Liquid Argon TPCs

Mike Kordosky

WILLIAM & MARY
CHARTERED 1693
SESAPS
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Outline

• What do particle detectors do?
• Physics motivation
• LArTPC detectors
• A little bit about the LArTPC neutrino program
What do particle detectors do?
What do particle detectors do?

Measure particle trajectories
What do particle detectors do?

Identify particles
What do particle detectors do?

Measure particle energy

\[ \gamma^*/Z \rightarrow ll \]

\[ \frac{1}{\sigma_{ll}} \frac{d\sigma}{dM(ll)} \text{ [GeV}^{-1}] \]

36 pb\(^{-1}\) at \( \sqrt{s} = 7 \text{ TeV} \)

Data (e+\(\mu\) channels)

NNLO, FEWZ+MSTW08

\[ M(ll) \text{ [GeV]} \]

Far Detector

Events / GeV

Reconstructed \(\nu_{\mu}\) Energy (GeV)

- MINOS, MINOS+ data
- Prediction, no oscillations
- MINOS, MINOS+ combined fit
- PRL 112, 191801 (2014)

10.71 \times 10^{20} \text{ POT } \nu_{\mu}\text{ mode MINOS}
3.36 \times 10^{20} \text{ POT } \nu_{\mu}\text{ mode MINOS}
5.80 \times 10^{20} \text{ POT } \nu_{\mu}\text{ mode MINOS+}

MINOS+ Preliminary

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Physics Motivation
Neutrinos

Ghostly, neutral and very light (less than $5 \times 10^{-8}$ of the electron)

Weak interaction couples neutrinos and charged partners

Very shy. $\nu + p$ interactions are $10^{11}$ times weaker than $p + p$ (@ 10 GeV)
Neutrinos

3 flavors
change flavor as they propagate
Neutrinos

2015 Nobel Prize!

Much left to discover:

“CP violation” (matter vs antimatter asymmetry)
Dark matter

Strong circumstantial evidence that $\sim 1/4$ of the energy/matter in the universe is invisible and weakly interacting.

Plausible that it is a new particle or particles
* Broad range of possible masses
* Must interact very weakly, like neutrinos
Neutrino ($\nu$) & DM ($\chi$) detectors

1) $\nu$ and $\chi$ are neutral so they do not make tracks
2) Only see them when they bump into a nucleus creating other particles
3) Detectors are both the target for $\nu$ & $\chi$ and the detector medium
4) Shy particles need huge or very quiet detectors
5) Still want to track and identify particles and measure their energy
LAr TPC detectors
What is a TPC?

Measurement of time projected on to distance

Time Projection Chamber

gas or liquid in volume

What is a TPC?

Charged particle

E field

V drift

ground

- High Voltage

Measurement of time projected on to distance

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What is a TPC?

Charged particle

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Measurement of time projected on to distance

Time Projection Chamber

gas or liquid in volume
Who thought of that?

David Nygren
1974

STAR at Brookhaven

Fig. 1. A schematic drawing of the TPC
Who thought of that?

Carlo Rubbia
1977

The Liquid-Argon Time Projection Chamber: A New Concept For Neutrino Detector, CERN-EP/77-08 (1977)

ICARUS Cryostat

Inside ICARUS

Why LAr? LXe?

- Non-reactive. No chemistry. Does not absorb e-
- High density = 1.4 g/cc (LAr), 2.95 g/cc (LXe)
- Argon: cheap ($1 / liter)
- Xenon: Z=54
Where does LAr come from?

Air liquefaction industry

http://www.uigi.com/

http://www.airproducts.com/
Cryostats

FNAL 35t prototype Membrane cryostat technology borrowed from LN₂ industry

LUX dewar-style cryostat Extreme radiopurity and cleanliness

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Purifying LAr

Need oxygen impurities $\sim 1$ ppb

LAPD @ FNAL demonstrated this was feasible w/o evacuating cryostat

Liquid Argon Purity Demonstrator

MicroBooNE @ Fermilab achieved less than 50 ppt

$\tau = 6$ ms corresponds to 9m drift at $|E| = 500$ V/cm
E&M-I problem

Q: I have a box with $V=0$ at one end and $V=V_{\text{high}}$ at the other. How do I get a uniform E field inside?

A: step down voltage linearly along sides.

Need a Field Cage

Field Cage

MicroBooNE

35t prototype

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High Voltage!

LAr TPCs require HV supplies of ~100kV.

Breakdown depends on material (LAr), O-purity, and geometry.

Practical detectors need to figure out how to avoid or mitigate.

Current area of study for upcoming DUNE experiment.

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How to readout a TPC

MicroBooNE

ICARUS

Wires @ -60°
Wires @ +60°
Horizontal Wires


Fermilab Visual Media Services
How to readout a TPC

Each wire is hooked up to a waveform digitizer

- Collection wire
- Induction wire

Δt
How to readout a TPC
real data from MicroBooNE (argo-microboone.fnal.gov)

N. Tagg
Otterbein College

Wire

time

wire number

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LArIAT is a small TPC exposed to a beam of charged particles.

\[ \mu^+ \rightarrow e^+ \nu \bar{\nu} \]
LArIAT is a small TPC exposed to a beam of charged particles.

LArIAT Events

an electron shower

LArIAT TPC before installation

LArIAT TPC inside the cryostat

cosmic rays

beam

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LArIAT is a small TPC exposed to a beam of charged particles.

LArIAT Events

- a long proton track

cosmic rays

beam

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LArIAT is a small TPC exposed to a beam of charged particles.
LArIAT is a small TPC exposed to a beam of charged particles

LArIAT Events

“charge exchange”

\[ \pi^- p \rightarrow \pi^0 n \]

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A neutrino event

Run 3493 Event 41075, October 23rd, 2015
Reconstruction of tracks & showers

simulated microBooNE Event

Two or 3 detector views can be combined to form a 3D image

EM shower

EM shower

\( \gamma \)

\( \nu_\mu \)

\( \mu \)

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LAr TPCs are slow!

- Relativistic particles travel about 1 ft / ns
- Typical neutrino beam spill is 10μs long
- Drift rate = 1.5 m/ms @ 500 V/cm
  - 2.5 m in MicroBooNE = 1.66 ms
- TPC sees a static “snapshot” of the whole spill
- Position along drift direction completely degenerate with time
LAr TPCs are **slow**!

This electron triggered the readout. We know where it entered the detector and when.

You don't have this information in neutrino events.

This muon either entered the detector early and on the left side...

or late and on the right side.
Scintillation in LAr

\[ \mu^- \rightarrow \text{Ar} \rightarrow \text{Ar}^+ \rightarrow \text{Ar} \rightarrow \text{Ar}^+ \rightarrow \text{ArAr}^+ \rightarrow \text{ArAr}^+ \rightarrow \text{ArAr} \rightarrow e^- \text{recombination} \]

\[ \text{ionization} \rightarrow \text{ionized molecule} \rightarrow \text{excited molecule} \]

\[ (I_1:I_3) = 50/50\% \]

\[ (I_1:I_3) = 35/65\% \]

Two timescales: \( \tau_1 = 6\text{ns} \) and \( \tau_3 = 1500\text{ns} \) corresponding to singlet and triplet spin states

After B. Jones and F. Cavanna
Reconstruction of tracks & showers

Photon detectors stare at the LAr volume and see flashes of light at the time of the interaction. This helps disambiguate time vs space.

Simulated microBooNE Event

128nm γ

Photomultiplier tubes

Collection wire

Voltage

Time

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Pulse shape discrimination

LUX DM experiment

TPCs used for dark matter searches have phototubes at the “top” and “bottom”.
Prompt light S1 from scintillation
Delayed light S2 from amplification of drift electrons

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Experiments Using LAr TPCs

I'll just concentrate on the neutrinos
Searches for Sterile Neutrinos
DUNE: Deep Underground Neutrino Experiment

Sanford Underground Research Facility

Fermilab

800 miles (1300 kilometers)

NEUTRINO PRODUCTION

PARTICLE DETECTOR

PROTON ACCELERATOR

EXISTING LABS

UNDERGROUND PARTICLE DETECTOR

CP Violation Sensitivity

DUNE CPV Sensitivity

Normal Hierarchy

\( \sin^22\theta_{13} = 0.085 \)

\( \sin^22\theta_{13} = 0.38 \)

\( \sin^22\theta_{13} = 0.45 \)

\( \sin^22\theta_{13} = 0.5 \)

\( \sin^22\theta_{13} = 0.64 \)
Summary

• At 87 K, LAr TPCs are literally cool
• Provide very high resolution images of particle interactions.
• Originally proposed in 1979. Decades long research program has made them feasible.
• Large future program centered in the US to build and operate LArTPCs to
  • measure fundamental parameters of the Standard Model
  • search for new physics (sterile ν, dark matter, proton decay).