NOvA: The NuMI Offaxis $\nu_e$ Appearance Experiment

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The NOvA Collaboration

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NOvA Overview

- **NOvA** is a second generation accelerator based neutrino oscillation experiment, optimized for detection of the oscillations:
  \[ \nu_\mu \rightarrow \nu_e \text{ and } \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

- **NOvA** is:
  - A 14 kton, “totally active”, far site detector
  - A 222 ton near detector, utilizing an identical detector technology and geometry
  - An upgrade of the NuMI beam intensity from 320 kW to 700 kW

- Both detectors are “totally active”, highly segmented liquid scintillator calorimeter designs

- The detectors are placed 14mrad off the primary beam axis to achieve narrow \( \nu_\mu \) energy spectrum, peaked at 2GeV.

- The far detect sits on a 810km baseline between Chicago and Northern Minnesota at the first oscillation maximum
Physics Motivations

NOVA SENSIVITIES
Questions for NOvA to Answer

• The NOνA experimental program addresses 7 of the 8 questions posed by the P5 strategic plan for neutrino physics:
  ▶ What is the value of $\theta_{13}$?
  ▶ Is $\theta_{23}$ maximal?
  ▶ Do neutrinos violate CP?
  ▶ What is the mass structure of the known neutrinos?
  ▶ Are neutrinos their own anti-particles?
  ▶ What can neutrinos tell us about physics beyond the standard model? Sterile Neutrinos?
  ▶ What can we learn from the neutrino burst of a near galactic Supernova?
**The Off-Axis Effect**

In the pion rest frame the kinematics are all completely determined for the decay.

But when we boost into the lab frame the neutrino’s energy depends on the angle relative to the boost direction.

This ends up projecting neutrino energy spectrum down till it’s almost flat.

\[ E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \Theta^2} \]

At 14 mrad ~all pion decays result in 2 GeV neutrinos.
The Effect of Going Off-Axis

By going off-axis, the neutrino flux from $\pi \rightarrow \mu + \nu$ is reduced at a distance $z$ to:

$$F = \left( \frac{2\gamma}{1+\gamma^2 \theta^2} \right)^2 \frac{A}{4\pi z^2}$$

But the energy narrows as $\theta^2$:

$$E_{\nu} = \frac{0.43E_{\pi}}{1+\gamma^2 \theta^2}$$

For NOvA, moving 14 mrad off axis makes the NuMI beam energy

– peak at 2 GeV
– $E_{\nu}$ width narrows to 20%

The detector is matched well to this narrow band beam with an energy resolution $\sim 4\%$ for $\nu_\mu$ CC events
The Advantage of Going Off-Axis

- This suppresses the high energy tail (NC background)
- Significantly reduces the backgrounds from Kaons by shifting the neutrino energy
  \[ E_{\nu_K} = \frac{0.96E_K}{1+\gamma^2\theta^2} \]
- Energy spectrum in the signal region becomes almost insensitive to the \( \pi/K \) ratio
- Results in neutrino peak primarily from \( \pi \) decays
- Essential for making the high precision \( \theta_{23} \) measurement
Measuring $\nu_e$ appearance in the NuMI $\nu_\mu$ beam will give evidence for $\nu_\mu \rightarrow \nu_e$ transitions and a non-zero $U_{e3}$ component to $\Delta m^2_{32}$.

This is done through the $\nu_e$ CC channel.

The $\nu_\mu$ NC is the dominant background, controlled through the identification of initial vertex and displaced shower conversion point.

NO$\nu$A’s energy (2GeV) and baseline (810km) and segmentation (0.15$X_0$) are chosen to maximize the physics reach of accessing these transitions.

The $U_{e3}$ contribution to the third mass state is small, requiring a precision measurement of $\nu_e$ appearance.
Sensitivity for $\theta_{13}$ from $\nu_\mu \rightarrow \nu_e$

- Nova is sensitive to electron neutrino appearance down to $\sim 0.01$ at 90% CL.
- The physics reach for $\theta_{13}$ is shown for 3 years of running each on $\nu$ and $\nu$-bar.
- There are hints that $\theta_{13}$ may be large.

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Sensitivity to $\sin^2(2\theta_{23})$

- The detector’s excellent energy resolution, allows NO$\nu$A to perform the disappearance measurement to 1%
- Typical 2GeV $\nu_\mu$ CC-quasielastic event has $\sim$120 hit cells

- If $\sin^2(2\theta_{23}) \neq 1$, we can then resolve quadrant of the mixing ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$, )
- Measure if $\nu_3$ couples more to $\nu_\mu$ or $\nu_\tau$
- If $\sin^2(2\theta_{23}) = 1$ then this could be a new basic symmetry

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CP Violation

- NOvA gives us our first access to CP violation in the neutrino sector
- The Large Mixing Angle (LMA) solution gives sensitivity in $\nu_\mu \rightarrow \nu_e$ transitions to the CP violating phase $\delta$.
- In vacuum, the transition probability is shifted with $\delta$. At the first oscillation maximum the shift is:
  $$|\Delta P_\delta(\nu_\mu \rightarrow \nu_e)| \sim 0.06\% \sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$
- Since the shift is proportional to $\sqrt{\sin^2 2\theta_{13}}$ the importance of the sub-leading terms grow, as $\sin^2 2\theta_{13}$ gets small.
- In matter, the ultimate sensitivity of NOvA for resolving the CP ambiguities depend on both $\theta_{13}$ and $\delta$
Mass Ordering

- From solar and atmospheric data we know:
  \[ m_1 < m_2 \]
  \[ \Delta m^2_{12} < \Delta m^2_{23} \]
  \[ \Delta m^2_{23} \approx 2 \times 10^{-3} \text{eV} \]

- This leads to two possible mass hierarchies:
  - A “normal” order which follows the charged lepton mass ordering
  - An “inverted” order where \( m_3 \) is actually the lightest

- NO\(\nu\)A can solve this by measuring the sign of \( m_{23} \) using the MSW effect over the 810km baseline
Matter Effect

• The forward scattering amplitudes for neutrinos and antineutrinos through normal matter differ due to the inclusion of the extra diagram for interactions off electrons.

• This difference breaks the degeneracy in the neutrino mass spectrum and modify the oscillation probability:

\[ P_{\text{mat}}(\nu_\mu \rightarrow \nu_e) \neq P_{\text{mat}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \]

• If the experiment is performed at the first peak in the oscillation then the matter effects are primarily a function of the beam energy and approximated by:

\[ P_{\text{mat}}(\nu_\mu \rightarrow \nu_e) \approx (1 + \frac{E}{E_R})P_{\text{vac}}(\nu_\mu \rightarrow \nu_e) \]

\[ E_R = \frac{\Delta m_{23}^2}{2\sqrt{2} G_F N_e} \approx 11 GeV \]

• In the normal hierarchy this matter effect enhances the transition probability for neutrinos and suppresses the probability for antineutrinos transitions.

• With an inverted hierarchy the effect is reversed.

• For the 2 GeV neutrino beam used for NO\nuA, the matter effect gives a 30\% enhancement/suppression in the transition probability.
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\[ P_{mat}(\nu) \]

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\[ \nu_e \rightarrow \nu_e \]

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Resolution of the hierarchy

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The high granularity of the NOvA detector makes clean measurements of the NC cross sections possible, and allows for Sterile neutrino searches.

If NOvA can establish the inverted mass hierarchy, then the next generation of neutrinoless double-$\beta$ decay experiments should see a signal, else it is highly likely that neutrinos are Dirac in nature.
• Primary SuperNO\textsubscript{\textnu}A Signal:
  \[
  \bar{\nu}_e + p \rightarrow e^+ + n
  \]

• For a supernova at 10kpc the total signal is expected to contain:
  – 5000 total interactions over a time span of \( \approx 10s \)
  – Half the interactions in the first second
  – Energy peaks at 20MeV and falls off to \( \sim 60\text{MeV} \)

• Challenge is triggering in real time
  – Need data driven open triggering
  – Long event buffering (\( \sim 30\text{sec} \))
  – Time window correlation & merging

• NO\textsubscript{\textnu}A – farm 180 trigger/buffer PCs
  (min 30s total event buffering)
The Experiment

THE NOVA DETECTOR
NOvA Detectors

Far Detector
• 14kTons – 930 layers
• Alternating X/Y measuring planes
• Design has 30 modular “blocks” for assembly
• Over 357,000 independent measurement cells
• > 70% of total mass is active
• Located 14mrad off axis
• 810km baselines

Near Detector
• 222 Tons – 206 layers
• 2 modules wide, six blocks deep
• Includes muon catcher for ranging out μ’s
• Located 14mrad off axis in NuMI, next to MINOS cavern
Far Site (Ash River)

• The Ash River site:
  – Provides 810km baseline
  – Sits 11.8 km (14.5 mrad) off the NuMI beam axis
  – Is the most northern site in the United States that was accessible by road (and we had to build an extra 3.6 miles of road to get there)

• Detector Hall
  – Designed for up to an 18kt detector
  – Detector is built in place using modules blocks which are assembled and raised.
  – Production physics data collection can start after commissioning of the first few blocks
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**Detector Cell**

**Fiber and Scintillator**

**NOνA Detection Cell**

- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- High reflectivity PVC gives ~8 reflections for emitted light before capture in a wave shifting fiber
- 0.7mm wave shifting fiber loop captures the light and transports it up the cell
- Both fiber ends are read out by a single pixel of the APD.

**Light Collection**

- The scintillator/fiber detection cell is measured to delivers 30-39 p.e. for a muon traversing the far end of the cell
- NOνA uses over 14,000km of fiber

There are 357,120 cells in NOνA

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**Fiber Attenuation Length**

The fiber is a double clad 0.7mm fiber doped with 300ppm of a K27 fluorescent dye. The fiber exhibits a long attenuation length for the peak emission spectrum with tests at 300ppm of dye concentration over 15m for the 550nm peak of the spectrum.

**Absorption/Emission**

- Emission peak at 600nm
- Absorption minima at 500nm and 650nm
**Detector Modules**

### NOvA Modules

- The NOvA detector module forms the base unit for the detector.
- Each module is made from two 16 cell high reflectivity PVC extrusions bonded into a single 32 cell module.
- Includes readout manifold for fiber routing and APD housing.

- Combined 12 module wide X or Y measuring planes.
- Each module is capped, and filled with the liquid scintillator.
- These are the primary containment vessel for the 3 million gallons of scintillator material.

- There are 11,160 detector modules with a total of 357,120 separate detection cells in the NOvA Far Detector.

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**PVC Extrusions**

Each extrusion is a single 15.7m (51.5ft) long set of 6x3.9cm cells. Two extrusions are joined to form a single 1.3m wide module.
The NOvA Readout

- Require 357,120 optical readout channels
- Custom designed 32 channel APD (*Hamamatsu*)
- High 85% Q.E. above 525nm
- Cooled to -15° to achieve noise rate < 300 electrons

- Operated at gain of 100 for detection of 30-39 photon signal from far end readout
- Signal to noise at far end 10:1
Front End Electronics

- Use a continuous digitization and readout scheme
- APDs are sampled at a 2MHz and a dual correlated sampling procedure is used for signal recognition/zero suppression
- Done real time on the FPGA, the signals are then dispatched to Collector nodes as “time slices”
- Data Concentrator Modules assemble/order the data and dispatch macro time windows to a “buffer farm” of 180 compute nodes
- Provides minimum 30sec full data buffer for trigger decision
- Dead-timeless system with software based micro/macro event triggering

Data Concentrators (DCM)
The digitized data streams from 64 front end boards are broadcast over 8B/10B serial links to an associated data concentrator module which orders, filters and buffers the data stream, then repackages the data into an efficient network packet and rebroadcasts it to a specific buffer node for trigger decisions.

FEB ASIC
A low noise device with expected designed ASIC is a noise < 200 e. rms. integrator/shaper with multiplexer running at 16MHz. The channels are Muxed at 8:1 and sent to a 40MHz quad ADC for digitization. For the higher rate near detector the channels are muxed at 2:1 and sent to 4 quad ADCs. ASIC is
NOvA Status & Funding

• NOvA Received 55M$ in American Recover & Reinvestment Act funding
• Ground was broken on the far site May 1\textsuperscript{st} 2009
• NOvA under went a CD-3b review last week
• NOvA will attempt to use the dramatic change in funding to advance the project schedule
• Near detector is now schedules for construction & commissioning on the surface in spring/summer 2010
Additional Materials

BACKUP SLIDES
• T2K+ Daya Bay can push the upper limit on $\sin^2 2\theta_{13}$ to 0.01.
• NOvA pushes the non-zero discovery past 99% CL.
• NOvA’s sensitivity to $\delta_{CP}$ can cover half the $\delta_{CP}$ space

M. Messier (NOvA CD-3b Review)
**νμ Neutral Current Background**

Event Parameters

Reaction:

\[ \nu_e N \rightarrow p\pi^0 \nu_\mu \]

- \( E_\nu = 10.6\text{GeV} \)
- \( E_p = 1.04\text{GeV} \)
- \( E_\pi = 1.97\text{GeV} \)

Suppressed by vertex/shower displacement identification
Event Parameters

Reaction:

\[ \nu_e p \rightarrow p \pi^+ e^- \]

- \(E_\nu = 2.5\text{GeV}\)
- \(E_p = 1.1\text{GeV}\)
- \(E_\pi = 0.2\text{GeV}\)
- \(E_e = 1.9\text{GeV}\)

Shower spans \(\sim 65\) of the 1178 planes
NuMI Accelerator Upgrade

**Beamline Upgrade**

- Proton source upgraded from 320kW to 700kW
- NuMI will deliver $4.9 \times 10^{12}$ protons per pulse
- 1.33s rep-rate.
- This results in $6 \times 10^{20}$ pot/yr.

**Changes**

- Recycler runs proton not anti-protons
- New injection/extraction lines for Recycler to Main Injector transfers
- Main Injector cycle time reduced from 2.2s to 1.5s (stack in the recycler)
- Cycle time reduced again to 1.33s with 2 more RF stations at MI-60 and with transition of the MI from 204 GeV/s to it’s design acceleration rate of 240 GeV/s.
- NuMI target redesign for high flux
Supernova Neutrinos

- Neutrinos and Antineutrinos are produced via:
  \[ NN \rightarrow NN\nu\bar{\nu}, \quad e^+e^- \rightarrow \nu\bar{\nu}, \ldots \]

- The neutrinos are trapped in core collapse, reach thermal equilibrium and then escape in a burst
- Duration of the neutrino burst: 1-10s
- The neutrino luminosity is upwards of 100 times greater than the optical luminosity
- Neutrino flash proceeds primary photons by 5-24 hours.

- Each flavor takes away the same energy fraction
- Different neutrino temperatures are due to allowed reaction channels
DAQ and Trigger

Data Ring

Data Driven Triggers System

Trigger Processor

Trigger Processor

Trigger Processor

Data Driven OR

Event builder

Trigger Reception

Data Slice Pointer Table

Data Time Window Search

Global Trigger Processor

Data

Broadcast to all Buff Nodes & Logger

Data Logger

Buffer Nodes

DCMs

Round Robin Data Slice Flow

Beam Spill Indicator

(Async from FNAL)

5ms data blocks

5ms data blocks

Data

Triggered Data Output

Data Ring

DCM 1

DCM 1

DCM 1

DCM 1

DCM 1

DCMs

Round Robin Data Slice Flow

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