Very Long Baseline Neutrino Oscillations, The BNL VLBNO Concept.

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A wide energy-band neutrino beam sent over a very long baseline to a massive detector can break the degeneracies in the neutrino oscillation parameters. It can measure the disappearance parameters with precision and determine the mass hierarchy. If θ_{13} is large enough the CP violating phase can be measured with neutrino running alone and anti-neutrino running can confirm CPV and improve the parameter measurements. Brookhaven National Laboratory is pursuing such an experiment.

1. Introduction

As shown at this conference and elsewhere, one of the main challenges in measuring neutrino oscillation parameters in most current and proposed experiments are degeneracies.

Brookhaven National Laboratory is designing an experiment that can break these degeneracies, measure or limit all neutrino parameters, determine the mass hierarchy and be sensitive to new physics. This experiment incorporates intense, wide band and high energy neutrino and anti-neutrino beams, a very long baseline and a massive far detector.

2. Motivation for Experiment Parameters

The primary motivation for this arrangement is to observe multiple neutrino oscillation periods. This provides two main benefits over traditional single oscillation LBNO experiments. First, since peak-to-valley and node-to-node features of the disappearance oscillation pattern can be resolved, a precision measurement of Δm^2_{32} and $\sin^2 2\theta_{23}$ can be made which is not strongly dependent on absolute event normalization. Second, the effects that govern $\nu_\mu \rightarrow \nu_e$ appearance have different strengths at different energies so by resolving multiple appearance peaks these, otherwise degenerate effects, can be disentangled.

Fermi motion of the nuclei in the active medium of the far detector begins to dominate the reconstructed energy resolution when the neutrino energy is below $\sim$ 500 MeV. Avoiding this requires high neutrino energies and placing the far detector at a baseline that is long enough for multiple oscillation periods to occur well away from this Fermi motion dominated energy region. Current best fits of Δm^2_{32}implies a baseline of $>$ 2000 km and an energy coverage from above the Fermi-motion dominated range up to $\sim$10 GeV.

Finally, in order to collect enough statistics a massive detector, a high intensity neutrino source and a sufficiently long running time are needed. We assume a Water Cherenkov detector of 500 kTon fiducial mass, such as UNO or HyperK with performance as good or slightly better than current Super-Kamiokande.

An upgrade[1] to the BNL Alternating Gradient Synchrotron (AGS) will initially produce a 1 MW proton beam. The Booster will be replaced by a 1.2 GeV super-conducting Linac that will increase the protons per pulse from 7 to 9×10^{13} and allow the fill time to be reduced from 0.6 second to 1.0 millisecond. Power supply and magnet upgrades will be needed to improve the AGS repetition rate from 0.5 Hz to 2.5 Hz.

The proton beam will be directed to a fixed target and conventional focusing horn system positioned on a $\sim$50 m tall hill. The secondaries will decay down a 200 m long, 4 m wide tunnel pointing towards the far detector producing the expected neutrino flux shown in Fig. 1. The far site is assumed to be either of the two DUSEL candidates, Homestake, SD or Henderson, CO at

2540 km and 2770 km from BNL, respectively. Initial running will determine the mass hierarchy and dictate the subsequent running mode. The nominal run plan is 5 years[1] neutrino running at 1 MW followed by 5 years anti-neutrino running at 2 MW.

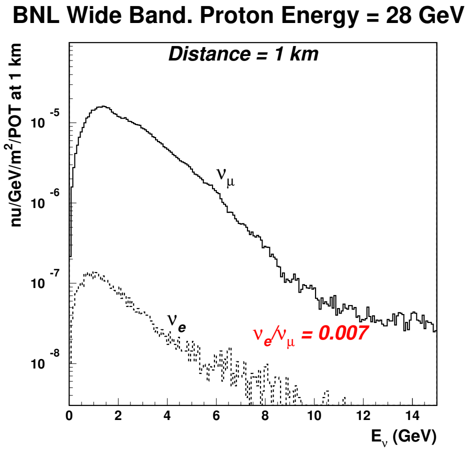

Figure 1. Expected neutrino flux at 1 km with 1 MW, 28 GeV proton beam, 60 cm carbon target and 4 m wide, 200 m long decay tunnel.

3. Illustrative Oscillation Probability Plots

This presentation attempts to focus on how the degeneracies in the parameters governing $\nu_\mu \rightarrow \nu_e$ appearance are broken through examining simple oscillation probability plots. The cost of this simplicity is to ignore the extremely critical issues of detector performance. These issues are being addressed in the larger context of the concept and other work[2,3] has gone in to more detail.

Unless otherwise stated, for these probabilities plots the nominal values are taken to be there current best fits: $\Delta m^2_{21} = 8.0\text{e-}5\ eV^2$, $\Delta m^2_{32} = 2.5\text{e-}3$ $e\text{V}^2$, $\sin^2(2\theta_{23}) = 1.0$, $\sin^2(2\theta_{12}) = 0.86$. For the unknown values we take $\sin^2(2\theta_{13}) = 0.04$ and $\delta_{CP} = 0$. The baseline is taken to be the BNL-Homestake one of 2540 km. The longer BNL-Henderson is essentially equivalent. The neutrinos are propagated through the PREM[4] Earth density profile.

Figure 2 shows four affects to the $\nu_\mu \rightarrow \nu_e$ appearance probability over the energy range covered by the VLBNO flux. Figure 2.a shows that the features are well centered in the region of flux coverage. If the true value of Δm^2_{32} varies within current uncertainties all features are still well within the flux coverage.

Figure 2.b shows the large matter effect and that it appears almost entirely in the first peak. The effect due to the sign of Δm^2_{32} will produce a clear result.

Figure 2.c shows that the effect of a CP violating phase increases as one goes to higher oscillations (lower energy).

Figure 2.d shows that with $\theta_{13} = 0$ the BNL VLBNO experiment is expected to see $\nu_\mu \rightarrow \nu_e$ appearance in the sub-GeV region due to subdominant Δm^2_{21} driven oscillations. This provides a unique terrestrial based measurement of solar neutrino parameters which can be checked against solar neutrino data from SK and SNO. Any deviation can be a sign of new physics.

Table 1 summarizes these effects and illustrates in what energy range they dominate. The value of θ_{13} effects the absolute event rate independently of energy. The mass hierarchy strongly influences the rates above 2 GeV. The value of δ_{CP} is greatest in the middle energy range of 1-2 GeV. Finally, $\nu_\mu \rightarrow \nu_e$ appearance due to solar oscillations is very strong, but only in the lower energy range below 1 GeV. It is this distribution of effects across the energy range that allows the BNL VLBNO experiment to break the degeneracies. Any LBNO experiment which targets a single oscillation will not be able to disentangle these effects without the proper addition of other detectors, baselines or completely separate experiments.

The plots in Figure 3 show expected spectra and parameter resolutions. The details of this study are presented elsewhere[2].

[1]We take 1 year = 10^7 seconds.

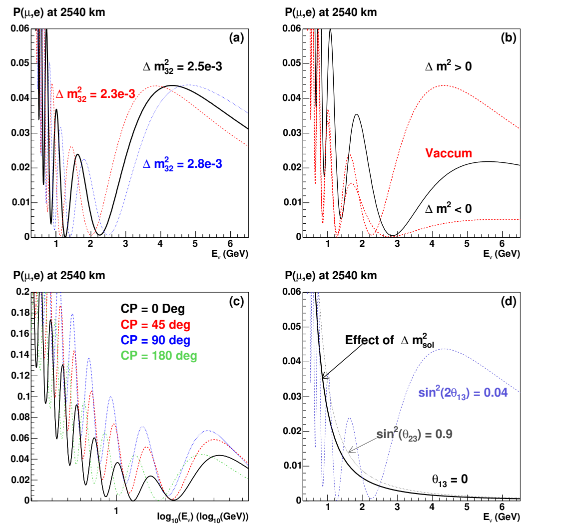

Figure 2. Different effects contributing to the appearance probability over the energy range covered by the BNL VLBNO. (a) Current best fit for Δm^2_{32} and at $\pm$ 90% CL (dot/dash resp.), (b) Oscillation in vacuum (solid line) and in matter with $\Delta m^2_{32}> 0$ (upper) and < 0 (lower dashed), (c) the effect of varying CP phase angle and (d) the effect of $\theta_{13} = 0$. See text for details.

4. Conclusion

Through the use of a wide band and high energy neutrino beam, a very long baseline and a massive far detector the BNL VLBNO experiment will determine the mass hierarchy, precisely measure or strongly limit all neutrino oscillation parameters and break parameter degeneracies.

REFERENCES

1. W. T. Weng, M. Diwan, and D. Raparia (eds.), The AGS-Based Super Neutrino Beam CDR, BNL-73210-2004-IR, 2004. http://nwg.phy.bnl.gov/papers/agsnbcdr1.pdf
2. M.V. Diwan, et al, VLBNO Experiment, Physics Review D 68, 012002 (2003).
3. C. Yanagisawa, Water Cherenkov Simulation Studies on Backgrounds and Resolution, 3rd BNL/UCLA Workshop (2005).

Table 1
Summary of strength of different appearance effects in different energy ranges.

E_ν (GeV):	< 1	1 - 2	> 2
$\sin^2 2\theta_{13}$	$\surd\surd$	$\surd\surd$	$\surd\surd$
$sign(\Delta m^2_{32})$	-	-	$\surd\surd\surd$
δ_{CP}	$\surd$	$\surd\surd$	$\surd$
solar	$\surd\surd\surd$	$\surd$	-

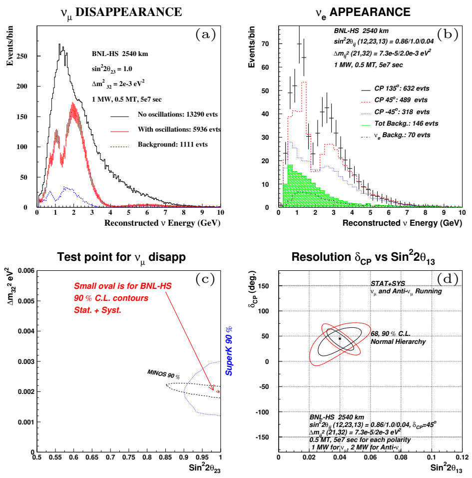

Figure 3. Expected disappearance (left) and appearance (right) spectra (top) and uncertainties for example test points (bottom).

4. As taken from, I. Mocioiu, R. Shrock, Phys.Rev. D62 (2000) 053017.