PROCEEDINGS OF SCIENCE

Prospects for resolving the ν mass hierarchy, θ_{23} octant ambiguity, and to observe leptonic CP-violation in US experiments NOvA and LBNE.

Carl Bromberg[*#]
Michigan State University
East Lansing, MI 48824, USA
E-mail: `bromberg@pa.msu.edu`

NOνA, an experiment observing muon neutrino oscillations at the energy of about 2 GeV with the 810 km baseline from FNAL to Ash River MN, is optimized to detect the appearance of electron neutrinos. The experiment will improve the knowledge of most neutrino oscillation parameters and has a good chance to resolve the neutrino mass hierarchy, determine the octant for θ_{23}, and perhaps find evidence for neutrino CP-violation. Briefly discussed are current plans for LBNE, the 1300 km baseline neutrino experiment from FNAL to Lead SD.

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[*] Speaker
[#] For the NOνA Collaboration, `http://www-nova.fnal.gov`

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1. Introduction

Due to the diverse attendance at this conference a short introduction to neutrino oscillation physics is appropriate. Since the award of the Nobel Prize in Physics to R. Davis, M. Koshiba, and R. Giacconi in 2002, neutrino oscillations have been observed by many experiments, in particular the recent definitive observations [1,2,3] of the disappearance of anti-electron neutrinos from reactors on baselines of ~1km. Neutrino oscillations are parameterized by a unitary mixing matrix (U_{ij}) relating neutrino flavor states (ν_e,ν_μ,ν_τ) and masses states (m_1,m_2,m_3) through mixing angles $(\theta_{12},\theta_{13},\theta_{23})$ and a CP-violating phase (δ), and can be expressed as a product of three matrices, each involving only 1 of the 3 mixing angle as shown in Fig. 1.

Transition probabilities between flavor states involve the difference in the squares of the neutrino masses $\Delta m_{ij}^2 = m_i^2 - m_j^2$, the energy (E), and the observation baseline L as given by the

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Figure 1: Matrices defining the mixing of neutrino flavor states and neutrino mass states.

equation,

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \frac{\Delta m_{ij}^2 L}{4E} \mp 2\sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \frac{\Delta m_{ij}^2 L}{2E},$$

where the interference term (coming from the complex 2nd matrix in Fig. 1) involves the phase δ, and has a minus sign for neutrinos and a plus sign for antineutrinos. The appearance or disappearance of electron neutrinos will occur if $\sin\theta_{13} \neq 0$, and in long baseline experiments will exhibit a CP-violation for $\delta \neq 0,\pi$. In the second (and dominate) term in the transition probability the oscillatory factor is squared and therefore leads to a "mass hierarchy" ambiguity

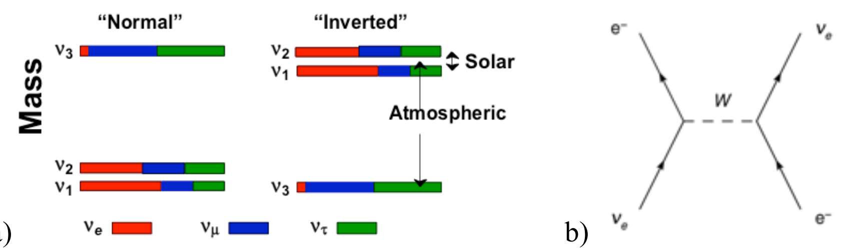


Figure 2: a) The mass hierarchy ambiguity with flavor content of each mass state shown in color and, b) the diagram leading to the MSW effect through the earth.

as shown in Fig. 2a, where it is not clear if m_3 is > or < m_1, the normal or inverted hierarchy, respectively, with the flavor content of each mass state shown in color. For long baseline experiments on the earth, the elastic scattering of electron neutrinos (but not antineutrinos) with electrons in the earth, as shown in Fig. 2b, modifies the interference term (the MSW effect) by a term proportional to $(1+E/E_R)$ with $E_R \sim 11\,\text{GeV}$ for experiments on a baseline of about 800 km. This complicates the CP violation analysis but allows a mass hierarchy determination.

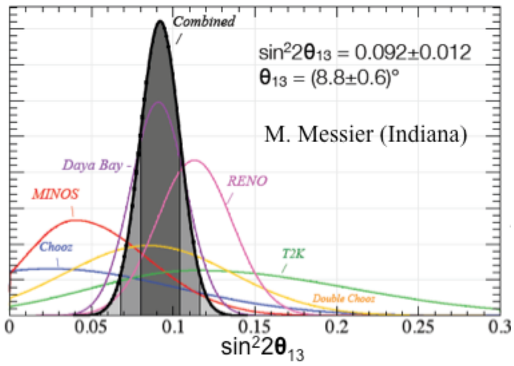


Figure 3: Compilation of measurements of the mixing angle θ_{13}

The disappearance of anti-electron neutrinos from reactors on short baselines has established a mixing angle $\theta_{13} \sim 9°$, as can be seen in a compilation of measurements, as shown in Fig. 3, the observation of a significant mixing angle, provides a windfall for the NOvA long baseline experiment described in the next section.

2. The NuMI Off-axis ν_e Appearance (NOvA) experiment

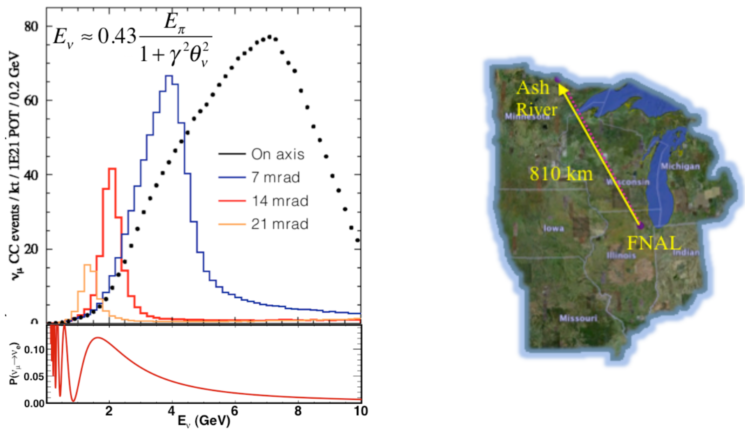


Figure 4: (left) Neutrino energy spectrum at various angles to the beam axis, and (below) is the yield of electron neutrinos vs. energy with the 810 km baseline (right) from FNAL to Ash River

The NOvA experiment with over 150 collaborators from 25 institutions in 5 countries, will measure the probability of the transitions $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ between the 30 ton Near Detector (ND) ~1 km from the neutrino source and the 14 kton Far Detector (FD). The NuMI source [4] is a horn-focused secondary beam of charged mesons and their decay yields a broad spectrum of ν_μ energies on axis, but at larger angles the beam energy spectrum becomes sharply peaked at lower energies, as shown in Fig. 4. At 14 mr off the beam axis, the neutrino energy is peaked near 2 GeV. By placing the FD 810 km from Fermilab near, Ash River, MN, the appearance signal (shown below the energy spectra) is near its maximum. In addition, the nearly monochromatic beam energy off-axis reduces a major source of background.

The ν_e appearance signal is the charged current (CC) reaction, $\nu_e N \rightarrow e^- + X$, with the electron generating a characteristic electromagnetic (em-) shower and with the total energy of interaction products close to the beam energy. Neutral Current (NC) reactions, such as $\nu_\mu N \rightarrow \nu_\mu + \pi^0 + X$, will produce gamma em-showers but the outgoing neutrino carries off a considerable energy making the total energy of the visible interaction products lower than the beam energy.

Figure 5: Aerial view of the FD (left), the 2nd block transported to the far end of the FD hall (center), and a top view of the first two blocks showing a total of 64 layers (right).

The NOvA FD is housed in a new building, as shown (from the air) in Fig. 5. Assembly of the FD has begun and 5 of the 28 blocks comprising its 14-kton mass have been installed. Each block has the approximate dimensions of 15x15x2 m^3 with a mass of 150 tons (empty) and 500 tons when filled with liquid scintillator. To form each block, layers of 384 cells (4x6 cm^2 in cross section) ~15m long are laid out flat, the 32 layers alternating in direction by 90°, with glue between each layer. Once the glue cures, the empty block is rotated 90 degrees to a vertical orientation by a massive block raiser, as shown in Fig. 5 (center) and transported to the previously stacked blocks. The wavelength shifting fiber in each cell is routed in groups of 32 in a manifold to a cookie, 12 manifolds in each a layer, as shown in Fig. 5 (right). Once a block is filled with scintillator a 32-channel APD chip with associated readout electronics is attached to the cookie.

A cavern in the NuMI tunnel has been excavated for a Near Detector (ND) off to the side by a 14 mr angle from the beam axis direction and just upstream of the on-axis MINOS near detector. The ND will be constructed with 6 blocks made with the same components as the FD except the length of each cell is reduced to 4m so that each block has the approximate dimensions 4x4x2 m^3.

3. NOvA physics reach

The appearance measurement can be thought of as the extraction of two numbers from the data: the probabilities for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at 2 GeV. These are best displayed in a "bi-probability" plot, as shown in Fig. 6. In this and following plots, reasonable choices have been made for the Δm^2 parameters and the mixing angles consistent with recent measurements, and 4 points for each hierarchy assumption locate the probabilities when the CP-violating parameter δ is 0, π/2, π, or 3π/2. In the inverted hierarchy (shown in red), the $\bar{\nu}_\mu \to \bar{\nu}_e$

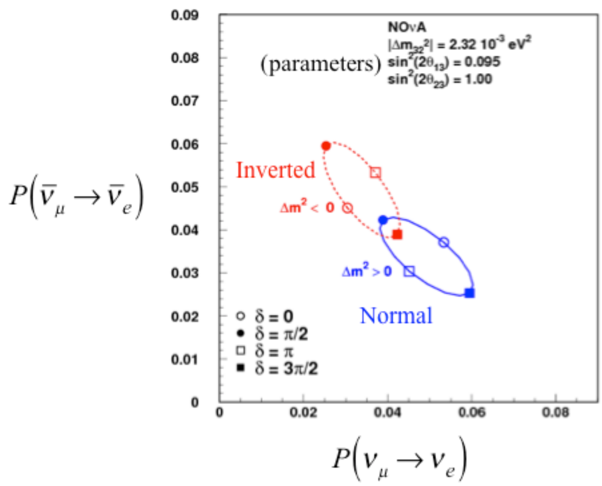


Figure 6: Plot showing hypothetical measurements of the probabilities for $\bar{\nu}_\mu \to \bar{\nu}_e$ vs. $\nu_\mu \to \nu_e$ in each mass hierarchy (Inverted or Normal) for four values of the CP-violating phase δ.

appearance probability is typically larger than the probability for $\nu_\mu \to \nu_e$ and vise-versa for the normal hierarchy (shown in blue).

There are extreme cases of these with $\delta = \pi/2$ in the inverted hierarchy and $\delta = 3\pi/2$ in the normal hierarchy, as shown (starred points) in Fig. 7. If the experiment results in one those measurements, the mass hierarchy is resolved by about 3σ, while CP conservation ($\delta = 0$ or π) is rejected by about 2σ. If the measurement shows equal probabilities for ν and $\bar{\nu}$ appearance there is no information on the mass hierarchy, but CP conservation ($\delta = 0$ or π) would again be rejected by about 2σ.

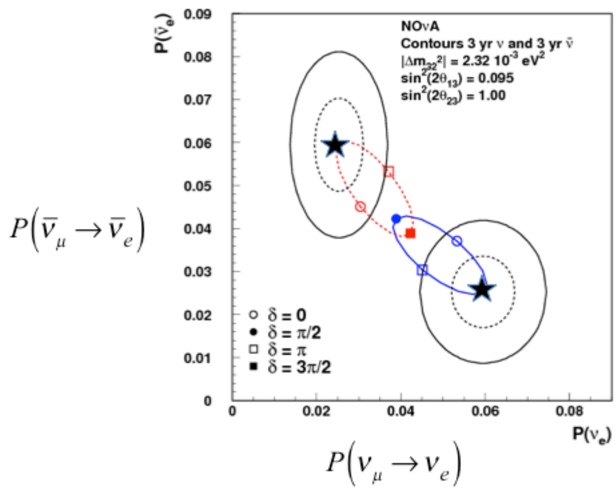


Figure 7: Bi-probability plot showing the 1 and 2σ error ellipses at two points where the mass hierarchy is resolved by about 3σ.

The significance for the mass hierarchy resolution, as shown in Fig. 8, varies from zero to nearly 3σ for the extreme cases. It is above 1σ for about 50% of the range of δ with either

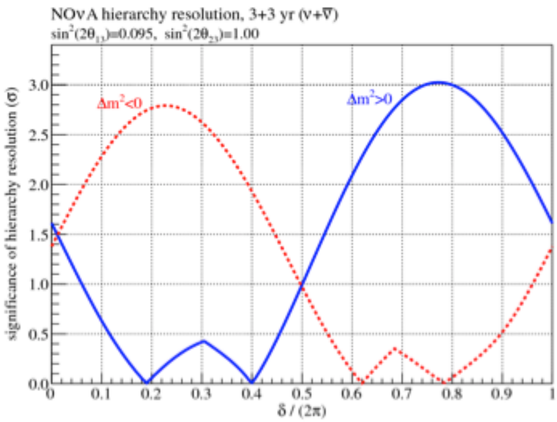


Figure 8. Significance for the resolution of the mass hierarchy is shown as a function of δ.

hierarchy. If the results expected from the T2K experiment [5] on a much shorter baseline are folded into the analysis the significance remains above 1σ for the entire range of δ.

While resolving the mass hierarchy and obtaining evidence for CP violation in oscillations are the primary goals of NOνA, the experiment can improve knowledge of the θ_{23} mixing angle. The value of $\sin^2 2\theta_{23}$ which controls the survival probabilities $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ is known to be very close to 1. How close it is to 1 can be ascertained by measuring the survival

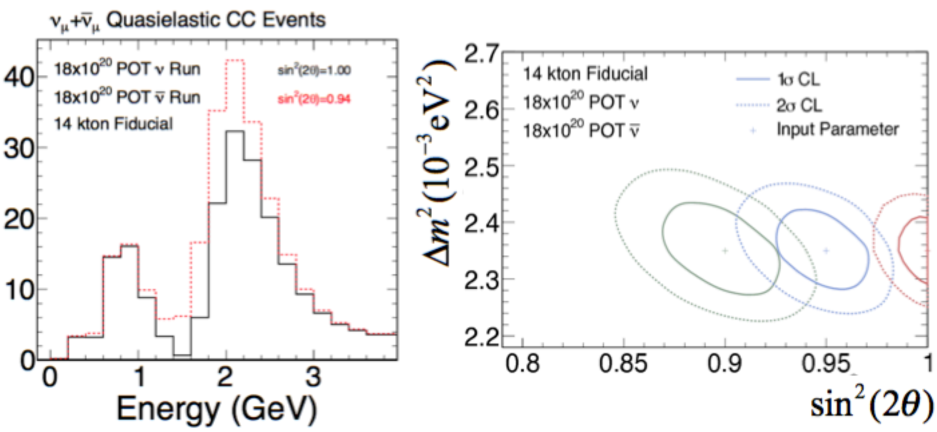
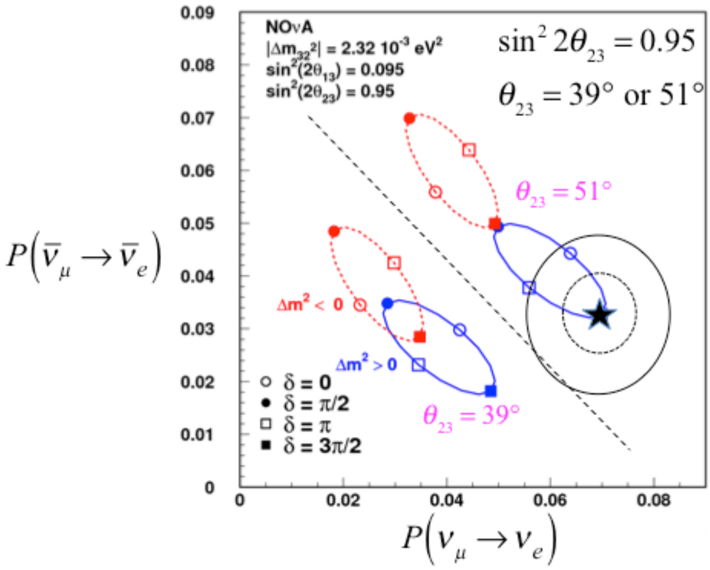


Figure 9: Energy dependence of the survival probabilities for (left) two values of the mixing angle and (right) the 1 and 2σ error ellipses for 3 values of the mixing angle.

probabilities for the quasi-elastic CC reactions, as shown in Fig. 9. The dip at 1.5 GeV in the survival probability occurs where the oscillation to tau neutrinos is a maximum. If $\sin^2 2\theta_{23}$ is not 1, the yield of quasi-elastic charge current events fills in near 1.5 GeV resulting in the error ellipses in the oscillation coefficient for three possible values of the angle shown.

If the mixing angle θ_{23} is significantly different from $\pi/4$, a measurement of the sum of the survival probabilities for ν and $\bar{\nu}$ can resolve the octant ambiguity through the interference term involving $\sin^2\theta_{23}$ as shown in Fig. 10, where the starred point has θ_{23} larger than $\pi/4$ by 2σ .



At the end of the 6 year run, the experiment will have a signal to background (from NC, beam ν_e, and misidentified ν_μ CC interactions) of > 2/1 in both beam modes, as shown in Fig. 11. Though dependent on the detailed assumptions of the oscillation parameters, NOvA will also obtain reasonable statistics for the appearance signals, and further development of the analysis used here [6] may be able to improve the signal efficiency and reduce the backgrounds.

3yr (ν) + 3yr ($\bar{\nu}$)

Background	ν	$\bar{\nu}$
NC	19	10
$\nu_\mu$cc	5	<1
$\nu_e$cc	8	5
tot BG	32	15
$\nu_\mu \rightarrow \nu_e$	68	32

Figure 11: After 6 years of running NOvA, the expected number of events in 3 background channels and the signal channel (red) for ν and $\bar{\nu}$.

4. Beyond NOvA

The LBNE collaboration submitted a proposal to build a 40kT Liquid Argon Time Projection Chamber (LArTPC) to be located underground in the former Homestake gold mine near Lead SD, and to build a new beam at Fermilab with a minimum power of 0.7 MW. The price tag, ~$1.5B for this facility proved too high for an immediate approval, so that a “staged approach” was adopted whereby a 10 kT would be built on the surface to be followed later by a larger detector underground. This configuration [7] received CD-1 approval in December 2012.

The LBNE collaboration is actively pursuing international collaborators and support so that plans for a larger detector at an underground location can be reinstated at an early date.

5. Conclusions

The NOvA experiment has achieved a number of milestones in preparing for its investigation of oscillation parameters using a near detector, a 14-kton far detector and an off-axis 2 GeV muon neutrino beam upgraded to 700 kW. The detectors have been optimized for detection of the electron showers characteristic of 2 GeV electron neutrino interactions appearing after traveling 810 km through the earth. Starting a 6 year running period in the spring of 2013 the experiment will collect data that will allow measurements of θ_{13}, θ_{23}, Δm^2_{23}, with up to a 3σ resolution of the mass hierarchy, and up to a 2σ observation of CP violation. These measurements will set the stage for LBNE and its further studies of neutrino oscillations using the powerful LArTPC technique.

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