to construct a 3.8 GeV muon storage ring for sterile neutrinos[27], as shown in Figure 7. This project is the initial phase towards a neutrino factory.

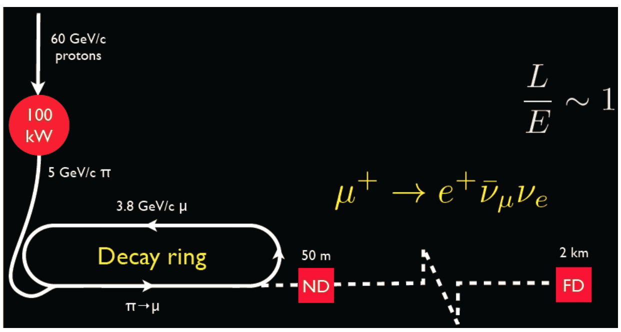

Figure 7: The idea of nuSTORM[27].

ULTIMATE MACHINES

Neutrino Factory

Indeed, the ultimate machine for everything is the Neutrino Factory, which can measure all the unknown parameters, θ_{13}, mass hierarchy and CP phase. The major advantage of this machine is that it provides neutrinos from muon decays, rather than from π decays as in the case of all the nowadays super-beams. Muon beam is basically free from beam-related backgrounds, hence more suitable for systematic limited case. A typical Neutrino Factory has a muon beam energy of 10 GeV, a beam power of 4 MW, and a neutrino yield of about 10^{21}ν/year[28]. Figure 8 shows the layout of the low energy Neutrino Factory.

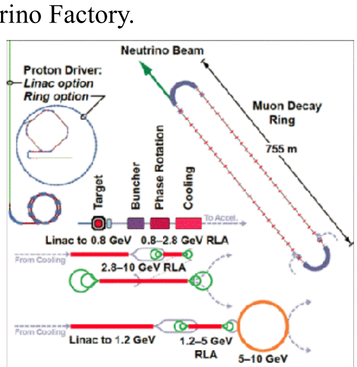

Figure 8: The layout of a Neutrino Factory[28].

There is already a global effort for the R&D of the related technology. Besides the proton driver which is already in the scope of all the super-beam attempts, the target is studied now by MERIT, muon cooling by MICE, and muon acceleration by EMMA[28]. Hopefully all the major issues can be resolved if we work hard together.

What do We Really Need?

Although Neutrino Factory is the dream machine for θ_{13}, mass hierarchy and CP, it is very expensive because of the requirements of high energy, high power and long baseline. We did not discuss the beta-beam option, which is actually similar in this sense.

Since θ_{13} is known, and mass hierarchy will likely be determined by DYBII, HyperK, LBNE or LBNO, we only need a machine for CP phase, if HyperK, LBNE or LBNO cannot find it.

Previous study shows that the sensitivity to the CP phase is not strongly dependent on the baseline, nor the neutrino energy[29]. Low energy neutrino beams are good enough, with a major advantage: cheaper.

But how low we should aim for ? By looking at cross sections of neutrinos interacting with matter, ~300 MeV is a good choice since it is just below all the in-elastic processes[30]. The best baseline is then 150 km, to be at the oscillation maximum. In this case, there will be no π^0 produced in all the charge and neutral current processes, hence no more this background. Although we lose statistics due to the lower cross section, we gain on systematic uncertainties which are the main concern when statistics is less a problem giving a large θ_{13}.

There are efforts in Europe to use low energy neutrino beams from pion decays. One is the CERN high power SPL, which plans to build a 4.5 GeV proton driver with a 4 MW beam power. The huge water Cerenkov detector, MEMPHYS, is expected to be at Fréjus with a baseline of 130 km[31].

Another one is the European Neutron Spallation Source at Lund[32]. The proton beam is 2.5 GeV with a 5 MW beam power. The detector site is not selected yet, and the baseline may vary from 260 km to 1140 km.

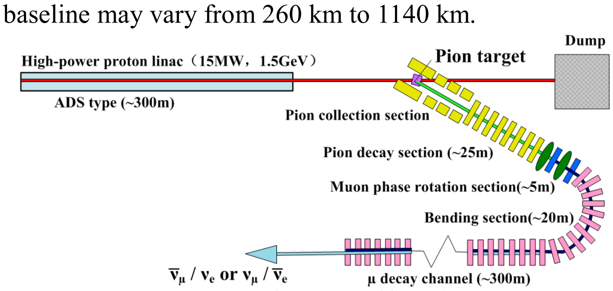

Figure 9: The layout of the neutrino beam from muon decays.

The effort at IHEP is trying to utilize results from the on-going R&D for ADS[33]. The idea to produce neutrinos from such a powerful proton driver is shown in Figure 9[34]. Over several phases, the proton driver, based on a superconducting LINAC in CW mode, will

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reach a beam energy of 1.5 GeV and a beam current of 10 mA, corresponding to a power of 15 MW. Pions from protons on target will be collected by a super-conducting magnet and then decay, to produce muons. These muons will be bended and then decay in the beam pipe, producing muon and electron neutrinos.

A detailed Monte Carlo simulation was developed to follow all the processes, and to determine collection efficiencies for muons. A preliminary study shows that the neutrino yield from muon decays is about $10^{21}\nu$/year, similar to the Neutrino Factory as we mentioned before. The energy spectrum of neutrinos from the muon decay pipe is shown in Figure 10. Neutrinos are mostly in the range of 200-300 MeV, as we hoped for.

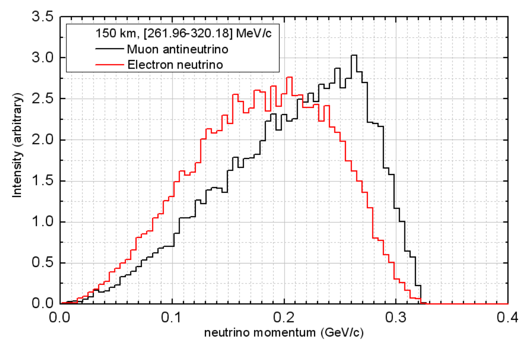

Figure 10: The energy spectrum of neutrinos from the muon decay pipe.

The detector has to be flavour sensitive, charge sensitive and can distinguish neutral current from charge current events. Its location is unknown yet, but the idea is to use the DYBII detector. Other than liquid scintillator, water doped with Gd is a good choice since the inverse β decay process is charge sensitive.

Of course, there are many technological challenges ahead of us, in particular, the target and the magnet. Once the concept is complete, R&D efforts may start.

SUMMARY

Neutrinos are very important in particle physics and in our Universe. Tremendous progresses have been seen in the past, and future prospects are really bright. Although we are facing a lot of technological challenges, particularly on accelerators, targets and magnets, we are confident that the neutrino CP phase δ will be discovered.

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