SCENARIOS FOR BNL NEUTRINO SUPERBEAM AND OSCILLATION EXPERIMENT

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Abstract

A Neutrino Superbeam at BNL and extra long base line oscillation experiment scenarios are described. A Superbeam facility allows probing of the neutrino mixing angles, mass hierarchy, and leptonic CP violation. Upgraded conventional Neutrino horn beams (Superbeam) are easier, cheaper, and competitive with the lower energy muon storage based Neutrino Factory. We discuss the neutrino superbeam and oscillation experiment scenarios for BNL.

1 INTRODUCTION

With the success of the atmospheric and solar neutrino experiments there has been an increased interest in neutrino oscillation searches using accelerator created neutrinos. Protons from an accelerator (e.g. BNL AGS or FNAL Main Injector) would hit a target (e.g. Mercury Jet, or graphite etc), and produce bursts of particles e.g., pions, kaons,etc. 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 section 2) Physics motivation; 3) Extra long baseline experiment; 4) AGS Upgrade and neutrino Superbeam; 5) Detector and 6) Outlook.

2 PHYSICS MOTIVATION

The Atmospheric Neutrino “Anomaly” suggests that GeV ν_μ's (from $p + N \rightarrow \pi \rightarrow \mu\nu_\mu$) disappear while traversing the Earth's diameter, $\Rightarrow \Delta m^2 = m_3^2 - m_2^2 \approx 2.5 \times 10^{-3}$ (eV)^2 for $\sin^2 2\theta \approx 1$.Increased interest in the Neutrino oscillation physics span from the solar neutrino deficit and some evidence for $\nu_\mu \rightarrow \nu_e$, 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 next generation of long baseline experiments (K2K, MINOS, OPERA, ICANOE) are expected to rule out or confirm e.g. the $\nu_\mu \rightarrow \nu_e$ oscillations fully or partially. LSND, SNO and KamLAND, together with further SuperK measurements should provide a limited viable region of parameter space for solar neutrino oscillations. But there will remain many unanswered questions. To answer these questions will require a new generation of beams and detectors beyond the next generation of experiments, e.g. with a new intense BNL- AGS based beam with detectors at extra-long baseline distances. The physics goals of the new beam sent from BNL along a baseline of 2540 km, will briefly be discussed in the next section.

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

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

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) &= 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{21}}{2} \\
&+ 2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\
&+ 4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2 s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos\delta \\
&- J_{CP} \sin\Delta_{31}) \sin^2 \frac{\Delta_{21}}{2} + 8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta \\
&- s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2} + matter\ effects
\end{aligned}
$$

Where, $c_i = cos\theta_i$, $s_i = sin\theta_i$, $J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta$, $\Delta_{31} = \Delta m_{31}^2 L/2E_\nu$, and $\Delta_{21} = \Delta m_{21}^2 L/2E_\nu$. 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 [4]. For $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ 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:

$$
\begin{aligned}
A_{\rm CP} &= \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \\
&\simeq \frac{2 s_1 c_1 c_2 sin\delta}{s_2 s_3} \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \frac{\Delta m_{31}^2 L}{4E_\nu} + O(\Delta_{21}^2) \qquad (1) \\
&+ matter\ effects.
\end{aligned}
$$

In Fig. 1 the matter effect is included. Since matter will enhance (suppress) neutrino (anti-neutrino) conversion at

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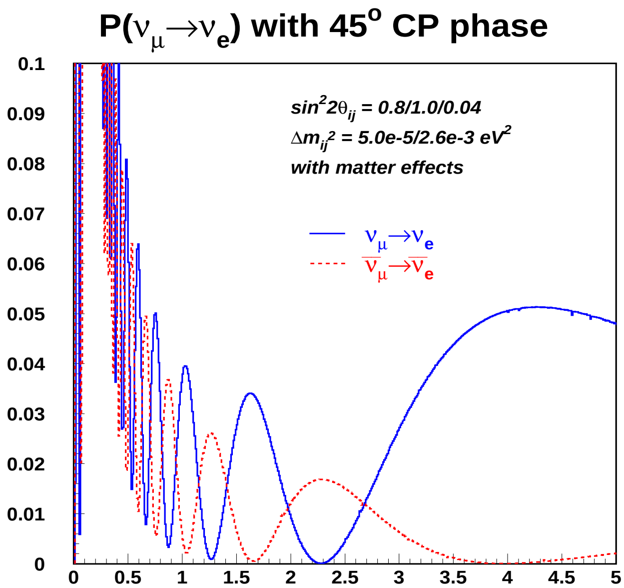

Figure 1: Probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at 2540 km assuming a 45^o CP violation phase, including matter effect. Here θ_{ij} notation is used [1] rather than θ_i.

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 $\nu_\mu \rightarrow \nu_e$ 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.

4 AGS UPGRADE AND νBEAM

The preliminary design of the BNL-AGS upgrades and the new neutrino beam has been produced by the AGS department [1] 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.

A preliminary design for a beam to Homestake is shown in figure 2. Due to the constraint at BNL to keep the beam line above the water table (which is at a shallow depth of $\sim$ 20 m) on Long Island, the beam line is to be constructed on a hill with 11.5 degree slope.

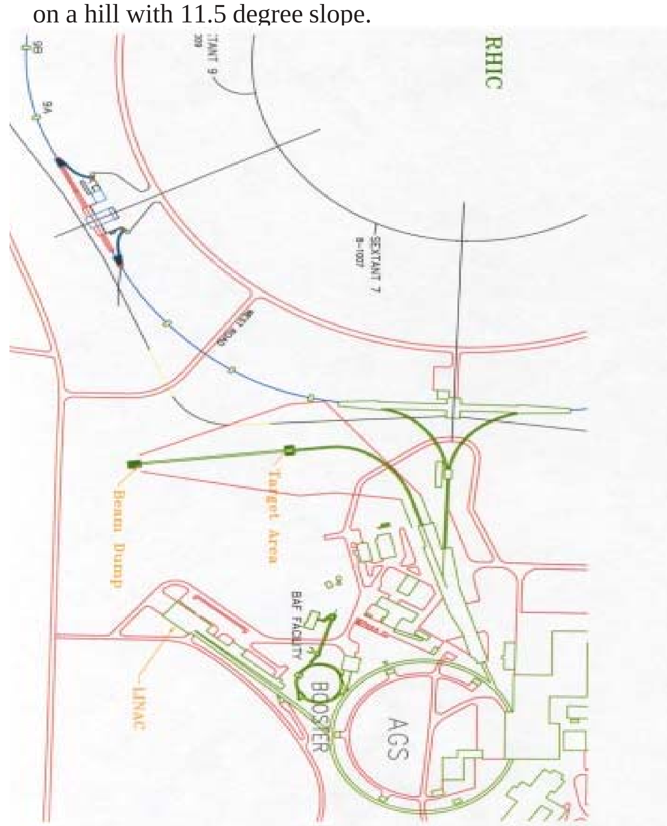

Figure 2: Schematic of the BNL-AGS RHIC facility showing location of the new beam-line for sending a neutrino beam to Homestake mine in South Dakota, and any detector in the Western direction.

The 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.)

5 DETECTORS

There is an interest to convert the Homestake Gold Mine in Lead, South Dakota into a National Underground Sci-

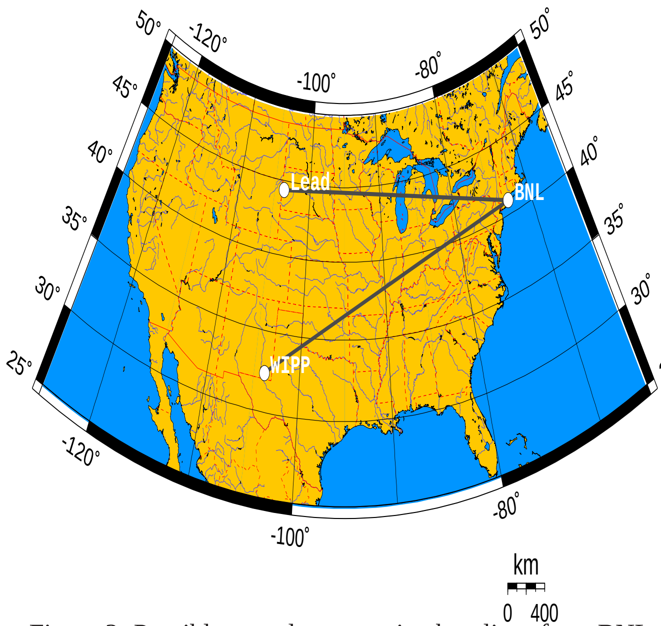

Figure 3: Possible extra long neutrino baselines from BNL to Lead (Homestake) SD ($\sim 2540Km$, 11.5 degrees dip angle), and to Carlsbad (WIPP) NM ($\sim 2900km$, 13.0 degrees).

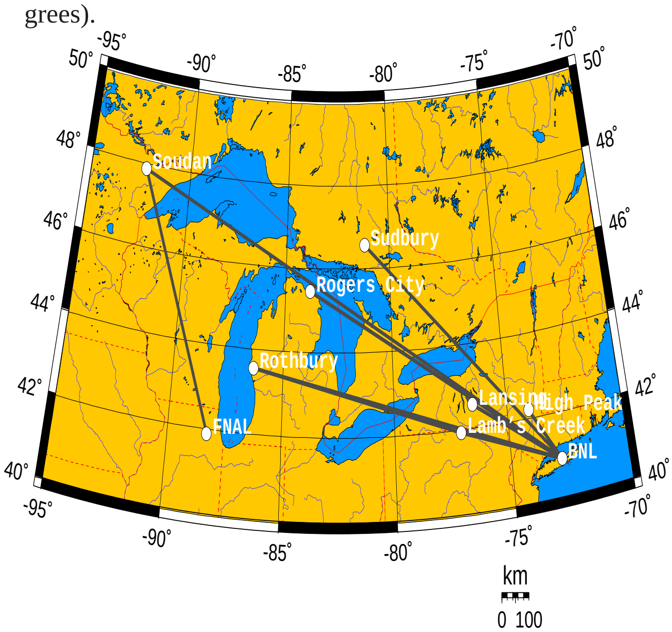

Figure 4: Some near/long baselines from BNL. With distances e.g. from BNL to Lansing $\sim$ 350, to Soudan is $\sim 1770km$.

ence 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, SouthDakota. 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, (Fig 5) see [6]), and sites are also being considered, e.g., the Waste Isolation Pilot Plant (WIPP) located in an ancient salt bed at a depth of $\sim 700m$ near Carlsbad, New Mexico. 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 $\sim 2500m$).

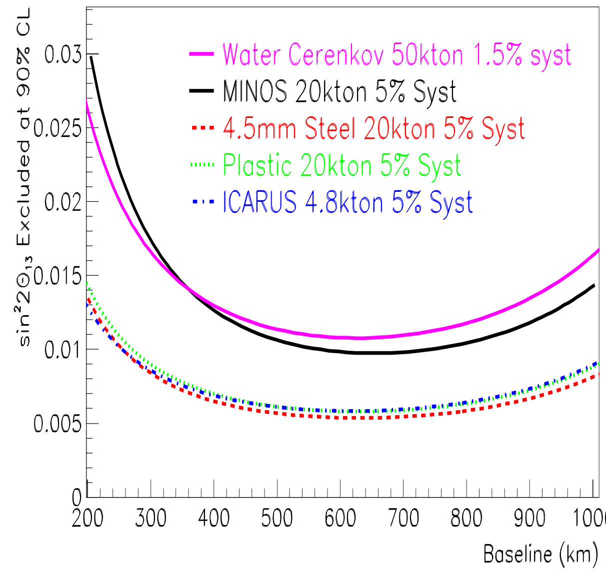

Figure 5: A comparison of the $\nu_\mu \to \nu_e$ exclusion potential for Water Cerenkov, Steel, plastic and Liquid Argon detectors[6].

6 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 beam from the Brookhaven AGS. Both extra long O(2500 km) and intermediate O(400 km) baseline experiments can be staged as the AGS is upgraded to as much as 2.5 MW or higher (4 MW for a Neutrino Factory). In the LOI, 2 phases of .53 MW and 1.3 MW were considered. AGS improvements will also allow rare muon and kaon decay studies, muon EDM measurements, etc. Thus providing additional windows for discovery.

7 REFERENCES

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[5] Homestake, see http://mocha.phys.washington.edu/NUSL/ WIPP, see http://www.wipp.carlsbad.nm.us/

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[7] http://www.bnl.gov/edm/, http://meco.ps.uci.edu/RSVP.

[8] due to space limitation and paper dateline, additional figures etc, we presented at EPAC2002, will be included in a followup BNL-Report.