Letter of Intent
Neutrino Physics with Detectors at Baselines of 100-1000 km from BNL

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This Letter of Intent describes a program of accelerator-based neutrino physics that will extend the measurements now underway of parameters Δm^2_{23}, $\sin^2 2\theta_{23}$ and $\sin^2 2\theta_{13}$, and could provide first measurements of CP violation on the neutrino sector under favorable circumstances. While an optimal measurement strategy awaits improved measurements of the three parameters mentioned, as well as improved measurements of the parameters Δm^2_{12} and $\sin^2 2\theta_{12}$ that govern solar neutrino oscillations, the desirable form of a next-generation experiment is now reasonably clear.

The neutrino beam will come from the decay of pions, with admixtures of decays of Kaons and muons, and so consists primarily of ν_μ with admixtures of ν_e and $\bar{\nu}_\mu$ at the 1 percent level. A large detector is required, with good particle identification and good rejection of backgrounds from neutral-current neutrino interactions. The detector should be located at a site hundreds of kilometers distant from the neutrino source. To have capability for nonaccelerator physics as well, such as proton decay or neutrino astrophysics, the detector should be underground.

A high-performance strategy emphasizes use of an off-axis neutrino beam [1, 2] that can deliver sub-GeV neutrino beams to two sites at distances 100-1000 km from BNL. The preferred detector is a liquid argon time projection chamber [3], with maximum performance achieved if the detector is immersed in a large magnetic field [4, 5, 6]. The main ingredients in the intermediate baseline strategy are summarized briefly below. See also [7].

The strategy is based on eight considerations of neutrino physics and neutrino beams:

- Improved measurements of the neutrino mixing parameters Δm^2_{23}, and $\sin^2 2\theta_{23}$, as well as new measurements of $\sin^2 2\theta_{13}$, are best accomplished with a detector located at the first oscillation maximum of $\nu_2 \leftrightarrow \nu_3$, namely $L[\mathrm{km}] = 1.24 E_\nu[\mathrm{GeV}]/\Delta m^2_{23}[\mathrm{eV}^2] \approx 500 E_\nu[\mathrm{GeV}]$, supposing $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2.

- Measurements of CP violation are possible (presuming the LMA solution to the solar neutrino problem holds) with roughly equal accuracy at any maximum of the $\nu_2 \leftrightarrow \nu_3$ oscillation pattern [8], but best accuracy is obtained at the lowest energy practicable.

- The sign of Δm^2_{23} can be determined via matter effects [9, 10], which grow with distance but are very small for $L \lesssim 1000$ km.

- If Δm^2_{12} is at or above the upper limit of the presently allowed value in the LMA solution, as should be clarified in a year or two by KamLAND [11], then two scales of oscillation will be discernible in very long baseline experiments [12].

- Accelerator-based neutrino beams from pion (and kaon and muon) decay are dominantly ν_μ (from positive mesons, and $\bar{\nu}_\mu$ from negative mesons) with admixtures of ν_e and $\bar{\nu}_\mu$ at the one percent level. These backgrounds limit the sensitivity of measurements of $\sin^2 2\theta_{13}$ and CP violation, which rely on detection of $\nu_\mu \to \nu_e$ oscillations. Furthermore, if the beam energy is high enough that $\nu_\mu \to \nu_\tau$ oscillations can materialize as τ leptons, the semileptonic decay $\tau \to eX$ causes undesirable backgrounds.

- Accelerator-based neutrino beams will have a broad energy distribution, unless special efforts are made to reduce this, which leads to background to the $\nu_\mu \to \nu_e$ signal from ν_μ neutral-current interactions, and ν_τ charged-current interactions, of higher than nominal energy.

- If we are confident about the value of Δm^2_{23}, it is therefore advantageous to narrow the energy spectrum of the beam, which can be accomplished for low-energy neutrinos by use of an off-axis neutrino beam [1, 2] that enhances the neutrino flux at an angle $\theta \approx 2^\circ/E_\nu[\mathrm{GeV}]$ (due to the Jacobian peak in the two-body decay kinematics of the pion), as shown in Fig. 1.

- Interactions of neutrino of energies below about 700 MeV with nucleons are primarily quasi-elastic with two body final states that permit further suppression of neutral-current backgrounds [13]. A remaining troublesome background is inelastic scatters with a single π^0 in the final state, whose decay photons can be mistaken for electrons.

Based on the above considerations, the intermediate baseline strategy is formulated as follows:

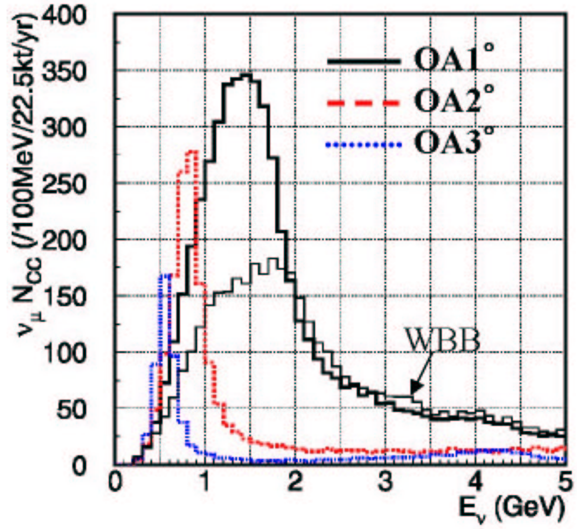

Figure 1: Comparison of neutrino spectra for off axis beams at 1°, 2° and 3° with a wideband beam (WBB) derived from a conventional neutrino horn [13].

- The broadest program of measurement of neutrino oscillation parameters in accelerator experiments should emphasize a low-energy beam, $E_\nu \approx 350-700$ MeV, and a detector at distance 150-300 km, while retaining the option for studies at longer baselines.

- Use of an off-axis neutrino beam at angle, say, 2° to the parent pion beam provides good flux of low-energy neutrinos in a second beam at 4° to the first. This permits use of a second detector simultaneously with the first, at a distance some 800 km farther away so as to be sensitive to matter effects (sign of Δm^2_{23}).

- Sites for near and far detectors in the low-energy, double-off-axis-beam between strategy that utilize an existing mine [14] at one of the two locations are shown in Fig. 2. It is, of course, possible to develop new sites along any direction, and an example of a pair of site that are in line with the Homestake Mine [15] in South Dakota is also shown in Fig. 2. Equivalent sites could, of course, be found along a line toward the WIPP Facility [16, 17] in New Mexico.

- The dip angle of the pion beam would be about 3°, so a 200-m-long decay tunnel would tilt by 10 m from end to end.

- The use of a double off-axis neutrino beam with dip angle about 3° permits easy siting of calibration detectors at the end of the pion-decay tunnel to measure neutrino cross sections, as well as a detector at 2 km distance (100 m depth) to determine the neutrino beam flux [1].

- Among various types of detectors, a liquid argon time projection chamber has the best rejection of background due to neutral-current interactions and low-energy π^0's. This permits measurements of $\sin^2 2\theta_{13}$ and CP violation via $\nu_\mu \to \nu_e$ oscillations with a much smaller detector mass of argon, as illustrated in Fig. 3 from a recent study [19].

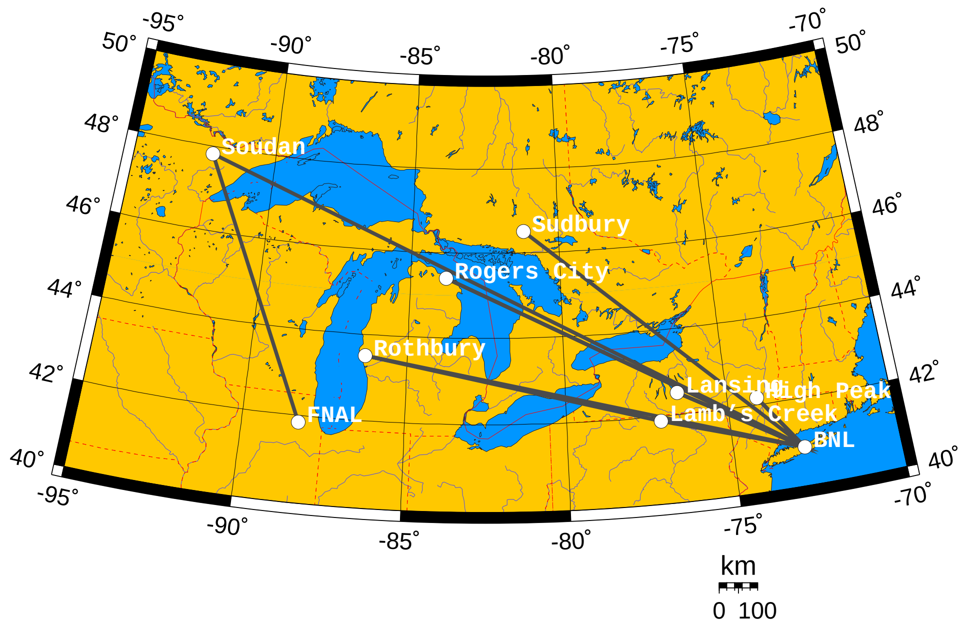

Figure 2: Possible intermediate neutrino baselines from BNL to detectors at the Cargill Rock Salt Mine in Lansing, NY (350 km, 1.7° dip angle) [14] and at a new site in Rogers City, MI (1020 km, 4.7° dip angle), or to detectors at a new site in High Peak, NY (165 km, 0.8° dip angle) and at the Sudbury Neutrino Observatory [18] in Ontario, Canada (920 km, 4.2° dip angle). Detectors at Lamb's Creek, PA (370 km, 1.7° dip angle) and Rothbury, MI (1150 km, 5.2° dip angle) are on a line to the Homestake Mine that is the proposed site of the National Underground Science Laboratory [15].

- A 300-ton liquid argon detector has recently begun operation [20], with high-quality tracking of particle interactions as shown in Fig. 4. To extend measurements of neutrino oscillation parameters beyond those that will be obtained by other experiments in the next decade, the detector mass must be of order 100 kton. A concept for such a detector is sketched in Fig. 5 [4, 5].

- The detectors for an accelerator-based neutrino experiment could be located on the surface of the Earth (or with a cover of $\approx$ 100 m to suppress the cosmic-ray rate) because the beam duty factor is $\approx 10^{-6}$. However, a large liquid argon detector can provide a factor of 100 improvement in the sensitivity [21] over present limits to proton decay via the mode $p \to K^+\bar{\nu}$ [22] that is favored in generic SO(10) supersymmetric grand-unified models [23]. For this, the detector should be located at least $1500'$ underground.

- Optimal performance of a large liquid argon detector would be obtained if it were immersed in a magnetic field of $\approx 0.5T$ [5, 24]. This is probably not required in a first detector.

- A significant advantage of the use of the AGS as the proton source for the neutrino

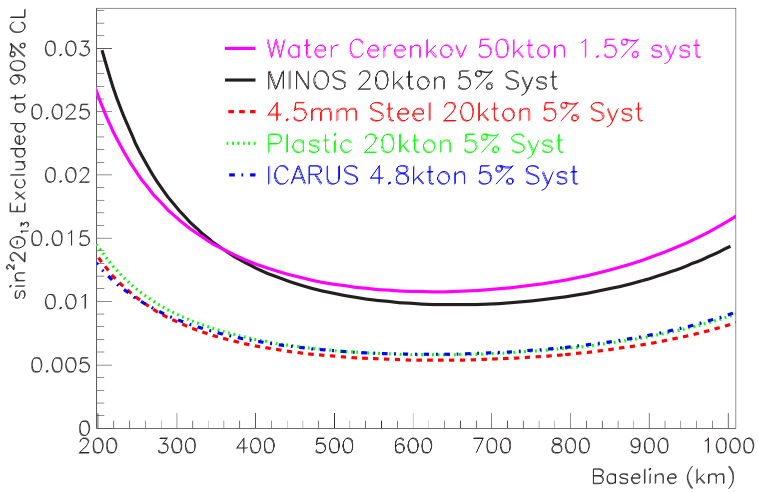

Figure 3: Comparison of several types of detectors in measuring $\sin^2 2\theta_{13}$ in the presence of backgrounds typical of a pion-decay neutrino beam at intermediate baselines [19]. The detector labeled ICARUS [20] is a liquid argon time projection chamber. With a 100-kton liquid argon detector, a 1-MW proton beam and an off-axis neutrino beam, as considered in this Letter of Intent, the sensitivity to $\sin^2 2\theta_{13}$ would be 20 times better.

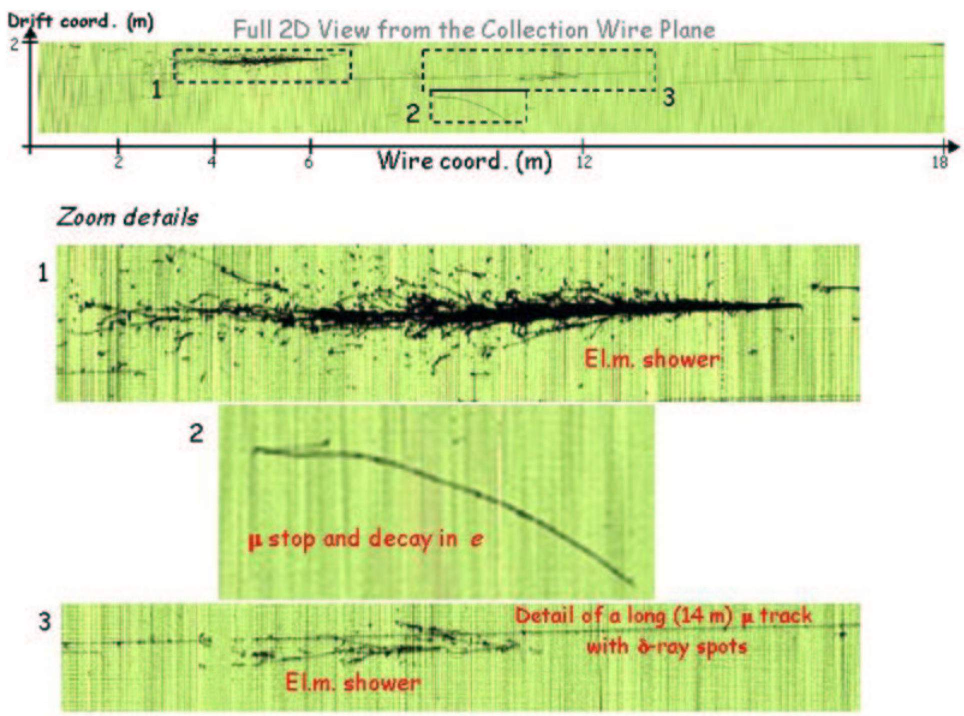

Figure 4: An event from the recent cosmic-ray test run of ICARUS [20], showing excellent track resolution over long drift distances in zero magnetic field.

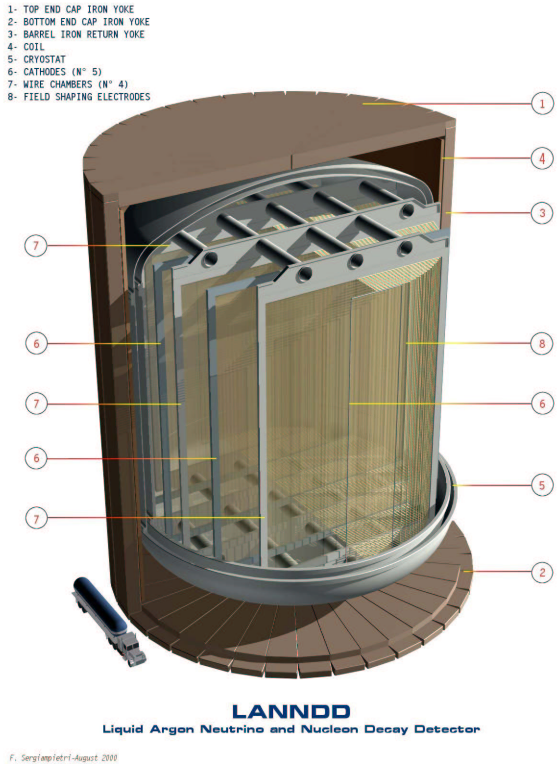

Figure 5: Concept of a 70-kton Liquid Argon Neutrino and Nucleon Decay Detector (LANNDD) [4, 5].

beam is that 4 MW beam power can be achieved in cost-effective upgrades [25]. At such high beam powers, solid targets and conventional neutrino horns may not be viable. A mercury jet target [26] and solenoid horn [27] may be the favored technology for a high-power upgrade [28]. The simplest implementation of a solenoid horn provides simultaneous beams of ν_μ and $\bar{\nu}_\mu$, which is statistically advantageous but requires that the detector have a magnetic field.

Thus, a magnetized liquid argon detector is the best choice for a long-range program of detailed measurement of neutrino-oscillation physics.

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