A SCENARIO FOR A BROOKHAVEN NEUTRINO SUPER BEAM EXPERIMENT

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This paper examines the feasibility of a long baseline neutrino beam facility based on a proposed upgrade to the AGS accelerator at Brookhaven National Laboratory. It assumes that the AGS is upgraded initially to a 1 MW proton driver and eventually to a 4 MW proton machine. This upgrade would provide a strong incentive for a long baseline low energy neutrino beam to study neutrino oscillations. In this paper we look at a possible long baseline experiment with a detector at Cornell, which is 350 km away from BNL.

I. INTRODUCTION

The new evidence for neutrino oscillations from the Super- Kamiokande[1] (SK) and SNO experiments[2] has rekindled interest in neutrino physics. A proposed upgrade to the existing Alternating Gradient Synchrotron at BNL to a 1 MW facility would make a long baseline neutrino facility feasible. This upgrade is likely to be a multistage program. The current AGS is a 0.17 MW proton machine with a 0.625 Hz repetition rate and an intensity of 60 TP on the target. An initial AGS upgrade to a 1 MW proton driver with a 2.5 Hz repetition rate and an intensity of 100 TP has been discussed[3]. This 1 MW proton driver can evolve to a 4 MW machine in a future stage with a modest additional expenditure. A 4 MW proton driver would have a 5 Hz rate and would deliver an intensity of 200 TP protons on target. A high power proton driver is required for the intense neutrino beams that a neutrino factory storage ring would produce. A neutrino factory is an expensive project that will take at least 12 years to realize in the most optimistic scenario. If a proton driver is built as a first stage toward a neutrino factory, one would be able to contemplate building a long baseline neutrino oscillation experiment based on conventional technology.

Neutrino beam fluxes have been calculated for a traditional horn and for a solenoid capture system. There is some concern whether a pulsed horn could survive the high repetition rate and high radiation environment of a high power proton driver, particularly at 4 MW. A solenoid capture system similar to that proposed for the Neutrino Factory Storage Ring Project[4] is compared to the horn system. Section 2 will describe these two neutrino beam systems.

In this study we assume a far detector is placed 350 km from BNL possibly in the vicinity of Cornell. We have assumed that the detector would be 50 kilotons (the size of the SK detector) and have a magnetic field so as to distinguish ν from $\bar{\nu}$. We shall assume that the LANNDD proposal[5] for a liquid argon detector in a magnetic field is a possible choice for such a detector. If one were able to use a horn system that selected one sign of ν, one could use a water cherenkov detector similar to SK. A close 1 kiloton detector of the same technology would be placed approximately 1-3 km from the source. A detector at 1 km would be close enough to the source to show the radial dependence of the ν beam and would provide an accurate alignment of the beam. A detector at 3 km would be far enough away from the source that the source would appear as a point in the same way that it would at 350 km. A detector at 350 km would be sensitive both to the disappearance of ν_μ events and the appearance of ν_e events. A 1 MW proton source should supply enough events to provide a decent measurement of Δm^2_{32} and θ_{13}. Estimates of the number of events expected in detectors placed at 1, 3 and 350 km are described in section 3. An experiment to investigate CP violation in the neutrino sector would require significantly more statistics. The higher statistics could be achieved by upgrading the proton source to 4 MW and aiming the neutrino beam at the 1 megaton detector

II. NEUTRINO BEAM

We have looked at using a 20 T solenoid magnet system similar to that proposed for the Neutrino Factory to capture pions from a mercury target. The field on the solenoid axis varies as $Bz(z) = Bo/(1 + az)$ where a is chosen to drop the field from 20 T to 2.5 T in 10 m so as to provide focusing for the captured π beam. A solenoid magnet will capture both π^+ and π^- producing both ν_μ and $\bar{\nu}_\mu$. ν and $\bar{\nu}$ events can be distinguished with a 0.5 T magnetic field at the detector. The radius of the solenoid around the target is 15 cm, which is chosen to collect pions with $P_T < 0.450$ GeV/c. This comprises $\sim 67\%$ of the pions produced in the target.

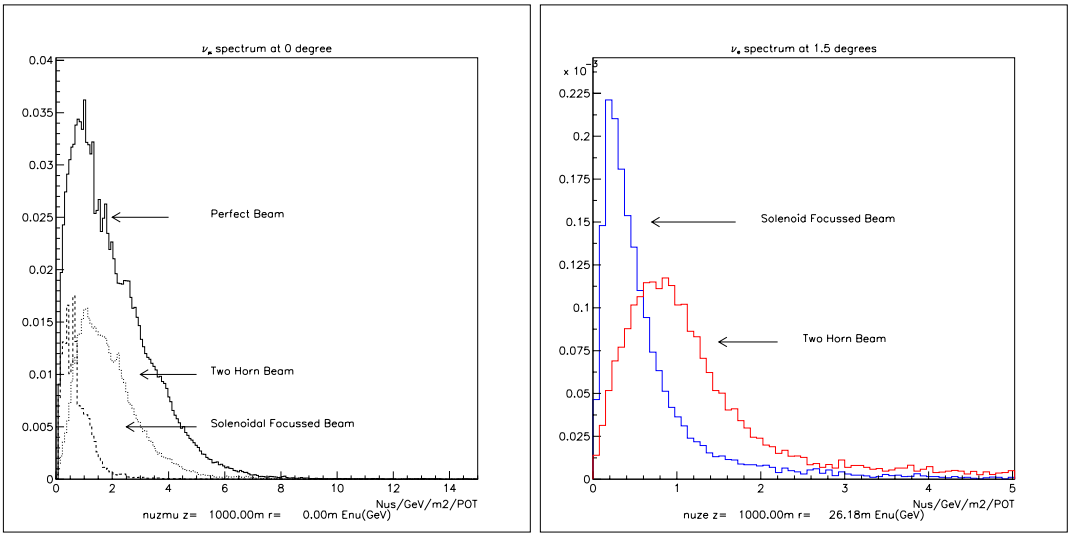

FIG. 1: a)ν_μ flux distribution at 1 km from the target. The figure shows the solenoid beam (dashed), the horn beam (dotted) and the perfect beam (solid). The flux per proton on target is given in units of $GeV^{-1}m^{-2}$. b) Comparison of ν_e flux solenoid and horn systems. The solenoid beam has only 100 m of decay path to control the contribution from μ decay.

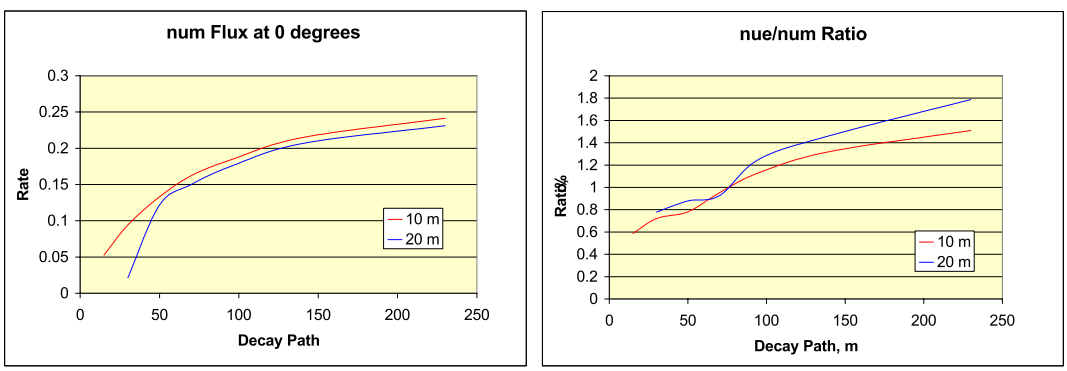

FIG. 2: a)ν_e/ν_μ ratio as a function of the decay channel length. b)ν_μ flux as a function of the decay path length for the solenoid beam. Curves for a 10 m and 20 m long solenoid magnet are shown.

The capture system is simulated with the GEANT program to track pions and muons through the magnetic field and to allow them to decay to ν. Fig. 1a shows the ν_μ flux at 1 km from the target. Also shown in the figure is the flux from the two horn ν beam that was designed for the E889 long baseline proposal. The solenoid beam produces a lower energy spectrum than the horn beam. The perfect beam shown in the figure the flux that would be obtained if all pions that were produced in the target were directed along the axis toward the detector.

A conventional neutrino beam has a small component of ν_e that come from the decay of K and μ. The ν_e contamination from K and μ decays is a background to the ν_e signal that appears from the oscillation of ν_μ. A horn beam has a ν_e contamination of $\sim 1\%$ that comes primarily from K decays. On the other hand, the ν_e component in the ν beam from the solenoid system comes dominantly from captured μ that decay. The size of the ν_e component from μ decay can be affected by length of the decay tunnel. Shortening the decay channel length will reduce the ν_e/ν_μ at the cost of reducing the ν flux. Fig. 2a shows the ν_e/ν_μ ratio as a function of the decay channel length and fig 2b shows the ν flux as a function of this decay channel length. Fig. 1b compares the ν_e flux of a solenoid beam to that of a horn beam. The solenoid beam in the figure has a decay path of 100 m. The ν_e flux from the horn beam is more energetic than that of the solenoid capture system.

TABLE I: Estimated events expected at the detectors situated at 1 km, 3 km and 350 km. The neutrino flux is generated by the solenoid capture system and contains both ν and $\bar{\nu}$.

Channel	D1	D3	D350
Mass	1 kton	1 kton	50 kton
$\nu_\mu n \rightarrow \mu^- p$	2.64×10^7	2.84×10^6	10582
$\bar{\nu}_\mu p \rightarrow \mu^+ n$	6.01×10^6	6.43×10^5	2353
$\nu N \rightarrow \nu N \pi^o$	2.64×10^6	3.27×10^5	1102
$\nu_e n \rightarrow e^- p$	7.22×10^5	71690	249
$\nu_e p \rightarrow e^+ n$	9.96×10^4	10027	150

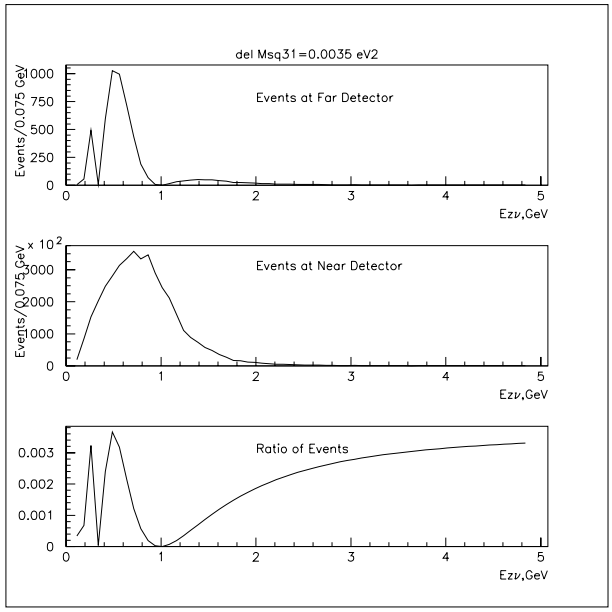

FIG. 3: E_ν distribution of quasi-elastic events at the far detector, the near detector, and their ratio.

III. EVENT ESTIMATES

Interactions from an 1 GeV ν beam is dominated by the quasi- elastic process, $\nu_\mu n \rightarrow \mu^- p$. The cross sections of these processes are well known. Let us assume that the first phase of a BNL neutrino super-beam experiment would have a 1 MW proton source and 1 kiloton detector placed at either 1 km or 3 km and a 50 kiloton placed detector at 350 km. Estimates of number of events at each detector, expected for a running period of 5×10^7 sec, can be determined by integrating the ν flux at that location with the appropriate cross section. Table 1 shows estimated events for the solenoid capture beam. These estimates do not include events from oscillations. The horn beam has approximately twice the number of ν_μ and approximately the same number of ν_e events.

The observation of fewer ν_μ events at the far detector than expected would be an indication of $\nu_\mu \rightarrow \nu_\tau$ oscillations. This disappearance signal can be used to measure Δm^2_{23}. Fig 3 shows the quasi-elastic event distribution as a function of E_ν for $\Delta m^2_{23} = 0.0035 eV^2$. The figure shows the event distribution at the far detector, the 3 km near detector and the ratio of events at the far detector to the near detector. The ratio would show no structure if there were oscillations. The dip in the ratio distribution at 1 GeV corresponds to the oscillation phase $1.27\ \Delta m^2_{23} L/Eo = \pi/2$ and measures Δm^2_{23}. A secondary dip occurs at 0.330 GeV, which corresponds to when the oscillation phase equals $3\pi/2$. This dip is likely be smeared out by the fermi motion of the target nucleus.

The measurement of θ_{13} requires the appearance of ν_e events in excess of the background expected from the ν_e contamination in the beam. Table II and III show event estimates for oscillation scenarios described in ref [6]. In these tables we assume that $\theta_{23} = \pi/4, sin^2 2\theta_{13} = 0.01$ and the experimental conditions previously mentioned. Table II shows the estimated number of events expected in the far detector from the solenoid capture system. Table IIIa and IIIb show similar estimates for the horn system set to focus π for ν and $\bar{\nu}$ production respectively. The estimate of the ν_e background at the far detector is dependent only on the statistics of the near detector

TABLE II: Estimated events for a solenoid capture beam at the far detector for various oscillation scenarios.

Δm^2_{23}, eV2	No Oscill.	0.002	0.0035	0.005
ν_μ	10582	3600	4282	5283
ν_e signal	-	58	50	43
ν_e BG	249	249	249	249
$\bar{\nu}_\mu$	2560	878	1090	1303
$\bar{\nu}_e$ signal	-	14.4	12.3	10.6
$\bar{\nu}_e$ BG	47	47	47	47

TABLE III: Estimated events for a horn beam focused for neutrinos (left) and antineutrinos (right).

$\Delta m^2_{23}, eV^2$	No Oscill.	0.002	0.0035	0.005
ν_μ	21645	8317	5165	9966
ν_e signal	-	83	95	69
ν_e BG	272	272	272	272
$\bar{\nu}_\mu$	228	115	84	90
$\bar{\nu}_e$ signal	-	1	1	1
$\bar{\nu}_e$ BG	5.4	5.4	5.4	5.4

$\Delta m^2_{23}, eV^2$	No Oscill.	0.002	0.0035	0.005
ν_μ	691	506	305	331
ν_e signal	-	4.0	4.7	4.5
ν_e BG	19	19	19	19
$\bar{\nu}_\mu$	4354	1576	1018	2074
ν_e signal	-	19.7	17.8	13.9
$\bar{\nu}_e$ BG	65	65	65	65

and the alignment of the ν beam, and should have much smaller errors than the statistical errors of the ν_e oscillation signal. The ν_e background shown in Tables II and III does not include $\nu_e \to \nu_\mu$ oscillations, which will certainly occur. Properly correcting the ν_e background for those oscillations would increase the significance of the signal. The significance of the ν_e and $\bar{\nu}_e$ signals is 3.2 and 1.8 s.d., respectively, for the ν beam from the 1 MW solenoid capture system in a running period of 5×10^7 sec. The horn beam would produce a statistical significance of 5.2 and 2.2 s.d. for ν_e and $\bar{\nu}_e$ appearance signals, respectively, but the horn beam would require separate running periods of 5×10^7 sec for the ν_e and $\bar{\nu}_e$ appearances.

Acknowledgments

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