Status Report of ANNIE

Fermilab PAC Meeting
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Mayly Sanchez (FSU)
Michi Wurm (Mainz)
ANNIE in a nutshell

ANNIE : Accelerator Neutrino Nucleus Interaction Experiment

- Physics goal: Study neutrino interactions in water (on oxygen), especially the neutron yield
- Setup: 26-ton Water Cherenkov detector with ~100 PMTs in the Booster Neutrino Beam (BNB)
- Detector R&D goals:
  - Demonstrate novel neutrino detector technologies
    - Gadolinium loaded water target → enhanced neutron tagging
    - Water-based liquid scintillator → detection of sub-Cherenkov particles
    - LAPPDs → sub-nanosecond timing, sub-cm spatial resolution photo sensors to improve event reco
ANNIE’s physics

Direct relevance for long-baseline neutrino program since kinematic parameters of BNB neutrino interactions largely overlap with DUNE and HK FDs

- ANNIE shares the BNB with several liquid-argon experiments → direct comparison of oxygen & argon cross-sections (MicroBooNE, SBND)
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- Neutron multiplicity from CC interactions and differential cross-sections on oxygen → important input for neutrino event generators

In CCQE interactions, primary neutrons are created by nuclear effects. Added to this are secondary neutrons caused by e.g. $^{16}\text{O}(n,2n)^{15}\text{O}$ reactions on neighboring nuclei.
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  → important input for neutrino event generators

- NC interactions: background for
  - Long-baseline oscillation experiments
  - Diffuse Supernova Neutrino searches
  - Proton decay searches

Search for the Diffuse Supernova Neutrino Background (DSNB) in SK-Gd: Atmospheric neutrinos (and especially NC interactions) make up the primary background.
ANNIE’s accomplishments

- First-ever physics experiment to operate multiple LAPPDs long-term and under experimental constraints (submerged on-board electronics, long transmission cables etc.)
- First-ever detection of neutrinos with LAPPDs
- Highest concentration Gd-water target in operation
- First neutrino experiment to deploy a close-to ton-scale vessel of WbLS (365kg) and detect neutrinos within

→ several technical papers in preparation, preprint with first WbLS results online [arXiv:2312.09335]
ANNIE’s plans for further R&D on hybrid detectors

ANNIE is in a unique position to evaluate performance of novel techniques for GeV neutrino detection

- Water-based Liquid Scintillator (WbLS) is a suitable target medium for a 4\textsuperscript{th} (non-LAr) DUNE module

- WbLS features fast fluorescence times and LAPPDs are ideal photo sensors for time-based separation of Cherenkov and scintillation signals

- Gen-II LAPPDs perform better in environment with large photon-hit occupancies

→ A high-statistics measurement in an expanded WbLS volume with additional Gen-II LAPPDs is a key step in demonstrating these technologies for long-baseline neutrino experiments.
ANNIE in the context of the US Physics Program

● ANNIE’s physics goals are **directly relevant to the US neutrino program** as measurements of neutron yield in neutrino interactions are essential input to the reduction of systematic uncertainties for long-baseline neutrino experiments.
  ○ Goals match the 2023 P5 driver: *Elucidate the Mysteries of Neutrinos*

● ANNIE’s R&D goals in demonstrating and testing detector technologies such as LAPPDs and WbLS are relevant to a potential **non-LAr DUNE FD4**.
  ○ From the P5 report, section 3.1.4: *A range of alternative targets, including low radioactivity argon, xenon-doped argon, and novel organic or water-based liquid scintillators, should be considered to maximize the science reach [of DUNE FD4], particularly in the low-energy regime.*

● ANNIE’s is an **exceptional training ground for early career scientists**.
  ○ 10+ Postdocs/PhD students are now university faculty or national laboratory staff.
ANNIE Status Overview

- Installed and commissioned in the BNB
- Progress on analyses with first Gd data set
  → Neutron multiplicity measurement
  → Water/LAr cross sections with MicroBooNE+SBND
- First deployment of multiple LAPPDs
  → commissioned and ready for neutrino data taking
- First ton-scale WbLS deployment
  → neutrino events and light yield estimates
- Plans for continuing R&D program using expanded WbLS volume and Gen-II LAPPDs
  → demonstrate hybrid event reconstruction for GeV neutrinos in future LBL experiments
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Experimental Setup of ANNIE

- Steel tank: 26t of Gd-water
- 132x 8”-11” bi-alkali PMTs
- 5x LAPPDs with 100ps timing
- MRD: iron-plastic scintillator sandwich to track outgoing µ’s
- Front Veto to catch dirt muons
Gadolinium loading for enhanced neutron detection

- General idea: recoil neutrons thermalize and capture on gadolinium with a 30µs delay

- Allows counting (multiplicity, including secondary neutrons) and potentially energy measurement by distance of capture point to vertex

- Technical challenge: keep Gd-water chemically stable over extended periods (circulation)
ANNIE’s physics: Neutron multiplicity

- Improve understanding of CC interactions on oxygen
- 3-dimensional differential cross-section measurement:
  a. Final-state lepton energy
  b. Scattering angle
  c. Neutron multiplicity
- High-statistics measurement, several $10^4$ neutrino events per beam year
- Comparison to LAr cross-sections measurements (neutrons versus recoil protons!)
On-time and delayed event reconstruction (PMT only)

- **On-time:** CC $\nu_\mu$ interaction, muon energy and scattering angle
- **Delayed:** 8 MeV gamma signals from neutron capture on gadolinium

Reconstruction of final-state muon energy and scattering angle based on light output in water tank and MRD muon track information
On-time and delayed event reconstruction (PMT only)

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- **Delayed:** 8 MeV gamma signals from neutron capture on gadolinium

$\rightarrow$ Preliminary measurement of neutron multiplicity without LAPPDs in progress

**From PhD thesis of M. Nieslony (2022):**

- **Time distribution of neutron captures recorded for beam data set (1.5 months):**
  - Neutron capture time (beam events)
  - Matches calibration with AmBe
  - $\tau_n = 30\pm9$ $\mu$s

**Basic neutron multiplicity in beam events**

- Multiplicity of neutron captures per beam event (1.5 months of data, no fiducial volume cut)

**M. Nieslony’s PhD thesis:**
Comparison of oxygen and argon cross sections

- **ANNIE + SBND or MicroBooNE** → unique opportunity for joint cross section measurements on water and argon targets

- **Same beam (BNB) means** → significant cancellation of flux systematics → precision $\sigma$ comparison

- **Goals:**
  - measure cross-section ratios
  - correlated measurements of hadron yield (neutrons vs. protons)

**Shaded areas:** Neutrino energy spectra expected for SBND and ANNIE
**Lines:** Systematic rate uncertainties based GENIE v3 MC
**Right-most plot:** systematics of a direct comparison of SBND/ANNIE data

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Status of joint ANNIE/MicroBooNE analysis

- O/Ar analyses need comparable data sets, e.g. CC events without pions (CC0pi)
- **ANNIE:**
  - Basic selection as for neutron multiplicity
  - Event ID for single-/multi-ring events
- **MicroBooNE:**
  - Corresponding analysis already existing
  - Adaptation of standard tooling to extract an ANNIE-like CC0pi sample
- Common handling of BNB flux and GENIE cross section systematics between SBN and ANNIE already implemented for joint analysis
- MicroBooNE-ANNIE MoU is under development for limited data sharing

Current status of Single-Ring (SR) vs. Multi-Ring (MR) discrimination based on PMT patterns (ML) (by Daniel Schmid)

Flux correlations ANNIE/MicroBooNE (by James Mynock)
Expected impact of LAPPDs

- Simulation studies show that X-shaped arrangement of 5 LAPPDs provides optimal performance for vertex reconstruction.
- Relevant for physics program: → improved energy and angular resolution of final-state muons.
- Integration of LAPPDs in vertex reconstruction on-going (see below).
  → collect data for differential cross-section analysis for 2 years.
  → explore potential for beam timing (by resolving substructure of spills).

Note: The diagram illustrates the X-array of LAPPDs compared to PMTs-only.
Sub-nanosecond timing with LAPPDs

- Electron amplification in flat geometry → excellent timing
- Incom’s Gen-I LAPPDs feature
  - Large detection area (8” x 8”)
  - Timing:  - in-situ ~ 50ps
  - absolute ~ 100ps
  - Anode structured in strips, 28 strips with double-sided readout → spatial resolution better ~1cm
- To maintain sub-ns resolution, signals have to be digitized directly at LAPPD → underwater electronics (10 GS/s) → waterproof housing
Deployment of first LAPPD in water

Spring 2022:

- Completed commissioning of LAPPD 40 and PSEC electronics in waterproof housing
- Full characterization of LAPPD 40 in local test stand (Lab 6)
- LAPPD deployed in the ANNIE water tank (center front position)
- Several months of integration work into ANNIE’s DAQ framework

→ successful integration of an LAPPD in a module suitable for neutrino detectors
→ first deployment of an LAPPD in a particle physics detector (done!)
First-ever detection of neutrinos on LAPPDs

- **LAPPD triggers** are issued within a 20µs window around the beam spill
- Dark noise accidentals can be substantially reduced by requiring a **time coincidence with tank PMTs**
- Further background reduction by requiring **MRD coincidences**
- **CC neutrino interactions** inside the water tank selected with front veto cut

→ LAPPDs are now fully integrated with all other detector systems
An ANNIE neutrino candidate on LAPPD – A first!

**Detector components of ANNIE**

- Coincident FMV hit
- Back-propagated muon trajectory
- Tank
- MRD
- Reconstructed MRD track

**ANNIE event display of an example neutrino event recorded with LAPPD 40:**
- MRD registers out-going muon, FMV quiet, forward Cherenkov ring/disc on PMTs.
An ANNIE neutrino candidate on LAPPD

- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)
An ANNIE neutrino candidate on LAPPD

- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)
- Information of hit time (and position along the strip) determined based on absolute (relative) time recorded on strip ends
An ANNIE neutrino candidate on LAPPD

- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)
- Information of hit time (and position along the strip) determined based on absolute (relative) time recorded on strip ends
- Reconstructed hit positions on strips compared to MRD prediction for Cherenkov ring → good agreement!
- Ongoing development of reco code forward-folding track hypothesis to predict (and fit) LAPPD hit pattern

Reconstructed photon hits on the LAPPD: Green dots mark reconstructed arrival times and positions, Blue dotted line is prediction based on the MRD track.
For comparison: Dirt muon with diagonal track

Horizontal muon track entering the water tank upstream and reconstructed diagonally by MRD.
First-ever multi-LAPPD system deployed

- Early 2023: LAPPDs 63+64 successfully deployed and commissioned
- DAQ has been expanded to receive data from multiple LAPPDs
- Commissioned time synchronization amongst individual LAPPDs and global trigger
- Lesson learnt: current LAPPDs are all different → electronics have to be configured to match e.g. the resistances of MCPs
- First data set with multiple LAPPDs acquired towards end of beam year → analysis in progress
Longest LAPPD operational experience

- Due to hints of humidity inside waterproof housings, we removed all three LAPPDs from the water tank during fall → no serious issues were found, will replace water-tight seals
- Characterized post-deployed LAPPDs:
  - found problem with resistance of 2\textsuperscript{nd} MCP of LAPPD 40 (significantly below specs)
  - sent to Incom for further investigation

  → ANNIE is providing essential feedback on long term operation of LAPPDs in realistic deployment scenarios
- During January, we will re-deploy LAPPDs 63+64 and add LAPPD 39 in center position (all already characterized)
- Two additional LAPPDs to be characterized and deployed during the upcoming beam year
A potential DUNE WbLS module

- Water-based Liquid Scintillator (WbLS) is being investigated as a target medium for DUNE FD4 “Module of Opportunity”

- P5 report highlights this module should keep long-baseline capability and expand physics capabilities (astrophysical neutrino detection, double-beta decay)

- Multi-pronged R&D program to demonstrate the versatility of WbLS
  - BNL1T/30T prototypes for online purification and chemical stability
  - EOS (Berkeley): MeV reconstruction
  - BUTTON (Boulby): WbLS radiopurity
  - ANNIE: GeV event reconstruction
Hybrid Cherenkov/scintillation detection in WbLS

Water Cherenkov detectors are great in identifying (multiple) high-energy leptons/pions but no signal from low-energy hadrons

WbLS has the potential to

- Detect hadronic recoils by scintillation → calorimetric energy reconstruction
- Enhance Particle ID using the Cherenkov/scintillation ratio
- Improve position reconstruction due to isotropic light emission at vertex
- Add gadolinium to enhance neutron sensitivity
- in ANNIE, Cherenkov/scintillation separation can be achieved by fast LAPPD timing
First deployment of WbLS in March 2023

- “SANDI” acrylic vessel with 365kg of WbLS
- Organic fraction of 0.5% (Gd-ready) → scintillation cf. Cherenkov light yield → high transparency
- 2 months: few $10^3$ events
First SANDI WbLS data

- Selecting neutrino candidates with (no) Front Muon Veto and track in Muon Range Detector
- Compare data with and without WbLS vessel
  → **WbLS**: new population of events with significantly more photons detected by upstream PMTs

- Selection of Michel electrons from stopped muons
- New population of **electrons in WbLS** produces significantly more photons than **electrons in water**
  → effective increase in light output: \((77 \pm 8)\%\)
Next steps in R&D: more WbLS hybrid detection

- **Existing data**
  - Demonstrate C/S separation based on LAPPD data
  - Look for scintillation-only hadronic neutral current events

- **Second SANDI vessel deployment (~1 month of data)**
  - Gadolinium-loaded WbLS → enhanced neutron detection
  - Larger data sample with multi-LAPPD read-out

- **Expanded WbLS fill (~1 year of data)**
  - Inflatable nylon vessel to separate inside WbLS volume (~8 tons) from outside pure-water volume (material compatibility)
  - Vertex and all recoil particles (but muons) contained in WbLS

→ full vertex fit comparable to future DUNE WbLS-module
Next steps in R&D: Addition of upstream Gen-II LAPPDs

- Isotropic scintillation signal will hit upstream PMTs first → add LAPPDs to enhance timing to enhance vertex position reco & hadronic signal

- Deploy Gen-II LAPPDs with pad readout → counteracts photon pile-up
  → as for Gen-I, offers possibility to test under realistic experimental conditions
  → substantial community interest

Recent Gen-II LAPPDs feature a pad-readout for the anode that reduces photon pile-up
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Status of ANNIE

ANNIE Collaboration (Fall 2023)

United States
- Iowa State
- UC Davis
- Florida State
- UC Irvine
- Ohio State
- Rutgers
- SDSMT
- Associate: LBNL/UC Berkeley
- BNL
- Livermore

Abroad
- Demokritos
- Erciyes
- Hamburg
- Kanpur
- Mainz
- Tübingen
- Warwick
- Associate: Sheffield

14 full member institutions (7 US/7 non-US) - 40+ collaborators
Expansion of the ANNIE collaboration

ANNIE unique R&D program continues attract new collaborators

- The WbLS component of the ANNIE program has already attracted several groups
  - LBNL/UC Berkeley (Gabriel Orebi Gann) → WbLS characterization & reconstruction
  - BNL (Minfang Yeh) → WbLS production
  - U Hamburg (Caren Hagner) → Advanced event reconstruction
  - U Mainz (Michael Wurm) → WbLS characterization, filling
  - U Tübingen (Tobias Lachenmaier) → C/S separation with LAPPDs

- Several new groups expressed interest to participate in continuing R&D
  - Further groups from BNL Instrumentation Division (David Asner) → Gen-II electronics
  - U Pennsylvania (Josh Klein) → Gen-II electronics, di-chroicons
  - Boston University (Christopher Grant) → WbLS, nylon bag
  - TU Munich (Hans Steiger) → WbLS, filling
ANNIE activities are funded by university groups with important support by the lab(s)

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<td>LAPPD integration</td>
<td>ISU, FSU, FNAL (technical)</td>
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<td>SANDI+WbLS</td>
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<td>PMT/MRD electronics</td>
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<td>DAQ &amp; Software</td>
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<td><strong>New detector hardware</strong></td>
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<td>New readout electronics</td>
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<td>Nylon bag &amp; Filling system</td>
<td>Mainz, UC Davis, Boston U</td>
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<tr>
<td>Water-based scintillator (8t)</td>
<td>BNL, LBNL/Berkeley, TUM</td>
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Resources for running ANNIE

Size of the collaboration

- Grown during past few years: healthy number of Postdocs and PhDs
- On-site crew plus steady stream of external visitors staying for few months, both national and international (10+ during last year)

Key resources of the lab

- Support concerning LAPPDs/electronics → working on expanding own expertise with university support (ISU/Rutgers)
- Minimal maintenance cost to the lab
  - Nitrogen dewars have been replaced by direct line from SBND
  - Using 4-5 hours a week for liaison and tech time over 2023
Summary

- ANNIE is in a unique position to measure neutrino-nucleus-cross sections in water, with complementary sensitivity to LAr-TPCs (neutron vs. proton yield!) and directly comparable due to MicroBooNE/SBND argon data in the same beam.

- ANNIE is a testbed for novel technologies: the very first experiment to use Gd-loaded water, water-based scintillator and LAPPDs for the detection of neutrinos.

- With 3+ LAPPD modules installed and commissioned, ANNIE is set for two years of high-quality data taking to profit from the excellent event reconstruction enabled by multiple LAPPDs.

- ANNIE is an ideal testing ground for WbLS for hybrid Cherenkov/scintillation reconstruction of GeV neutrino events in future long-baseline experiments.

- Plans for R&D program with an enlarged WbLS volume and new upstream LAPPDs → Critical R&D milestones to be demonstrated before long accelerator shutdown.