BNL Very Long Baseline Experiment With a Super Neutrino Beam

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Abstract. An upgrade to the BNL AGS could produce a very intense proton source at a relatively low cost. This proton source could produce a conventional neutrino beam with a very significant flux at large distances from the laboratory. In this paper we examine the possibility of using this neutrino beam for a very long baseline oscillation experiment where a 500 kiloton water Cherenkov detector is situated at the Homestake mine in South Dakota. We study the physics potential of a high intensity neutrino oscillation experiment with a 2540 km baseline and a peak neutrino energy of ~1 GeV.

INTRODUCTION

Recent results have shown that neutrinos can oscillate between flavor states. This has created interest in understanding the fundamental aspects of neutrino oscillations. To explore the physics of the neutrino masses and mixing angles will require new facilities with intense proton beam sources. A working group at Brookhaven National Laboratory is studying the feasibility of upgrading the AGS to a 1.0 MW proton sources and using it to create an intense neutrino super-beam capable of producing a significant flux at a large distance from BNL. The AGS upgrade would increase the repetition rate of the accelerator from 0.5 to 2.5 Hz with 8.9×10^{13} protons per pulse. The expected integrated intensity for a typical year of operation (10^7 sec.) is expected to be 2.2×10^{21} 28 GeV protons on target. A description of the accelerator, target and horn system, and ν beamline of this super-beam facility is given in a report by the working group [1]. The physics potential of this proposed long baseline experiment is described in another report [2, 3]. The goal of this facility is to have the ability to measure all of the parameters of the SMN matrix in a single experiment. This includes:

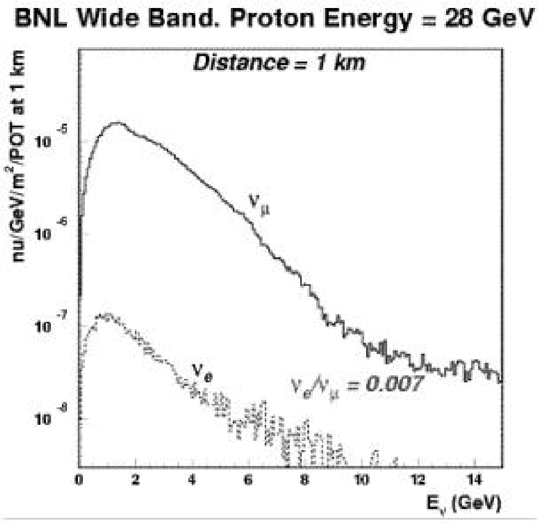
- A precise determination of the oscillation disappearance parameters Δm_{32}^2 and $\sin^2 2\theta_{23}$.
- The detection of the appearance oscillation $\nu_\mu \rightarrow \nu_e$ and the measurement of $\sin^2 2\theta_{13}$.
- The measurement of $\Delta m^2_{21} \sin^2 2\theta_{12}$ in a $\nu_\mu \rightarrow \nu_e$ appearance mode.
- The verification of the matter enhancement and the sign of Δm_{32}^2.
- The determination of the CP-violation parameter δ_{CP} in the neutrino sector.

The useful neutrino energy range is restricted at ~1 GeV on the low end by Fermi motion in the nucleus and by ~6 GeV on the high end by background from inelastic ν

interactions. Placing the detector at the Homestake Mine, which is 2540 kilometers from BNL, allows the oscillation phase to vary from below $\pi/2$ to above $5\pi/2$ for Δm_{32}^2=0.0025 eV^2, which would clearly demonstrate oscillations in the energy distribution and provide a precise measurement of Δm_{32}^2. For the purposes of calculating expected event rates and backgrounds a 0.5 megaton water Cherenkov detector is used. A neutrino beam directed at the Homestake Mine must be inclined into the ground by 11.3° with respect to the surface. This incline restricts the location of the close-in detector to be just outside the beam dump at 275 m from the target.

FLUX CALCULATIONS AND EVENT ESTIMATES

Neutrino flux spectra have been calculated for the upgraded AGS with a horn design proposed for this beam [4]. Fig 1a shows the expected ν_μ and ν_e flux distributions for this beam in units of ν/GeV/m^2/Proton-on-target at 1 km from the target. The expected ν_e event contamination is ~1% in this wide-band beam. At distances greater than 1 km the spectrum is not strongly dependent on the on the ν source position and the consequently the flux at the detector scales with r^{-2}. The table in Fig 1b shows the number of events expected at 2540 km in a 0.5 megaton water Cherenkov detector for a 5×10^7 sec running period. We expect to see 52000 charged current and 17000 neutral current events during that run. The event analysis in a water Cherenkov detector will concentrate on the quasi-elastic samples since the neutrino energy is better known and the backgrounds in the ν_e appearance are better understood. A liquid argon detector would be a better detector to analyze the multiple particle channels.



Channel	Number of Events
CC $\nu_\mu N \to \mu^- X$	51800
NC $\nu_\mu N \to \nu_\mu X$	16908
CC $\nu_e N \to e^- X$	380
QE $\nu_\mu n \to \mu^- p$	11767
QE $\nu_e n \to e^- p$	84
CC $\nu_\mu N \to \mu^- \pi^+ N$	14574
NC $\nu_\mu N \to \nu_\mu N \pi^0$	3178
NC $\nu_\mu O^{16} \to \nu_\mu O^{16} \pi^0$	574
CC $\nu_\tau N \to \tau^- X$	~110

Figure 1a: The ν_μ and ν_e flux spectra from 28 GeV protons on a graphite target seen at 1 km. **b:** Table of events seen in neutrino induced channels at 2540 km during a 5×10^7 sec run in a 0.5 megaton water Cherenkov Detector.

ν_μ DISAPPEARNCE

Figure 2a shows the energy spectrum of ν_μ quasi-elastic channel for a running period of 5×10^7 seconds with a 1 MW beam and a 0.5 megaton water Cherenkov detector at 2540 km. The top curve shows the event spectrum without oscillations. The middle curve with error bars shows the event spectrum with oscillations when $\Delta m_{32}^2=0.0025$ eV^2 and $\sin^2 2\theta_{23}=1$. In this figure we have assumed that the resolution in the reconstructed ν energy (E_ν) is 10%, which should be achievable with 10% photo multiplier tube coverage. This does not include a systematic error from the calibration of the overall detector energy scale. A great advantage of the very long baseline and the multiple oscillation pattern is that the systematic errors for flux normalization, background subtraction, and nuclear effects are small. The background shown in the lower curve of the figure comes from non quasi-elastic charged current events that also oscillate and will tend to smear the nodal pattern.

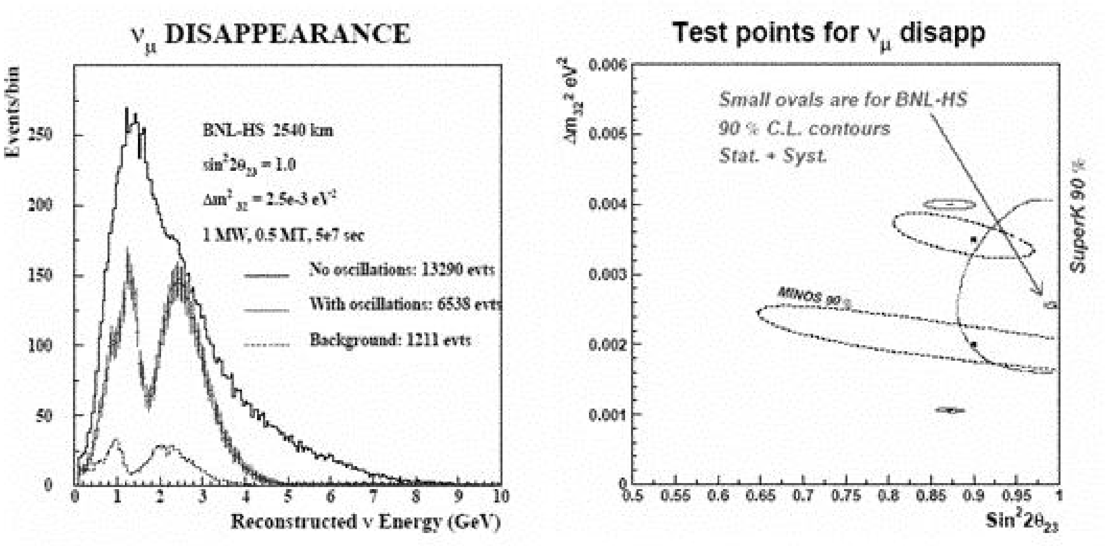


Figure 2a: ν_μ Quasi-elastic event spectrum. Curves show events without oscillations, with oscillations, and the background to oscillated QE events. The oscillated events assume that $\Delta m_{32}^2=0.0025$ eV^2. **b:** A comparison of the precision of the measurement of Δm_{32}^2 and $\sin^2 2\theta_{23}$ for this experiment and that expected by the MINOS experiment and seen by the Super-Kamiokande experiment.

Figure 2b shows a comparison of the experimental precision of Δm_{32}^2 and $\sin^2 2\theta_{23}$ expected in this experiment with those seen in the Super-Kamiokande experiment and expected in the MINOS experiment.

$\nu_\mu \rightarrow \nu_e$ APPEARANCE

The measurement of θ_{13}, δ_{CP} and Δm_{21}^2 and the sign of Δm_{32}^2 can be extracted from the wideband ν_e appearance spectrum. The probability for the appearance of $\nu_\mu \rightarrow \nu_e$ oscillations from 3-generation mixing including matter effects can be expressed analytically [3]. Figure 3a shows the expected ν_e event distribution for $\sin^2 2\theta_{13}=0.04$

and Δm_{32}^2=0.0025 eV^2 and the same running conditions previously mentioned. The matter enhancement (suppression) for the normal (reversed) Δm_{32}^2 sign ordering dominates the spectrum for E_ν>3 GeV. Sensitivity to the CP phase is greatest for E_ν range from 1 to 3 GeV. The effect of the solar oscillation from Δm_{21}^2 is largest at low E_ν. Figure 3b shows the event spectrum with $\sin^2 2\theta_{13}$=0. The appearance mode is more sensitive to the presence of backgrounds. The main sources of background come from ν_e contamination in the beam and neutral current reactions that have a single π° that are misidentified as electrons. An estimate of these backgrounds is shown in figure 3. There is concern at this point that the detection efficiency of π° is overestimate in the current simulation. This is being investigated.

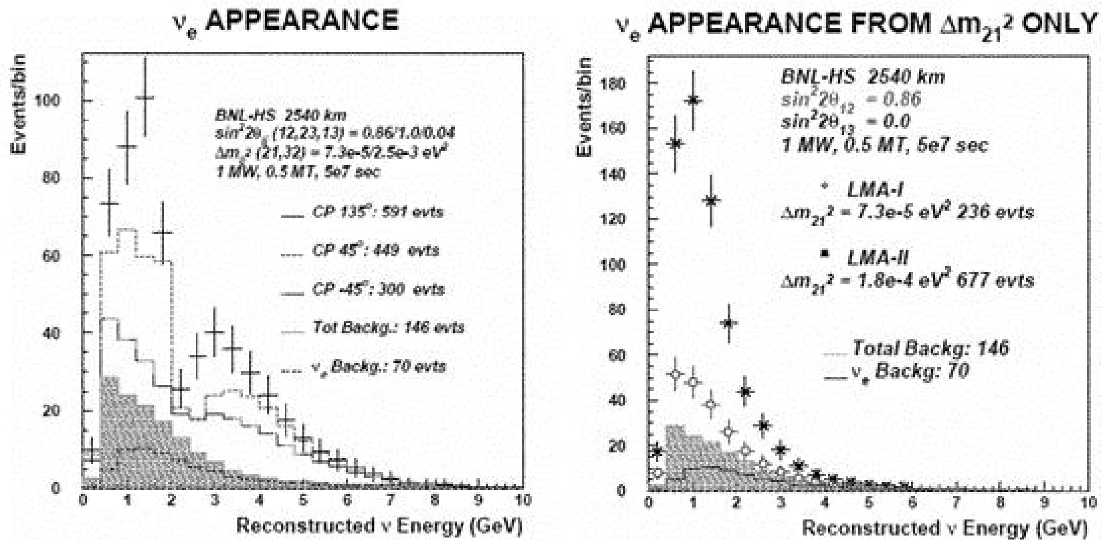


Figure 3a: The expected ν_e event spectrum for $\sin^2 2\theta_{13}$=0.04 and for 3 values of δ_{CP}. The figure also shows the total background for $\nu_{e.}$ **b:** The expected spectrum for $\sin^2 2\theta_{13}$=0. The resultant spectrum shows Δm_{21}^2 oscillations.

ACKNOWLEDGMENTS

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