Conf-9406269--3
ANL-HEP-CP-94-82
NuMI-L-44

LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENTS*

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Abstract

The status and capabilities of long-baseline neutrino oscillation experiments are reviewed.

1 Introduction

There is no unambiguous definition for long baseline neutrino oscillation experiments. The term is generally used for accelerator neutrino oscillation experiments which are sensitive to $\Delta m^2 < 1.0\ eV^2$, and for which the detector is not on the accelerator site. One earlier review of possible long-baseline (LBL) experiments is out of date.[1] The Snowmass N2L working group met to discuss the issues facing such experiments. The Fermilab Program Advisory Committee adopted several recommendations concerning the Fermilab neutrino program at their Aspen meeting immediately prior to the Snowmass Workshop.[2] This heightened the attention for the proposals to use Fermilab for a long-baseline neutrino experiment at the workshop.[3, 4, 5, 6] The plan for a neutrino oscillation program at Brookhaven was also thoroughly discussed.[7, 8] Opportunities at CERN were considered, particularly the use of detectors at the Gran Sasso laboratory.[9, 10] The idea to build a neutrino beam from KEK towards Superkamiokande was not discussed at the Snowmass meeting, but there has been considerable development of this idea since then.[11] Brookhaven and KEK would use low energy ($< E_\nu > \sim\ 1\ GeV$) neutrino beams, while FNAL and CERN would plan have medium energy beams ($< E_\nu > \sim\ 15\ GeV$).

Long-baseline Neutrino Oscillation Experiments are motivated in part by the atmospheric neutrino deficit.[12] This is well matched to the capabilities of LBL experiments, $2 \times 10^{-3} eV^2 < \Delta m^2 < 1 eV^2$; $\sin^2(2\theta) > 0.1$. However, there is also theoretical interest in lower mixing angles,[13] ($\sin^2(2\theta) \sim 0.03$) which provides motivation to design experiments with higher statistics in order to achieve lower statistical and systematic errors.

This report will summarize a few topics common to LBL proposals and attempt to give a snapshot of where things stand in this fast developing field.

2 Generic Issues for Long-baseline Experiments

The probability that a neutrino will oscillate is given as

$$P_{\nu_1 \to \nu_2} = \sin^2(2\theta)\sin^2\frac{1.27\Delta m^2 L}{E} \qquad (1)$$

with L given in kilometers, E_ν in GeV and $\Delta m^2 = m^2_{\nu_1} - m^2_{\nu_2}$ in eV^2. The figures of merit for comparing one neutrino oscillation experiment to another are the sensitivity curves in the $\Delta m^2 - \sin^2(2\theta)$ plane. Usually these are constructed as 90%CL contour curves for limits or favored regions, and unless there is only sensitivity to high mixing angle, a log-log plot is used. For most limits, the curve corresponds to a minimum probability of oscillation, defined as P_{min}. It depends on the details of the test, neutrino source, energy distribution, possible backgrounds and systematic errors, and statistics. Adequate statistics is a key challenge of long-baseline experiments. A complete comparison of one experiment vis-a-vis another, however, goes somewhat beyond the limit curve, as discussed in the summary.

For the purpose of designing an "optimum" experiment it is useful to consider an approximation to the 90% CL limit curves. At high Δm^2 where the oscillations from different parts of the energy spectrum average out, $P_{min} = 0.5\sin^2(2\theta)$ for all Δm^2, so that $\sin^2(2\theta_0) = 2P_{min}$. Likewise, at maximal mixing, $\Delta m_0^2 = (< E_\nu > \times \sqrt{P_{min}})/1.27L$. Also at maximal mixing the slope on the log-log plot is

*This work supported by the U.S. Department of Energy, Division of High Energy Physics under contract No. W-31-109-ENG-38. This paper contributed to the, "Proceedings of Particle and Nuclear Astrophysics and Cosmology in the Next Millenium," June 22 - July 14, 1994, Snowmass, Colorado

DISCLAIMER

-1/2 because

$$\left.\frac{\partial \Delta m^2}{\partial \sin^2(2\theta)}\right)_{\sin^2(2\theta)=1} = -\frac{1}{2} \qquad (2)$$

The two lines intersect at $\Delta m_1^2 = \Delta m_0^2/\sqrt{2P_{min}}$. Such a two line curve is shown in Figure 1. (The approximation to the actual limit curve is quite good.)

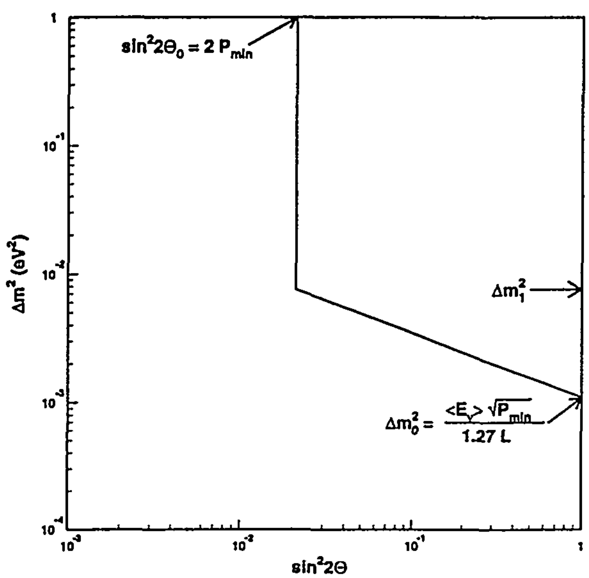

Figure 1: Approximation to a neutrino oscillation limit curve showing the relationship between P_{min} and the intercepts for $\sin^2(2\theta) = 1$ and high Δm^2.

P_{min} can be derived exactly for a variety of tests. We list here the results of these calculations for long-baseline neutrino oscillation tests which have been discussed. We consider the case with no cosmic ray backgrounds or systematic errors:

- Background-free test $P_{min} = 2.3/N_{cc} \times \eta \times \epsilon$
- Disappearance $P_{min} = 1.29/\sqrt{N_{cc}}(1 - \eta B)$
- NC/CC ratio

$$P_{min} = \frac{1.29 R^{true}(1 + R^{true})}{\sqrt{N R^{true}} \times [\eta(1-B) + R^{true}(1 - B\eta)]}$$

- Kinematic cuts $P_{min} = 1.29\sqrt{\kappa N_{cc}}/\epsilon\eta N_\mu$

where N_{cc} is the total number of charged current events, N is the total number of neutrino events (CC+NC), R^{true} is the expected NC/CC ratio, η is the ν_τ to ν_μ CC cross section ratio, B is the branching ratio for τ decay to muons, ϵ is the τ event analysis efficiency including branching ratios, and κ is the ν_μ CC background rejection from the kinematic cuts being used, expressed as a fraction from 0 to 1. Numerical constants such as 1.29 depend on the choice of 90% CL limits. $\eta(E)$ is energy dependent, but we estimate $< \eta > \sim \eta(< E_\nu >)$. For $\nu_\mu \rightarrow \nu_\tau$ neutrino experiments at Brookhaven or Fermilab energies, typical values for P_{min} are:

FNAL disappearance	$1.35/\sqrt{N_{cc}}$
FNAL $R_{``nc"/``cc"}$	$1.87/\sqrt{N}$
FNAL kinematic cuts	$1.43/\sqrt{N_{cc}}$
BNL disappearance	$1.29/\sqrt{N_{cc}}$
BNL $R_{``nc"/``cc"}$	$3.03/\sqrt{N}$

No neutrino oscillation test is the clear preference based on statistical power alone. The extension to include systematic errors and backgrounds in the formulae is relatively straightforward.[3]

An accurate curve can be calculated in lieu of the approximate lines in Figure 1 by integrating over the neutrino energy spectrum. The approximation is useful, however, for seeing how the limit scales as parameters are changed. For example, to see the effect of placing a fixed size detector at different distances (L) from an accelerator, the statistics $N \propto 1/L^2$. Then $P_{min} \propto 1/\sqrt{N} \propto_L$, so $\Delta m_0^2 \propto \sqrt{P_{min}}/L \propto L^{-1/4}$ for a fixed size detector. Also, $\sin^2(2\theta_0) \propto L$.

In contrast, the variation as a function of beam energy is quite complicated. As the proton beam energy E_p is raised, there are more secondaries per proton, the secondary beam is more forward, and the average neutrino energy rises logarithmically so that there are more events due to the higher ν cross section, as well as relatively more ν_τ events as $\eta(E)$ increases. However, there would be less proton spills in a fixed calendar time, less secondaries would decay in a fixed length beam pipe, and Δm^2 sensitivity decreases as $< E_\nu >$. The result of detailed calculations for the $R_{``nc"/``cc"}$ test show a broad optimum from 100 GeV to 400 GeV for a detector at 700 km.

One important facet of the neutrino energy is the relationship to ν_τ charged current threshold. Below or just above $< E_\nu >\sim 5GeV$, an experiment can measure the change in ν_μ CC event rate, or the NC event rate which does not change. At higher energies, ν_τ CC events contribute and a larger number of neutrino oscillation signatures is possible.

3 Review of Specific Proposals

Plans for long-baseline neutrino experiments are being made for nuclear reactors at San Onofre and Chooz and for accelerators at Brookhaven, KEK, Fermilab, and CERN. The reactor experiments are sensitive to $\nu_e \rightarrow \nu_\mu$ (or $\nu_e \rightarrow \nu_\tau$) oscillations. Accelerator experiments are sensitive to $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_e$ oscillations.

3.1 Reactor Experiments

Nuclear reactors are abundant sources of $\bar{\nu}_e$'s with energies up to about 8 MeV. Several neutrino oscillation experiments have been conducted at nuclear reactors.[14] The event rate of $\bar{\nu}_e p \rightarrow e^+ n$ is measured at two or more locations. Systematic errors probably restrict this kind of experiment to $\sin^2(2\theta) > 0.05$. At present, there is no evidence for oscillations from these experiments. Recent limits from Krasnoyarsk[15] and Bugey[16] have pushed the limits to lower Δm^2 below $10^{-2}eV^2$. New experiments are being planned at San Onofre and Chooz. The San Onofre experiment plans a .13 ton target 24m from the core, along with a 12 ton target at a distance of 650 m. Either experiment should see a large effect if the atmospheric ν_μ deficit is due to $\nu_e \rightarrow \nu_\mu$ oscillations.

3.2 Brookhaven

There are two ideas to use the AGS at Brookhaven to do a long-baseline disappearance experiment. One involves a collaboration led by Al Mann which plans to build four two-kiloton water Cerenkov detectors.[7] Two of them would be 24 km away on the shore of Long Island at Northville. The other two would be on site, one and three km away respectively. In 120 days of running the AGS, they would expect 4400 $\nu_\mu n \rightarrow \mu^- p$ events and 1100 $\nu N \rightarrow \nu N \pi^o$ neutral current events at the far detectors. The systematic errors would be small and verifiable through the use of four identical detectors. Statistical errors would be on the order of 1%. The sensitivity to neutrino oscillations has been increased by aiming the beam off axis in order to favor low energy neutrinos in the beam. The experiment has been approved, but not yet funded. The cost estimate when the proposal was made was $33M.

An alternative idea for a long-baseline experiment at Brookhaven has been developed by Ted Kycia.[8] He would use steel plates and optical spark chambers with video camera readout, and has operated a prototype at Brookhaven. Beam which is extracted from the AGS could be made into a neutrino beam aimed at Connecticut without a large bend. A detector in Collinsville Connecticut would be about 100 km away.

3.3 CERN

An attractive possibility for CERN is to aim a neutrino beam from the SPS to the Gran Sasso Underground Laboratory, 732 km away. The targeting for a neutrino beam to Gran Sasso could be done in the extraction tunnel from the SPS to the LHC.

One proposal has been made by the ICARUS collaboration[9]. They plan to build a 5 kiloton time projection chamber in Hall C of the Gran Sasso. They have built a successful prototype ionization chamber using liquid Argon that is continuously sensitive, self-triggering, able to provide three-dimensional images of ionizing events, and able to identify particles (by dE/dx) and their direction. Such a detector is also an excellent calorimeter with high granularity and resolution. The cost estimate for the ICARUS detector is 62M Swiss Francs.

Another idea suggested by the Genius collaboration led by Barry Barish and Doug Michael is for a 17 kT magnetized iron calorimeter in Hall B of the Gran Sasso.[10] The detector would have 4 cm iron plates and use resistive plate chambers. Studies have shown that a 2 cm pitch for the readout strips give reasonable separation and resolution for tracking. The estimated cost is $28M.

3.4 Fermilab P-822

A collaboration including the Soudan 2 group proposed to use the existing Soudan 2 Detector with a neutrino beam from the Fermilab Main Injector 733 km away (P-822).[3] The Soudan 2 detector is a fine-grained 1 kiloton iron calorimeter designed to measure 1 GeV proton decay events. It is thus well suited for the 2-10 GeV visible E_{had} from neutral current events in the Fermilab beam. The best test for $\nu_\mu \rightarrow \nu_\tau$ oscillations is the neutral current to charged current test. Some Soudan modules would be placed behind the short baseline experiment (E-803) at Fermilab, and $R_{``nc"/``cc"} = \frac{NC}{CC}$ would be measured in two locations by detecting the presence or absence of a muon in the neutrino event. In the far detector, the number of events in the denominator would go down for $\nu_\mu \rightarrow \nu_\tau$ oscillations, while the number of events in the numerator would rise due to ν_τ charged current events.

P-822 could measure 1200 events per Main Injector year with a 320 meter decay pipe. Enhancements such as a toroid magnet for muon momentum measurement and the near detector would cost about $4M.

3.5 Fermilab Expressions of Interest

The Fermilab PAC was intrigued with P-822, but preferred a more ambitious program. They established two broad characteristics for a Long-baseline experiment: "1. It must extend the limit in Δm^2 or $\sin^2(2\theta)$ by a significant factor. This suggests that an acceptable sensitivity in the exclusion plot for such an experiment is $\Delta m^2 \sim 10^{-2}eV^2$ and $\sin^2(2\theta) \sim 10^{-2}$. *and* 2. It will be necessary that a positive signal capability be convincing, which implies the capability of measuring backgrounds and quantitatively determining systematics."[17]

In March of 1994, Fermilab called for Long-baseline Expressions Of Interest (EOI) assuming a Main Injector intensity of 5×10^{13} protons in a pulse every 1.9 s. Three were received. Stan Wojcicki (EOI-7) proposed a narrow band beam and several large water Cerenkov detectors located at SLAC.[4] Barry Barish and Doug Michael (EOI-8) assembled a large group with the idea of constructing a 17 kiloton magnetised iron calorimeter at either IMB or Soudan.[5] Maury Goodman and the P-822 group also suggested a large iron calorimeter with magnetic measurement at a new hall at Soudan (EOI-9) to supplement the existing detector.[6] The large detector cost estimates were $30M - $40M.

At their 1994 Aspen meeting, the Fermilab PAC endorsed a joint short-baseline(E-803)/long-baseline program at the Fermilab Main Injector, and encouraged the three long-baseline groups to merge.[2] A schedule for experiment approval and beam design was spelled out, in order to obtain DOE approval and a congressional line item in the FY1998 budget.

3.6 KEK

A neutrino beam from the KEK 12 GeV PS could be used in conjunction with the SuperKamiokande experiment. Superkamiokande is a 30 kT water Cerenkov detector under construction 245 km from KEK. They will detect 500 ν events for 10^{20} protons on target (*pot*). Another 2kT detector at 25 km located on the surface would be 1.34^o off axis from the neutrino beam, and could measure 1700 ν events for 10^{20}*pot*.

4 Summary and Prospects

Options for Long-baseline experiments for the United States are at Brookhaven and Fermilab, or to participate in programs abroad. The high energy (FNAL, CERN) and low energy (BNL, KEK) opportunities are complementary, but fiscal constraints may well prevent major participation in all options. It is likely that a HEPAP subpanel will consider the alternatives in the next year. As mentioned above, the major figure of merit is the limit plot on the $\sin^2(2\theta) - \Delta m^2$ plane, and the related sensitivity for discovery of oscillations should they exist. This is affected not only by the statistics, but also detailed consideration of possible systematic effects and backgrounds, and also the number of independent tests which could measure neutrino oscillations. There are also several other important factors to be considered, which are more difficult to quantify:

1. Other physics capabilities of the experiment, relating to low energy neutrinos or cosmic rays.
2. Civil construction feasibility and costs.
3. Detector feasibility and costs.
4. Complementarity or incompatibility of an experiment within an accelerator program.
5. Possible public concerns about off-site accelerator facilities.
6. The schedule for getting a compelling positive or negative result.

It seems likely that one or more of the proposed long-baseline experiments will proceed. If ν oscillations are lurking in the area of parameter space $10^{-3}\ eV^2 < \Delta m^2 < 1\ eV^2; \sin^2(2\theta) > 0.02$, as suggested both by the atmospheric neutrino anomaly and independently by several theoretical ideas, long-baseline neutrino oscillation experiments will become a long and active part of our experimental high energy physics program well into the next millenium.

Acknowledgments

Over 100 individuals participated in the N2L session of the Snowmass Workshop, including 34 presentations. Special thanks to Al Mann and Douglas Michael for their work in organizing the sessions. This work was supported in part by U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

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