CAPTAIN Program

Jelena Maricic for CAPTAIN Collaboration
University of Hawaiʻi at Manoa
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Motivation

• CAPTAIN is 7-ton LAr TPC to study interaction of Ar with neutrons and low energy neutrinos.

• Why?

• In the light of the DUNE (Deep Underground Neutrino Experiment) future 40 kton LAr TPC, it is essential to measure interaction cross-sections for interaction of neutrons and neutrinos with Ar that are currently unknown

• DUNE goals – use neutrino oscillations to:
  • Determine the neutrino mass ordering
  • Measure lepton CP-violation phase
  • Execute underground physics program: detection of galactic-core supernovae neutrinos, search for nucleon decay
DUNE and LBNF

DUNE consists of:
- Far Detector (FD):
  4 LAr TPC at SURF
- 40 kton (fiducial) at 1.5 km depth (4300 mwe)
- Near Detector (ND)
- International science collaboration

Unprecedented beam power:
1.2 MW → 2.4 MW (2026) (II phase)

$\nu_{\mu}/\bar{\nu}_{\mu}$ beam: FNAL → FD 1300 km Long Baseline

The longest baseline to be built and likely the largest neutrino collaboration (~1000 already)
Measure transition probabilities for muon neutrinos and antineutrinos through matter! 

\[ P_{\nu_e \nu_\mu}(\bar{\nu}_e \bar{\nu}_\mu) = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{13}}{\tilde{B}_+} \right)^2 \sin^2 \left( \frac{\tilde{B}_+ L}{2} \right) \\
+ c_{23}^2 \sin^2 2\theta_{12} \left( \frac{\Delta_{12}}{A} \right)^2 \sin^2 \left( \frac{A L}{2} \right) \\
+ \tilde{J} \frac{\Delta_{12} \Delta_{13}}{A} \sin \left( \frac{A L}{2} \right) \sin \left( \frac{\tilde{B}_+ L}{2} \right) \cos \left( \pm \delta - \frac{\Delta_{13} L}{2} \right) \]

Change of sign for antineutrinos

\[ \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \]

\[ \theta_{13}, \Delta_{12} L, \Delta_{12}/\Delta_{13} \text{ are small} \]

\[ \Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu}, \quad \tilde{B}_+ = |A \mp \Delta_{13}|, \quad A = \sqrt{2} G_F N_e \]

- Measure transition probabilities for muon neutrinos and antineutrinos through matter!
- Prob. depends on L&E and nu flavor.
- Oscillations in wide band beam effective for simultaneous measurement of MO, \( \delta_{\text{CP}} \) and \( \nu \) mixing angles.
Expectations in Case of NMO and IMO
**Expected event rates for measurements: $\delta_{CP}$, MO and Oscillations**

- Measurements ($\delta_{CP}$, MO, $\theta_{23}$, $\theta_{13}$) rely on analysis of 4 combined samples (optimized beam, 56% LBNF uptime, $\delta = 0$, $\theta_{23} = 45^\circ$, NuFIT parameters, fast MC det. response):

<table>
<thead>
<tr>
<th>$\nu$ mode / 150 kt-MW-yr</th>
<th>$\nu_e$ appearance</th>
<th>$\nu_\mu$ disappearance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal events (NH / IH)</strong></td>
<td>945 (521)</td>
<td>7929</td>
</tr>
<tr>
<td>Wrong-sign signal (NH /IH)</td>
<td>13 (26)</td>
<td>511</td>
</tr>
<tr>
<td>Beam $\nu_e$ background</td>
<td>204</td>
<td>–</td>
</tr>
<tr>
<td>NC background</td>
<td>17</td>
<td>76</td>
</tr>
<tr>
<td>Other background</td>
<td>22</td>
<td>29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anti-$\nu$ mode / 150 kt-MW-yr</th>
<th>$\nu_e$ appearance</th>
<th>$\nu_\mu$ disappearance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal events (NH / IH)</strong></td>
<td>168 (438)</td>
<td>2639</td>
</tr>
<tr>
<td>Wrong-sign signal (NH /IH)</td>
<td>47 (28)</td>
<td>1525</td>
</tr>
<tr>
<td>Beam $\nu_e$ background</td>
<td>105</td>
<td>–</td>
</tr>
<tr>
<td>NC background</td>
<td>9</td>
<td>41</td>
</tr>
<tr>
<td>Other background</td>
<td>13</td>
<td>18</td>
</tr>
</tbody>
</table>
Neutrino spectra in DUNE

Long baseline: Matter effects are large ~ 40%
Wide-band beam: Measure $\nu_e$ appearance and $\nu_\mu$ disappearance over range of energies: MO & CPV effects are separable.
Dependence of CP Violation on MO

- Sensitivity to CPV after 300 kt-MW-yrs
- Software configuration available on arXiv: 1606.09550
- Bands represent range of beam configurations
DUNE: CPV and MO sensitivity

- Sensitivity to MO as:
  - function of exposure in kton-MW-yrs and
  - Fraction of $\delta_{CP}$ values with given sensitivity or greater.

![Graph showing sensitivity to MO for all values of CPV phase.](image)

100% MH Sensitivity (Covers all values of $\delta_{CP}$)

- DUNE Staging
- Normal Hierarchy
  - $\sin^2\theta_{13} = 0.085$
  - $\sin^2\theta_{23} = 0.45$

$\Delta \chi^2$ vs Years

- CDR Reference Design
- Optimized Design

- The shaded regions represent the range in sensitivity corresponding to the different beam design parameter

- Example: 30 kt x 1.07 MW x (3.5 v + 3.5 anti-v) year
# Nucleon Decay Sensitivity

- Proton decay – test of baryon number conservation.
- May explain matter-antimatter asymmetry.
- Many accessible modes, including SUSY favored: $p \rightarrow K^+ \bar{\nu}$
- Sensitive, bkg. free searches thanks to imaging, $dE/dx$ and calorimetry in LAr TPC.

<table>
<thead>
<tr>
<th>Year</th>
<th>Lifetime Sensitivity (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^32</td>
<td>02468 1 0 1 4 1 6 1 8 2 0</td>
</tr>
</tbody>
</table>

DUNE – assumes 40kt after 4 yrs*

DUNE 40 kton

Hyper-K, 1900 & 5700 kt-yr (projected from SK)

Current Super-K limit, 260 kt-yr

*Actual plan is 8 yrs to reach 40kt;

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Simulated $p \rightarrow K^+ \bar{\nu}$

- Automated reconstruction
- Sensitive, bkg. free searches thanks to imaging, $dE/dx$ and calorimetry in LAr TPC.
**Supernovae Neutrino Burst Detection**

- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos → few thousand events expected for galactic SN.

- Dominant process:
  \[ \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* \]

- LAr uniquely sensitive to CC current electron neutrino interactions and neutronization process at ≈30ms.

- Elastic event – may give directionality.

- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3500 neutrinos in DUNE for SN.

*Contrary to water/LS Detectors – antinu dominate*

DUNE CDR

- **Distinct time profile**
- **Distinct energy spectrum**
FD technology – Liquid Argon Time Projection Chamber

- LAr TPC: excellent tracking and calorimetry
- High resolution, 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (≈ms) for xy coordinate; drift time – z coordinate
- Ar scintillation light (≈ns) detected by photon detectors – provides \( t_0 \)
Why use LArTPCs for neutrino physics?

- Dense target for neutrino interactions
- Ample ionization/scintillation for detection
- Good efficiency and background rejection
  - Good e/gamma separation – important for electron neutrino appearance searches
**DUNE Physics Requirements**

- DUNE utilizes a broad-band neutrino beam – must reconstruct the true neutrino energy based on visible particles to succeed;
- Oscillations depend on true neutrino energy!
- Critical to understand the correlation between true and reconstructed neutrino energy – especially any differences between neutrinos and anti-neutrinos

![DUNE Neutrino Energy Spectrum](image.png)

DUNE true neutrino energy spectrum

Reconstructed neutrino energy without neutrons

Energy into neutrons from neutrino interactions

Energy into neutrons from anti-neutrino interactions
**DUNE Physics Challenges**

- **Challenges:**
  - Neutron event signatures in Ar; # and E of emitted neutrons in nu int. with Ar unknown
  - Higher-energy neutron-induced processes that could be backgrounds to e nu appearance, e.g. $^{40}\text{Ar}(n,\pi^0)^{40}\text{Ar}^*$ not measured
  - Neutron production of spallation products on Ar unknown
  - CC and NC cross sections in the neutrino energy range relevant for supernova neutrino detection not measured (only theoretical predictions available)
  - Correlation between true neutrino energy and visible energy for events in the neutrino energy range relevant for supernova neutrino detection unknown

- **How can CAPTAIN, and its prototype mini-CAPTAIN detector, help?**

  ➔ deployment of LAr TPCs in a wide energy neutron beam at LANL and subsequent deployment in the stopped pion source for low energy neutrino run
CAPTAIN - and MiniCAPTAIN

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

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5 tons of instrumented liquid argon
- TPC:
  - Hexagonal prism, 1 m vertical upward drift
    \( E = 500 \text{ V/cm}, v_d = 1.6 \text{ mm/μs} \)
  - 2001 channels (667/plane), 3 mm pitch and wire spacing
- Laser calibration system
- Photon detection system

- Mini-CAPTAIN (mC): a smaller prototype detector, yet large enough to make interesting physics measurements:
  - 0.4 tons of instrumented LAr & 30 cm of vertical upward drift
CAPTAIN Hardware Status

- Many components used in Mini-CAPTAIN will be utilized for CAPTAIN, but some are still missing:
  - All electronics has been tested as part of Mini-CAPTAIN’s commissioning
  - Recirculation system for liquid argon purification is in hand and installed on Mini-CAPTAIN (switch from gas to liquid recirculation)
  - Some wire plane and field cage components are in hand; wire planes and full TPC have not been assembled
  - Cryostat has been built and pressure tested
  - Motorized optical feedthrough for the laser system (computer-controlled laser alignment) fabricated
Mini-CAPTAIN Status

• Built as a prototype for CAPTAIN, but due to its large size \( \rightarrow \) excellent opportunity for physics running

• A couple of engineering and one physics runs in the past two years:
  • liquid nitrogen fill to test electronics and TPC
  • test cryogenic and purification system, DAQ development, laser system testing
  • installation of gas (now changed to liquid) recirculation system, integration with muon system
  • more development of electronics and recirculation system
Mini-CAPTAIN Detector

• 400-kg instrumented mass of liquid argon – 2-tons of total liquid argon
• Hexagonal TPC, 3-mm wire pitch, 1000-channels, 0.5-meter apothem, 32-cm height
• Field cage generates 500-V/cm electric field – electrons drift upward
• Photomultiplier Tube-based photon detection system (PDS) for time-of-flight
• 266 nm NdYag laser system and laser positioning system for accurate laser beam positioning
Mini-CAPTAIN in neutron beam

- Mini-CAPTAIN utilizes neutron beam at Los Alamos Neutron Science Center (LANSCE) at LANL
- Initial run – one week in February 2016
  - Data had limited quality (good photon detection, BUT short tracks)
  - Next run – two weeks in July 2017
  - Will utilize laser calibration to cross-check purity via laser induced tracks across the detector

Planned measurements:

- High intensity neutrons: a single day of running will produce years worth of neutron spallation events
- Low-intensity high-energy neutrons: address neutron energy reconstruction for DUNE by studying the signature of neutrons of known kinetic energy (by time-of-flight): the multiplicity and identity of the visible particles in the final state and their kinematic properties.
- Low-intensity low-energy neutrons: Identifying de-excitation events in LAr, i.e. study n\textsuperscript{40}Ar \rightarrow n\textsuperscript{40}Ar\textsuperscript{(*)} to gain insight into identifying NC interactions of supernova neutrinos n\textsuperscript{40}Ar \rightarrow n\textsuperscript{40}Ar\textsuperscript{(*)}
Neutron Flux at mini-CAPTAIN

- 20 MeV neutron mean free path in LAr ~ 25 cm -> almost all neutrons will interact
- No more than few neutrons/drift time (200 µs for Mini-CAPTAIN)
- Achieved by narrowing the shutter jaws thanks to their wedge-like shape along the beam direction
- The incoming flux will be measured using a ~1cm thick scintillator + PMT
  - Thin enough to intercept ~ 1 neutron in 100
  - Thick enough to obtain an overall 5% statistical accuracy in 1 minute at 3 n/macropulse
Mini-CAPTAIN Neutron Run Setup

• Using time-of-flight techniques, correlate a visible interaction in $\text{mC}_\text{w}$ with a neutron of a specific kinetic energy.

• Photon detection system and scint. counter used for TOF.

Electronics and DAQ
LAr purification system
LAr cryogenic system

Beam
TPC
Outcomes of the February 2016 neutron run - PDS

- 16 1-inch PMTs immersed in LAr, facing the TPC up to observe scintillation in LAr.
- Excellent performance of 15 out of 16 PMTs in the PDS – good enough for $t_0$.
- Adequate time resolution to observe gamma peak in TOF spectrum.
Outcomes of the February 2016 neutron run - TPC

- TPC electronics and field cage stable during the run.
- Oxygen and water < 1 ppb required, but oxygen sensor stopped working before the run above 1 ppb. Initially, Ar fill at 1 ppm.
- LAr purity not adequate to see tracks across the whole drift distance.
- Electrons lifetime measured from data ~ 20 ms.
- Need ~200 ms lifetime to see ionization produced near the cathode plane – 1 ppb of oxygen and water.
Improvements toward July 2017 neutron run with mC

- New in-liquid purification system installed in April 2017 – a similar system was used to achieve 5m drift in a different detector.
- Added 16 more PMTs to the top of the TPC to light collection efficiency for low energy n-Ar int-s.
- Added laser calibration system for in-situ calibration of the tracks (laser calibration performed 2 years ago during commissioning, but not in the beam run).
- Added laser positioning system to mC field cage on the outside.
CAPTAIN Future

• CAPTAIN was scheduled to run at Fermilab in their medium and low energy neutrino beams – but the program was terminated in late Spring 2016.

• As an alternative, we have been investigating opportunities to run at the Spallation Neutron Source (SNS) at Oakridge national lab.

• Provides intense neutrino beam from stopped pion source in the energy range of interest for supernovae neutrino detection.

Goal: Study neutrino-argon interactions in the energy range relevant for supernova detection. Cross sections have never been measured in this energy range and have large theoretical uncertainties.

Measure the neutrino-argon xsec to about 10% for neutrino energies of $O(10)$ MeV. Test the ability of detecting SNe with LAr detectors (triggering, timing).

Figure 1. Time and energy distributions for different neutrino flavors produced at the SNS.
Summary and Outlook

• DUNE will provide the most comprehensive measurement of CP-violation angle and mass ordering, and will have unique detection abilities for supernovae neutrinos and nucleon decay.

• If not determined before, DUNE will measure MO with 5σ C.L. by 2032.

• However, crucial to this program is:
  • accurate reconstruction of true neutrino energy based on visible particles including neutrons.
  • Measurement of neutrino-Ar interaction c-s in the low energy range, known only theoretically at this point, and important for supernovae neutrino measurement.

• Mini-CAPTAIN is in unique position to characterize neutron interactions in Ar with July 2017 run.

• CAPTAIN will measure neutrino-Ar xsec at 10% and validate ability of Ar TPC to detect neutrinos in the supernovae neutrino energy range.
Thank you!

• **CAPTAIN Collaboration:**
  
  • Scientists from: Alabama, ANL, LBL, BNL, UC Davis, UC Irvine, UCLA, UPenn, FNAL, Hawaii, Houston, Indiana, LANL, LSU, New Mexico, South Dakota, South Dakota State, Stony Brook

  • Spokesperson: Christopher Mauger (Upenn)
  • Deputy Spokesperson: Clark McGrew (Stony Brook)