ANNIE

WIN conference
06/03/2019-06/08/2019

Michael Nieslony
on behalf of the ANNIE collaboration
The **Accelerator Neutrino Neutron Interaction Experiment**

- **Gd-loaded water Cherenkov detector** placed 100m downstream from target of the Booster Neutrino Beam (BNB) at Fermilab
- measurement: **final state neutron multiplicity & CCQE cross-section** in water
- test of **new technologies** in the fields of fast photosensors and detection media
Main Injector and Recycler: $E_p = (120-150) \text{ GeV}$

BNB: $E_{\nu, \text{peak}} \approx 0.7 \text{ GeV}$

Booster: $E_p = 8 \text{ GeV}$

BNB: Be target

ANNIE hall

Main Injector and Recycler: $E_p = (120-150) \text{ GeV}$
ANNIE - Location

The ANNIE hall!

Neutrinos
Physics motivation

- Knowledge of cross-section important for long-baseline neutrino oscillation studies
- Distinguishing between elastic & inelastic processes is important for correct energy reconstruction (minimize bias)
- Neutron presence indicative of inelastic process → measurement of multiplicity
neutron capture cross-section: ~50,000 barn
total emitted gamma energy: ~8 MeV
loading in water possible as sulfate or chloride

\[ \text{v energy reconstruction} \]
reduce bias by correct tagging of (in-) elasticity

\[ \text{DSNB searches} \]
background: atmospheric neutrinos
\[ \rightarrow \] study their neutron yield

\[ \text{proton decay searches} \]
> 90% of decays involve no neutron
background: atmospheric neutrinos
Research & Development: LAPPDs

LAPPD: Large Area Picosecond Photo Detector

fast detection capabilities (time resolution ~60 ps)

20 cm x 20 cm imaging detector with intrinsic position resolution (mm-cm scale)

microchannel plate structure with resistive & emissive coating microstrip anode readout
Research & Development: LAPPDs

Position Resolution

- 25 ps single-PE differential resolution $\rightarrow$ **5 mm horizontal** position resolution
- $< 1\text{ cm vertical}$ position resolution (charge centroid)
Research & Development: LAPPDs

Specifications

Test stand @ Iowa State University

σ = 64 ps
< 4% afterpulsing

single-PE gain: $2.54 \times 10^6$
Both angular and spatial resolution profit substantially from using 5 LAPPDs:

- 68th percentile vertex resolution: $38 \text{ cm} \rightarrow 12 \text{ cm}$ (factor 3 improvement)
- 68th percentile angular resolution: $11^{\circ} \rightarrow 5^{\circ}$ (factor 2 improvement)
3 phases of the experiment

**Phase I**
- June 2016
- Partially instrumented detector
- 60 PMTs (veto) & Gd-loaded scintillator
- Fiducial volume (NCV)
- Feasibility demonstration & background evaluation

**Phase II**
- Summer 2019
- Physics phase
- First Gd-doped water Cherenkov detector in neutrino beam
- CCQE cross-section and multiplicity measurement

**Phase III**
- Water-based liquid scintillator volume
- Testbed for new technologies

- Summer 2020
- First LAPPD deployment in neutrino beam
- \( \sim 10,000 \text{ CC interactions per ton per year expected} \) (2\( \times \)10^{20} POT)
- Possible additional LAPPD deployment in fall 2020 → broader physics program

202x?
Phase I - Backgrounds measurement

 neutrons from beam dump, scattered by molecules in the atmosphere

 neutrons originating from neutrino interactions in the rock (upstream of ANNIE)

 Results

• bg rate < 0.02/m³/spill
• no problem for phase II
• publication of results soon
Phase II - Physics run

Phase II detector

- 26 scintillator paddles
- reject muons from upstream

- 26 tons water volume
- loaded with Gd$_2$(SO$_4$)$_3$ (0.1% by weight)

- 134 PMTs
- 20 % coverage
- 8-, 10-, and 11-inch

- 310 scintillator paddles
- 5 vertical layers
- 6 horizontal layers

- 5 LAPPDs
- located downstream

- VME acquisition system for PMT signals (500MHz)
- ACDC cards sampling LAPPD response (10 GHz)
Phase II - Physics run

Phase II measurement: $\nu_\mu$ CCQE event

1. a) muon gets created in CC-interaction
   b) vertex reconstruction by LAPPDs
   c) muon momentum reconstructed in MRD

2. neutron(s) travel, scatter around the detector

3. neutron capture 1, detection by PMTs

4. neutron capture 2, detection by PMTs
Phase II - Physics run

Tank Design

lid

top view

LAPPD deployment (cassettes)

side view
Phase II - Physics run

MRD

- Subdetector consisting of sandwiched scintillator paddles and 2” iron layers
  - 6 horizontal layers (156 paddles)
  - 5 vertical layers (154 paddles)
- inherited from the SciBooNE experiment
- fully refurbished & operational
- capable of muon direction and energy reconstruction

plot by Marcus O’Flaherty (University of Sheffield)
**Phase II - Physics run**

**Vertex & energy reconstruction**

- time-based FOM → vertex, time
- charge-based FOM → cone edge, track direction
- LAPPDs significantly improve resolution

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**Energy**

*input for BDT for energy reconstruction:*
- track length in water and MRD
- # PMT + #LAPPD hits
- distance to walls
- angle difference beam / track

*plots by Jingbo Wang (UC Davis)* & *Evangelia Drakopoulou (University of Edinburgh)*

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06/05/2019  ANNIE  16
Detector construction - current events

- PMT characterisation + waterproofing
- Mounting PMTs on side panels
- Teflon wrapping structure
- Mounting top PMTs
- Bottom PMTs mounted
Detector construction - current events

Current status of other subsystems

- Side panels partly mounted on the Inner Structure
- Water filtration system ready for water fill
- MRD fully refurbished & operational
- Tank deployment at ANNIE hall planned ~ June 2019

EVERYTHING ALMOST READY

SOON
Detector calibration

PMT timing and single-p.e. calibration: LED fibers with attached diffuser tip

LAPPD timing calibration: 405nm picosecond laser + diffuser ball calibration strategy

Neutron calibration: AmBe source, tag neutron events by using coincidently emitted gamma
100 μs detection window
100 μCi source → 100 tagged neutrons/second (<1% pile up)

\[
\alpha + ^9\text{Be} \rightarrow ^{13}\text{C}^{(*)} \rightarrow ^{12}\text{C} + \gamma(4.4\text{MeV}) + n
\]
Phase II - Physics run

Timeline - Next steps

June 2019

- Water fill & commissioning
- Gd-loading & commissioning
- LAPPD deployment

Summer 2020

- Calibration
- Data taking
- Up to 20 additional LAPPDs

Fall 2020

- More detailed reconstruction:
  - Multi-track final states
  - NC cross section measurement
- 202x

Phase III

- Testbed for water-based Liquid Scintillators
- Separation of Cherenkov and scintillation light
Phase II - LAPPD Upgrade

Additional LAPPD reconstruction possibilities

- additional LAPPD coverage would probably enable ANNIE to do topological reconstruction via time-reversal imaging techniques
- multi-track event reconstruction would broaden ANNIE's physics program

M. Wetstein, ANT11

B. Wonsak et. al, "Topological track reconstruction in unsegmented, large-volume liquid scintillator detectors"
Phase III - Water-based LS

• Best of both worlds:
  • Directionality & kinematic reconstruction (Cherenkov)
  • High light yield & calorimetric reconstruction (scintillation)
  • High transparency + low cost of water

• Tunable liquid scintillator concentration, isotope loading

• Charged particle detection below Cherenkov threshold → enables detection of protons

• Need surfactant to bind liquid scintillator oil in water
Future detectors

ANNIE → WATCHMAN → Theia

Use of WbLS + fast photosensors in a large detector

Demonstration and R&D for WbLS + fast photosensors

Mass

~50,000 tons
~100,000 sensors

~4,000 tons
~5000 sensors

~30 tons
~150 sensors

2019+

2022+

202?

Data taking

40-60 m

diagram by Steven Gardiner
**Summary**

- **ANNIE** is a Gd-loaded water Cherenkov detector (26 tons mass) located in the BNB at Fermilab

- Testbed for **new technologies**:
  - LAPPDs (phase II)
  - First Gd-loaded water Cherenkov detector in a beam (phase II)
  - Water-based Liquid Scintillators (phase III)

- **Last preparations for phase II** taken at the moment:
  - Mounting the last PMTs onto the Inner Structure
  - Transport and installation of tank into ANNIE hall
  - Finalization of LAPPD deployment structure
  - Development & integration of calibration systems

- **Commissioning and first physics data** starting mid June 2019
THANK YOU!

... ANY QUESTIONS?

- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Iowa State University
- Johannes Gutenberg University Mainz
- Lawrence Livermore National Laboratory
- Ohio State University
- Queen Mary University
- The University of Hamburg
- The University of Sheffield
- University of California, Davis
- University of California, Irvine
- University of Chicago
- University of Edinburgh
**Backup - BNB**

**Composition:** 93% of $\nu_\mu$, 6.4% of $\overline{\nu}_\mu$, and 0.6% of $\nu_e$ and $\overline{\nu}_e$.

**Repetition rate:** $\sim$7.5 Hz, $5 \times 10^{12}$ protons-on-target per 1.6 $\mu$s spill on average.


Source: www-boone.fnal.gov
Backup - Neutron production

True CCQE

- Undetected neutrons
- Secondary intra-extra-nuclear neutrons
- Boil-off neutrons

No neutrons!

Inelastic CC0pi

- 2p-2h
- Stuck pions

Neutrons!

diagram by Vincent Fisher, UC Davis
→ move to **event topologies** \((1\mu + 1/0\pi + Xn + Yp)\) instead of **MC generator-based categories**

- **neutrons** as possible signs of **inelasticity**
- final state **neutron multiplicity** measurement → **ANNIE**
Backup - Inelastic processes

dotted: multi-nucleon contributions to energy reconstruction bias
Backup - Neutron detection efficiency

- Neutron detection efficiency as a function of the interaction position in X (the transverse direction) and Z (the beam direction)

- The detector is large enough to fully contain neutrons
- Requested PMT coverage is sufficient to efficiently detect neutrons.

Simulation & plots by Vincent Fischer
Backup - DSNB & Proton decay

backgrounds for DSNB searches

backgrounds for proton decay searches

improve signal-to-background discrimination by better models of atmospheric neutron yield

Beacom & Vagins, PRL, 93 (2004) 171101

PRL 102 (2009) 141801
• Super-K measurement of neutron multiplicity only as a function of the visible energy, since precise information about the initial particle conditions are missing

• ANNIE will provide a complimentary measurement since the beam properties like neutrino energy, angle, flavor and the interaction type are much better known
## Backup - PMT types

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• ANNIE will have a **dual readout design** to accommodate deep-buffered PMT signals (neutron capture) alongside ultra-fast LAPPD digitization

• **PMTs:** VME-based data acquisition system (500 MHz), global trigger for all PMTs

• **LAPPDs:** **ACDC card** hosting **5 PSEC sampling ASICs with multi-channel readout (10 GHz)**, independent triggers for every single LAPPD

• DAQ processes interfaced by **ANNIE central card** (8 nodes)
A. Lyashenko et al, "Performance of Large Area Picosecond Photo-Detectors (LAPPD)"

plot by M. Wetstein
Backup - LAPPDs

Dark Count Rate:

A. Lyashenko et. al, “Performance of Large Area Picosecond Photo-Detectors (LAPPD)”

Gain:
Backup - Gen-II LAPPDs

- new method developed at University of Chicago for photocathode production, eliminate need for vacuum transfer procedure
- use ceramic body with capacitive coupling to external anode
- enabling faster production cycles for LAPPDs, compatible with high rate applications
Gd$_2$(SO$_4$)$_3$ not corrosive, but reactions with different materials possible

need to make sure that Gadolinium loaded water does not degrade tank materials

at the same time tank materials should not degrade water transparency

- all materials put in 1% Gd solution
- reasonably low absorption lengths after an extended period of time required for all materials
• combination of different subsystems to obtain filtered Gd-loaded and ultrapure water

  ‣ **pumps**: transport water

  ‣ **UV lamps**: microbes, biological contamination

  ‣ **TOC lamp**: plastic (carbon) compounds

  ‣ **microfilters**: bacteria, sediments, microbes (5 μm & 0.2 μm version)

  ‣ **ultrafilters**: iron removal (30nm pore size)

  ‣ **anion resin**: nitrates and TOC lamp products
Backup - Gd sulfate vs. chloride

~52 kg of sulfate required for one detector loading

compatibility:
- known problematic materials: nylon, copper, steel
- known “safe” materials: PTFE, polypropylene, acrylic, 304/316 stainless steel