The Status of the NOvA Experiment

Sarah Phan-Budd
Argonne National Laboratory

Miami 2011
December 16, 2011
The NOνA collaboration is made up of scientists and engineers from 24 institutions:

ANL, Athens, Caltech, Institute of Physics of the Czech Republic, Charles University, Czech Technical University, FNAL, Harvard, Indiana, Iowa State, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Twin Cities, INR Moscow, South Carolina, SMU, Stanford, Tennessee, Texas/Austin, Tufts, Virginia, WSU, William and Mary
The NO$\nu$A Experiment

- **NuMI Off-Axis $\nu_e$ Appearance Experiment**
  - 14kT Far Detector, 810 km from FNAL
  - 220T Near Detector, at FNAL
  - Beamline upgrade
  - Run for 6 years

- **Goals**
  - Measurement of $\theta_{13}$
  - Measurement of $\text{sin}2(2\theta_{23})$
  - Determination of mass hierarchy
  - Begin to localize $\delta_{CP}$
NOνA Long Baseline

- Sensitivity to Neutrino Oscillation depends on the distance (L) the neutrino travels and the energy of the neutrino beam (E)
- For NOνA, L=810 km, E~2GeV
- Neutrinos travel through matter
- Provides sensitivity to mass ordering via matter effects
Why is NOνA off-axis?

- Off-axis yields a narrow band beam
- More flux and less background
  - Backgrounds: $\nu_e$’s from $K$ decay and higher-energy NC events

\[
E_\nu = \frac{0.43 \gamma m_\pi}{1 + \gamma^2 \theta^2}
\]
The NO\textsubscript{v}A Detectors

- FD: 65% Active Volume, 928 planes
- Planes consist of PVC extrusions w/15\% TiO\textsubscript{2}  
  - Alternate vertical & horizontal orientation
- Liquid Scintillator
- Wavelength shifting fiber
- PVC cell for primary containment
- Avalanche Photodiode
- Low noise amplifier

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The Far Detector

- Cells are in 16-cell PVC extrusion.
- Glue 2 extrusions together to make a 32 cell module.
- 12 modules make up a plane.
- Planes alternate horizontal and vertical.
The Near Detector

- 6 blocks of 31 planes plus a muon catcher.

- Downstream of the active region is a 1.7 meter long muon catcher region of steel interspersed with 10 active planes of liquid scintillator.

Basic detector unit is 1 block of 31 planes alternating horizontal and vertical.

Veto region, fiducial region
Shower containment, muon catcher
NuMI (Neutrinos at the Main Injector) Beam

- Beam spectrum tunable by horn currents, relative placement of target and horns.
- Can select $\nu$ or $\bar{\nu}$ predominant beam depending on horn current polarity.
- 10μs beam spill (every 2.2 sec).

- Operating since 2005 (MINOS, MINERvA, ArgoNEUT)
- Routinely delivers ~340kW beam power.
- Most operations to-date in “Low Energy” mode optimized for MINOS on-axis location.
NOvA Upgrades:

-700 kW power to NuMI using existing accelerator complex.

-Reduce cycle time from 2.2 to 1.33 seconds.
PVC NOvA Cells

• NOvA cell:
  • 3.8 cm X 5.9 cm X 15.5 m; ~4 mm thick
  • Titanium dioxide loaded PVC (~90% reflectivity at 430 nm)
  • 8 reflections on average
  • 0.15 radiation length per layer filled
  • ~385,000 for 15 kTon. 32 in a sealed module.
Detector Components: Liquid Scintillator/Fiber

**Liquid Scintillator**
- 70% of detector mass
- Mineral oil, 5% pseudocumene and wavelength shifters
  - Produces light at 400 – 450 nm
- 3.9 million gallons of liquid scintillator at far site

**Wavelength Shifting Fiber**
- Single sided readout from 0.7 mm diameter looped fiber
- Shifts light to green 490 - 550 nm
- 13,000 kilometers of wavelength shifting fiber for far detector

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Avalanche Photodiodes

- APD is a classic linear APD manufactured by Hamamatsu operated at a gain (M) of 100
  - S11211(X) custom variant of commercial S8550 SiAPD

- Operating temperature is -15°C to keep shot noise at the same level as the amplifier noise

- Signal-to-noise > 10 for muon at far end of a 15m long cell

- Both ends of the fibers in each cell are read with a single APD

- 32 APDs in a single 4 × 8 array to readout one module

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Pixel Active Area</th>
<th>1.95 mm × 1.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Pitch</td>
<td>2.65 mm</td>
<td></td>
</tr>
<tr>
<td>Array Size</td>
<td>32 pixels</td>
<td></td>
</tr>
<tr>
<td>Die Size</td>
<td>15.34mm × 13.64mm</td>
<td></td>
</tr>
<tr>
<td>Quantum Efficiency (&gt;525 nm)</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Pixel Capacitance</td>
<td>10 pF</td>
<td></td>
</tr>
<tr>
<td>Bulk Dark Current (I_B) at 25°C</td>
<td>12.5 pA</td>
<td></td>
</tr>
<tr>
<td>Bulk Dark Current (I_B) at -15°C</td>
<td>0.25 pA</td>
<td></td>
</tr>
<tr>
<td>Peak Sensitivity</td>
<td>600 nm</td>
<td></td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>375 ± 50 volts</td>
<td></td>
</tr>
<tr>
<td>Gain at Operating Voltage</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Operating Temperature (with Thermo-Electric Cooler)</td>
<td>-15°C</td>
<td></td>
</tr>
<tr>
<td>Expected Signal-to-Noise Ratio (Muon at Far End of Cell)</td>
<td>10:1</td>
<td></td>
</tr>
<tr>
<td>APD channels per plane</td>
<td>384</td>
<td></td>
</tr>
<tr>
<td>APD arrays per plane</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Total number of planes</td>
<td>930</td>
<td></td>
</tr>
<tr>
<td>Total Number of APD arrays</td>
<td>11,160</td>
<td></td>
</tr>
<tr>
<td>APD pixels total</td>
<td>357,120</td>
<td></td>
</tr>
</tbody>
</table>
NOvA Block Construction

Glue machine

Near Detector lifting fixture

Compression fixture
Near Detector on the Surface (NDOS)

- Full test of construction techniques to create a working prototype near detector
  - PVC Extrusions
  - Module construction
  - Block construction
  - Electronics and Outfitting
  - DAQ and NOvA software

- Finished Winter/Spring 2010-2011

- At the intersection of the FNAL NuMI and Booster beams
NDOS Commissioning

- Currently commissioning the NDOS detector
- Understanding the data
- Looking for beam neutrinos
- Developing $\nu_e$ identification tools
- And more…
  - Calibration, software development, Monte Carlo background simulation development, physics analysis development, much more than be covered here
Early NDOS Analysis

Simulated neutrino events

Small shower from 2\textsuperscript{nd} \gamma

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Early look at contained events indicates NuMI Monte Carlo event rate prediction agrees with data
Finding Neutrinos

- Running parasitically, a long way off axis, in the Fermilab NuMI beamline
- We can see peak of events created by the neutrino beam above the cosmic ray background
- Beam optimized for antineutrino production: 1001 beam events (69 cosmic BG)
- Beam optimized for neutrino production: 253 beam events (39 cosmic BG)
Neutrinos

NOvA - FNAL E929
Run: 106938
Event: 314724
UTC Tue Dec 21, 2010
11:48:18.997623872

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Neutrinos
NO\textsubscript{v}A NDOS Operation: Calibration

**Top left:** Path length-corrected response to \(\mu\) for different distances from fiber end for a single example cell.

**Above:** Measured and fitted fiber attenuation for the example cell.

**Bottom left:** Response to \(\mu\) after att. length corrections.
NOvA NDOS Operation: Michel Electron Calibration

Random coincidences
These are clusters that are matched to muons recorded 20 seconds prior to event
Project Timeline

• Beam:
  – March 2012: Accelerator shutdown to install upgrades for beam

• FD:
  – Jan 2012: Start construction at Ash River
  – 50% detector by end of shutdown
  – Early 2014: Detector Complete

• ND:
  – 2012-13: Cavern excavation during shutdown
  – Current: Prototype in operation at FNAL on the surface
Sensitivity to $\Theta_{13}$

- The blue curves assume normal mass hierarchy while the red curves show the inverted hierarchy case.

- Sensitivity depends on mass hierarchy and $\delta$.

- Solid line is planned beam energy (700kW), dashed curves represent beam upgrades.
NOvA Sensitivity compared to Recent $\theta_{13}$ Results

90% CL Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

- L = 110 km, 15 kT
- $\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$
- $\sin^2(2\theta_{23}) = 1$
- 3 years at 700 kW, 1.2 MW, and 2.3 MW for each $\nu$ and $\bar{\nu}$

$\Delta m^2 > 0$
$\Delta m^2 < 0$

normal ordering
$\Delta m^2 = 2.35 \times 10^{-3}$ eV$^2$
dashed: CHOOZ

3σ

69%, 95% CL (2 dof)

curves: T2K+MINOS
shaded: T2K+MINOS+DC
What are the relative masses of neutrinos?

- Assumes 15 kt detector, 6 years of running (neutrino and antineutrino)

- Intensities at the baseline 700 kW (upgrades of 1.2 MW and 2.3 MW)

- NOvA may resolve the mass hierarchy if $\theta_{13}$ is large enough

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Do Neutrino Oscillations violate CP?

- NOvA provides the first look into the CP violating parameter space

- 1- and 2-σ measurement contours for NOvA Oscillations with parameters chosen at the starred point.

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Is $\sin^2(2\Theta_{23})$ maximal?
Conclusions

• The NDOS prototype near detector has been successfully constructed

• Commissioning is underway for the NDOS

• The larger far detector and beam upgrades will be finished by 2014

• We are in for an exciting few years!
Backup
Liquid Scintillator Composition

- Liquid scintillator for NOvA is composed of a primary scintillant (pseudocumene) that gives off light at 300 nm,
- waveshifters (PPO & bis-MSB) that downshift the UV photons to longer wavelength to facilitate absorption by the wavelength shifting (WLS) fibers (convert the photons to 420 nm),
- anti-static agent (Stadis) that prevents the build-up of static electricity.
- The “fluor mix” + anti-static are dissolved in a mineral oil solvent

<table>
<thead>
<tr>
<th>component</th>
<th>mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>mineral oil</td>
<td>94.90%</td>
</tr>
<tr>
<td>pseudocumene</td>
<td>4.99%</td>
</tr>
<tr>
<td>PPO</td>
<td>0.110%</td>
</tr>
<tr>
<td>bis-MSB</td>
<td>0.0015%</td>
</tr>
<tr>
<td>Stadis-425</td>
<td>0.0010%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>
WLS Fiber

Need ~ 12,000 km of 0.7 mm diameter wavelength shifting fiber from Kuraray. So far ~10% received and tested

- MSU Quality Assurance Scanner (duplicate at Kuraray factory)
  - Fiber wound on a drum in a 27 m long groove with holes on 1 m intervals
  - Fiber is NOT cut from the spool,
  - Light source illuminates fiber from within the drum
  - Total light output (photodiode) and spectrographic scans, each ~ 1 minute

K27 dye @ 300 ppm, S-type
• Hamamatsu Si Avalanche Photodiode (APD)
  – Custom design to match to fiber aspect ratio
  – APD’s are being ordered for the near detector
APD tests

Bias V for Gain = 100

- Bias voltage ~40 V lower at -15 °C than +25 °C
- Batch 1 APDs bias voltage lower than batch 2

Average Dark Current

- Average dark current ~20x lower at -15 °C than +25 °C
- Batch 1 APDs average dark current ~10x lower than batch 2

Dark current at room temp about 0.2na (40x better than specification)

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Tests of APDs

Gain vs. Bias Voltage

Bias V drops ~0.8 V/°C cooling

Gain=100 bias voltage linear vs. temperature

- Measured average QE with RMS spread across 32 channels
- Average across all channels (84.8 ± 2.5)% – expected 85%
## Proton Plans

<table>
<thead>
<tr>
<th></th>
<th>Present Operating Conditions (May 2007)</th>
<th>Proton Plan Multi-batch Slip-stacking in MI</th>
<th>NOvA Multi-batch Slip-stacking in Recycler</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 GeV Intensity (p/Batch)</td>
<td>4.3 - 4.5x10^{12}</td>
<td>4.3x10^{12}</td>
<td>4.3x10^{12}</td>
</tr>
<tr>
<td>Number of 8 GeV Batches to NuMI</td>
<td>7</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>MI Cycle Time (sec)</td>
<td>2.4</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td>MI Intensity (protons per pulse or ppp)</td>
<td>3.3x10^{13}</td>
<td>4.5x10^{13}</td>
<td>4.9x10^{13}</td>
</tr>
<tr>
<td>MI to NuMI (ppp)</td>
<td>2.45x10^{13}</td>
<td>3.7x10^{13}</td>
<td>4.9x10^{13}</td>
</tr>
<tr>
<td>NuMI Beam Power (kW)</td>
<td>192</td>
<td>320</td>
<td>700</td>
</tr>
<tr>
<td>Protons/year to NuMI</td>
<td>2x10^{20}</td>
<td>3x10^{20}</td>
<td>6x10^{20}</td>
</tr>
<tr>
<td>MI Protons/hour</td>
<td>4.95x10^{16}</td>
<td>7.3x10^{16}</td>
<td>1.3x10^{17}</td>
</tr>
</tbody>
</table>
Current Situation
The Booster injects 11 batches (9 for NuMI and 2 for antiproton production) into the Main Injector at 15 Hz

The Main Injector then ramps up, extracts the beam and ramps down in a 2.2s cycle time

Upgrades for NOvA:
- Use Recycler Ring to store 12 Booster batches while the Main Injector ramps
- Inject the Recycler beam in a single turn into the Main Injector
- Cycle time of 1.33 s
- New target design for medium intensity running

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APD Advantage

APD has the best photodetection efficiency matched to our WLS fiber spectrum.

APD operation more stable than PMT.
• Front-end electronics operate in continuous digitization mode.
• Data from the ADC is processed on-board with correlated sampling.
• 64 FEBs feed a Data Concentrator Module which passes the data to a processing farm.
• Data is buffered until the arrival of a software spill trigger.
• Data rate driven by cosmic ray muons (0.5 GB/s) (Mimicked at NDOS).