News from the ANNIE Experiment: LAPPDs

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The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

- ANNIE is a neutrino detector deployed on the Fermilab Booster Neutrino Beam.
- Physics: Measure final-state neutron yield from neutrino-nucleus interactions.
- Technology: R&D platform for new neutrino detection technologies/techniques:
 - Fast photosensors (LAPPDs)
 - New detection media (Gd-loaded water and water-based liquid scintillator).





ANNIE is an international collaboration of 45 collaborators from 16 (8 non-US) institutions from 5 countries.

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ANNIE and LAPPDs





Goal: Measure multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction.



The ANNIE Detector

- Steel tank holding
 26 tons of **Gd-loaded water**
- **132 PMTs** (8"-11")
- Initially 5+ LAPPDs
 (20 LAPPDs or more possible)
- Front muon Veto (FV):
 2 overlapping layers of scintillator paddles
- Muon Range Detector (MRD): 11 X-Y alternating scintillator layers with 5cm iron absorbers





LAPPD System



Plastic Frame Ζ LAPPD trigger-board bridge-board Analog Pickup Board SAMTEC connector Ζ Mechanical LAPPD mount points SAMTEC connector BACK FRONT **Trigger Board** waterproof connectors LVHV board

ACDC cards

LAPPD Assembly

- Specially designed waterproof housing with the electronics package.
- Two waterproof cables handle power, data transfer, and slow controls communications.
- Data concentrator boards (ACCs) at surface.

LAPPD Locations for 2022-2023

- All LAPPDs positioned in path of beam
- Striplines are vertically oriented
- Data shown today includes central LAPPD only







LAPPD 40: First ANNIE LAPPD

- First LAPPD was deployed March 29 of 2022.
- Position of the LAPPD on the mounting board is determined to sub-cm level.
- Operated stably for over a year.
 - Removed Summer 2023 after drop in gain observed (unexpected change in MCP resistance)



First LAPPD deployed in a HEP experiment! Produced useful beam neutrino data.



ANNIE First LAPPD Neutrinos

 The 1.6 µsec wide excess = LAPPD-triggered events in-time with the BNB spill.



World's first: neutrinos observed with an LAPPD!

LAPPDs now fully integrated with other detector subsystems.

- Dark noise accidentals reduced by requiring coincidence with tank PMTs
- Reduce further by requiring MRD coincidence (muon)
- CC neutrino interactions selected by removing events that interact in the forward veto



ANNIE neutrino candidate





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LAPPD "Event Display"







Neutrino event consistent with expectations





1D LAPPD Reconstruction

- In principle LAPPD allows 2D reconstruction
 - Relative arrival time of pulses at each end of stripline provide vertical position localization
 - (requires either photon disambiguation or model fitting).
 - Strip positions + charge-sharing interpolation = horizontal position.
- First test: "1D" reconstruction where we average arrival times of pulse (piled-up photons) from both ends of a stripline.
 - Look at relative pulse arrival times at each stripline.
 - Compare to predicted arrival time profile (gradient) from muon track information.



LAPPD (1D) imaging capability



Predicted gradient (dashed line) agrees well with actual data.

The State of ANNIE



- ANNIE has taken Gen-I LAPPDs from test stands to technology in an actively running experiment.
 - First neutrinos with an LAPPD!
 - First steps to event reconstruction with LAPPDs (1D imaging)
 - Single- and Multi-LAPPD data integrated with rest of the experiment.
 - LAPPD 40 under investigation by Incom.
 - Currently taking multi-LAPPD beam data (2 LAPPDs currently in water, return to three LAPPDs imminent).



Exciting times ahead!

Additional Slides



ANNIE Neutrino Beam Data

- Selecting PMT cluster times relative to the beam shows an excess in-time with the expected timing of the BNB.
- For beam triggers

 (<2 µsec) an extended
 window (2-66 µsec) is
 recorded to enable
 neutron detection.



ANNIE First LAPPD Neutrinos



 The 1.6 µsec wide excess above background are LAPPD-triggered events in-time with the BNB spill.



World's first: neutrinos observed with an LAPPD!

What the LAPPD sees





Expect hits on multiple striplines



- Strips oriented vertically in tank (strip # = horizontal position)
 - 4.62mm strip width, 2.29 mm gaps
- Relative timing of signals from each strip end = vertical position information

$$t = \frac{t_L + t_R - D/\nu}{2}$$
$$d_L = D/2 - \nu \left(\frac{t_L - t_R}{2}\right)$$

ANNIE neutrino candidate on an LAPPD





Interaction in tank, track passing LAPPD