CAPTAIN:
Current Neutron and Future Stopped Pion Measurements

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for the
CAPTAIN
Collaboration

(C)ryogenic (A)pparatus for (P)recision (T)ests of (A)rgon (I)nteractions with (N)eutrinos†
†or (N)eutrons
CAPTAIN Physics Program

• Low-energy neutrino physics related
  – Measure neutron production of spallation products
  – Benchmark simulations of spallation production
  – Measure the neutrino CC and NC cross-sections on argon in the same energy regime as supernova neutrinos
  – Measure the correlation between true neutrino energy and visible energy for events of supernova-neutrino energies

• Medium-energy neutrino physics related
  – Measure neutron interactions and event signatures (e.g. pion production) to improve understanding of neutrino interactions emitting neutrons.
  – Measure higher-energy neutron-induced processes that could be backgrounds to $\nu_e$ appearance e.g. $^{40}\text{Ar}(n,\pi^0)^{40}\text{Ar}(*)$
DUNE Neutrino Energy Reconstruction \((E_\nu > 2.5 \text{ GeV})\)

- The DUNE inclusive cross section measurement can calculate the neutrino energy as the total energy visible in the detector.
  - Typically DIS

Measure the muon momentum

\[ \nu \rightarrow q \rightarrow \mu^{-} \]
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Assume quark is at rest

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Hadronization

$\mu^-$
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Reconstruct neutrino energy with what is left

Assume quark is at rest

Neutrino energy is the sum of the muon energy and hadron energy, but you need to correct for energy that escapes detection.

Measure the muon momentum

Hadronization

\[
\begin{align*}
\mu^- & \quad \text{Assume quark is at rest} \\
\pi, K, p & \\
\end{align*}
\]
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Neutrino energy is the sum of the muon energy and hadron energy, but you need to correct for energy that escapes detection.

Still doesn’t address nuclear corrections and situation becomes more complicated at lower energies

Measure the muon momentum

Hadronization

\(\mu^-\)
Fraction of $E_\nu$ Creating Ionization in Argon

- The ratio of visible energy to neutrino energy is different for neutrinos and anti-neutrinos
  - Intrinsic CP violation term in the energy scale in addition to effects of oscillation

Muon Neutrino

Muon Anti-neutrino
Reconstructed $E_\nu$ without Neutrons

LBNF Neutrino Energy Spectrum

- True neutrino energy spectrum
- Reconstructed neutrino energy without neutrons

Outgoing energy in neutrons

- Energy into neutrons from neutrino interactions
- Energy into neutrons from anti-neutrino interactions

Elena Guardincerri

23 June 2017
McGrew for CAPTAIN @ WIN 2017
Neutrons in Argon

- Cross-section data only published to 50 MeV (kinetic)
- There is a predicted negative resonance makes argon transparent at 55 keV
  - Neutron above the resonance should survive 100’s μs
  - Significant discrepancy between data and ENDF

![Graph showing cross-section data and ENDF comparison](image-url)
Neutrons in Argon

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   ➢ Also a discrepancy between different calculations
Neutrons in Argon

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- Measure the cross-section with mini-CAPTAIN
  - Up to 800 MeV
  - We will look for presence neutron capture signature
The CAPTAIN Detectors

➢ CAPTAIN
  ➢ hexagonal TPC with 1m vertical drift, 1m apothem, ~1800 channels, 3mm pitch, 5 instrumented tons
    ➢ Disambiguate most hits in 3D
  ➢ Cryostat with indium seal
    ➢ Can be opened and closed
  ➢ Photon detection system
  ➢ Laser calibration system
  ➢ Moving toward commissioning in ’18

➢ miniCAPTAIN
  ➢ Hexagonal TPC with 32 cm drift, 50cm apothem, ~600 channels, 3 mm wire pitch, 400 kg instrumented
  ➢ Cryostat on loan from UCLA
    ➢ Indium seal for access
  ➢ 24 PMT light detection system

➢ Both use same same cold electronics and electronics chain as MicroBooNE
  ➢ front end same as DUNE
CAPTAIN Cryostat Delivered to LANL in 2014
The miniCAPTAIN Detector

➢ Hexagonal (50 cm apothem or “1m diameter”) with 32 cm drift
  ➢ 500 V/cm drift
➢ 3 wire planes with 3mm pitch (332 wires per plane)
➢ 24 PMT photon detection system (above and below drift region)
➢ Laser calibration system
Neutron Beam at LANL

- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum similar to the cosmic-ray spectrum at high altitude

- Time structure of the beam
  - sub-nanosecond micro pulses 1.8 μs apart within a 625 μs long macro pulse
  - Repetition rate: up to 40 Hz
Neutron Time Of Flight

Time of flight measured in the LANSCE WNR neutron beam
- Extremely low beam power
- 1 micropulse per macropulse is filled with protons

Neutron t.o.f. measured by Argon scintillation in miniCAPTAIN using the photon detection system.

Neutron t.o.f. measured using plastic scintillator (to normalize flux). Efficiency vs energy calibrated vs a well known fission detector.
Neutron Kinetic Energy Spectrum on Argon

- Photon detection system data from engineering run analyzed
- Neutron energy is determined event by event using the time of flight for events in Argon
  - Not efficiency corrected
  - Not flux normalized
  - Interaction length is shorter than TPC

- Full TPC & PDS will be used at WNR this year
  - Currently being filled in beam-line

- 2017 Physics run goals
  - Cross-sections
    - Differential partial cross-section on Ar.
      - e.g. $\pi^0$, p, $\pi^\pm$ production
  - Library of event signatures
    - Light yield vs energy
    - Ionization vs energy
    - Ionization vs light yield
Neutronization only visible in $\nu_e$

- Burst is only 20 ms long and is essentially all $\nu_e$
- Mean energy of events is 10-12 MeV
- IMB/Kamiokande detected higher energy cooling neutrinos
  - Not neutrinos from neutronization
- DUNE has potential for $\nu_e$ detection

K. Scholberg: arXiv 1205.6003 astro-ph
GKVM model: arXiv 0902.0317 hep-ph
(Gava, Kneller, Volpe, McLaughlin)

P5 recommendation:
“The (ELBNF) experiment should have the demonstrated capability to search for SN bursts...”
Supernova neutrinos in DUNE

Charged-current absorption:
\[ \nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^- \]

Transition levels are determined by observing de-excitations (γ’s and nucleons)

Reconstructing true neutrino energy:
\[ Q \text{ is determined from de-excitation gammas and nucleons} \]

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

Outgoing e⁻ Energy
Energy donated to transition
Nuclear Recoil Energy (negligible)

We have limited knowledge the transition intensities

Chris Grant (BU) at recent CAPTAIN meeting
SNS as a D.A.R. $\nu$ Source

➢ Possible measurement at SNS
   ➢ 1 GeV beam at 1 MW
➢ Physics Questions
   ➢ Total neutrino cross section below 50 MeV
   ➢ Electron differential cross section $[dE_e / d(DAR)]$

➢ Detector development questions:
   ➢ Rate consistency with cross-section
   ➢ Light yield
   ➢ Neutrino/background discrimination
   ➢ Triggering for a large detector
Final Thoughts

➢ CAPTAIN provides an ideal set of instruments to make crucial supporting measurements for DUNE physics program.
   ➢ All of the questions are driven by a need to understand neutrino-nucleus (Ar) interactions.
     ➢ Even the neutron-argon measurements

➢ A large LAr detector will provide critical measurements if we can observe a SN
   ➢ But we need to understand the neutrino cross section below 50 MeV to design the detector (DUNE), and understand any signal if we see it.

➢ The current CAPTAIN run plan includes several measurements
   ➢ Neutrons on argon
     ➢ Data at WNR starting on July 11
   ➢ Low energy neutrino cross sections
     ➢ Measured at a stopped pion neutrino source

➢ There are opportunities with CAPTAIN for new collaborators
   ➢ Data almost here for neutron running
   ➢ Important low energy $\nu + Ar$ data in the future
Backup Slides
mini-CAPTAIN Operation

Assembled at LANL with cosmic ray commissioning during Summer 2015
WNR @ LANSCE engineering run during January 2016
WNR @ LANSCE physics run from 11-28, July 2017
First signals in miniCAPTAIN

➢ First drift signals collected during summer 2015 commissioning
  ➢ Electron lifetime was \( \sim 20\mu s \)
    w/o indium seal to ease access to TPC (will add for physics run)
mini-CAPTAIN Events
(From the Engineering Run)

Event 8307.39: Calibrated charge on U wires

Event 8307.39: Calibrated charge on V wires

Event 8307.39: Calibrated charge on X wires

eff vs Proton energy

<table>
<thead>
<tr>
<th>Rece3</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75</td>
<td>78.36</td>
<td>41.3</td>
</tr>
</tbody>
</table>

23 June 2017
Neutron Cross Section Measurement

The total cross section is measured by determining the extinction rate for a particular event topology.

We will use $n + \text{Ar} \rightarrow p + X$ (not seen)
Neutron Kinetic Energy Spectrum
Neutron Cross-Sections on Argon


Data is in black
ENDF cross-section models are shown for reference
Reconstructing CAPTAIN Events

The true energy deposition information (from GEANT)

12 GeV muon neutrino producing:
- 4.0 GeV $\pi^+$
- 2.2 GeV neutron
- 2.2 GeV photon
- 2.0 GeV $\pi^0$
- 1.7 GeV muon
- 390 MeV $\pi^+$
- 312 MeV $\pi^-$

Hit clustering before track finding

3D objects found in event
Supernova Neutrinos

- Supernova bursts in our galaxy are a fantastic source of neutrinos
- Proto-neutron star deep in the core
- Infalling matter bounces – creates shock
- Shock stalls – reheated by neutrino interactions
- Significant fluxes in < 10 seconds
- Argon uniquely sensitive to CC electron neutrino interactions – complementary to water Cherenkov detectors sensitive to CC electron anti-neutrino interactions

P5 recommendation:
“The (ELBNF) experiment should have the demonstrated capability to search for SN bursts...”

- $\nu + \text{Ar}$ cross-sections have never been measured
  - Absolute cross-sections uncertain
  - Visible energy vs. neutrino energy
- We want to measure CC electron neutrino interactions at supernova energies
  - Test ability to detect SNe with LAr
    - Triggering, timing, reconstruction

"Core collapse scenario" by Illustration by R.J. Hall. Redrawn in Inkscape by Magasjukur2 - File:Core collapse scenario.png. Licensed under CC BY-SA 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/
O(10 MeV) Neutrino Source: Stopped Pion Facilities

DAR flux: very well understood (analytic):

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]
What (might be) measured in LAr

Muon decay-at-rest νₑ spectrum

Supernova cooling spectrum (T = 3.5 MeV)

➢ Where does the energy go?
  ➢ ⁴⁰K* deexcitation (predicted)
    ➢ 58% photons
    ➢ 36% single n + photons
    ➢ 4% single proton + photons
    ➢ 1% everything else

Flux is precisely known
What (might be) measured in LAr

Muon decay-at-rest $v_e$ spectrum

Where does the energy go?

$^{40}$K* deexcitation (predicted)

- 58% photons
- 36% single n + photons
- 4% single proton + photons
- 1% everything else

Flux is precisely known

Supernova cooling spectrum ($T = 3.5$ MeV)

Electron energy also challenging
“Typical” SN $\nu_e$ interaction in LAr

- Neutrino interaction predicted by MARLEY
- Detector simulation vs LArSoft
  - Hit reconstruction via “cheated analysis”
- Typical event radius will be several 10’s of cm
  - Determined by argon radiation length
- Neutrons not visible in this plot
  - GEANT4 says event radius is meters

Steven Gardiner (UCD)
DUNE Physics Challenges

- Observation of Supernova Neutrinos
  - In SN1987a we saw several hands full of events in about 4 kton of world-wide target
  - Next SN?
    - 10’s of kton of $\bar{\nu}_e$ target world wide (e.g. Water, Oil)
    - LAr will see $\nu_e$
- Search for Proton Decay
  - LAr is largely background free for several modes favored by supersymmetric models (e.g. $p \rightarrow K^+\nu$)
- Long Baseline Neutrino Oscillation Physics
  - Determination of mass hierarchy
  - Maximum $\theta_{23}$?
    - See recent tension between NOvA and T2K
  - Observation/Measurement of CP violation in neutrino oscillations
    - Maximal CP Violation? (see hints from DayaBay/NOvA/T2K)