The CAPTAIN Experiment

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University of Minnesota

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Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos - CAPTAIN

• Funded by Los Alamos National Lab (LANL) Laboratory Director Research & Development (LDRD). Now a multi-institutional collaboration.
• A portable full-scale liquid argon TPC (CAPTAIN) and a prototype (Mini-CAPTAIN).
• Study interactions in liquid argon with neutron source at LANL and neutrino beams at Fermilab.

Hamamatsu R8520-PMTs
MicroBooNE electronics
LAPD style Purity Monitor

7700L cryostat
1 meter drift
5-ton fiducial mass
500 V/cm drift field
3-mm wire spacing

Jianming Bian - DPF2015
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5 National Labs
13 Universities
Neutron studies at the Weapons Neutron Research Facility

**Mini-CAPTAIN** positioned in the WNR neutron beam at LANL and will characterize neutron interactions in argon.

- **High-energy neutrons** will produce pions and can be used to develop techniques to identify neutron interactions in Argon that will later help with neutrino energy reconstruction.

- **Low energy** neutrons can be used to study the neutrino-like argon reaction:

  \[ n + {}^{40}\text{Ar} \rightarrow {}^{40}\text{Ar}^* + n \]

  Important for identifying NC scattering from supernova neutrinos in argon.

*Help DUNE to understand neutrons better, benefit both energy reconstruction and background rejection.*
CAPTAIN in the Booster Neutrino Beam

- Expected CC neutrino absorption event rates of about 200 / year for $2 \times 10^{20}$ POT

- Neutron backgrounds have to be mitigated - plan to measure with SciBath detector during the fall of 2015

- Could get 3x the event rate with lower neutron backgrounds if the beam is run in off-target mode (for the current MiniBooNE dark matter search)

Close enough to collect low energy neutrino produced by pion decay at rest. First time LAr run for lowE neutrino, great help for DUNE supernova study.
CAPTAIN-MINERvA in the NuMI Beam

- Running CAPTAIN-MINERvA in NuMI beamline (on-axis with medium energy tune) will probe cross-section data between 1.5 – 5 GeV

**Complementary measurements to MicroBooNE for the full DUNE energy spectrum**

- MINERvA(±MINOS ND) will act as a calorimeter for the final state particles that exit CAPTAIN

**Great improvement for flux/cross-section measurements that benefit existed NuMI experiments like NOvA**

<table>
<thead>
<tr>
<th>Predictions for CAPTAIN-MINERvA(±MINOS ND)</th>
<th>Events w/ reco μ</th>
<th>Events w/ reco μ and charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE-like</td>
<td>915900</td>
<td>783600</td>
</tr>
<tr>
<td>CC1π±</td>
<td>1952700</td>
<td>966000</td>
</tr>
<tr>
<td>CC1π⁰</td>
<td>1553100</td>
<td>596700</td>
</tr>
</tbody>
</table>

Assuming 6x10^{20} POT
Mini-CAPTAIN (prototype) constructed and started testing

- TPC has 1000 wires (3 planes) and a max. drift length of 32 cm (1 m diameter)
- 16-1” PMTs facing the TPC volume
- Purity monitor attached to the side of the TPC
Other systems/detectors

Laser Calibration System @ LANL

Nd-YAG frequency quadrupled Quantel Brilliant-b laser: 4.66 eV
LAr ionization potential: 13.78 eV (3 photons)

Purity Monitor assembly

PMT test
Minnesota lab for purification and material study
X-ray Photoelectron Spectroscopy (XPS) test at UMN for photocathodes degraded in LAPD/Luke @ Fermilab

Elements on the surface of photocathodes

<table>
<thead>
<tr>
<th>XPS Line</th>
<th>Atom %</th>
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<tbody>
<tr>
<td>Au 4f</td>
<td>51.299</td>
</tr>
<tr>
<td>C 1s</td>
<td>37.623</td>
</tr>
<tr>
<td>O 1s</td>
<td>10.716</td>
</tr>
<tr>
<td>I 3d5</td>
<td>0.361</td>
</tr>
</tbody>
</table>

LAPD PrM signal

<table>
<thead>
<tr>
<th>XPS Line</th>
<th>Atom %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au 4f</td>
<td>9.048</td>
</tr>
<tr>
<td>Si 2s</td>
<td>3.932</td>
</tr>
<tr>
<td>C 1s</td>
<td>45.279</td>
</tr>
<tr>
<td>O 1s</td>
<td>38.326</td>
</tr>
<tr>
<td>I 3d5</td>
<td>0.535</td>
</tr>
<tr>
<td>F 1s</td>
<td>2.88</td>
</tr>
</tbody>
</table>
Purification test for Mini-CAPTAIN with H$_2$O/O$_2$ analyzers

MiniCAPTAIN Cryogenics and Purification system consists of:
1) An inline liquid argon filter
2) A gas recirculation system including a condenser and filters

<table>
<thead>
<tr>
<th></th>
<th>O$_2$</th>
<th>H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial high-purity liquid argon</td>
<td>2.7 ppm</td>
<td>0.5 ppm</td>
</tr>
<tr>
<td>Required for 32 cm drift distance</td>
<td>1.5 ppb</td>
<td>0.3 ppb</td>
</tr>
</tbody>
</table>

From Qiuguang Liu @ LANL
CAPTAIN construction is underway

- Cryostat and electronics are in hand
- TPC wiring will take place soon
- Purification system is at the vendor
Conclusions

The CAPTAIN physics program will navigate the neutrino detection uncertainties related to DUNE in two critical energy regimes:

- **Low-energy neutrinos and neutrons (< 100 MeV)**
  - Measure and characterize, for the first time ever, the CC and NC interactions relevant for supernova neutrino detection in argon
  - Directly identify the most intense transitions to bound excited states and measure the unbound states

- **High-energy Neutrinos (1.5 – 5 GeV) and neutrons (0.4 – 0.8 GeV)**
  - Measure the inclusive and exclusive CC and NC cross-sections from neutrino interactions in the few GeV energy range – joint collaboration with MINERvA
  - Develop ways to identify and tag neutrons produced in FSI and improve the neutrino energy reconstruction

Neutron beam running will take place in January 2016 using the Mini-captain detector system.

**Two LOIs for Fermilab PAC:**

1) **Run CAPTAIN at the BNB for supernova-like neutrinos**
2) **Run CAPTAIN-MINERvA in the NuMI beam for long-baseline neutrinos**

We submitted a full proposal to the Fermilab PAC and received Stage 1 approval for CAPTAIN-MINERvA from the Fermilab director.
Backup
Diagram of the purity monitor

\[ \frac{Q_{\text{anode}}}{Q_{\text{cathode}}} = e^{-t_{\text{drift}}/\tau} \]

G. Carugno et al., NIM A292 (1990) and ICARUS-TM/02-14
The purity monitor
Long-Baseline Neutrino Event Reconstruction

At 1300 km, DUNE will measure neutrino interactions between 1.5 – 5 GeV (near first oscillation maximum), where neutrino-nucleus interactions are poorly understood:

- ArgoNEUT has the first and only inclusive cross-section measurement at these energies (~3200 ν and anti-ν events) from NuMI beam
- In the 1.5 – 5 GeV energy window, rich and complex neutrino-nuclei interactions will take place - more than half of neutrino interaction events will occur in the baryon resonance channel
- Neutrons produced in neutrino interactions will complicate energy reconstruction of incoming neutrinos (missing energy = uncertainty in L/E)

Understand neutrons better to improve neutrino Energy reconstruction.
Supernova Neutrino Event Reconstruction

A supernova burst will result in a continuous spectrum of neutrino energies < 100 MeV. Neutrinos in this energy regime have NEVER been detected in a liquid argon TPC. Extracting physics from supernova neutrinos requires reconstructing true neutrino energy.

CC reaction: \[ E_\nu = E_e + Q + K_{\text{recoil}} \]

We need to know dominant transition intensities very well (at least 28 levels observed)

Also need to know all the de-excitation gammas and their branching fractions

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Events / 10 kt</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CC) ( \nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^* )</td>
<td>(~700) [1]</td>
</tr>
<tr>
<td>(CC) ( \bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^* )</td>
<td>(~60) [1]</td>
</tr>
<tr>
<td>(ES) ( \nu_x + e^- \rightarrow \nu_x + e^- )</td>
<td>(~85) [1]</td>
</tr>
<tr>
<td>(NC) ( \nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^* )</td>
<td>(~90) [2]</td>
</tr>
</tbody>
</table>

(SN at 10 kpc)
X-ray Photoelectron Spectroscopy (XPS) test at UMN for photocathodes degraded in LAPD/Luke @ Fermilab

**Photo-Emitted Electrons** (<1.5 kV) escape only from the very top surface (70 - 110Å) of the sample

**Focused Beam of X-rays** (1.5 kV)

Samples are usually solid because XPS requires ultra-high vacuum (<10⁻⁶ torr)

**Electron Energy Analyzer** (0-1.5 kV)
(measures kinetic energy of electrons)

**Electron Detector**
(counts the electrons)

**Si (2p) XPS signals**
from a Silicon Wafer
Inline filter and condenser