NEUTRINO BEAM FACILITIES AND PROJECTS*

W.T. Weng[#], M.V. Diwan, BNL, Upton, NY 11973, USA

Abstract

Neutrino oscillations have been firmly established by the experimental results on Atmospheric and Solar neutrinos. As impressive as the results from these experiments are, it is clear that we are just getting started on a long-term experimental program to understand neutrino masses, mixing, and possibly leptonic CP violation. Many new facilities and experiments are underway to explore the detailed oscillation mechanism for comparison with theoretical predictions. Also, further improvements on neutrino oscillations using a muon storage ring based on Neutrino Factory will be covered.

INTRODUCTION AND NEUTRINO OSCILLATION

Dr. Ray Davis of BNL and Prof. Masatoshi Koshiba of Japan shared the 2002 Nobel Prize in Physics for their path-breaking measurement of the terrestrial fluxes of Solar and atmospheric neutrinos. Their research established that neutrinos have mass and oscillate among three flavor states as they propagate through space and time. Neutrino oscillations can arise if the flavor and mass eigenstates are not the same. Assuming three flavors and mass eigenstates, a specific form of the mixing matrix for the three known active flavors has been developed by Maki, Nakagawa and Sakata and is known as the "MNS matrix" [1]:

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}c_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. This is completely analogous to the CKM matrix for the quark sector. Of importance, we note that a CP-violating phase δ is possible. Interpretation of the experimental results is based on oscillations of one neutrino flavor state, ν_e, ν_μ, ν_τ, into the others, and described quantum mechanically in terms of neutrino mass eigenstates, ν_1, ν_2, and ν_3. For example, for a ν_μ-beam coming from a neutrino facility, the ν_e appearance probability to leading order is given by

$$P_{\nu_\mu \to \nu_e} = \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{1.27\Delta m^2_{32}(eV^2)L(km)}{E_\nu(GeV)}\right) \quad (1)$$

A detector must be placed at an appropriate distance from the neutrino source to allow the neutrino enough time to oscillate. The combined experimental results indicate that, the mass differences involved in the transitions are measured to be approximately $\Delta m^2_{21} = (5-10)\times 10^{-5}\,eV^2$ for the solar neutrinos and $\Delta m^2_{32} \equiv m(\nu_3)^2 - m(\nu_2)^2 = \pm(1.6-4.0)\times 10^{-3}\,eV^2$ for the atmospheric neutrinos, with large mixing strengths, $\sin^2 2\theta_{12} \sim 0.8$ and $\sin^2 2\theta_{23} \sim 1.0$ in both cases. These parameters will be measured with better accuracy in the experiments that are now either under construction or taking data. Nevertheless, the parameters are now sufficiently well-known that they open the possibility for accelerator based very long baseline experiments that can explore the complete set of neutrino oscillation parameters, perform precise measurements of the mixing parameters, and search for new physics.

SURVEY OF EXISTING AND APPROVED FACILITIES

For an effective experiment to study neutrino properties, one needs a good neutrino source and a reliable way of detection. For an accelerator-based system, a powerful proton accelerator and a well-designed target and beam focusing system are required. When the protons hit the target, copious number of pions are generated which quickly decay into muons and neutrinos. To increase the flux of neutrinos at a detector far away from the target, a pulsed horn is usually deployed to provide additional focusing of the pion beam. In table 1 we list the world-wide neutrino facilities and their design parameters. The first type of facilities are those already in use, or under construction. The second type are those in the planning, or proposal stage.

As shown in Eq. (1) the ν_μ oscillation probability is governing by the ratio of L/E_ν indicating that the distance from the target to the detector, L, and the neutrino beam energy, E_ν, are important parameters for a design of the neutrino beam facility. Therefore, in Table 1 those two parameters are listed in addition to that of the proton beam. Total flux per year for each facility is arrived at by assuming 10^7 seconds of operation per year. E_ν usually is chosen according to Eq. 1 to be around the first peak of oscillation, where $1.27\Delta m^2_{32}L/E = \pi/2$. However, for the proposal by BNL, all energies from about 1.0 GeV to 7.0 GeV are included in the analysis, since it aims at seeing the pattern of several oscillations. Another quantity included is the fiducial mass, FM, of the far detector which determines the event rate and resolution of the data.

*Work performed under the auspices of the U.S. Department of Energy.
[#]weng@bnl.gov

Table 1. High Intensity Proton Sources for Neutrino Experiments

Machine	Flux (10^{13}/pulse)	Rep Rate (Hz)	Ep (GeV)	Power (MW)	Eν (GeV)	L (km)	Detector	FM (kT)
Existing and Approved								
KEK PS	0.8	0.5	12	0.005	1.3	250	SK	22.5
Fermilab Booster	0.5	7.5	8	0.05	0.7	0.5	Mini Boone	0.4
Fermilab Main Injector	3	0.54	120	0.4	3.5	735	MINOS	5.4
CERN SPS	4.8	0.17	400	0.5	17	732	ICARUS OPERA	2.35 1.65
J-PARC 50 GeV	32	0.3	50	0.75	0.8	295	SK	22.5
Proposed Facilities								
Fermilab MI Upgrade	15	0.65	120	1.9	3.5	735	MINOS	5.4
BNL AGS Upgrade	9	2.5	28	1	1.0-7.0	2540	UNO or 3M	500
J-PARC Upgrade	32	0.9	50	2.2	0.8	295	HK	540
CERN SPL	23	50	2.2	4	0.26	130		40

Since the location and distance of the detector are important aspects of neutrino oscillation experiments, we show in Fig. 1 maps of the three existing facilities.

K2K uses a “standard” neutrino beam configuration. The 12 GeV protons impinge on a target to produce pions. The pions are focused using a double-horn system in the direction (on-axis) of Super-Kamiokande and directed down a decay pipe which is ~150m long. The peak neutrino energy is about 1.3 GeV. To date, a total of 5.6×10^{19} protons have been delivered to the K2K neutrino beam target. This has resulted in a total of 29 single-ring muon-like events observed at Super-Kamiokande with the expected number being 42 ± 6 events with no oscillations. An oscillation analysis on these events shows that the resulting oscillation parameters are in good agreement with those measured from the atmospheric neutrinos [2], although the result is still statistically limited.

A new Japanese construction project, J-PARC, is in progress at JAERI-Tokai site aiming the completion by March 2007 [3]. Using the 50 GeV proton synchrotron in J-PARC, a long baseline neutrino oscillation experiment is being planned. In the first phase of the project, the power of the 50 GeV PS will be 0.75 MW, and SK will be used as the far detector. The intensity of the neutrino beam is expected to be about 2 orders of magnitudes higher than K2K. The baseline length between JAERI and SK is 295 km. The goals of the first phase are the precise measurements of oscillation parameters in ν_μ disappearance and the discovery of ν_e appearance. Also, $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$ oscillation can be tested by measuring the number of NC interactions in SK.

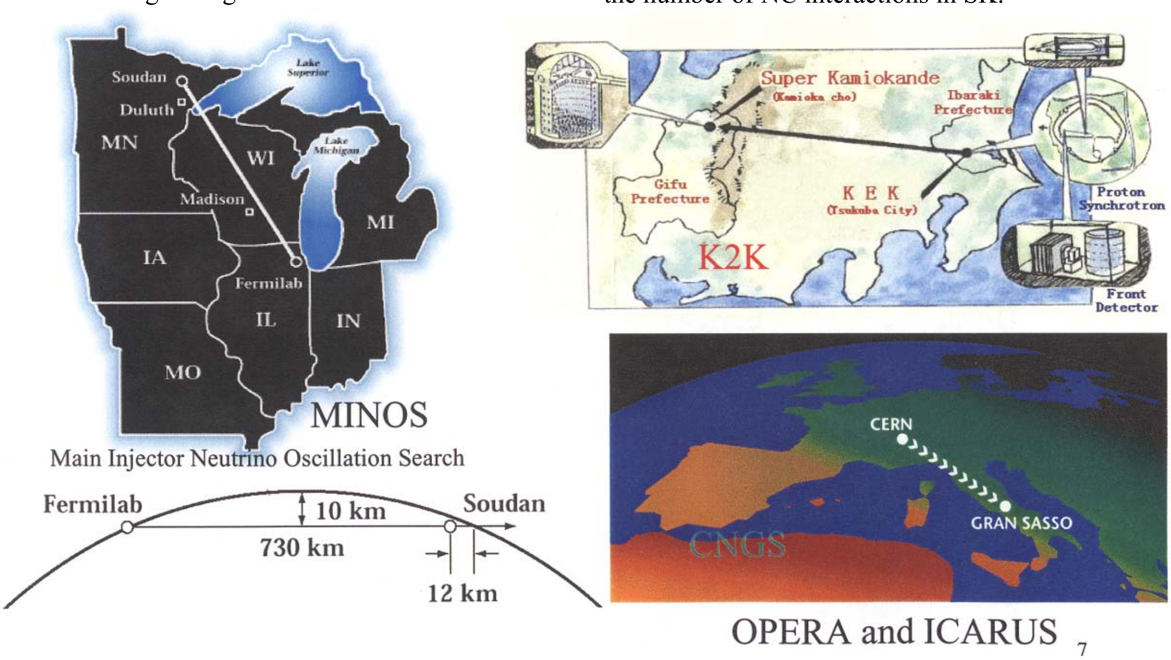

Figure 1: Map for K2K, NUMI, and CNGS Experiments

In the US, the current long-baseline project is the MINOS (Main Injector Neutrino Oscillation Search) experiment using the NuMI (Neutrinos at the Main Injector) beamline at Fermilab[4]. MINOS will make use of the intense neutrino beam afforded by the Main Injector to make precise measurements of neutrino oscillations associated with the "atmospheric" signal. By 2005, the Main Injector is expected to provide 120 GeV, 4×10^{13} protons per pulse every 1.9 sec to the NuMI target. This operation corresponds to 0.4 MW of proton power for ν-productoin.

The NuMI beamline is larger than that of the K2K beamline. It uses a graphite target because of higher beam power. It is also tunable to scan a wider ν energy spectrum.

The MINOS experiment utilizes a near and far detector of very similar construction in order to permit precise measurements of oscillation parameters, clear demonstration of the oscillation signature and precise determination of the flavor participation of all neutrino types involved in the oscillations. The MINOS detectors are sampling calorimeters with 2.54 cm thick iron absorbers interleaved with 1.0 cm thick plastic scintillator strips, which are 4 cm wide. The iron in the detectors is magnetized with typical field of 1.5 T.

The MINOS far detector has a total mass of 5.4 kT. Roughly 5000 ν_μ charged-current events are expected, in the absence of oscillations, in the far detector for two years of running. A picture of the MINOS detector assembly at the Soudan mine is shown in Fig. 2.

Figure 2: Installation of MINOS Detector

The third near-term long-baseline project which is also in construction is the CERN to Gran Sasso (CNGS) beamline and experiments [5]. The CNGS beamline will use 400 GeV protons from the SPS to create a high energy neutrino beam (E_{avg} = 17 GeV) aimed at the Gran Sasso. The primary goal of this beamline and the experiments at the Gran Sasso will be to demonstrate the direct appearance of ν_τ CC events from the ν_μ beam. This beam will be commissioned in 2006.

The two detectors which will initially utilize this beam at the Gran Sasso are Opera and Icarus. Opera will use plates of emulsion interleaved with thin lead plates to look for CC ν_τ events where the τ is produced in the lead and then subsequently decays in a gap downstream where a kinked track will be observed in the emulsion. Opera plans a total detector mass of about 2 kT, dominated by the mass of the lead. Icarus is a large liquid argon TPC that can identify CC ν_τ events on a statistical basis through the transverse momentum imbalance which results when a τ decays to a muon or electron.

SURVEY OF PROPOSED FACILITIES (SUPERBEAM)

The existing and approved projects were designed before the neutrino oscillations had been unequivocally confirmed and were also limited by proton beam power. Typical event rates are about few tens to a hundreds per year. With the advent of recent discoveries and interest, many more powerful facilities have been proposed. All of them aim to reach proton beam power in the range of 1.0 to 4.0 MW to substantially increase the event rate to several thousands. Recent progresse on the design of the high power proton drivers were reviewed in references [6] and [7]. Such facilities allow precision measurements of most of the mixing parameters and mass differences. The BNL proposal based on a 1 MW upgraded AGS and a 2540 km baseline intends to observe the oscillation pattern as a function of neutrino beam energy, covering three full oscillations yielding precise resolution of all interested parameters. An unique aspect of the BNL proposal is the ability to measure CP parameters with ν_μ beam alone.

When upgrade paths are discussed for various neutrino beam facilities, usually only the accelerator is presented. However, the most difficult part is the target and associated pion decay channel and radiation shielding. Much R&D effort needs to be expended on a reliable target system for more than 2 MW power, and the associated infrastructure is very difficult to revamp after operation due to the intense radiation environment.

As shown in Table 1, NuMI can be upgraded to about 2 MW by increasing the Main Injector intensity from 3×10^{13} ppp to 15×10^{13} ppp and increase the repetition rate by 20%. Similarly, J-PARC can upgrade the proton beam power to 2.2 MW by tripling the repetition rate of the 50 GeV synchrotron. Both the NuMI upgrade project and the J-PARC stage 2 project are designed to provide a "narrow band" off-axis ν beam [8]. Such a beam is expected to reduce the neutral current interaction background to the ν_μ-ν_e appearance search.

In Europe, there is an idea of a superbeam LBL experiment in which the neutrino beam is produced by a superconducting Super Proton Linac (SPL) at CERN and detected by a detector at Modane laboratory in the Furejus tunnel, 130 km from CERN [9]. The proposed SPL is a 2.2 GeV LINAC with 4 MW beam power operated at 75-Hz repetition rate and 1.5×10^{14} protons/pulse. The neutrino beam is a conventional wide-band beam with the expected neutrino ranges < 500 MeV. This matches with the oscillation maximum of ~ 300 MeV at $\Delta m^2 = 3 \times 10^{-3}$ eV^2.

In BNL's superbeam proposal, the neutrino beam is produced by the 28 GeV proton beam from the Alternating Gradient Synchrotron (AGS) at BNL and is detected by a large detector of 500 kT, most likely of the water Cherenkov type, at a distance of 2540 km. For this discussion, the detector is assumed to be located at the Homestake mine in Lead, South Dakota. The primary purposes are precise determination of oscillation parameters, search for ν_e appearance and CP violation. The main ingredients of this new facility are (1) construction of a superconducting LINAC to raise the injection energy to 1.2 GeV, (2) increase the repetition rate of the AGS from 0.6 to 2.5 Hz, and (3) construction of a 1.0 MW target station and neutrino beam channel. [10,11]

The layout of the proposed addition of the 1.2 GeV SCL and the AGS is shown in Fig. 3. The target and horn system are designed in such a way that neutrinos with energy from about 1 GeV to 7 GeV are copiously produced.

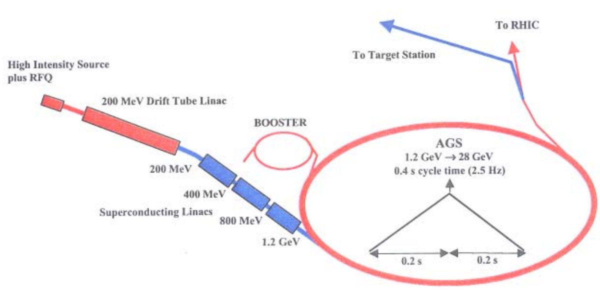

Figure 3: AGS Upgrade to 1 MW

To achieve the 1 MW upgrade option of the proton driver at BNL serious consideration has been given to both the target material and horn configuration. A solid target is a viable choice for a 1 MW beam. Low and high Z materials have been investigated both in terms of the material endurance as well as the feasibility of target/horn configuration. Results of the parametric studies on material choices regarding pion production are shown in Fig. 4.

A graphite-based carbon-carbon composite is selected as a target material both for its low-Z and thermo-mechanical properties. Various aluminum-based materials are being considered for horn conductors.

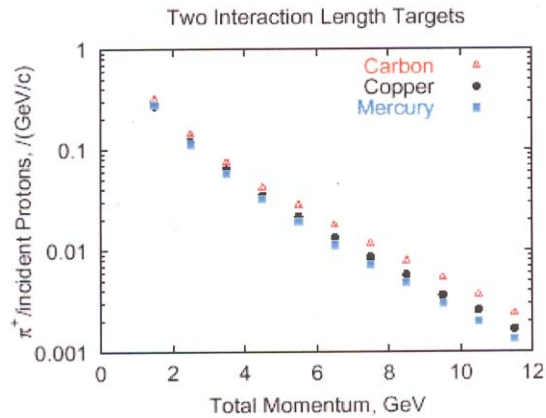

Figure 4: Pion production as function of proton momentum for different materials

The main source of ν_μ is the two body pion decay $\pi^+ \rightarrow \nu_\mu\mu^+$. The pions are produced in interactions of the proton beam with a target. Neutrino energy from the above decay is

$$E_\nu \cong \frac{0.43E_\pi}{1+\gamma^2\theta^2}, \qquad (2)$$

where γ is the pion relativistic boost and θ is the neutrino emission angle at decay. It is seen from the above equation that in order to get a neutrino beam of the energy of 1.0 – 7.0 GeV in a detector placed on the facility axis, one would need to focus pions of 2.3 to 11.7 GeV energy. This wideband spectrum can be achieved by a careful design of a multiple horn system.

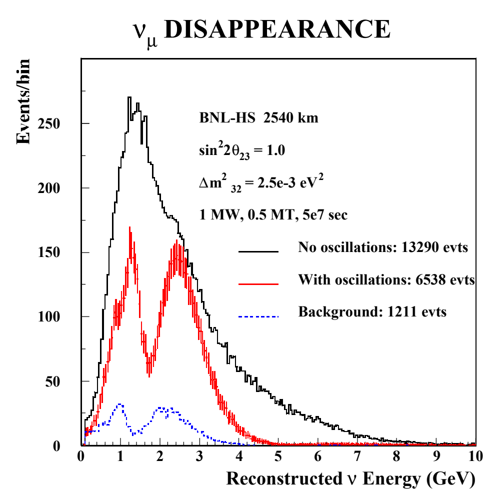

Figure 5: ν_μ Disappearance

With a target located at 2540 km away, more than two full neutrino oscillations can be detected to yield much better determination of mixing parameters and mass squared differences. Shown in Fig. 5 is the expected reconstructed neutrino energy spectrum of detected single muon track events in a 0.5 MT detector at 2540 km from BNL in which quasielastic events are expected to dominate. 1.0 MW of beam power and 5 years of running are assumed. The top histogram is without oscillations; the middle error bars are with oscillations and the bottom histogram is the contribution of the background to the oscillated signal only. The oscillated plot is for $\Delta m_{32}^2 = 0.0025\, eV^2$. The AGS neutrino facility can be upgraded to 4 MW by doubling both the intensity and the repetition rate of the AGS.

As shown in reference [10], if $\sin^2 2\theta_{13} \geq 0.01$ then the wide band BNL spectrum of ν_e events from the $\nu_\mu \rightarrow \nu_e$ oscillation contains sufficient information to determine both δ_{cp} and θ_{13} with good resolution and few ambiguities. One of the simulation results is shown in Fig. 6.

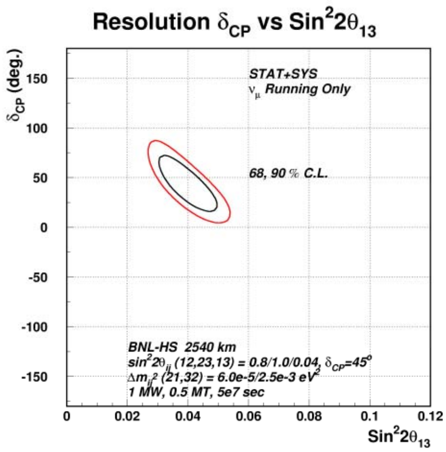

Figure 6: Mass-ordering and CP-violation parameter δ_{cp}

NEUTRINO FACTORY

Around 1998, it was realized that neutrino beams generated from muon storage rings could be very intense and pure. The muon storage ring designed to produce a large number of neutrinos for experiment is called a "Neutrino Factory" [12]. The design calls for a 4 MW proton driver to produce about 5×10^{20} μ/year at about 300 MeV. The muons are then quickly accelerated to about 10-20 GeV to be stored in a storage ring with long straight sections that produce the neutrino beam aiming at the detector. Depending on the size and distance of the detector, typically $10^5 \sim 10^6$ neutrino events can fall into the fiducial volume of the detector for experiment. Such beams will have unique properties:

- Very intense beams, on order tens to hundreds of times more intense than planned superbeams.
- Relatively clean narrow-band beams.
- Intense, high energy ν_e and $\overline{\nu}_e$ beams.

The comparison for the determination of the parameter θ_{13} for Superbeam and Neutrino Factory is given in Fig. 7 [13]. It is shown that the Neutrino Factory can give a reliable determination of $\sin^2 \theta_{13}$ down to about a few 10^{-5}.

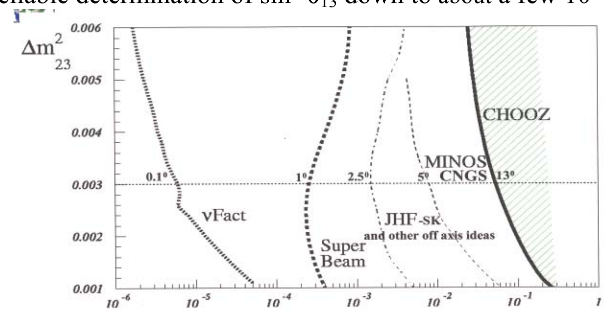

Figure 7: The reach of $\sin^2 \theta_{13}$ by various experiments

While the sensitivity of experiments with conventional horn focused ν_μ beams are limited by the intrinsic background of ν_e to about $\sin^2 2\theta_{13} > 0.005$, the ν factory approach is much more sensitive. Nevertheless, unlike the wide band approach promoted by the BNL group, the CP measurement with the ν factory must be done by comparing the probability of $\nu_\mu \rightarrow \nu_e$ versus $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$. Such an approach naturally makes the running time much longer and the interpretation of the result is considered to have ambiguities unless the experiment is performed with many different baselines [14,15].

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