The ArgoNeuT Experiment

Andrzej Szela

for the ArgoNeuT Collaboration

Yale University

NuINT 2012, Rio de Janeiro
Outline

1. Introduction
   - The LArTPC

2. The ArgoNeuT Detector

3. ArgoNeuT@NuMI

4. Physics Results and Analyses
   - The LArSOFT Software package
   - On-Going analyses

5. The Future

6. Conclusions
Noble liquids for $\nu$ detection

- Abundant ionization electrons and scintillation light can both be used for detection.
- Noble liquids are dense, so they make a good target for neutrinos.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point [K] @ 1 atm</td>
<td>4.2</td>
<td>27.1</td>
<td>87.3</td>
<td>120.0</td>
<td>165.0</td>
<td>373</td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>0.125</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3.0</td>
<td>1</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>755.2</td>
<td>24.0</td>
<td>14.0</td>
<td>4.9</td>
<td>2.8</td>
<td>36.1</td>
</tr>
<tr>
<td>Scintillation [$\nu$/MeV]</td>
<td>19,000</td>
<td>30,000</td>
<td>40,000</td>
<td>25,000</td>
<td>42,000</td>
<td></td>
</tr>
<tr>
<td>dE/dx [MeV/cm]</td>
<td>0.24</td>
<td>1.4</td>
<td>2.1</td>
<td>3.0</td>
<td>3.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Scintillation $\lambda$ [nm]</td>
<td>80</td>
<td>78</td>
<td>128</td>
<td>150</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
LArTPC Concept

- Pioneered by the ICARUS collaboration
- Energy deposition in argon results in ionization and scintillation
- Electrons are drifted in the Electric field towards the anode.
- Signal is induced and then collected on subsequent wire planes (2D location).
- Drift time provides 3rd coordinate → 3D reconstruction.
- Quantity of charge provides calorimetric reconstruction.

![LArTPC Diagram](image-url)
LArTPC Program in the US

Yale TPC
- Location: Yale University
- Active volume: 0.002 ton
- Operational: 2007

Bo
- Location: Fermilab
- Active volume: 0.02 ton
- Operational: 2008

ArgoNeuT
- Location: Fermilab
- Active volume: 0.3 ton
- Operational: 2008
- First neutrinos: June 2009

MicroBooNE
- Location: Fermilab
- Active volume: 0.1 kton
- Construction start: 2011

LAr1
- Location: Fermilab
- Active volume: 1 kton
- Construction start: 2016

LBNE
- Location: Homestake
- Active volume: 10 kton
- Construction start: 2020

Luke
- Location: Fermilab
- Purpose: materials test
- Operational: since 2008

LAPD
- Location: Fermilab
- Purpose: Ar purity demo
- Operational: 2011

LAriAT
- Location: Fermilab
- Purpose: LArTPC calibration
- Operational: 2013 (phase 1)

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The ArgoNeuT Experiment
ArgoNeuT Goals

- First TPC in a beam in the US LAr R&D program
- Measure CC cross-sections on argon in the 1-5 GeV range.
- Examine effects of FSI using the TPC’s great Granularity
- Examine dE/dx particle ID, especially e/γ separation, crucial for future ν experiments.
- Develop automated reconstruction techniques.
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The ArgoNeuT TPC

- Two wire planes instrumented (3 present)
- E-field between planes optimized to maximize transparency
- Wire spacing at 4mm. MicroBooNE will use 3mm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>500 Liters</td>
</tr>
<tr>
<td>TPC Volume</td>
<td>175 Liters</td>
</tr>
<tr>
<td># Electronic Channels</td>
<td>480</td>
</tr>
<tr>
<td>Wire Pitch</td>
<td>4 mm</td>
</tr>
<tr>
<td>Electronics Style (Temperature)</td>
<td>JFET (293 K)</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>0.5m (330μs)</td>
</tr>
<tr>
<td>Light Collection</td>
<td>None</td>
</tr>
</tbody>
</table>

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ArgoNeuT Electronics

- “Warm“ JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Current trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PreAmp stage - FET Voltage Gain</td>
<td>0.5 mV/fC</td>
</tr>
<tr>
<td>Digitizer Module (ADF-2)</td>
<td></td>
</tr>
<tr>
<td>ADC range</td>
<td></td>
</tr>
<tr>
<td>ADC Gain</td>
<td></td>
</tr>
<tr>
<td>Sampling Time (FPGA)</td>
<td>δt=198 ns (0.03cm)</td>
</tr>
<tr>
<td>Electronics Charge Sensitivity</td>
<td>0.1881 ADC/mV</td>
</tr>
<tr>
<td>Tot. Capacitance (Det. and Cables)</td>
<td>7.49 ADC/fC</td>
</tr>
<tr>
<td>Response to mip (Coll. wires)</td>
<td>230 pF</td>
</tr>
<tr>
<td>S/N</td>
<td>≥ 15</td>
</tr>
</tbody>
</table>

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Cryogenics + Recirculation System

- Cooling with 330W CryoCooler
- Electronegative impurities, like O$_2$ and H$_2$O attach drifting electrons weakening the signal on the wires.
- Their quantity in argon can be diminished by pushing the argon through filters
- Used regenerated filters developed at Fermilab →  
  *Nucl.Instrum.Meth.A605:306-311,2009*
- Obtained sufficient purity ($\sim$700 $\mu$s) using gas recirculation. Liquid is faster.

<table>
<thead>
<tr>
<th>LAr volume (mass)</th>
<th>550 liters (0.77 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation</td>
<td>Vacuum Jacket ($10^{-4}$ mbar) with SuperInsulation</td>
</tr>
<tr>
<td>Total Heat Load</td>
<td>$\approx 120$ W</td>
</tr>
<tr>
<td>Cooling</td>
<td>CryoCooler (330 W cool. capacity)</td>
</tr>
<tr>
<td>Ar Recondensation</td>
<td>LAr Flow Rate: $\approx 3$ lt/hr</td>
</tr>
</tbody>
</table>

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The ArgoNeuT Experiment
Introduction

The ArgoNeuT Detector

ArgoNeuT@NuMI

Physics Results and Analyses

The Future

Conclusions

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NuMI Beam

**Neutrino mode**
- $\nu_\mu$: 91.7%
- $\bar{\nu}_\mu$: 7.0%
- $\nu_\mu + \bar{\nu}_\mu$: 1.3%

**Anti-neutrino mode**
- $\nu_\mu$: 39.9%
- $\bar{\nu}_\mu$: 58.1%
- $\nu_\mu + \bar{\nu}_\mu$: 2.0%
ArgoNeuT in the MINOS hall

- Remote, shiftless operation for 5 months.
- Acquired $1.35 \times 10^{20}$ POT, mainly in $\bar{\nu}_\mu$ mode.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>#events in AV ($\sim 1.35E20$ POT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>$\sim 6600$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>$\sim 4900$</td>
</tr>
</tbody>
</table>
Purity and Electron Lifetime

- Electron lifetime calculated using passing muons.
- Converts to $O_2$ concentration
- Recirculation in gas.
- G10 in gas causes problems due to water outgassing
- Lesson learned: purity is important → Material Test Stand and LAPD
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LArSOFT is a software package developed for LArTPCs
- Detector agnostic
- Constructed from separate modules - highly configurable

**LArSOFT structure**

- Wire Calibration
- Hit Finding
- Hit Clustering
- Endpoint Finding
- 3D Shower Finding
- 3D Tracking
- Vertex Finding
- Calorimetry
ArgoNeuT Events (2)

Low charge  High charge

ArgoNeuT Data

47 cm

$4 \times \pi^0$
The presence of the MINOS ND allows for energy reconstruction and charge identification \((q)\) of muons.

We gratefully acknowledge the help of the MINOS collaboration in these analyses.
Measurement of the $\nu_\mu$ CC inclusive Cross-section

Used data acquired in neutrino mode (8.5\times10^{18}POT)

C. Aderson et al., PRL 108, 2012

Simple cuts applied:
- vtx in fiducial volume
- track matched to muon in MINOS ND
- MINOS $q < 0$

first CC-inclusive cross-section measurements in argon
Calorimetry on Through-going Muons

- Calorimetry tested on through-going muons.
- The final sample contains 14322 $\mu^-$ and 2607 $\mu^+$.
- C. Anderson et al., arxiv.org:1205.6702, accepted by JINST

<table>
<thead>
<tr>
<th>Negative Tracks</th>
<th></th>
<th>Positive Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>14322</td>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
<td>0.6089</td>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
<td>10.52</td>
<td>RMS</td>
</tr>
</tbody>
</table>
See talk by K. Partyka on Friday.

- Muon (ArgoNeuT+MINOS reconstruction): $p = 2.85$ GeV/c
- Proton (ArgoNeuT reconstruction): track length = 10.88 cm, $T = 118$ MeV, $p = 0.485$ GeV/c
- Reconstructed Neutrino Energy $\simeq 3.1$ GeV

$E_\nu = p_\mu \cos\theta_\mu + p_h \cos\theta_h$

see event on slide 17
Nuclear Effects in ArgoNeut

- (See talk by O. Palamara on Friday)
- Due to the LArTPC’s excellent granularity ArgoNeuT is able to shed some light on vertex activity and multiple proton events
- Residual Range (distance from end of track) allows for Particle ID

![Graph showing dE/dx curves from simulation, test beam data, and GEANT4 MC predictions]

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CC - inclusive analysis of $\bar{\nu}_\mu$ data

- Sample size 8 times larger.
- CC inclusive measurements can be made on $\bar{\nu}_\mu$, but also on $\nu_\mu$ due to beam composition.
- Sample shown here is $\nu_\mu$!

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The ArgoNeuT Experiment
Energy resolution

Energy resolution $\approx 5\%$ for Minimum Ionizing Particles

$\delta \frac{dE}{dx} = 0.042 + 1.78 \times 10^{-4} \frac{dE}{dx}^2$
Electrons resulting from an energy deposition has a chance to reattach to the positive ions.

This effect depends on $dE/dx$ and is nonlinear.

Measurements in LAr are not very precise, especially at high $dE/dx$.

ArgoNeuT observes many stopping proton events, mainly from background interactions.

$$dE/dx = \frac{dQ}{dx} = \frac{A}{W_{ion}} - \frac{K}{E_{field}} \cdot \frac{1}{\rho} \frac{dQ}{dx}$$
Separating electrons from $\gamma$s is important in precision $\nu$ measurements. For example, understanding whether the MiniBooNE anomaly is an effect of oscillation or background. LongBaseline measurements, such as CP violation, etc. The $dE/dx$ of a shower can be a powerful discrimination tool: an electron is a Minimum Ionizing Particle, a $\gamma$ pair converts, so the ionization should be double.

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3D axis Showers calculated based on the angles of the 2D projections.

Correction for Birk’s recombination factor $f(dE/dx)$ and lifetime applied

$\nu_e$ CC candidate.
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\[ \text{dE/dx e/\gamma ID (2)} \]

\[ \nu_e \text{ CC candidate} \]
dE/dx e/γ ID (3)

$\nu_\mu$ CC + $\pi^0$ candidate

PRELIMINARY
Other Ongoing Analyses

- NC $\pi^0$ cs
- Hyperon Production
- $\mu + n$ protons + npions
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Future LAr Experiments in the US

- See talk by G. Karagiorgi (Friday)
- LAriAT (in construction) - LAr at a TestBeam
- MicroBooNE (in construction) - Short Baseline
- LAr1 - 1kT detector (LOI) - Short Baseline
- LBNE - Long Baseline
The ArgoNeuT detector will be resurrected as LArIAT (Liquid Argon in a Testbeam) phase 1.

- The objective calibration of single tracks and collective topologies
- Characterization of response at a range of energies relevant for future experiments (MicroBooNE, LBNE, etc.)
- Known input particle type and energy → calibrated output response
- Done at Fermilab Test Beam Facility
LArIAT phase 1

- Use Tertiary (low momentum) Beam developed by MINERVA collaboration.
- Provides protons, pions, electrons and muons.
- Modifications to the ArgoNeuT detector include a light readout system, recirculation in liquid and front flange.
- Planned start of data taking - spring 2013.
- A larger TPC, geared towards hadronic shower containment is planned to follow as LArIAT phase 2.
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Conclusions

- First LArTPC in a $\nu$ beam in the US
- Provided important know-how which is used by subsequent LArTPC experiments
- First $\nu$ data collected in the GeV region in Liquid Argon
- First results already published.
- Data analysis is ongoing and more results should come soon.
- The Detector itself will be reused as to calibrate the response of LArTPC to charged particles.
Muito Obrigado
Measurement of electron drift speed

- Measurement of electron drift velocity confirms understanding of detector.
- Difference of maximum and minimum hit drift gives time.
- Distance is size of detector
- Corrected for different field strengths between planes.