The ArgoNeuT LArTPC:

a dedicated Experiment for
neutrino Cross Section measurement at FNAL

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In the recent years, due to the increasing interest on LAr-TPC technology in the US, a dedicated experiment (ArgoNeuT, 2007) has been included as a first step in a graded program towards massive LBL neutrino oscillation experiments.

One of the main uncertainties in the next generation long baseline oscillation experiments is given by the neutrino-nucleus interaction cross section in the “few-GeV region”.

The (CC-QE) Cross Section (how well we measured it)

- Charged-Current Quasi-Elastic Scattering
  - Second generation measurements

(T. Katori)

- KEK/Booster
- NuMI
- CNGS

- MiniBooNE/SciBooNE in agreement, but tension with higher energy NOMAD results. All three on carbon. This is not understood.
- Single point, first and so far unique investigation with Ar target, in agreement with NOMAD data (same, high energy ν beam - WANF)

50t ICARUS LAr-TPC (preliminary errors)
ArgoNeuT Physics Goals

• Measure charged-current cross-section in the “few GeV” (1-5 GeV) range:
  • CC Quasi-Elastic (QE) channel
  • CC Resonant (RES: Δ→ π N) channel

  with unprecedented sensitivity to products of FSI (vertex activity characterization)

• e/γ separation study and optimization ⇒ superior background rejection
  • Important for ν_e appearance: excellent signal (CC ν_e) efficiency and background (NC π^0) rejection
  • Particle identification from energy deposition (dE/dx) measured along track

• Develop reconstruction techniques useful for all future LArTPCs:
  • full 3D reconstruction of the event topology
  • precise calorimetric reconstruction of deposited energy and Particle Identification
ArgoNeuT

✓ ArgoNeuT is a 175 liter (active) Liquid Argon Time Projection Chamber (LArTPC)
✓ Jointly funded by DOE/NSF
✓ Designed and assembled in 2007-08, first commissioned (on surface) at FNAL in Summer 2008
✓ Moved underground in the NuMI beam at FNAL, in front of MINOS Near Detector, early 2009
✓ Phase I: Exposure to $\nu/\bar{\nu}$ beam (LE beam option): June‘09 $\oplus$ Sept’09-Feb.’10

✓ Phase II - (second run): in the BOOSTER low-energy nu-beam (SciBooNE enclosure) - 2011

Fermilab, NuMI beam line

MINOS Hall: ArgoNeuT just upstream of the MINOS ND
The TPC, about to enter the inner cryostat

2 read-out planes: *Induction and Collection*

each channel: 2048 samples in 400 microseconds

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Cryostat Volume</td>
<td>500 Liters</td>
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<tr>
<td>TPC Volume</td>
<td>175 Liters</td>
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<tr>
<td># Electronic Channels</td>
<td>480</td>
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<tr>
<td>Wire Pitch</td>
<td>4 mm</td>
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<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>Electric field</td>
<td>500 V/cm</td>
</tr>
</tbody>
</table>
ArgoNeuT’s physics run in the NuMI beam

Schematic of NuMI experiments

NuMI beam Fluxes - Low Energy (LE) mode
$<E_{\nu}> = 3.7 \text{ GeV}$

- Neutrino mode
  - Horns focus $\pi^+, K^+$
  - $\nu_\mu$: 91.7%
  - $\overline{\nu}_\mu$: 7.0%
  - $\nu_e + \overline{\nu}_e$: 1.3%

- Anti-neutrino Mode
  - Horns focus $\pi^-, K^-$
  - Enhancing the $\nu_\mu$ flux
  - $\overline{\nu}_\mu$: 39.9%
  - $\nu_\mu$: 58.1%
  - $\nu_e + \overline{\nu}_e$: 2.0%

ArgoNeuT POT delivered and accumulated

- Stable, shift-free operation for >5 months!
- The first 1000s of (anti-)neutrino LArTPC events collected in a low-energy ($\sim3 \text{ GeV}$) neutrino beam ever!
(Neutrino) Event Display

The detector provides two 2D-views of the event.

The color scale is indicative of the energy deposited along the track.

- m.i.p. yield: \( \sim 6000 \, \text{e/mm} \)
- Very fine pixel size (4mmx4mm x 0.3mm)
- Dark "shadow bands" are due to electronics returning to baseline...

- Fourier decomposition (FFT) to remove electronics response (Filtering).
Neutrino Event – $\nu_e$

El.m. shower (not fully contained) + short densely ionizing track at the vertex

- This (beam-intrinsic) event demonstrates what a signal-like electron-neutrino event looks like in LArTPC.
- Current and future long baseline neutrino oscillation experiments (MINOS, T2K, NoVA, LBNE, ...) search for electron-neutrino appearance in order to measure $\theta_{13}$ and $\delta_{\text{CP}}$. 
ν event Reconstruction

Offline reconstruction procedure:
1. Hit identification
2. Hit reconstruction
3. Cluster/Vertex reconstruction
4. 3D track reconstruction
5. Matching ArgoNeuT tracks with downstream MINOS ND for escaping muon momentum reconstruction and sign determination
6. Calorimetric reconstruction
7. Particle Identification (dE/dx along the track)
\( \mu \) from upstream \( \nu \) beam interaction

2D views

3D reconstruction

Muon calorimetric reconstruction

Muon angular distribution

\[ <dE/dx> = 2.2 \text{ MeV/cm} \]
\[ dE/dx_{m.p} = 1.7 \text{ MeV/cm} \]
(Landau-Gauss fit)

Beam direction
(\( \approx 3^\circ \) downward to MINOS Far Detector)

(many) crossing \( \mu \)'s superimposed in 3D view
Tracks whose direction extrapolated from ArgoNeuT matches a MINOS track

Difference between horizontal coordinates and vertical coordinates of the “matched tracks”
μ from upstream $\bar{\nu}$ beam interaction:
Matching with MINOS ND (II)

MINOS:
reconstruction of the “matched muon” energy

Muon momentum reconstruction from MINOS ND:
- by curvature in magn. field - 12% resolution for a 10 GeV muon
- by range for stopping muons ~6% resolution)

MINOS:
measurement of the “matched muon” sign

NuMI

Anti-neutrino Mode
Horns focus $\pi, K^-$ enhancing the $\bar{\nu}_\mu$ flux

$\bar{\nu}_\mu$: 39.9%
$\nu_\mu$: 58.1%
$\nu_e + \bar{\nu}_e$: 2.0%

Preliminary
Entries 182
Mean 5.183
RMS 2.738

Preliminary
Entries 182
Mean -0.002972
RMS 0.5253

Higher energy distr. (63%)
Lower energy distr. (37%)
Minimum ionizing ptcl: \textit{muon or pion}

Track length = 52 cm
Kinetic Energy = 160 MeV
(in agreement with expectations GEANT)

Muon-Pion separation possible only in same cases
Muon-Pion separation possible only in same cases
νμ CC QE event reconstruction

ν Interaction in LAr volume

μ+p (νμ CC QE event) +
uncorrelated tracks from upstream neutrino interaction
Heavy ionizing ptcl.

Proton
Track length=25 cm
Kin. Energy=194 MeV
(in agreement with expectations
[GEANT-Nist tables])

Muon

dE/dx along the track ~ 2 MeV/cm

Preliminary
ν interaction in LAr

μ + π event + proton track

2 m.i.p. particles (μ + π) at vtx
[faking a QEL signature (μ + p)]
+ proton track (far from vtx.)

νμ

Track length=5.6 cm
Kinetic Energy=80 MeV
(in agreement with expectations
[GEANT-Nist tables])

(Preliminary)
**PID: e/γ separation study and optimization**

- Photon conversion background to νₑ interactions
  - Separation from primary vertex or by double ionization
  - γ-conversion over a minimum ionizing track requires excellent pair resolution

Careful inspection yields a minimum ionizing track with overlapping γ conversion

\[ \pi^0 \rightarrow \gamma \gamma \rightarrow (e^+e^-) (e^+e^-) \]

For \( e^+e^- \) efficiency > 80%,
\( e \) contamination < 5%
“Final State (re)-Interactions” - the main source of uncertainty:

even the “easiest” topology (CC-QE) is not so simple

\[ \nu_\mu + n \rightarrow \mu^- + p \]  
(reaction on free nucleon)

\[ \nu_\mu + A(n) \rightarrow \mu^- + p + (A-1)^* \]  
nucleon bound in the nuclear target

- proton Spallation (intranuclear interactions with \( p \) and \( n \) emission ...but also \( \pi^\pm, \pi^0 \))
- Nuclear evaporation (lower kin.en. \( p \) and \( n \))
- (and/or) Fission (nuclear fragments, \( \alpha \)'s,..)
- Nuclear de-excitation with \( \gamma \) emission

These products are usually neglected because not detectable, unless... .... a high quality imaging detector is in use !!
Understanding vertex activity

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\[ \nu_{\mu} + A(n) \rightarrow \mu^- + p + (A-1)^* \] (nucleon bound in the nuclear target)

These products are usually neglected because not detectable, unless...
.... a high quality imaging detector is in use!!
The ArgoNeuT Collaboration

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Conclusions

Next-generation neutrino physics experiments require precision Particle IDentification and fine grained 3D imaging on very large scale. Liquid Argon TPC combines an ideal detection medium with a modern imaging and calorimetric readout technique, scalable to very large volume/mass.

ArgoNeuT is a fully operational LArTPC: during the (first) ν-run, large samples of neutrino/antineutrino events have been collected for the 1st time ever in a low-Energy beam.

The extension to a second run period is being proposed at FNAL

Extensive Real data/experience is invaluable in improving LArTPC technique. Analysis software is being developed as general purpose tool for future LArTPCs. Highly sophisticated/detailed MonteCarlo codes are needed, and are currently under test/optimization.