Hunting for sterile neutrinos: short baseline neutrinos at FERMILAB

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Considerations on a strategy for future neutrino experiments

• In neutrino oscillation physics it is mandatory working on long-term projects, through short/mid term initiatives

• However, Nature can provide surprises (e.g. large $\theta_{13}$ angle!)

• Be ready to cope with unexpected results. Example: discovery of sterile neutrinos might change the global experimental priorities

• Work on specific studies, R&D and planning. Keep both eyes open…

• Liquid argon TPC: an excellent technique for (present and) future detectors

• Still selected R&D work needs to be done

• Our choice in Bern: UV laser calibration, HV studies, long drift, prototype detectors

• R&D graded strategy: Micro $\rightarrow$ Mini $\rightarrow$ ARGONTUBE $\rightarrow$ ARGON-CUBE

• Physics: address the sterile neutrino signals/indications/hints…

new physics or old background?
Research and development
R&D issues for LAr TPCs

- realize future XXL observatories: drift length might be an issue (according to the specific approach). In any case, go safely beyond 2-3 m drift length
- readout: wire planes with cold electronics (low noise), double phase, ...
- purity, recirculation, diffusion, recombination
- high voltage (how to supply and limitations)
- cryostat, insulation, evacuation, mechanics,...
- calibration
- magnetized TPC
- event reconstruction: exploit the rich information from raw data
Evolution of LAr TPCs at LHEP Bern

0.5 cm
JINST 4, P07011 (2009)

25 cm

57 cm
JINST 5, P10009 (2010)

AE - DPNC - March 2014
The Bern ARGONTUBE (up to 5 m drift length)
• Up to 4.76 m drift length
• About 200 l active volume (total 1200 l), 280 kg LAr
• HV generated inside by a Greinacher circuit (up to 500 kV, 1 kV/cm design values)
• 2 wire planes, 20x20 cm², 3 mm wire pitch, 64x64 channels
• PMT’s, scintillator planes and UV-laser beams for triggering
• LAr purity: better than 0.1 ppb contaminant
• S/N ratio >10
- Greinacher circuit: 125 stages, input 4 kV AC
- COMSOL finite element analysis software to optimize the geometry of the field-shaping rings
- Goal: drift field of 1 kV/cm
- Reached 170 kV (0.34 kV/cm)

The use of Greinacher for LAr detectors was originally proposed by the ETHZ group: J. Phys. Conf. Ser. 308 (2011) 012027
R/O electronics

- e⁻ speed: 2mm/µs → max drift time: 2500 µs (@ 1 kV/cm)

- ARGONTUBE operation: 100-1000 ns sampling time

CAEN v1724 (ADC) + v2718
Cryogenics & purity

LAr recirculation system:

- first cleaning stage at filling, continuous liquid recirculation through filters with bellow pumps
- standard purification cartridges: active copper

Cryo-cooler to run 24/7 long term without refilling
Long drift tracks (cosmic-rays) routinely detected

(compressed aspect ratio!)
Cold electronics

- Preamplifiers immersed in LAr at 87 K

- Advantages:
  - Directly on the wire planes, close to signal source. Avoids long cables between wires and preamps (reduce noise from pickup on the way, cable capacitance,...)
  - @at 87K: CMOS technology gives lower thermal noise, higher gain and higher speed
  - Easier design of cryostat and cable feedthroughs

- Configurable (gain, timing, ...) CMOS ASIC chip (LARASIC) designed by BNL: V. Radeka et al, BNL and FNAL

- ARGONTUBE: test chips in a real environment with long tracks and make comparison with warm electronics
Warm, for impedance matching (gain 1)

(Warm electronics running in parallel for comparison)
Cathode @ 4.76m

S/N (mip) = 15.7 ± 3.8
Cold electronics
Cold electronics
Cold electronics
UV-laser calibration

LHEP Bern pioneered the use UV laser-beams to ionize LAr by a multi-photon process

2009 JINST 4 P07011
NJP 12 (2010) 113024

Exploit the technology to generate calibration “tracks” to correct for:
- space charge effects,
- local accumulation of ions leading to field distortions
Example of track correction for E-field disuniformities
Moving UV-laser beam in LAr
(for the needs of the MicroBooNE experiment, see later)
Application: measurement of purity by UV-laser tracks

\[ E_{\text{drift}} = 200 \text{ V/cm} \]

Recirculation system running for 6 h. at \(~50\text{l/h.}\)

- Electron life time increased by a factor 10
- Night stop and morning measurement
- Re-fill with argon

ARGONTUBE routine operation: 2.5 ms lifetime (0.12 ppb Oxygen equivalent)
Physics result from ARGONTUBE: measurement of transverse charge diffusion (by laser beams)

\[
D = \frac{\sigma^2 - \sigma_0^2}{2t}
\]

\[D = 4.21 \pm 0.42 \text{ cm}^2/\text{s}\]
Study of liquid Argon electric strength

A. Blatter et al.,
Experimental study of electric breakdowns in liquid argon at centimeter scale
arXiv:1401.6693
Slow motion camera movie:
What next? From ARGONTUBE to ARGON-CUBE
ARGON-CUBE: a modular LAr test-detector design

Main features:
- Common bath to all sub-modules
- Thin walls separated independent modules
- Incremental detector mass
- Short horizontal drift (~2m), low HV
- Small dead space
- Each module has its own purification and readout systems
- Cold electronics

Advantages:
- “Short” drift distance, tuned to achievable HV and purity
- Scalable with currently known and proven technology
- Extractable modules for staged installation and maintenance/repairs
- Detector will be built in Bern (ARGONTUBE facility) then shipped to CERN
- In house expertise and infrastructure
Option for a future large-size, scalable, incremental observatory?
Option for a future large-size, scalable, incremental observatory?

Our plan:

R&D in house and LoI to the SPSC for further tests in the forthcoming CERN LAr infrastructure
Physics
we entered the era of precision measurements of neutrino oscillations

liquid argon TPCs also perfectly suited for X-section studies (particle ID) and SBL accelerator experiments

physics goal: assess the completeness of the 3-flavor mixing scenario vs additional sterile neutrinos (LSND and MiniBooNE signal/indications)

long standing issue with anomalies in:

\[ \nu_\mu - \nu_e \text{ and } \bar{\nu}_\mu - \bar{\nu}_e \text{ oscillations} \]

is it a real signal of new physics or an unknown background?
MiniBooNE electron-like event excess

![Graph showing event excess](image)

- Data (stat err.)
- $\nu_e$ from $\mu^+$
- $\nu_e$ from $K^{+}$
- $\nu_e$ from $K^{0}$
- $\mu^+$ misid
- $\Delta \rightarrow N\gamma$
- dirt
- other
- Constr. Syst. Error

- Events/MeV
- $E_{\nu}$ (GeV)

muon  electron  neutral pion

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The excess translates into allowed oscillation parameters
Another mass splitting parameter? Then (at least) another (sterile) neutrino
Address the LSND/MiniBooNE signal with an advanced detection technique

**MiniBooNE**
- Electron, Photon
- Muon
- Proton

$\pi^0 \to \gamma + \gamma$

*(Cherenkov Detector)*

**MicroBooNE**
- Electron, Photon
- Muon
- Proton

$\pi^0 \to \gamma + \gamma$

*(LArTPC)*
ArgoNeuT detector at Fermilab (first LAr TPC in USA)

Pixel size: 4mm x 0.3mm

Color is proportional to amount of charge collected
ArgoNeuT: 175 l of liquid Argon
Placed in the NUMI neutrino beam at Fermilab
3 wire planes oriented at 60° relative to each other
Each plane: 240 wires with 4 mm pitch
Electric field of 500 V/cm
2048 samples in 400 µs

Large samples of low-energy neutrino interactions (0.1-10 GeV) collected and analyzed:

JINST 7 (2012) P10019
JINST 7 (2012) P10020
JINST 8 (2013) P08005
The experiment will measure low energy neutrino cross-sections, and investigate the excess of events observed by the LSND/MiniBooNE experiments.

The collaboration includes groups from:

MicroBooNE: a “classical” SBL oscillation experiment

Start data taking 2014: in 3 years expect $6.6 \times 10^{20}$ pot and ~140 k events (BNB)
e/\gamma \text{ separation performance (dE/dx + topology)}
if assume an electron signal
and have analyzed for an e⁻
(>5σ)

if assume a photon background
and have analyzed for a γ
(tell if part of the MiniBooNE signal is due to γ’s)
(>4σ)

unlike MiniBooNE, MicroBooNE can
distinguish e⁻’s from γ’s.

(projections for 6.6x10²⁰ POT)
The MicroBooNE detector

Dimensions: 10 m x 2.3 m x 2.5 m
125 kV high voltage, 2.5 m drift length
3 wire planes (3 mm pitch) Y, U, V
32 8” PMT’s
Y: vertical plane (2.5 meter long wires), U,V planes: +/- 60 degrees from vertical (5 meters long)
The experimental hall
The outside building

The realization/installation of the various sub-systems and infrastructure is on schedule
One example: the UV-laser calibration system

Two independent laser lines on either side of the cryostat
Remote controlled steered beam (mirrors) with easy slow control
The laser source has to be in a box, due to its UV radiation.
Full scale test of the MicroBooNE laser system
The next step: the LAr1-ND detector

A LArTPC Near Detector (82 t active mass) in the SciBooNE hall, to run in conjunction with MicroBooNE on the BNB, for an exposure of $2.2 \times 10^{20}$ POT (in the last year of the MicroBooNE run)
LAr1-ND Physics Goals

❖ **MiniBooNE low-energy excess**
  ❑ Directly test the anomalous excess of electron neutrino events reported by MiniBooNE

❖ **Oscillations: $v_\mu \rightarrow v_e$ appearance**
  ❑ In combination with MicroBooNE, much improved sensitivity with a near detector (ND)

❖ **Oscillations: $v_\mu$ disappearance**
  ❑ Only possible with a ND

❖ **Oscillations: Neutral-current disappearance**
  ❑ Direct test for sterile neutrino content. Only possible with a ND

❖ **Neutrino-argon interactions**
  ❑ 15x the rate compared to MicroBooNE. ~1M events per year.
  ❑ If low-energy excess determined to be a Standard Model photon production mechanism, LAr1-ND can make measurements of the rate and kinematics with 100s of events per year
$\nu_\mu \rightarrow \nu_e$ Appearance

6.6x10$^{20}$ POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on $\nu_e$ background prediction

Same MicroBooNE exposure + 2.2x10$^{20}$ POT exposure for LAr1-ND to constrain background prediction

$\nu_\mu 4 \rightarrow 4 \nu_e$ Appearance

$\delta=6.6 \times 10^{20}$ POT exposure for MicroBooNE alone, assuming 20% systematic uncertainties on $\nu_e$ background prediction

Same MicroBooNE exposure + 2.2x10$^{20}$ POT exposure for LAr1-ND to constrain background prediction
$\nu_\mu$ Disappearance

6.6x$10^{20}$ POT exposure for MicroBooNE alone, assuming 15% systematic uncertainties on the absolute $\nu_\mu$ event rate

Same MicroBooNE exposure + 2.2x$10^{20}$ POT exposure for LAr1-ND to measure unoscillated $\nu_\mu$
The cryostat is designed so that the bulk of the cryostat surface is wetted with liquid (*signal feedthrough immersed in liquid, to limit outgassing from signal cables*). Only a small volume of gas is contained in an insulated “expansion” tank, sitting on the top of the cryostat.
LAr1-ND Timeline

Based on experience from MicroBooNE, the LAr1-ND detector construction could be completed in about two years.

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<th>Year</th>
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<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tr>
<td><strong>2014</strong></td>
<td>Develop full technical design &amp; project schedule</td>
<td>Procurement and fabrication of detector sub-components (wire planes, photon detectors, etc)</td>
<td>TPC component assembly (APAs, CPA, FCA) Cryostat and cryogenic system construction</td>
<td>Install TPC components in cryostat Liquid Ar fill Commissioning</td>
<td>LAr1-ND running</td>
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<td><strong>2015</strong></td>
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<td><strong>2016</strong></td>
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<td>MicroBooNE running</td>
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The LAr1-ND Collaboration

10 US institutions
- 3 DOE National Laboratories
- 6 NSF institutions

7 European institutions
- CERN
- 1 Swiss institution
- 5 UK institutions

11 institutions also on MicroBooNE
Nearly all interested in longer term long-baseline FNAL program

Possibility for NSF contributions and significant in-kind hardware contributions from non-US institutions currently being explored
Thank you for your attention!
e/\gamma \text{ separation performance (dE/dx + topology)}