Physics of an Intense Neutrino Beam from BNL to a Very Long Baseline Detector

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Abstract. An intense neutrino facility allows probing of the neutrino mixing angles, mass hierarchy, and leptonic CP violation. Physics potential, for making precision measurements of all neutrino oscillation parameters (θ_{ij}, Δm^2_{ij}, δ) using a wide band ν_μ beam, to a (very long baseline) detector is presented. Potential of a Neutrino beam from Brookhaven National Laboratory to a 2540 km baseline (with 0.5 megaton) detector at Homestake Mine in South Dakota, is (under study by our neutrino working group) discussed. Schemaics of the beam facility for the AGS upgrade to 1 MW with a cycle time of 2.5 and 10^{14} protons on target at 28 GeV; and a map with possible detector sites are also included.

INTRODUCTION

Success of the atmospheric and solar neutrino experiments that has provided evidence for non - zero neutrino masses and mixing has increased our interest in neutrino oscillation searches using accelerator created neutrinos. Protons from an accelerator (e.g. AGS) would hit a target (e.g. Mercury Jet, or graphite), and produce bursts of particles e.g., pions, that decay to muons, which then decay to neutrinos. To focus the beam a magnetic horn (and/ or solenoid) can be used to keep the particles from spreading and to direct the beam in the detector(s) direction. After leaving the horn pions decay into neutrinos.

Upgraded conventional Neutrino horn beams (Superbeams) are being considered (at BNL) for probing of the neutrino masses, mixing angles, leptonic CP violation, matter effects, new interactions, etc. We discuss in the following sections: Physics & Extra long baseline experiment; AGS Upgrade; Neutrino Superbeam; Detector; and Outlook.

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PHYSICS

The Atmospheric Neutrino "Anomaly" suggests that GeV ν_μ's (from $p + N \to \pi \to \mu\nu_\mu$) disappear while traversing the Earth's diameter, indicating $\Delta m^2_{32} = m^2_3 - m^2_2 = \pm 2.0^{+1.0}_{-0.7} \times 10^{-3} \mathring{(eV)}^2$ for $\sin^2 2\theta_{23} \simeq 0.85 - 1.0$. The value of Δm^2_{32} has decreased over the years, with recent reductions from [3] $3.0 \to 2.5 \to 2.0 \times 10^{-3}\mathrm{eV}^2$. Fortunately this change is good, for experiments with very long baselines ($L \simeq$ 2000–4000) such as our BNL to HomStake, (WIPP or Henderson) proposal .

Solar neutrino ($\nu_e \to \nu_e$ and $\nu_e \to \nu_k$) oscillation experiments and the Kamland reactor study of $\bar{\nu}_e$ disappearance prefer [4] $\Delta m^2_{21} = m^2_2 - m^2_1 = 7.3 \pm 1 \times 10^{-5}\mathrm{eV}^2$, and $\sin^2 2\theta_{12} \simeq 0.84 \pm 0.10$.

Increased interest in the Neutrino oscillation physics span from the solar neutrino deficit and some evidence for $\nu_\mu \to \nu_e$, oscillations (from the LSND experiment), as well as the exciting atmospheric neutrino results including measurements of the atmospheric Muon - Neutrino deficit from the SuperK (Superkamiokande) experiment that has provided convincing evidence for lepton flavor violation. The experimental results interpeted is based on oscillation of one neutrino flavor ν_e,ν_μ and ν_τ, (state $|\nu_\ell >, \ell = e, \mu, \tau$) into others and are related to the neutrino mass eigenstates $|\nu_i >, i = 1, 2, 3$ (with masses m_i) by U a 3×3 unitary matrix, with $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Extra Long-Baseline Physics

Extra-long neutrino flight paths provide the possibility of observing multiple nodes of the neutrino oscillation (probability) in appearance and disappearance experiments. Observation of such a pattern will directly demonstrate the oscillatory nature of the flavor changing phenomenon. For fixed distance L, the oscillation maxima will occur roughly at energies of

$$E_\nu(n) = \frac{\Delta m^2_{32} L}{2(2n-1)\pi}, \quad n = 1, 2, 3, \ldots$$

For a given E_ν and L, the oscillation of $\nu_\mu \to \nu_e$ appearance can be described by:

$$P(\nu_\mu \to \nu_e) = 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2\frac{\Delta_{21}}{2} + 2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21}$$

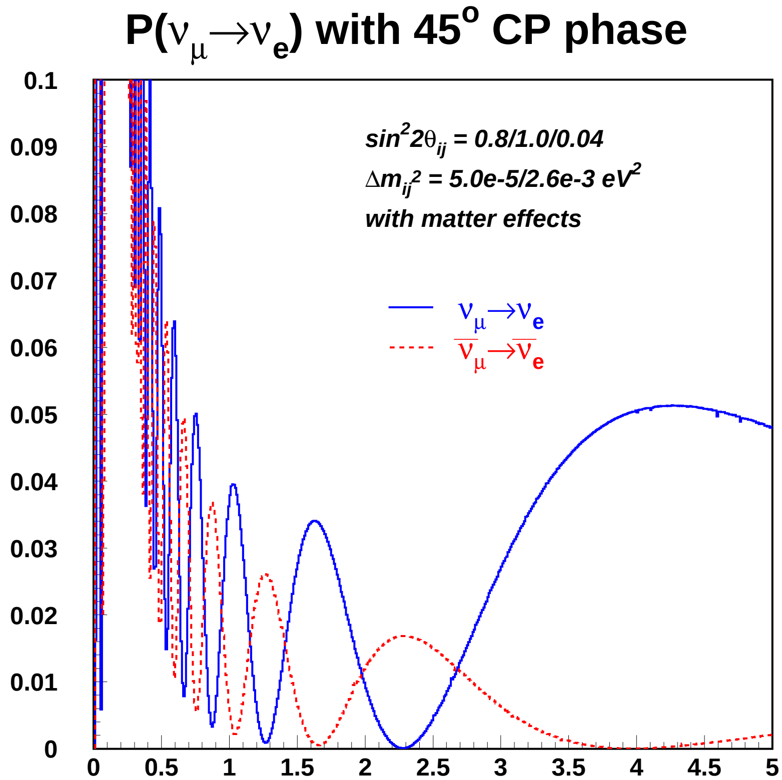

FIGURE 1. Probability of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at 2540 km assuming a 45^o CP violation phase, including matter effect.

$$
\begin{aligned}
&+4(s_1^2c_1^2c_2^2c_3^2 + s_1^4s_2^2s_3^2c_3^2 - 2s_1^3s_2s_3c_1c_2c_3^2\cos\delta \\
&-J_{CP}\sin\Delta_{31})\sin^2\frac{\Delta_{21}}{2} + 8(s_1s_2s_3c_1c_2c_3^2\cos\delta \\
&-s_1^2s_2^2s_3^2c_3^2)\sin^2\frac{\Delta_{31}}{2}\sin^2\frac{\Delta_{21}}{2} + \text{matter effects}
\end{aligned}
$$

Where, $c_i \equiv cos\theta_i$, $s_i \equiv sin\theta_i$, $J_{CP} \equiv s_1s_2s_3c_1c_2c_3^2\sin\delta$, $\Delta_{31} \equiv \Delta m_{31}^2 L/2E_\nu$, and $\Delta_{21} \equiv \Delta m_{21}^2 L/2E_\nu$.

J_{CP} is an invariant that quantifies CP violation in the neutrino sector; Δ_{31} is the atmospheric term and Δ_{21} is the solar term [7]. For $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ the above formula holds except J_{CP} terms will have opposite sign and matter effect will change.

The oscillation is primarily due to the first term linear in $\sin^2\frac{\Delta_{31}}{2}$, and oscillation probability rises for lower energies due to the terms linear in $\sin^2\frac{\Delta_{21}}{2}$.

The interference terms involve CP violation and they create an asymmetry between neutrinos and anti-neutrinos. The CP asymmetry grows linearly with distance:

$$
A_{\text{CP}} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}
$$

$$\simeq \frac{2s_1c_1c_2 sin\delta}{s_2s_3}\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\frac{\Delta m^2_{31}L}{4E_\nu} + O(\Delta^2_{21})$$
$$+\text{matter effects.}$$

(1)

or is given by (to order of Δm^2_{21} assuming $\sin^2 2\theta_{13}$ is not too small)

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$
$$+\text{matter effects}$$

In this expression, the asymmetry grows linearly with distance and increases as θ_{13} gets smaller, noted earlier.

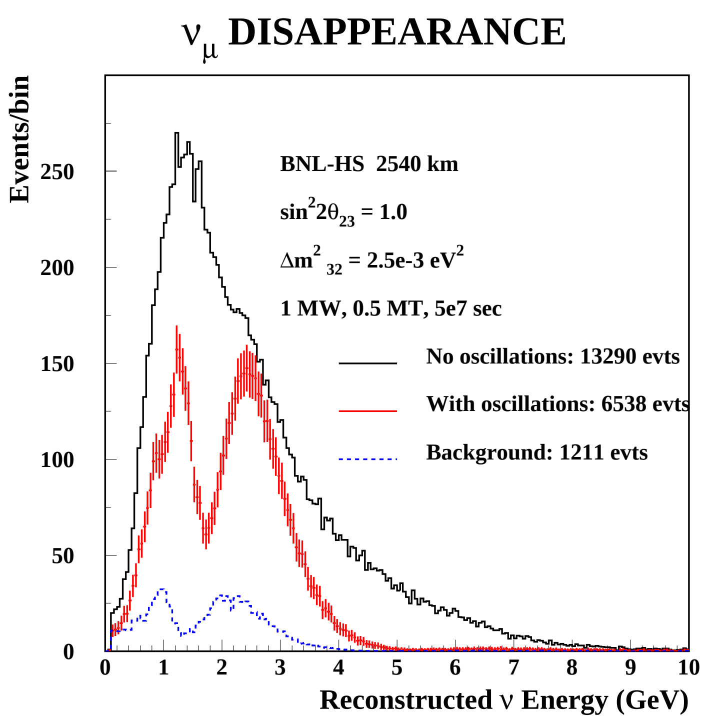

FIGURE 2. Example of expectected ν_μ disappearance spectra, without oscillations; (the middle) with oscillation and (the bottom histogram shows) the background contribution to the oscillating spectrum. This spectrum has improved with decrease in Δm^2_{32}, with recent reductions from [3] $3.0 \rightarrow 2.5 \rightarrow 2.0 \times 10^{-3}\text{eV}^2$.

Fig. 1 includes the matter effect since matter will enhance (suppress) neutrino (anti-neutrino) conversion at high energies and will lower (increase) the energy at which the oscillation maximum occurs, detection of matter enhancement effect can be made by measuring the asymmetry between neutrino and anti-neutrino oscillations (or by measuring the spectrum of electron neutrinos which also provide the sign of Δm^2_{32}).

If both the CP violation and the signal to $\nu_\mu \to \nu_e$ is large then effects of CP violation can be measured with only the (ν_μ) neutrino beam. It grows linearly with decrease in energy or the increase in baseline. For extra-long baseline experiments, comparison of the signal strength in the $\pi/2$ node versus the $3\pi/2$ (or higher) nodes will provide measurements of CP violation.

AGS UPGRADE AND νBEAM

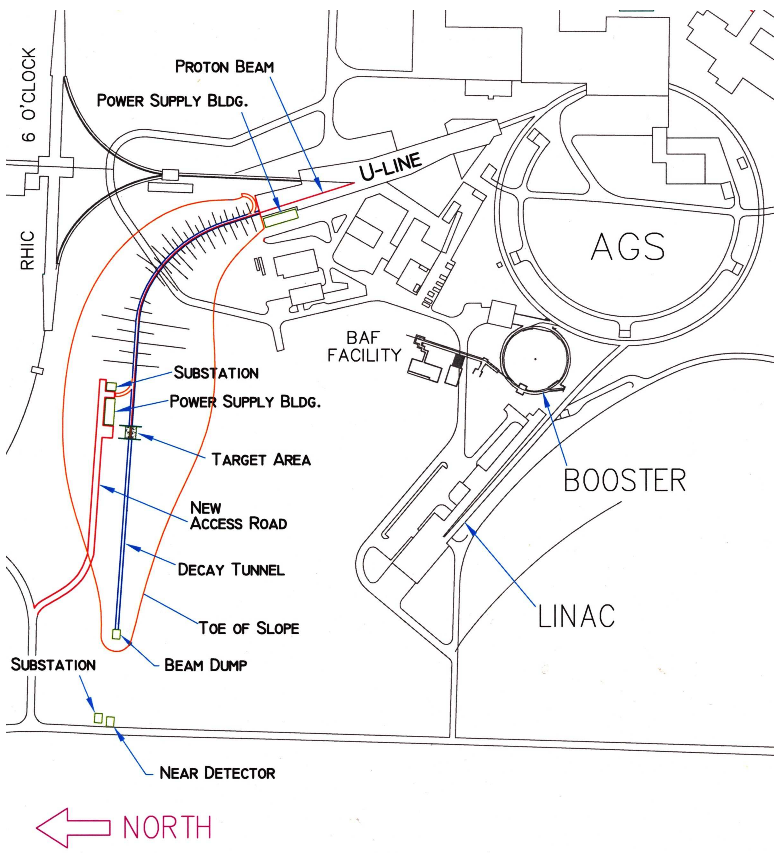

FIGURE 3. Schematic of the BNL-AGS RHIC facility showing location of the new beam-line for sending a neutrino beam to Homestake mine in South Dakota, and any detector in the Western direction.

The preliminary design of the BNL-AGS upgrades and the new neutrino beam has been produced by the AGS department [8] to reach an AGS power of e.g. 0.53 MW ($1.2 \times 10^{21} ppp$) in its first phase and 1.3 MW ($1.2 \times 10^{21} ppp$) in the second phase.In the first phase the LINAC will be improved to inject protons to the booster at 400 MeV (at present it is 200 MeV), and the booster energy increases to 2.5 GeV from 1.8 GeV. The addition of a fixed field accumulator storage ring between the booster and the AGS main ring will increase the AGS input beam from the present 4 booster pulses per AGS acceleration to 6 booster pulses per AGS acceleration and, at the same time, increase the AGS frequency from 0.6 Hz to 1.0 Hz. The AGS power increase would be from 0.14 to 0.53 MW. The new accumulator will be in the same tunnel as the AGS. In the second phase of the upgrades the AGS repetition rate will be increased to 2.5 Hz to reach a total beam power of 1.3 MW.

The proton beam is to be elevated to a target station on top of the hill. And the new proposed fast extracted proton beam line in the U-line tunnel will come off the line feeding RHIC. And will turn west, a few hundred meters before the horn-target building. In addition to its 90 degree bend, the extracted proton beam will be bent upward through 13.76 degrees to strike the proton target. The downward 11.30 degree angle of the 667.8 ft meson decay region will then be aimed at the 2500 meter level of the Homestake Laboratory. This will require the construction of a 39 meter hill to support the target-horn building, so as to avoid any penetration of the water table. At its midpoint (about Lake Michigan) the center of the neutrino beam will be roughly 120 km below the Earth's surface. (For a shorter baseline e.g., to Lansing NY in approximately the same direction as Homestake the hill won't be needed. Various combinations of the proton transport and the target station for the extra-long, (short/intermediate) baselines are being considered.)

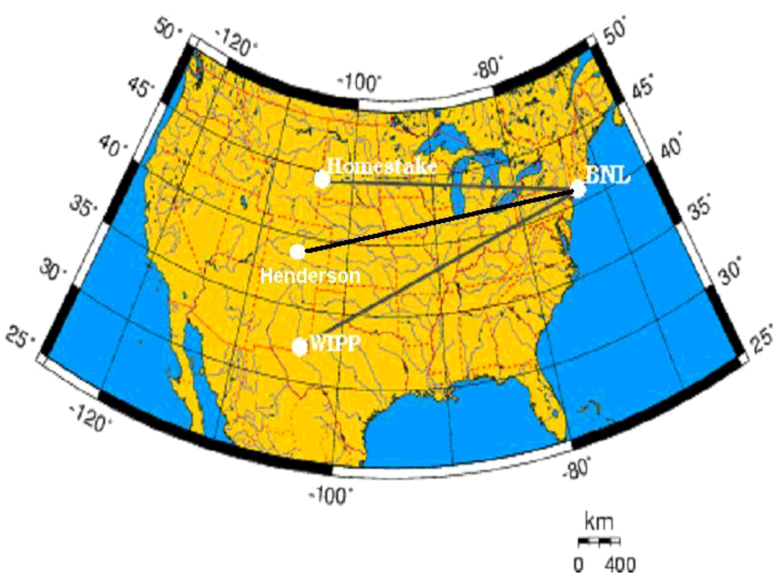

FIGURE 4. Possible extra long neutrino baselines from BNL to Lead (Homestake) SD ($\sim 2540Km$, 11.5 degrees dip angle), to Carlsbad (WIPP) NM ($\sim 2900km$, 13.0 degrees), and to the Henderson Mine in Colorado.

DETECTORS FOR THE VERY LONG BASELINE EXPERIMENT

There is an interest to convert the Homestake Gold Mine in Lead, South Dakota into a National Underground Science Laboratory (NUSL). This will provide unique opportunity for an extra-long baseline neutrino oscillation experiments from BNL. The extra-long baseline is 2540 km from the (Brookhaven National Laboratory) BNL to Lead, South Dakota. The proposed NUSL facility is to accommodate an array of detectors with about 1 Megaton total mass. Most of these will be water Cerenkov detectors that can observe neutrino interactions in the desired energy range with sufficient energy and time resolution.

Other detector types (e.g. Liquid Argon), and sites are also being considered, e.g.,Henderson Mine in Colorado, the Waste Isolation Pilot Plant (WIPP) located in an ancient salt bed at a depth of $\sim 700m$ near Carlsbad, New Mexico, etc. The distance from BNL to WIPP is about 2880 km,. The cosmic ray background will be higher at WIPP because the facility is not as deep as Homestake (with levels as deep as $\sim 2500m$).

OUTLOOK

Four goals of neutrino physics: precise determination of Δm^2_{32}, observation of $\nu_\mu \to \nu_e$ appearance, measurement of matter effects, and detection of CP violation are all possible with an intense neutrino broad band beam, very long distance baseline, and large detector. Both very long O(2500 km) and intermediate O(400 km) baseline experiments can be staged (from Brookhaven) as the AGS is upgraded to .5 MW, as much as 2.5 MW or higher (4 MW needed for a Neutrino Factory). AGS improvements will also allow rare muon and kaon decay studies, muon EDM measurements, etc. Thus providing additional windows for discovery.

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