Long-Baseline Neutrino Oscillation Experiments in North America

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This contribution to the proceedings of the 2008 NOW Workshop summarizes current and future long-baseline neutrino oscillation experiments in the United States.

1. Introductory comments about long-baseline neutrino experiments

Since the pioneering experiment of Schwartz et al. [1,2], accelerator laboratories around the world have a long history of performing experiments with neutrino beams. Even in the early days, many neutrino experiments searched for the phenomenon of neutrino oscillations, as first discussed by Pontecorvo[3]. One manifestation of the difficulty of experiments with neutrino beams is that several analyses of early experiments gave hints for neutrino oscillations now known to be false. Since the conclusive demonstration of neutrino mixing by the Super-Kamiokande experiment[4], and the understanding of the solar neutrino problem[5–7], we now have a picture of neutrino oscillations and mixing described by a 3×3 mixing matrix known as the MNS matrix, similar to the CKM matrix describing the quarks[8].

While the earliest searches for neutrino oscillations were clearly negative, newer experiments sought to increase the sensitivity. They could get additional sensitivity to the mixing angle by increasing event rates and/or lowering background. They could get additional sensitivity to Δm^2 by increasing L/E, usually by increasing L. These two approaches were called "short-baseline" and "long-baseline". Of course, there is no unambiguous meaning to this separation. One dictionary definition of "long" is "having considerable linear extent in space"[9]. There are two other length scales that might be considered in defining "long-baseline", one having to do with the beam, and the other with physics.

An important distance scale for the beam is the length of the decay pipe. To maximize the neutrino flux, it is desirable to have a decay pipe that is long enough for most of the πs and Ks that are produced at the target to decay. This length is several $\gamma c \tau$ which is about 1 km for a π energy of 18 GeV/c^2. Many early experiments had decay pipes of a few hundred meters, and the detectors were not more than a few hundred meters further. In this case, there was an extended source of neutrinos and a complicated radial dependence to the energy spectrum at the detector. For the long-baseline experiments, the distance from the target to the detector is much larger than the length of the decay pipe. Thus, the far detector is seeing a point source of neutrinos, and this simplifies the kinematics considerably. A measurement of the neutrino spectrum at the near detector is sufficient to predict the neutrino spectrum at the far detector. The reverse would not be true.

One can also imagine a physics definition of a long-baseline accelerator experiment, based on the oscillation length. When long-baseline experiments were first proposed in the 1990's, that length wasn't known. We now know Δm^2_{32}, and a beam that would be many oscillation lengths would be at a distance

$$L >> \pi E_\nu/(2.54 \Delta m^2_{32}) \sim 1500\ km \quad (1)$$

for the mean energy of the NuMI beam from Fermilab to Soudan. Since that baseline is 735 km, by this definition, it is not a long-baseline experiment, and in fact, there have been none to date.

As a practical matter, we usually use the term long-baseline to describe any detector that is not on the same site as the accelerator.

2. Introductory comments about North America

The present and future High Energy Physics program in the United States involving neutrinos is expected to be at Fermilab. Several creative ideas for experiments using the Brookhaven ZGS have been proposed, but this report will concentrate on three experimental programs, all involving Fermilab. The current NuMI beam at Fermilab is aimed at the Soudan mine, 735 km to the north in Minnesota. The MINOS experiment has shown some results, most recently at Neutrino 2008[10], and will continue to run through 2010 and likely beyond. It has made the best measurement to date of Δm^2_{32}. The NOνA experiment is planning to build a large liquid scintillator detector 810 km from Fermilab, and slightly off-axis of the existing NuMI beam. A major goal is to measure a non-zero value for θ_{13}. A future major project is a new neutrino beam from Fermilab to be aimed at the Deep Underground Science and Engineering Lab (DUSEL) at Homestake South Dakota. DUSEL is a facility under consideration by the National Science Foundation. A panel known as P5 (Particle Physics Project Prioritization Panel) recommended in mid 2008 that this be a major component of future HEP planning in the United States.

The funding agencies of High Energy Physics in the United States are the Department of Energy and the National Science Foundation. They get advice on planing from a group of physicists on the High Energy Physics Advisory Panel or HEPAP. Long term planning has been done every five years or so by subpanels which look at the long-term needs of the field. They produced a report in 2001, known by some as the Bagger-Barish report[11], which recommended that the highest priority project be the International Linear Collider (ILC). The ILC design group produced a Reference Design Report in August 2007[12], which included a cost estimate of \$6.6B. The estimated U.S. project cost was \$21.9B[13]. (These two seemingly disparate numbers are based on the same estimate. One is a base cost, and the other includes such things as engineering, management, overhead and profit, contingency and escalation, based on a particular schedule.) When this cost estimate was announced, US effort towards the ILC seemed to noticeably slow down. In particular, Raymond Orbach, the undersecretary for science at the U.S. Department of Energy (DOE), asked for a new report on possible future paths for HEP in the US. This is the P5 report[14] dated May 29, 2008. This new report emphasized three overlapping fields of endeavor in HEP: 1) The energy frontier, including the LHC and a future ILC; 2) The intensity frontier, including neutrinos; and 3) The Cosmic Frontier. The specific projects that they advocated, if implemented, would represent a large increase in the spending on projects for neutrinos in the US. Much of that increase would be towards the end of the ten-year planning period considered by P5. It is in that context that the recommendation for a Fermilab to DUSEL beam should be considered.

3. Results from MINOS

Detailed results from the MINOS experiment which uses the NuMI beamline at Fermilab are presented elsewhere in these proceedings[15]. The most important recent result from MINOS is a measurement of $\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3} eV^2$ (68% CL) based on a measurement of the energy distribution of charged current events at the far detector. The energy distribution that would be expected in the absence of oscillations is measured in a similar near detector located on the Fermilab site. This result is based on 3.21×10^{20} protons-on-target (POT) using data recorded between May 2005 and July 2007. The allowed MINOS parameter space in $\sin^2 2\theta$ and Δm^2, including systematic errors, is shown in Figure 1 along with a previous MINOS result and other high precision experiments[16].

One other result from MINOS on cosmic rays is not directly related to neutrinos, but is quite interesting. The ratio of atmospheric muons μ^+/μ^- has been previously measured over a range of three orders of magnitude, from 100 MeV to 100

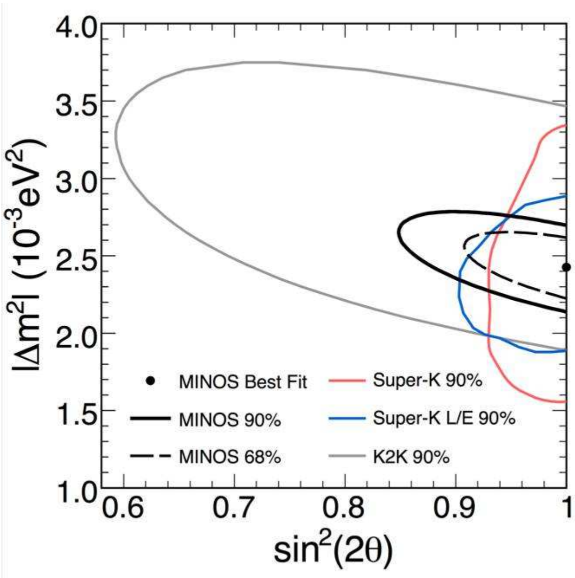

Figure 1. Allowed neutrino oscillation parameter space from the 2008 MINOS result with other results.

GeV. It has a value slightly higher than one because cosmic rays are positive. The value, about 1.25, did not vary over that energy range. With a magnet, MINOS precisely measured a higher value[17], determined that the relevant variable was $E_\mu^{surface}\cos\theta_z$ (where θ_z is the zenith angle) and not $E_\mu^{surface}$, and related the ratios K^+/K^- and π^+/π^- secondaries from cosmic rays. This additional rise is related to TeV associated production (ΛK^+). The rise at this value of $E_\mu^{surface}\cos\theta_z$ is not due to increased particle production, but rather to the different mix of π and K decay contributions from their different critical energies in the atmosphere, 115 GeV and 850 GeV respectively, i.e. the energies at which their interaction and decay rates are equal[18].

MINOS has also made a number of other measurements involving both neutrinos and cosmic rays. A measurement of the neutral current events from the NuMI beam provides a method to search for sterile neutrinos[19]. It has also measured atmospheric neutrinos[20,21]. The rate of interactions at the near detector provided a chance to search for violations of Lorentz Invariance[22]. The long-baseline itself provides a new regime for measuring neutrino time-of-flight[23]. And the atmospheric muons provide a high-statistics sample for traditional cosmic ray studies such as moon/sun shadows and seasonal variations[24].

4. Further running for MINOS

The measurement of Δm^2_{32} by MINOS is currently limited by statistics, and will be for the foreseeable future. Through September 2008, there have been 5×10^{20} POT delivered, and the rate has increased to over 2×10^{20} protons per year. Continued running of MINOS by Fermilab depends on a more complicated set of priorities in the US. The Tevatron program is expected to come to an end when the LHC turns on. This will provide forces that both increase and decrease the desirability of continuing to run the accelerator program through the Main Injector complex, which is needed for the neutrino program.

MINOS itself has two additional physics goals which will benefit from additional protons. These are the search for θ_{13} by looking for $\nu_\mu \to \nu_e$ appearance, and the study of oscillations using antineutrinos. Currently there is intense analysis for $\nu_\mu \to \nu_e$ appearance and a result based on 3.25×10^{20} POT is expected in early 2009. The expected sensitivity has been presented, and for many values of the CP violation parameter δ, it is slightly better than the CHOOZ limit[8]. Another major current analysis of MINOS is to measure the $\nu_\mu \to \nu_\tau$ parameters with antineutrinos. This could be done either using the antineutrinos in the current MINOS beam, or with future dedicated antineutrino running, i.e. with the horn current reversed to focus π^- and K^-. Again, results and sensitivities are expected in early 2009.

5. NOνA

NOνA is a new Fermilab project to put an off-axis detector in the NuMI beam. NOνA is designed to search for $\nu_\mu \to \nu_e$ appearance by comparing electron neutrino rates at Fermilab with the rates observed in a large detector 810 kilometers from Fermilab. A search for this oscillation channel has three main backgrounds: 1) ν_e in the beam; 2) ν_μ NC and CC events which cannot be distinguished in the detector from an electron shower; and 3) $\nu_\mu \rightarrow \nu_\tau$ oscillation where the τ decays into an electron. Due to a variety of kinematic effects, all three of these backgrounds become less important when you go off-axis of the neutrino beam, even when you take into account the lower average neutrino energy and flux, which lead to a lower event rate.

As currently envisioned[25], the 15 kiloton NOνA far detector will be composed of 385,000 cells of extruded PVC plastic in a cellular structure. Each cell will be 3.9 centimeters wide by 6.0 centimeters deep and 15.5 meters long. The cells are filled with 3.3 million gallons of liquid scintillator. The liquid scintillator comprises 70% of the total detector mass, making it a totally active tracking calorimeter, optimized for identification of ν_e interactions. The detector will be read out by 0.7 mm diameter optical wave-shifting fiber into 12,000 avalanche photodiodes. A 222 ton Near Detector will be constructed with identical components.

NOνA is sensitive to θ_{13} and also the mass hierarchy (See Figure 2) and CP violation in a complicated way. Event rates and backgrounds also depend on θ_{12}, θ_{23}, Δm^2_{32} and the mass hierarchy. The most recent sensitivities for NOνA can be found in Reference [26].

During the dramatic FY2008 budget jolts to HEP in the US, the fate of NOνA itself went through some dramatic oscillations. Fermilab had approved and given some funding to the construction, but the December 2007 continuing resolution specifically provided zero funds and stopped much work on the project. A supplemental appropriation in the summer provided some money to continue, but the initial continuing resolution for FY2009 led the DOE to state that NOνA could be canceled if that was the final budget for 2009. As this article is being written, however, most activities on NOνA have resumed, and there is cautious optimism that NOνA will continue.

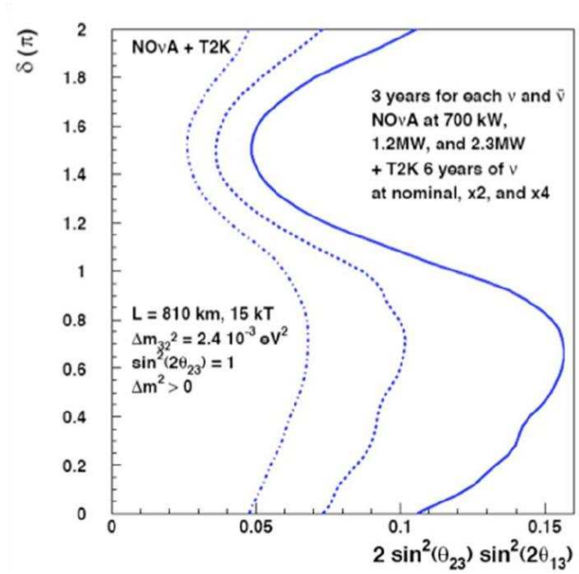

Figure 2. Regions of parameter space where NOνA (3 power assumptions) together with T2K can determine the mass hierarchy.

6. DUSEL and LB-DUSEL

The Deep Underground Science and Engineering Lab (DUSEL) is a proposed new facility at the site of the former Homestake mine and Davis Solar Neutrino Experiment in South Dakota where a large amount of space for underground science in the US is planned. Currently, much of the useful lab space is under water, as the pumps were turned off after mining was halted early in the 21st century. Homestake was chosen by the NSF as the preferred site for a deep underground facility from 7 proposed sites. A significant donation by philanthropist Denny Sanford is allowing some work to go forward before a final decision on DUSEL is made by the National Science Board.

The possibility of a large multi-purpose detector at DUSEL that could serve as a new long-baseline neutrino detector, as well as other fundamental particle physics such as proton decay, was attractive to the 2008 P5 panel. I will here quote three places from their report[14]:

"The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab."

"The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technology for a large detector at DUSEL."

"The panel further recommends that in any funding scenario considered by the panel, Fermilab proceed with the upgrade of the present proton source by about a factor of two, to 700 kilowatts, to allow a timely start for the neutrino program in the Homestake Mine with the 700-kilowatt source."

The upgrade to 700 KW is part of the NOνA project, and has been also known as ANU (for Accelerator project for NeUtrinos.) The further upgrade to a multi-megawatt proton source has been previously known as the proton driver, but currently is called Project X. Whatever the future neutrino program at Fermilab, increased proton intensities are a logical component of that program, and a variety of scenarios, too long to describe here, have been considered.

An LB-DUSEL collaboration is forming to design and implement the beam and detector required for a long-baseline physics program from Fermilab to DUSEL. Much of the physics case has been described in several documents. For example, see Reference [27].

A specific configuration for a long-baseline detector could be three cavities for water Cherenkov detectors, with each one containing a fiducial volume of 100 kilotons. Preliminary engineering drawings for this configuration at the 4850 level are being developed. Major issues of detector design are still being considered, however. Some feel that the concept of a liquid argon detector offer substantial advantages over a water Cherenkov detector, even though considerable R&D is needed to show that large liquid argon detectors are feasible. New developments in phototube design could reduce the anticipated cost of large water Cherenkov detectors. Arguments can also be made for both on-axis and off-axis location of the detectors.

At this stage, the schedule for a possible Fermilab to DUSEL beam has a large uncertainty. Physics goals and fiscal reality inevitably pull in opposite directions. Even though DUSEL is a planned NSF project, a new beam line from Fermilab, Project X and a large multi-purpose detector would either be DOE or joint NSF-DOE endeavors. The time-consuming DOE critical decision step-by-step process would be followed, which includes CD0, CD1, CD2, CD3 and CD4. A start of operations in 2020 could be imagined.

P5 emphasized that the idea for a new long-baseline project from Fermilab to DUSEL was a vision, not a plan. It consists of several parts, which can alternately be regarded as a strength and a weakness. To put a scale on the vision, I have attached my own cost estimates to some of the parts, with all the dangers and none of the required caveats that this entails: 1) DUSEL which is a \$500M+ facility; 2) A new beam line at Fermilab; \$250M; 3) Project X; \$1B; and 4) A new huge detector; (\$500M-\$1B). None of these components currently exist or are approved. However, all elements of the vision have independent motivations, and could be part of a future US HEP roadmap if there is the continued scientific motivation and will to do so.

7. Other ideas for long-baseline experiments

In this presentation, I have concentrated on a particular evolution of long-baseline neutrino projects in the U.S.

$$\mathrm{MINOS} \rightarrow \mathrm{NO}\nu\mathrm{A} \longrightarrow \mathrm{long-baseline\ DUSEL} \quad (2)$$

It is worth mentioning that other ideas have been investigated, and that even though they are not on the current roadmap, sometimes when conditions change, we return to such ideas. One possibility is to construct an additional detector along the NuMI beamline, such as a 5 kiloton liquid argon detector at Soudan. Another thought is to build a detector further off-axis at the 2nd oscillation maximum. The AGS at Brookhaven has been considered as the source of a high energy neutrino beam, possibly using a hill rather than digging underground to aim such a beam. Many U.S. scientists are participating in an international effort to consider coupling a muon storage ring to a neutrino factory, which could be a source of both high energy nu_μ and ν_e for oscillation studies. We point out here that a good road map includes both our desired destination, but also places that we do not go.

8. Conclusions

Together with recent results from MINOS, a future program incorporating NOνA and a long-baseline beam from Fermilab to DUSEL represents one possible scenario for a future U.S. High Energy Physics program with a significant neutrino component. Other futures are also possible. Depending on the value of θ_{13}, we may find that the future involves serious consideration of intercontinental neutrino beams, with the concomitant additional challenges in planning within an international framework.

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