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PROSPECTS FOR NEXT GENERATION LONG-BASELINE OSCILLATION EXPERIMENTS

DEBORAH A. HARRIS
Fermi National Accelerator Laboratory P.O. Box 500
Batavia, IL 60510-0500, USA
E-mail: dharris@fnal.gov

ABSTRACT

This document describes some of the exciting possibilities for the next steps in the field of long baseline neutrino oscillation measurements. Because the primary goals of these new experiments are so different from those of the current generation, one cannot simply increase the running time or detector mass of the current programs. There are several new strategies which have been discussed for taking the next steps: sometimes the detectors, sometimes the beamlines, and sometimes both are radically different from what is now in place.

1. Introduction

The current long baseline neutrino oscillation experiments are designed to unequivocally confirm or refute the anomaly that has been seen with atmospheric neutrinos, and to etsablish the oscillation framework itself. The next step after this, assuming there are only three generations of neutrinos, is to determine whether the last unseen mixing matrix element, known as U_{e3}, is non-zero. Once evidence for a non-zero U_{e3} is found then measurements of oscillations between muon and electron neutrinos can potentially determine not only the neutrino mass hierarchy but also if there is CP violation in the lepton sector. All three of these measurements ($|U_{e3}|$, CP violation, and the mass hierarchy) have profound effects on our understanding not only of neutrinos themselves, but also of the role they play in the universe and its formation.

2. Probabilities and Mixing Angles

In the standard 3-generation mixing scenario, the leptonic mixing matrix, which translates between the mass eigenstates and the flavor eigenstates, can be expressed in terms of three angles (usually denoted θ_{12}, θ_{13}, and θ_{23}) and a cp-violating phase (δ). The solar and KamLAND neutrino measurements constrain and will eventually measure θ_{12} and the "solar mass splitting" or Δm^2_{12}. The atmospheric and current long-baseline neutrino measurements constrain (and again hopefully measure precisely) θ_{23} and the size of the "amospheric neutrino mass splitting", or $|\Delta m^2_{23}|$. Because the two mass splittings differ roughly by a factor of 30, and because one of the mixing angles (θ_{13}) is known to be much smaller than the other two, the disappearance measurements can be interpreted largely in a 2-generation framework[1).

However, not knowing the size of θ_{13} *a priori*, to be complete the *appearance* probability for electron neutrino in a muon neutrino beam should be expressed as follows [2]:

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4 \quad (1)$$

where

$$\begin{aligned}
P_1 &= \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2} &(2)\\
P_2 &= \cos^2\theta_{23}\sin^2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2} &(3)\\
P_3 &= J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} &(4)\\
P_4 &= \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2} &(5)
\end{aligned}$$

and

$$\begin{aligned}
\Delta_{ij} &= \frac{m_i^2 - m_j^2}{2E_\nu}\\
J &= \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\\
A &= \sqrt{2}G_F n_e\\
B_\pm &= |A \pm \Delta_{13}|
\end{aligned}$$

and E_ν is the neutrino energy, n_e is the electron density in the material the neutrinos pass through, and of course L is the distance the neutrinos travel between production and detection. The $\pm$ signifies neutrinos or antineutrinos.

In the case of vacuum oscillations, or $n_e = 0$, the only difference between the neutrino and antineutrino oscillation probabilities comes from the $\pm$ sign in front of P_4. Because of the electrons in the earth, however, there is a difference in the potential between electron neutrinos and antineutrinos, which also changes the probabilities between neutrino and antineutrino, independent of the phase δ. The way these probabilities get altered is a known function of Δm^2_{23}, but a priori one does not know the sign of Δm^2_{23}, so this can complicate the issue of extracting δ. However, for a long enough distance (giving a large enough matter effect) the size of the effect is larger than any possible effect from CP violation, making it possible to determine the mass hierarchy (or the sign of Δm_{23}) before reaching the precision required to see a non-zero value for δ. Because of the four different terms listed in equation 5, extracting θ_{13} once oscillation probabilities are measured will be far from trivial. There is a consensus among many that $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ measurements at more than one energy or baseline (or both) will be required to get to the underlying physics[3)].

3. Challenges to $\nu_\mu \leftrightarrow \nu_e$ measurements

While precisely measuring θ_{13} will be hard theoretically because of the various contributions to the oscillation probability, measuring the probabilities themselves will be hard experimentally for several reasons. Because of the CHOOZ limit on $\bar{\nu}_e$ disappearance, it is already known that θ_{13} is small, less than about 8° [4)]. This translates to a $\nu_\mu \to \nu_e$ appearance probability limit of about 5% at the appearance maximum. For conventional muon neutrino beams which are made of two-body pion and kaon decays, there is always an intrinsic electron neutrino background which is due to three-body decays of both kaons produced in the beamline, and tertiary muons, which are produced by both pion and kaon decays. This intrinsic background, when averaged over all energies, is on the order of a per cent or so. Furthermore, for high energy neutrino beams, there will be a significant number of ν_τ charged current interactions in a detector. Since τ's decay to electrons a large fraction of the time, these too represent a possible background. Finally, depending on what detector is used, neutral pions created in a neutrino interaction can also fake an electron, and so both neutral current events, or charged current events with very low muon energies can also provide a possible background.

4. Strategies for Beamline Optimization

The current long-baseline oscillation experiments (K2K, MINOS, OPERA and ICARUS) are designed to verify the oscillation hypothesis in several ways: first, by measuring the ν_μ survival probability as a function of neutrino energy, and second, by searching for evidence of active (τ) neutrinos in an initial μ neutrino beam. The beamlines that are in use today (and in the near term future) are broad-band neutrino beams which point to detectors at baselines such that the oscillation argument $\Delta m^2 L/4E$ is near or less than $\pi/2$.

One noticeable characteristic of these experiments is that while they can search for $\nu_\mu \to \nu_e$ beyond the CHOOZ limit, they are not optimized to do that search. There are several new strategies being considered which try to minimize the backgrounds described in the previous section. Figure 1 shows the neutrino beam fluxes for some of the various experiments which are being proposed for the future–both near and far term. Note that some of the fluxes are very broad band in energy, while some are narrow. Some are quoted for extremely long baselines (2500km), some for only 130km baselines. In the following sections we describe the motivation behind each of these various designs.

4.1. Rejecting Convention: Neutrino Factories and β-Beams

One class of strategies is to reject conventional beams altogether and to make a neutrino beam with decays of either radioactive isotopes (so-called "beta-beams") or with decays of muons (a "muon storage ring"). In both cases the beam-related background is reduced to the 10^{-5} level or below, because there is only one parent decaying to neutrinos, with no subsequent daughter decays. Also, because the experiment measures $\nu_e \rightarrow \nu_\mu$, the neutral current background poses much less of a problem. In contrast, the technical challenges associated with building either a beta beam or a muon storage ring are much greater than those associated with a conventional beam [5]. For this reason the nearer term solutions all involve conventional beams, as described in the following sections.

4.2. Narrow Band Neutrino Beams

If one can design a conventional beamline to produce a nearly monochromatic beam of muon neutrinos, the ratio of signal to background in conventional beams can be improved over what one would normally see. The neutral current background will be steeply falling as a function of visible energy in the detector, because the outgoing neutrino can carry a large fraction of the incoming neutrino's energy. The intrinsic electron neutrino background is also broader by definition than the muon neutrino beam width, since these backgrounds come entirely from three-body decays.

In order to make a narrow band neutrino beam, the "off axis" technique, first suggested in reference [6] is being proposed by several groups. This technique involves designing a beamline which can produce and focus a broad range of pions in a given direction, but then putting the detectors at an angle with respect to that direction. Because the pion decay is a two-body decay, a given angle between the pion direction and the detector location corresponds to a given neutrino energy. For detectors on axis with the focused pions the neutrino energy is simply proportional to the pion energy. However, off that axis the relation is no longer true, and for a given pion momentum bite there is an angle for which the outgoing neutrinos fall in a much narrower and lower energy momentum bite.

The one down-side to using a narrow band beam to search for $\nu_\mu \rightarrow \nu_e$ is that the width of these beams tends to be lower than the oscillation modulation, and so the total statistics for these experiments for a given detector mass are not as large as would be there for a broad band beam.

4.3. Low Energy Neutrino Beams

Another strategy to look for $\nu_\mu \rightarrow \nu_e$ is to use neutrino beams with energies significantly less than 500MeV. Although the neutrino cross section is very low at these energies, the neutral current background is proportionally lower because of the effect of π^0 mass suppression. Also, the neutral pions that are produced in the event are such low energy that in a water Cerenkov detector the two electromagnetic rings are much easier to separate than in higher energy neutrino interactions.

The one down-side to very low energy beams is that by going this far from the

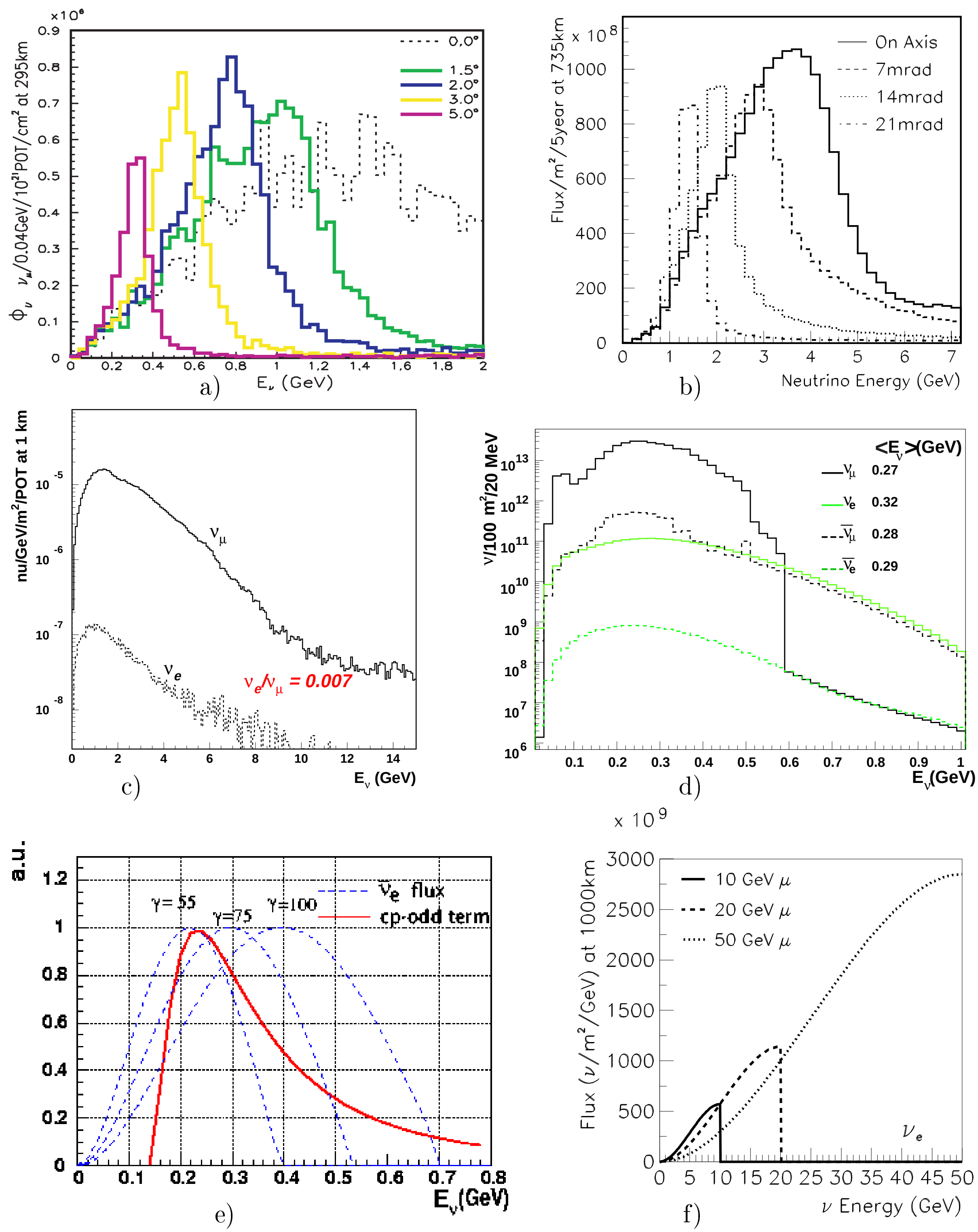

Figure 1: Neutrino Fluxes or Event rates, starting at the upper top left: a) J-PARC to SuperK ν_μ's,b) NuMI Off-Axis ν_μ's, c) BNL proposal (ν_μ and ν_e) , d) CERN SPL (all four flavors in beam), e) beta beam ν_e's, and finally f) neutrino beam ν_e's. References are given in the text.

earth's matter resonance (which occurs at about 12GeV) there are no distinguishable matter effects. Therefore, although this might be an ideal way to look for CP violation this would not suffice to determine the neutrino mass hierarchy.

4.4. Very Long Distance Baselines

One very aggressive approach which optimizes for seeing CP violation in the neutrino sector is to run an experiment at such a long baseline length that part of the neutrino spectrum is at the second appearance maximum, not the first. If you consider the CP-violating difference in equation 5 it is proportional to the baseline length L. So for events where $\Delta m^2_{23} L/4E_\nu = 3\pi/2$, this CP-violating difference is three times as large as events where $\Delta m^2_{23} L/4E_\nu = \pi/2$. So one is measuring a larger effect albeit with less statistics which results in approximately the same statistical significance [7], but in this case systematic errors become much less important. Another possible advantage to running at a very long baseline length ($> 2000km$) is that the matter effects become very large, at least at the first oscillation maximum.

5. Detector Choices

5.1. Water Cerenkov Detectors

For most of the proposals for future $\nu_\mu \rightarrow \nu_e$ searches the detector being assumed is a water Cerenkov detector. Its ability to distinguish between electron and muon neutrino quasi-elastic events has been demonstrated time and again, and is in fact the reason this field has turned into one of precision rather than "solar and atmospheric anomaly speculation". Electrons can be identified easily because they have high multiple scattering in the detector and lose energy quickly, thereby producing Cerenkov rings of light that are "fuzzy" on both the outer and inner edge. Muons by comparison travel much farther in the water and scatter less, thereby producing much fatter rings that are sharp on the outer edge and "fuzzy" only on the inner edge. Neutral pions, when they decay, will produce in principle two electron-like rings. However, as the neutrino energy rises above 1GeV or so, the quasi-elastic cross section stays constant while the cross section for multiparticle final states starts to rise. Also, as the neutral pions produced in neutral current interactions rise in energy, the two photon rings tend to overlap more and more. One idea which still keeps the backgrounds low is to continue to use only quasi-elastic-like events in a water Cerenkov device, and just build a detector large enough to compensate for the signal inefficiency[19].

5.2. Fine-Grained Calorimetry

Another detector technology that has a long history in neutrino physics is calorimetry, or planes of absorber interspersed with planes of active material. In MINOS, where the primary goal is both the identification and energy measurement of ν_μ charged current events, the absorber planes are 2.5cm thick magnetized steel and the active medium is solid scintillator. However, to optimize a detector for ν_e appearance, one would want to sample much more frequently than 1.4 radiation lengths, and a magnetic field would not be necessary. Furthermore, by building a detector out of a low Z material, one can benefit from the fact that for a given radiation length sampling, one can get up to a factor of 3 more mass per readout plane over steel. Currently the NuMI Off-Axis proposal is considering for a first stage detector a fine-grained calorimeter, with 0.3 radiation-length thick particle board as the absorber material [8)]. If the transverse readout sampling is fine-grained enough, a digital readout would suffice for the active medium, and then both energy and event classification would be made by measuring the number and longitudinal distribution of the hits, respectively. The active media being considered are either Resistive Plate Chambers, such as being used in Belle and BABAR, or scintillator [8)].

5.3. Liquid Argon Time Projection Chamber

Finally, a newer option which nevertheless shows promise is a Liquid Argon Time Projection Chamber, such as is being developed and used by the ICARUS experiment [9)]. This detector consists of a large vessel of liquid argon filled with planes of wires strung in two dimensions. Reading out two dimensions plus time provides a signal which is analogous to an electronic bubble chamber, and should provide a wealth of information for each neutrino event– not only tracking would be available, but also particle ID from dE/dx measurements. In this way neutral pions could easily be distinguished from electrons simply because there would be two highly-ionizing particles from a photon conversion, rather than the single highly-ionizing particle in an electron neutrino charged current interaction. For detectors located at the surface of the earth, a large single volume would be feasible from a safety standpoint, and could have a competitive cost per physics reach, because of the very high efficiency (and the fact that larger detectors simply have longer wires in each plane). Industrial solutions for making large cryogenic vessels at ground level have been identified; the challenge will be to understand what the drift distance of electrons is, which implies what the largest spacing between planes of wires can be [10)]. Also, it remains to be seen whether or not this detector performs as well in a 2GeV neutrino beam as the simulations predict. Certainly much will be learned about this detector with higher energy neutrinos from the ICARUS experiment. Also, if a small prototype could be placed in the near hall of the MINOS experiment a great deal could be learned about this technology for the long term future.

6. On the Need for a Near Detector

Regardless of what combinations of beamlines and detectors are ultimately chosen in this field, there will no doubt be a need for a near detector for each experiment.

Given the detector mass and expected neutrino rates from each of the beamlines proposed, there will be background events in the final event sample regardless of the oscillation probability, and making even a discovery claim will require a background subtraction. Near detectors are required to make not only measurements of the initial electron neutrino content of the beam, but also to determine precisely the neutral current background rejection capabilities of any detector. Low energy neutrino cross sections (and particularly, neutral current π^0 production) are extremely poorly known, some of the most precise neutral current measurements come from only handfuls of bubble chamber events [11]. All of the proposals described in this paper expect to use a near detector. Based on the experience of the K2K experiment, a suite of near detectors including some with different (or improved) capabilities over the far detector might also prove critical for the most precise far detector measurements [12].

7. Near Term Options

There are proposals for taking this next step in neutrino oscillation measurements that take advantage of already existing investments that have been made in this field. Because either the detector or the beamline is already in place, the total cost in units of both time and money is substantially less than other farther term options. It must be stressed, however, that these near term proposals represent initial and not final steps in this field!

7.1. J-PARC to Super-Kamiokande and Beyond

At the time of this writing a new accelerator laboratory is being constructed in Japan, called the Japanese Proton Accelerator Research Complex (J-PARC) [13]. This facility will house a 50GeV proton synchrotron which could provide on the order of 1×10^{21} 50 GeV protons on a target for neutrino physics over a 5 year period (with an instantaneous rate corresponding to 0.75MW). The facility is being constructed for a variety of hadronic physics topics, but it is expected that the neutrino beamline will also play a significant part in the program. By constructing the beamline to point near (but not exactly at) the Super-Kamiokande detector, a new experiment, called J-PARC to SuperK, can use an off-axis beam to search for $\nu_\mu \rightarrow \nu_e$ [14]. The baseline length for the experiment is fixed at 295km. The decay region for the beamline will be trapezoidal in shape, so that off axis angles between two and three degrees will be available–this implies narrow band neutrino beams with energies from .5 to .8 GeV, depending on the off axis angle (see figure 1 for the range of neutrino fluxes). The beamline is expected to start construction around 2006 and the experiment expects to start taking data around 2007. The expected sensitivity of this first stage is about a factor of 10-20 past the CHOOZ limit.

To extend the sensitivity of the experiment, improvements both to the proton source and to the detector are envisioned. Although the first stage of the J-PARC facility has a goal of 0.75MW of proton power on the target, there are plans to upgrade to even higher proton powers, with a goal of 4MW. Designing a neutrino beamline to withstand such a high power on target is not trivial–in particular it is expected that above 1MW or so most conventional solid targets would yield. But the remainder of the J-PARC to Super-K beamline will have enough shielding to allow such high powers on the eventual target design. And although the Super-K detector is currently the most massive low energy neutrino detector in the field, R& D is also being pursued to understand how to make a larger version of a water Cerenkov detector [15]. The goal for the detector is to have a fiducial mass which is 20 times that of the Super-Kamiokande detector, with a total mass approaching a megaton. This new detector, called Hyper-K, could be located under the same mountain range as the Super-K detector, and there would see the same range of off-axis beams as the first generation of this experiment. The sensitivity of this next stage would be another factor of 10 past the previous experiment, and would have enough neutrino flux times detector mass to allow antineutrino as well as neutrino measurements.

7.2. NuMI Off-Axis and Beyond

The NuMI Beamline, while sending neutrinos to the MINOS detector in Soudan, Minnesota, is also sending narrower, lower energy, very intense "off-axis" beams to a broad range of baselines in both northern Minnesota and even southern Canada. Because the duty cycle of the beamline is low (10 microseconds every two seconds) there is a proposal to put a detector at a surface location and search for $\nu_\mu \rightarrow \nu_e$ oscillations. The off axis energies range from 1 to 2GeV depending on the angle one chooses, and have appreciable fluxes even while the NuMI beamline is running for MINOS at its nominal low energy configuration (which on axis has a peak neutrino energy of about 3.5GeV). For a 2GeV off axis beam one could get a beamline as long as 900km, while for a 1GeV off axis beam (at a higher angle) the baseline could be as far as 1100km.

A first stage detector for this new experiment could be a low-Z fine grained calorimeter, as was discussed in section 5.2. The current goal is to make a 50kton detector with this technology, which could be housed in a modular structure [8]. For a second stage, a very large liquid argon calorimeter might prove to be the best upgrade path. Because the background rejection for this kind of detector is substantially larger than that of a fine-grained calorimeter, while keeping the signal efficiency high, a 100kton liquid argon detector might represent a factor of 5-7 increased effective mass compared to a 50kton fine grained calorimeter [10].

The proton source for the NuMI Off-axis experiment could also be upgraded during the course of this project. Currently there exist two designs[16] for a replacement of the Booster at Fermilab, which supplies 8GeV protons to the Main Injector, which then accelerates protons to 120GeV. Either of these designs, plus a relatively minor upgrade to the Main Injector, would mean up to 2MW of beam power at a target for the NUMI beamline. The shielding and other modifications for the NuMI beamline itself depend on what is learned during the operating of the first stage of the experiment, but as with the J-PARC upgrades, it is expected that the target design would need to change considerably. The goal for these later projects is a factor of 25-35 overall in increased neutrino flux times detector mass, leading to a factor of 5-6 increase in measurement sensitivity or probability reach.

7.3. Complementarity of Near-Term Options

The two proposals described above at first glimpse may seem slightly redundant– the first stage of each proposal has a sensitivity of $\sin^2 2\theta_{13}$ roughly a factor of 10 to 20 better reach than the current CHOOZ limit. However, if either one or both experiments sees a signal, then the information gained from the combination of results is actually better than if one had simply run one experiment for twice as long [17]. The reason for this, besides just the role of the second experiment confirming the discovery of the first, is that the NuMI experiments can be sensitive to matter effects, while the J-PARC experiments are not. So that means that even if NuMI and J-PARC were designed such that L/E were identical, they should still measure different oscillation probabilities. Therefore, if NuMI measures an oscillation probability that is larger than J-PARC, then the mass hierarchy would be determined to be normal, independent of the actual values of θ_{13}, δ, or Δm^2_{23} [18].

8. Far Term Options

There are several longer term options which are also being suggested to address the longer-term goals of getting to precision measurements of the mixing matrix elements. These options involve building not only new beamlines but also new detectors, and like the proposed Hyper-K detector, the detector mass scale is at least a factor of 10 larger than what currently exists in the field.

8.1. Brookhaven Long Baseline Proposal

By upgrading the proton source at the AGS at Brookhaven a new neutrino beam could be used in conjunction with a new National Underground Science Laboratory (NUSL), which is hoped would contain a Megaton-scale water Cerenkov detector [19]. Because NUSL is likely to be very far from Brookhaven ($> 2500km$), the proposal takes advantage of both matter effects and the idea of going to the second appearance maximum to look for CP violation. The Brookhaven beamline uses a 1MW proton source to make a broad band beam whose peak energy is about 1GeV but has significant flux even out to about 6GeV. The events at high energy (i.e. above 4GeV) will have very dramatic matter effects to either enhance or suppress the probability, while the events at low energy, should have very dramatic CP-violating effects, since the CP-violating difference will be three times as large as at high energy.

8.2. CERN: SPL and BetaBeams

There are two ideas for future neutrino measurements based at CERN: both a conventional neutrino beam at extremely low energies, and a beta beam, which produces electron neutrinos (or antineutrinos) at a few hundred MeV[20]. Both kinds of beams could make use of a large water Cerenkov device, which would be located in the Frejus tunnel, which is 130km from CERN. There are already plans to excavate a new escape tunnel there in case of accidents, so the civil construction costs are hoped to be small, certainly when compared to excavating a new site.

The conventional neutrino beam proposed at CERN starts with 2.2GeV protons accelerated by the LEP cavities, and makes a very intense proton source and horn-focusing system which could also serve as the front end for a neutrino factory.

The "beta-beam" would be made by creating and accelerating bunches of radioactive isotopes, and then injecting them into a long storage ring where they would then produce an extremely pure electron neutrino or antineutrino beam. The techniques for creating the beams are straightforward and have been demonstrated at ISOLDE, but to get an appreciable rate at the far detector the storage ring would have to be on the order of 2km long. Because the neutrino energies are so low, and the nominal ring would be filled with radioactive isotopes, there would be substantial background simply from atmospheric neutrinos. Therefore, work to understand how these beams could be bunched is required for a final design. But the availability of pure ν_e beams would allow for not only tests of CP violation but CPT violation as well, all with the same final neutrino state detector [20].

8.3. Neutrino Factory

What remains the ultimate place to get high statistics measurements of $\nu_\mu \leftrightarrow \nu_e$ transition probabilities is the neutrino factory, based on a muon storage ring. By collecting pions and focusing the daughter muons and then accelerating them, one can make extremely intense ν_μ and $\bar{\nu}_e$ or $\bar{\nu}_\mu$ and ν_e beams. At a neutrino factory the signal is simply a hadronic interaction along with a muon. The charge of that muon indicates whether the parent neutrino was a ν_μ or a $\bar{\nu}_e$, and at muon storage ring energies at 30GeV and above the backgrounds are at least two orders of magnitude lower than in conventional beams, simply by building a magnetized detector like the one being used for MINOS [21]. Although the high energies of the neutrinos mean the baselines must be long, the matter effects are then also very large, which allows enormous statistics in either neutrino or antineutrino running, or both.

But while the detector challenges are minimized in a neutrino factory over those for a conventional beam, the beamline challenges are much greater. Both high intensity neutrino beams and neutrino factories assume megawatt scale proton sources which are themselves far from trivial, but a muon storage ring requires the muons to be focused and accelerated on an extremely short time scale. Recent progress in addressing these challenges can be found in reference [5].

9. Conclusions

Table 1 gives the salient features of the various new long baseline proposals: the detector mass, the proton power, how low in $\sin^2 2\theta_{13}$ an experiment would be sensitive to the 90% confidence level, and whether or not matter effects would be large in that experiment. Although many of these experiments can see evidence for CP violation in some region of parameter space, the actual parameter space varies somewhat from experiment to experiment. Which experiments make the most sense to do depends on what the next generation of experiments find. For example, if Δm^2_{23} is at the lower edge of the currently allowed region, then the sensitivities for $\sin^2 2\theta_{13}$ will change differently depending on the proposal. Also, if θ_{13} itself is large and is discovered in the next generation of experiments then background rejection and intrinsic electron neutrino contamination may not be as important as getting a high detector efficiency. What we do already know is that the rewards will be high for these extremely challenging measurements.

Table 1: Salient features and physics sensitivities of many future long baseline proposals (references given in the text). The $\sin^2 2\theta_{13}$ sensitivities are evaluated at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$,at 90% CL. The sensitivities to the CP-violating phase δ should not be compared between experiments because many are evaluated in different regions of the currently allowed parameter space.

Beam Name	E_ν (GeV)	L (km)	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.	δ	Matter Effect
OPERA[22]	17	732	1.8	0.15	0.04	-	
ICARUS[22]	17	732	2.4	0.15	0.03	-	
MINOS[23]	3.5	735	5	0.4	0.05	-	
CNGS modified[24]	2	735	2.35	.15	~ 0.02	-	$\geq$CP
J-PARC to SK	0.7	295	22.5	0.8	0.006	-	-
NuMI-OA	2	700-900	50	0.4	0.004	-	$\geq$CP
CNGT[25]	2	1100	500	0.4		-	$\geq$CP
SJ-PARC 2HK	0.7	295	450	4	~ 0.001	$\|\delta\| > 20^\circ$	$<$CP
SNUMI-OA	2	700-900	100	2	~ 0.001	135 ± 20	$\geq$CP
BNL2NUSL	1	> 2500	500	1	0.004	45 ± 20	$>$ & $<$
					CP		
CERN SPL	0.22	130	400	4	0.0016	90 ± 30	$\ll$CP
β Beam	0.2	130 400	.04		T viol.	$\ll$CP	
ν Factory	20-40	3000	50	4	$< 10^{-4}$	90 ± 20	**huge!**

10. References

1) G.L. Fogli *et al*, Phys. Rev. **D66** 093008, 2002, and G.L. Fogli *et al*, hep-ph/0303064
2) Notation from H. Minakata and H. Nunokawa JHEP **110** 001, 2001
3) V. Barger, D.Marfatia, K.Whisnant, Phys. Lett. **F560** 75, 2003, and K. Dick, M. Freund, P. Huber, M. Lindner, Nucl. Phys. **F598** 543, 2001, and J. Burguet-Castell, M.B.Gavela, J.J. Gomez-Cadenas, P. Hernandez, O. Mena, Nucl.Phys. **B646** 301,2002
4) M. Apollonio *et al.*, Phys.Lett.**B466** 415, 1999
5) K.Peach, these proceedings
6) D. Beavis et al., BNL No. 52459, April 1995
7) W.J. Marciano, hep-ph/0108181, August 2001
8) D. Ayres *et al*, hep-ex/0210005 and http://www-off-axis.fnal.gov
9) Updated Icarus Technical Design Report, CERN/SPSC 2002-027, see also http://pcnometh4.cern.ch/
10) G.Barenboim *et al*, hep-ex/0304017 November 2002
11) See G.P.Zeller, talk given at NuINT02 for a summary of the current status of low energy neutrino cross section data.
12) K2K near/far prediction talk: see talk and proceedings by T. Kobayashi, NuFact02, http://www.hep.ph.ic.ac.uk/NuFact02/Scientific-programme/files/wg2.html
13) J-PARC web page: http://neutrino.kek.jp/jhfnu/ JKJ Home link
14) Itow *et al*, J-PARC to SK Letter of Intent, hep-ex/0106019
15) K. Nakamura, talk at Neutrinos and Implications for Physics Beyond the Standard Model conference, Stony Brook, NY October 2002 http://insti.physics.sunysb.edu/itp/conf/neutrino/talks/nakamura.pdf
16) http://www-bd.fnal.gov/pdriver/8GEV
17) P. Huber, M. Lindner, W. Winter, Nucl.Phys.**B654** 3, 2003
18) H.Minakata and S.Parke, hep-ph/0301210
19) M.V.Diwan *et al* hep-ph/0303081 March 2003, M.V.Diwan *et al* hep-ex/0211001 October 2002, and D.Beavis *et al*, hep-ex/0205040, April 2002
20) The physics potential of both the CERN SPL beam and beta beams is described in the CERN yellow report M. Apollonio *et al.*, hep-ph/0210192
21) A. Cervera et al., Nucl. Phys. **B579** 17, 2000
22) M. Komatsu, P. Migliozzi, F. Terranova, J.Phys.**G29** 443, 2003
23) M.Diwan, M.Messier, B.Viren, L.Wai, NUMI-L-714
24) A. Rubbia, P. Sala, JHEP **209** 4,2002
25) http://dydak.home.cern.ch/dydak/oscexp.ps