ANNIE: The Accelerator Neutrino Neutron Interaction Experiment:

Phase I Status and Phase II plans

Jingbo Wang
Department of Physics, UC, Davis
Outline

- ANNIE goals
- ANNIE detector
- Status of ANNIE Phase I
- Plans of ANNIE Phase II
- Summary
ANNEIE physics goal

- A Water Cherenkov detector deployed at the Fermilab BNB beamline.

Primary Physics goal:
- A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in Gd-doped water, as a function of energy. (arXiv:1504.01480).
- Significant impact in:
  - Neutrino-nucleon interactions physics
  - Proton decay searches
  - Supernova neutrino observations

- **Theoretically:** This depends on nuclear physics that is not well understood
- **Experimentally:** to date, the neutron yield has not been well measured
ANNIE technical goals

ANNIE is a test for new technologies:

- The first use of Gd-doped water in a beam experiment: large capture cross section for final state neutrons from neutrino interactions.
- Large-Area Picosecond Photodetectors (LAPPDs) (<100 ps time resolution) in a neutrino experiment for the first time! Use of precision timing to localize interaction vertices in the small fiducial volume.
ANNIE detector

FACC to veto muons not originating in the tank

Gd-loaded water for neutron captures from neutrino interactions

Fiducial volume selected by offline analysis

At Fermilab booster neutrino beam

Front Anti-coincidence Counter (FACC)

Gd-loaded water volume

3m x 4m

Muon Range Detector (MRD)

MRD for muon range measurement. Vertical and horizontal paddles for track reconstruction

DAQ system

electronics racks

>100 PMTs for gammas from neutron capture

LAPPDs with < 100 ps time resolution for improved track and vertex reconstruction.

Jingbo Wang, TIPP, 2017-5-25, Beijing
ANNIE phased approach

- **Phase I - Test experiment (2015 - 2017):**
  - Build detector
  - Measure neutron backgrounds
  - Ready to test first LAPPDs

- **Phase Ib (2017)**
  - Demonstrate LAPPD readiness
  - Test and characterization of LAPPD+PSEC

- **Phase II: Physics run (2017 - 2021)**
  - Physics Run (1 year) with full Gd-doped water, enhanced PMT coverage (130), limited LAPPD coverage (about 5 LAPPDs), focus on CCQE-like events.
  - Physics Run (2 years) with full LAPPD coverage (up to 20 LAPPDs), study neutron yields for CC, NC and inelastic scattering.
Phase I status

- **Built and commissioned the detectors**
  - Filled with **26 tons of ultrapure water**
  - Equipped with 60 8-inch PMTs at the bottom
  - 2 MRD layers

- **Measured rate of background neutrons**
  - Movable neutron capture volume (NCV)
  - NCV filled with **0.25% Gd-loaded liquid scintillator** (EJ-335)
  - NCV optically coupled to two PMTs
  - NCV isolated from the rest of the tank
  - NCV calibrated by 2.5 μCi Cf-252 source.

- **Achieved stable data taking gained experience**
Phase I data analysis

- Observed cosmic muons and beam neutrinos using 60 bottom PMTs
- Measured neutron captures using NCV, both from the beam and a calibration 252-Cf source
- The long-lived excess events after the beam indicates neutron capture detection
Moving to Phase Ib

- Completed an LAPPD test facility and characterized one 6 cm MCP detector (from ANL) and two prototype LAPPDs (from Incom.)
- Tested a working PSEC electronics
- Began work on the waterproof housing and the LAPPD holder
- New mechanical design allows LAPPDs to be installed in the existing ANNIE detector
Plans for Phase II

- Need **additional PMT coverage and up to 20 LAPPDs as well as electronics** in order to carry out the physics measurement of ANNIE
  - Move the tank to staging area
  - Refurbish the MRD to enable all 10 layers
  - Reconfigure the inner structure to install full complement of PMTs and LAPPDs.
  - Fill ultrapure water loaded with 0.2% of Gd sulfate
- A lot of simulation/analysis work ongoing
PMT status

- Sufficient PMTs have been identified for Phase II run
- Need to design PMT holders to mount PMTs to the top and side of the inner structure.
- PMTs to be tested at UC Davis
Incom has now produced multiple LAPPD prototypes, quickly approaching the specifications needed by ANNIE
- Tile #9 fully sealed detector with an aluminum photocathode
- Tile #10 sealed detector with multi-alkali photocathode (~5 % QE)
- Tile #12: ~10% QE
- Tile #13: half the photocathode with >20% QE
- Tile #15: uniform photocathode >25% QE

Tile #12 tested at ISU: 32 ps time resolution for multi-PE (see backup slide)

Please refer to Incom’s talk in the photodetector session
Basic reconstruction concept

1\textsuperscript{st} Step:
- Conceptualize Cherenkov light as coming from a point source...
- Calculate hypothesized time ($\Delta t_{hyp}$) for the photon to reach the detector
- Adjust the point location to minimize the point time residual

2\textsuperscript{nd} Step:
- Adjust the point location and the track direction to minimize the extended time residual ($\Delta t_{hyp}$)

\[ \Delta t_{hyp} = \frac{s_1}{c_0} + \frac{ns_2}{c_0} \]

Fit parameters: $x_v, y_v, z_v, T_0$
**Comparison between LAPPDs and PMTs**

- Sandbox simulation files: 20% LAPPD coverage VS 20% PMT coverage
- 500 events
- 122 LAPPDs (100 ps time resolution) or PMTs (1 ns time resolution)
- Simulate a range of neutrino energies
- Reconstruct full muon tracks

![Graphs showing vertex reconstruction](image-url)
Vertex reconstruction in Phase II

- Study on the number of LAPPDs

Longitudinal vertex resolution

- 21 LAPPDs, $\Delta r_L$
  - Entries: 482
  - Mean: $-0.1459$
  - RMS: 26.63

- 9 LAPPDs, $\Delta r_L$
  - Entries: 475
  - Mean: $-1.002$
  - RMS: 31.88

- 5 LAPPDs, $\Delta r_L$
  - Entries: 462
  - Mean: $-4.388$
  - RMS: 36.77

Transverse vertex resolution

- 21 LAPPDs, $\Delta r_T$
  - Entries: 482
  - Mean: 11.22
  - RMS: 17.68

- 9 LAPPDs, $\Delta r_T$
  - Entries: 475
  - Mean: 14.18
  - RMS: 22.16

- 5 LAPPDs, $\Delta r_T$
  - Entries: 462
  - Mean: 21.26
  - RMS: 27.22
Summary

- **ANNIE Physics goal:**
  - Measure the neutron yield from neutrino interactions in Gd-doped water, as a function of energy

- **ANNIE Technical goal:**
  - First Gd-doped water Cherenkov detector to run in a neutrino beam
  - First application of LAPPDs in water and for high energy physics

- **ANNIE Phase I** is measuring the neutron background at different positions

- **LAPPD readiness** is well underway: currently being tested, water proof housing and mechanical design available.

- **ANNIE Phase-II (2017 - 2021)** with the deployment of LAPPDs is being planned. Simulations and analysis are under way to determine the track reconstruction capability as a function of the number of LAPPDs
Thanks for your listening!
**Vertex figure of merit (time property)**

- Adjust the vertex position around the true vertex
- The time figure of merit (FOM) is obtained from the time residual distribution
- The reconstructed vertex takes the position with Maximum FOM
- Cone FOM is not taken into account in these plots

**Event# = 0**
- **True vertex**
- **Reco vertex**

---

**Parallel profile of FOM**

**Transverse profile of FOM**

**Figure of merit 2D**
Neutron Capture Volume (NCV)

- **Neutron background source:**
  - Dirt neutrons: Neutrons originating from neutrino interactions downstream of the dump.
  - Skyshine neutrons: Neutrons from the beam dump entering the detector.

- **Neutron Capture Volume (NCV) vessel**
  - Movable 50 cm x 50 cm acrylic
  - Filled with 0.25% Gd-loaded liquid scintillator (EJ-335)
  - Optically coupled to two PMTs
  - Optically isolated from the water volume

- **NCV calibration**
  - 2.5 μCi Cf-252 source (5.4 mCi in Jan 1988) and LYSO crystals
  - Gammas from fissions (3.092% branching ratio) induce scintillation in LYSO crystal
Neutron source calibration

- A triggered Cf252 source is used to understand the NCV response to neutron captures
- LYSO crystals
  - 176-Lu (2.6% natural abundance) is unstable to beta decay
  - High threshold to suppress beta decay background (low trigger rate)
- Trigger PMT watches scintillating LYSO crystal for prompt $\gamma$ rays from fissions
- Two PMTs watch the NCV
- Tank PMTs used to veto cosmic ray muons
- Goals:
  - prove we can see neutrons
  - measure the efficiency of the NCV
PMT test stand at UC Davis

PMT Data Acquisition Setup

- HV power supply
- function/signal generator
- Helmholtz coils
- LED
- counter
- scope
- black box

Julie. He, UC Davis
LAPPD test at ISU

multi-PE Transit Time Spread (Tile #12)

Note: the laser pulse duration is 30 psec

<table>
<thead>
<tr>
<th></th>
<th>Entry</th>
<th>Mean</th>
<th>RMS</th>
<th>$\chi^2$/ndf</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>5000</td>
<td>7.244e+04</td>
<td>33.02</td>
<td>190.7 / 27</td>
<td>411.9 ± 6.8</td>
<td>7.244e+04 ± 0.5</td>
<td>32.02 ± 0.25</td>
</tr>
</tbody>
</table>

example single-PE pulses (Tile #9)

Tile #9 gain distribution

M. Wetstein, ISU

Jingbo Wang, TIPP, 2017 -5-25, Beijing