LONG-BASELINE NEUTRINO EXPERIMENTS*

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(Received October 24, 2007)

We briefly review experiments using accelerator neutrinos and large detectors hundreds of kilometers away. Several projects based on powerful conventional beams of neutrinos are prepared for the next decade. We describe two most promising of them, which are T2K in Japan and NOνA in North America.

PACS numbers: 14.60.Pq, 14.60.Lm, 95.30.Cq, 95.55.Vj

1. Introduction

The neutrino oscillation, implying neutrino masses, was first discovered through a direction dependent deficit of muon atmospheric neutrinos in the Super-Kamiokande detector (SK) [1]. The neutrino mixing $\nu_\mu \leftrightarrow \nu_\tau$ explaining the atmospheric observations was later confirmed by two long-baseline accelerator experiments. First the K2K Collaboration observed ν_μ disappearance using the neutrino beam from KEK and SK detector 250 km away [2]. Recently MINOS Collaboration published its first results [3] obtained using NuMI beam at Fermilab and Soudan detector 730 km away in Minnesota. They observed the ν_μ disappearance also consistent with the SK data.

The SK data also show some supporting evidence that muon neutrinos are transformed primarily into τ neutrinos [4]. Studies have however ruled-out any significant mixing with a hypothetical sterile neutrino [5, 6].

A deficit of solar neutrinos has puzzled physicists since the first results of the Homestake chlorine experiment (see the review in Ref. [7]). However, the final proof of the oscillation of electron neutrinos into a combination of muon

* Presented at the XXXI International Conference of Theoretical Physics, "Matter to the Deepest", Ustroń, Poland, September 5–11, 2007.

and tau neutrino states $\nu_e \leftrightarrow \nu_{\mu\tau}$ was provided by the SNO experiment [8]. Recently the Borexino Collaboration reported the first direct observation of the ^{7}Be neutrinos [9].

The oscillation parameters which provide the explanation for solar neutrino data could be probed by reactor antineutrinos in a detector at sufficiently large distance. The measurements by KamLAND Collaboration found the evidence for $\overline{\nu_e}$ disappearance with the parameters consistent with the solar results [10].

Finally, the Mini-Boone Collaboration [12] has recently published the results of the experiment which was designed to check the observation of neutrino oscillations claimed by the LSND Collaboration [11] in 2001. The oscillation parameters obtained by LSND had implied an existence of a fourth neutrino mass state. However the Mini-Boone results are incompatible with the LSND allowed region of parameters.

The exciting epoch of finding solutions to the neutrino puzzles has thus come to the end and now we have the firm evidence for neutrino oscillations with three mass states. Still several of the oscillation parameters are either not well measured or not known at all. The next goal is to complete our understanding of neutrino mixing, to determine the ordering of the neutrino mass spectrum and to search for CP violation among neutrinos.

In this brief review we will first present the data obtained in the K2K and MINOS long-baseline experiments which were designed to verify the oscillation parameters in the 'atmospheric Δm^2 dominance' region and then we will describe measurements which are planned for the next decade using accelerator neutrino beams.

2. Long-baseline experiments: K2K and MINOS

After the discovery of the atmospheric neutrino oscillations an independent check using a controlled accelerator beam became essential. An obvious option was to take advantage of the world's largest neutrino detector, SK, and the KEK accelerator at a distance of 250 km. This led to the K2K (KEK to Kamioka) experiment [2, 13] using the neutrinos of a mean energy of 1.3 GeV. On the basis of the data corresponding to 0.9×10^{20} protons on target (POT) the collaboration published evidence for ν_μ disappearance in Ref. [2]. In total 112 events of ν_μ interactions were observed in SK, while 158 ± 9 would be expected without oscillations. A distortion of the energy spectrum is also seen in 58 single-ring muon-like events with reconstructed energies. The probability that the observations are explained by the expectation for no neutrino oscillation is 0.0015% (4.3σ). The validity of the neutrino beam MC simulation and consequently the expected event rate was confirmed by hadron cross-section measurements in HARP experiment [14].

The results are best described by oscillation parameters coming from a two-flavor fit to the $\nu_\mu \leftrightarrow \nu_\tau$ transitions. They are given in Table I together with the atmospheric SK results. The K2K results provide thus the first evidence for oscillations in the "atmospheric Δm^2 dominance" region [15] obtained using the accelerator neutrino beam.

TABLE I

Oscillation parameters from two-flavor disappearance fits to the Super-Kamiokande (SK), K2K and MINOS data.

Experiment	Best fit Δm^2 $[\times 10^{-3}\ \mathrm{eV}^2]$	Best fit $\sin^2 2\theta_{23}$	Limits at 90% c.l. Δm^2 $[\times 10^{-3}\ \mathrm{eV}^2]$	Limits at 90% c.l. $\sin^2 2\theta_{23}$	Refs.
SK-I (ang. distr.)	2.1	1.00	1.5–3.4	> 0.92	[16]
SK-I (L/E analysis)	2.4	1.00	1.9–3.0	> 0.90	[1]
K2K	2.8	1.00	1.9–3.5	> 0.60	[2]
MINOS	$2.38^{+0.20}_{-0.16}$			> 0.84	[3]

In May 2005 the MINOS Collaboration started to accumulate the data using intense neutrino beam derived from 120 GeV protons extracted from the Fermilab Main Injector. The peak neutrino energy is around 3.5 GeV (in the 'LE' beam configuration). They use two magnetized-iron and scintillator detectors: a 0.98 kton near detector located around 1 km downstream of the target and a 5.4 kton far detector located in the Soudan Underground Laboratory 735 km away. Recently the Collaboration announced preliminary results after 2.5×10^{20} POT exposure [3]. They have found 563 charged-current ν_μ interaction candidates in the far detector, while 738 ± 30 events were expected in the absence of oscillations. The observation is consistent with oscillation parameters given in Table I. The result is then consistent with SK atmospheric and K2K accelerator neutrino results.

In summary, the current results of the "atmospheric Δm^2 dominance" experiments tell us that at least one of the neutrino masses is larger than 44 meV. The best estimates point to a maximal mixing angle $\theta_{23} = 45°$.

3. Measurement of θ_{13} mixing angle

A very important goal of the future experiments is the determination of the small parameter θ_{13}. A non-zero value for θ_{13} is necessary to probe both the CP violation phase δ as well as to resolve the ordering of neutrino mass states. In order to measure θ_{13} one should probe a small component of ν_e in one of the atmospheric doublet states. To this aim two types of experiments are performed: using reactor and accelerator beams.

With reactor $\overline{\nu_e}$ energies of a few MeV the optimal distance is around 1 km. As a consequence the matter effects are insignificant at that energy and neutrino path length. Also CP-violation terms vanish as required for a disappearance experiment. It then follows that reactor experiments offer the "cleanest" way of the θ_{13} determination.

A successor of CHOOZ will be the Double-CHOOZ experiment [20] planned to start in 2008 with two detectors, with a goal to reduce systematic errors down to 0.6% and to reach a sensitivity on $\sin^2 2\theta_{13} \simeq 0.024$ (90% c.l., $\Delta m^2 = 2.5\times10^{-3}$) in a 3 year run.

In an accelerator $\nu_\mu \to \nu_e$ experiment neutrino energy and a distance to a detector have to be optimized keeping L/E close to the first oscillation maxima. It follows that the optimal energies are around a few GeV's and neutrino travel distances of hundreds of kilometers.

On top of the ν_μ disappearance analysis a search for ν_e appearance has been performed by K2K Collaboration [17]. A single electron candidate has been found, consistent with background expectation coming mostly from neutral current π^0 production by ν_μ. This allows to exclude at 90% c.l. $\nu_\mu \leftrightarrow \nu_e$ appearance with parameters: $\sin^2 2\theta_{\mu e} > 0.13$ at $\Delta m^2 = 2.8 \times 10^{-3}\mathrm{eV}^2$, the best fit value of the K2K ν_μ disappearance analysis. The upper bound on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13} \sin^2 \theta_{23}$ can be translated into $\sin^2 2\theta_{13} > 0.26$ for $\sin^2 \theta_{23} = \frac{1}{2}$.

The most restrictive limits on θ_{13} have been obtained by the CHOOZ reactor experiment [18] which searched for $\overline{\nu_e}$ disappearnce . CHOOZ established an upper limit on the disappearance probabilities in function of Δm^2. Maltoni *et al.* [19] performed global fits to all existing data with the assumption of one mass scale dominance ($\delta m^2 = 0$) and obtained $\sin^2 \theta_{13} < 0.022$ at 90% c.l. for $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2.

4. Neutrino beams

Neutrinos in the next decade will come from conventional beams *i.e.* ν_μ's from meson decays produced by intense beams of protons. Beams with (proton) power above 0.5 MW are sometimes called Super Beams.

Important conditions for the experiments are: ν_μ beam of high intensity, a small contamination by ν_e and $\overline{\nu_\mu}$ and narrow band neutrino spectrum. Detectors should provide a good identification of ν_e interactions (*i.e.* secondary electrons) for efficient reduction of π^0 background.

Both K2K and MINOS detectors were positioned along the neutrino beam axis. Future experiments are, however, designed for off-axis beams. The advantage of the off-axis beam is a smaller spread of neutrino energies and smaller contamination with ν_e. With much reduced tail of higher energies the background coming from NC interactions is much smaller.

Using NuMi medium energy beam at an angle of 14 mrad the spectrum will peak around 2 GeV with a FWHM of 800 MeV [22] and will have little background from a contamination of ν_e from K decays.

The existing NuMI neutrino beam at Fermilab is produced by 120 GeV protons from the Main Injector (MI). It has reached 315 kW and has a designed power of 400 kW. Planning is in progress to increase the total power from the MI to 1.2 MW after the Tevatron program ends and to upgrade the NuMI beam. Further upgrades in beam power to 2 MW are under consideration [30].

In Japan a powerful ν_μ beam is currently being built in Tokai, at J-PARC (Japan Proton Accelerator Research Complex) laboratory [24]. The beam design aims at 0.75 MW power for 40 GeV protons. The ν_μ beam intensity is 100 times larger than that of K2K. At the peak energy the ν_e contamination is estimated at 0.4%. For the second phase an upgrade of linac and main ring is planned which would allow to achieve a power of 4 MW. With 2–3 degrees off axis the beam will cover both SK and a site chosen for Hyper-Kamiokande (see below).

There are also proponents of the wide-band beam approach with a detector located up to 2600 km from a source [30]. With neutrino energies up to several GeVs more than one oscillation maxima could be observed which would help in lifting degeneracies.

5. Future long-baseline experiments

Two experiments in advanced stages of preparation (or planning) are T2K (Tokai to Kamioka) and NOνA (see Table II).

TABLE II

Basic specifications of T2K and Nova experiments (1st phases).

	T2K	NOνA
Accelerator	J-PARC at Tokai	Main Injector at Fermilab
Beam status	being constructed	NuMI (upgraded)
Proton energy	40 GeV	120 GeV
Neutrino energy (peak)	0.76 GeV	2.22 GeV
Far detector	Super-Kamiokande	to be built
Total mass	50 kton	14 kton
Fiducial mass	25 kton	14 kton
Distance	295 km	812 km

T2K (Tokai to Kamioka) experiment will use J-PARC beam 2.5° off axis and the Super-Kamiokande detector 295 km away [23, 24]. To control the beam, muon monitors will be located 140 m downstream from the target. The first front detector will be at 280 m and later a second detector is planned along the off-axis beam, 2 km from the target. The data taking is planned to start in April 2009.

The T2K Collaboration will profit from the experience gained while running the K2K experiment. Also the SK detector feasibility, in particular for selection of ν_e interactions from the background, is well explored and understood.

The sensitivity to θ_{13} depends on a value of CP violating phase δ. Assuming $\delta = 0$ the sensitivity for $\sin^2 2\theta_{13} > 0.008$ is expected after an exposure to 5×10^{21} POTs. It is hoped that this exposure will be obtained in 5 years. For the worst case of $\delta = 90°$ the significant signal for $\sin^2 2\theta_{13} > 0.02$ may be expected. Also the precision $\delta(\sin^2 2\theta_{23}) \sim 0.01$ and $\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4}$ should be achieved.

Due to relatively short distance of 295 km T2K (phase I) will not be sensitive to mass state ordering. However, its potential in θ_{13} determination may be unique [21].

If non-zero θ_{13} is established during the phase I of the experiment it is planned to upgrade the proton beam the to 4 MW. Also a larger, megaton water Cherenkov detector, Hyper-Kamiokande (HK), is considered. With the present beam line configuration the J-PARC neutrino beam is aimed at Korea. There are plans to build there a large underground detector [25].

The NOνA experiment is designed to use NuMI beam at 14 mrad off the axis. The far detector located 810 km from Fermilab will be constructed of PVC extrusions of 15.7 m length, filled with liquid scintillator, and organized in alternating planes with horizontally and vertically arranged extrusions. The total detector mass will be 14 kton (fully active) and length of 90 m [27]. In each intrusion the scintillation light will be captured by a wavelength-shifting fiber read by 32 pixel avalanche photodiode [26]. The detector will be located on the surface, possibly with a few meter overburden. The efficiency for saving ν_e interactions after cuts reducing π_0 background is expected at 24%.

The sensitivity to $\sin^2 2\theta_{13}$ is expected to get down to 0.02 for all δ values and to approximately 0.008 for some δ. Owing to higher energy and larger distance NOνA will have three-fold bigger matter effects and thus is expected to resolve the mass hierarchy problem for a large fraction of possible δ values [29].

In order to tackle the problem of degeneracies an interesting second-phase experiment is proposed under the name of Super-NOνA. Mena *et al.* [28] consider two detectors characterized by the same L/E ratios but at different baselines L and different off-axis angles leading to different neutrino spectra.

6. Summary.

The neutrino oscillation program for the next decade has ambitious goals to answer a few basic questions. What is the ordering of the neutrino mass states? Is θ_{23} exactly equal to $\pi/4$ or $\theta_{13} = 0$ suggesting an unknown symmetry? Are the neutrino and antineutrino oscillations the same? An answer to the latter question is fundamental for leptogenesis and baryon asymmetry in the Universe.

In order to settle these problems the precision of the oscillation parameters, especially in the atmospheric domain, has to be improved. Determination of θ_{13} will be the critical issue for further studies because its value is decisive for strategies how to measure CP phase and determine mass hierarchy.

Reactor experiments, insensitive to CP effects, will most probably provide first estimates of θ_{13} values or limits. However, they will not be able to measure δ_{CP}, $\mathrm{sign}(\Delta m^2_{23})$ nor to improve accuracy on $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$. This will be the task of accelerator experiments using powerful neutrino beams. Resolving multiple degeneracies may be very challenging, requiring more than one experiments.

Combining the NOνA and T2K results will facilitate a separation of CP violation from matter effects. Interesting projects to use complexes of two large detectors in Japan and Korea or/and in North America (Super-NOνA) may be necessary to lift some degeneracies.

The author is thankful to organizers for the kind invitation and the hospitality extended to her at the workshop.

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