PROCEEDINGS OF SCIENCE

Status of the ANNIE experiment

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ANNIE is a Gadolinium-loaded water Cherenkov detector located in the Booster Neutrino Beam at Fermilab. One of its primary physics goals is to measure the final state neutron multiplicity of neutrino-nucleus interactions. This measurement of the neutron yield as a function of the outgoing lepton kinematics will be useful to constrain systematic uncertainties and reduce biases in future long-baseline oscillation and cross-section experiments. ANNIE is also a testbed for innovative new detection technologies. It will make use of pioneering photodetectors called Large Area Picosecond Photodetectors with better than 100 picosecond time resolution, which will enhance its reconstruction capabilities and demonstrate the feasibility of this technology as a new tool in high energy physics. The status of the experiment is reported here in terms of the overall progress, the deployment of the first Large Area Picosecond Photodetector and an overview of recently taken beam and calibration data. Additional future R&D efforts and analysis opportunities involving the use of the novel detection medium of Water-based Liquid Scintillators are also briefly highlighted.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

[*] Speaker

PoS(ICHEP2022)581

1. Introduction

A good understanding of neutrino-nucleus interactions is vital for reducing systematic uncertainties in next-generation neutrino oscillation experiments searching for leptonic CP-violation, the mass ordering or beyond the Standard Model (BSM) physics. Intranuclear processes need to be understood well in order to correctly account for all final state particles produced in such interactions. In this context, particularly the neutron yield is not very well understood and warrants further investigation by a small detector with high neutron detection efficiency.

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a Gadolinium-loaded water Cherenkov detector located 100 m downstream of the Booster Neutrino Beam (BNB) target at Fermilab. It aims to characterize the neutron multiplicity in neutrino interactions as a function of the muon kinematics as well as to measure the charged current quasi elastic (CCQE) neutrino cross-section in water. In addition, the close proximity to the Short-Baseline Near Detector facility [1] enables the possibility to perform a joint cross-section measurement on water and Argon with reduced systematic uncertainties.

2. Detector overview

The ANNIE detector consists of several subsystems as shown in figure 1. When looking along the beam, the Front Muon Veto (FMV) is the first subsystem consisting of two layers of scintillator paddles, followed by the water tank instrumented with 132 conventional photomultipliers and a planned number of 5 Large Area Picosecond Photodetectors (LAPPDs), and finally the iron-scintillator sandwich Muon Range Detector (MRD) containing 11 scintillator layers with a total of 306 paddles. While the FMV is used to veto neutrino interactions that happened in the rock upstream of the main water tank, the MRD makes it possible to determine the momentum and direction of muons produced in charged current (CC) neutrino interactions in the water. The Gadolinium (Gd)-loaded water tank is the central detector in ANNIE and is used to detect both the prompt Cherenkov disk of the charged muon produced in the interaction as well as the delayed signatures of neutrons being captured primarily on the Gd nuclei.

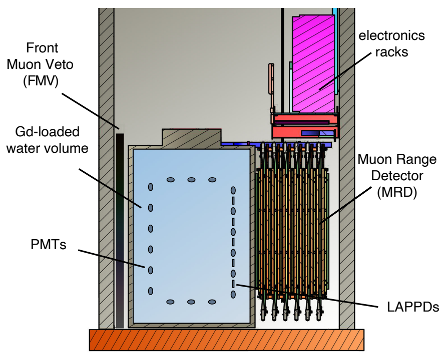

Figure 1: Schematic cross-section view of the ANNIE detector.

ANNIE is loaded with a weight fraction of 0.2% $Gd_2(SO_4)_3$, meaning that roughly 90% of all neutron captures happen on Gd instead of free protons [2]. The high total energy of the Gd gamma cascade ($E_{\text{total,Gd}} \sim 8\,\text{MeV}$) allows for a much better efficiency of neutron detections in comparison to the 2.2 MeV gammas which are produced in the case of captures on hydrogen in water Cherenkov detectors. [3]

Before the physics data taking phase (Phase II) of ANNIE started in the beginning of 2021, a reduced experimental configuration was used in the years 2016 and 2017 in the scope of Phase I to assess the beam-correlated neutron background levels. The background levels were found to be low enough to enable a successful measurement in Phase II, with $R_{\text{bg,FV}} < 0.02/\text{m}^3/5 \cdot 10^{12}\text{POT}$ for events in the Fiducial Volume of ANNIE [4].

3. Analysis of beam data

Currently ongoing analyses investigate the neutron yield of CC neutrino event candidates in ANNIE in the 2021 beam data sample. In order to identify CC beam neutrino candidates, the following event selection criteria are applied: Firstly, a stopping reconstructed track is required in the MRD in order to select ν_μ events with a contained muon, enabling the determination of the primary charged lepton energy E_μ. Secondly, a Cherenkov disk is necessary within the central water tank and should match the expected orientation based on the topology of the MRD track. Lastly, no hits are allowed on any of the scintillator paddles of the FMV in time with the event in order to exclude muons that entered the detector from the outside. Figure 2 shows an exemplary event display of such a beam neutrino candidate in the 2021 ANNIE beam data which was selected by applying all the aforementioned cuts.

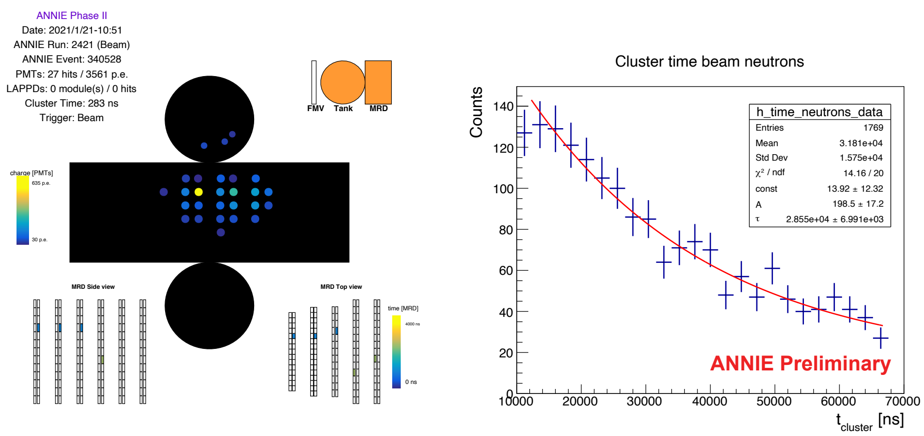

Figure 2: Left: Event display of an exemplary CC ν_μ event candidate in ANNIE. **Right:** The neutron candidate time distribution of captures that were recorded following beam neutrino candidate events.

After identifying such neutrino event candidates, the ANNIE data is scanned for additional activity in a total time window of 70 µs in order to identify associated neutrons. If a certain number of photomultipliers (PMTs) detect hits simultaneously and the light is distributed isotropically enough, a neutron candidate is identified. The right image in figure 2 shows the time distributions of such neutron candidates following neutrino interactions in ANNIE alongside an exponential fit. The fitted capture time constant of $\tau = (29 \pm 7)\,\mu\text{s}$ is in good agreement with the expected theoretical value of $\tau_{\text{theo}} = 30\,\mu\text{s}$ [5], validating that the identified neutrons behave according to expectations.

4. Deployment and data of the first Large Area Picosecond Photodetctor

Large Area Picosecond Photodetectors are microchannel plate-based photosensors with an active surface of 20 cm × 20 cm, manufactured by Incom [6] and schematically depicted in figure 3 on the left. In comparison to conventional PMTs, LAPPDs feature a much better timing resolution of less than 100 ps as well as an intrinsic position resolution of less than a centimeter for the photon hits on the tile [7]. Due to their excellent timing resolution and their ability to resolve individual photon positions, the deployment of five LAPPDs enables a precise track and vertex reconstruction and is estimated to improve the vertex resolution in ANNIE by a factor of two [8]. The ANNIE detector features 8 removable panels which can be used to insert the LAPPDs in a modular fashion into the main water tank.

The first LAPPD to be deployed in ANNIE was extensively characterized in terms of its quantum efficiency, gain and timing properties at a dedicated test stand before being assembled in a waterproof housing alongside all the necessary electronics, including the LAPPD itself, a Low-Voltage High-Voltage (LVHV) board providing both the Low Voltage for other electronic components as well as the High Voltages for the microchannel plates and the cathode, and two ACDC cards for digitization purposes. Figure 3 shows a picture of the complete waterproof housing package for the first LAPPD. It was mounted on one of the 8 LAPPD panels and inserted into the ANNIE water tank on March 30, 2022, as shown in the same figure on the right.

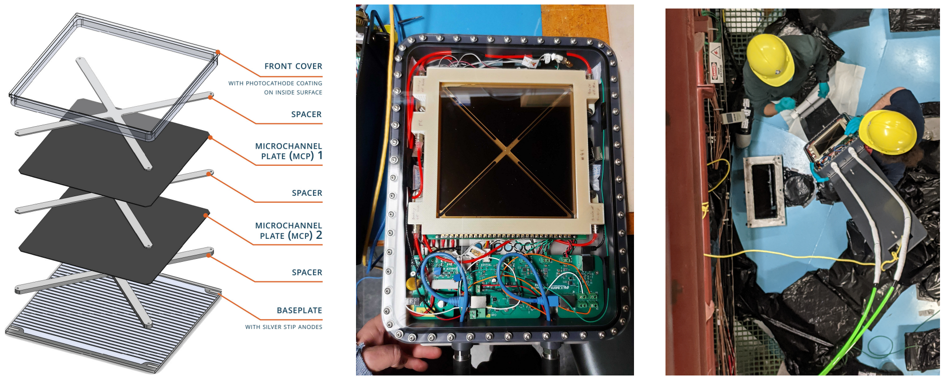

Figure 3: Left: Schematic depiction of a LAPPD [6]. **Center:** LAPPD mounted inside the waterproof housing. **Right**: Picture of the deployment process.

Since then, the LAPPD has been closely monitored in terms of the humidity and temperature inside of the waterproof housing and successfully recorded both beam neutrino and laser data while being under water. The properties of the recorded beam events are displayed in figure 4 both in terms of the timing of the hits with respect to the beamgate as well as the strip multiplicity of recorded events. The timing distribution features a clear elevated region of 1.6 μs width between 8 and 10 microseconds, corresponding to the BNB signal spill. The strip multiplicity distribution reveals a higher number of hits observed during periods where the beam was on. Both observations highlight the fact that the LAPPD deployed in ANNIE was able to successfully record neutrino events. The remaining four LAPPDs are currently being assembled in their own waterproof housings and prepared for their anticipated deployment in fall of 2022.

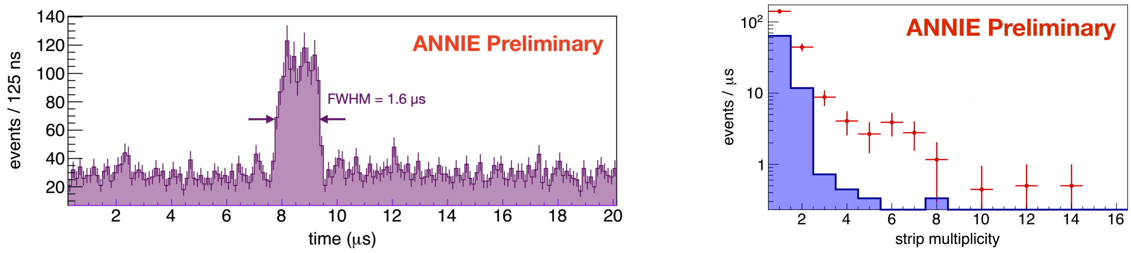

Figure 4: *In-situ* data taken with the first LAPPD in ANNIE after deployment in the tank. **Left:** Timing distribution of pulses recorded on the LAPPD, with respect to the start of the beamgate signal. **Right:** The number of strips recording pulses for beam-on (*red, markers*) and beam-off (*blue, filled*) data taking periods.

5. Water-based Liquid Scintillator (WbLS) in ANNIE

Water-based Liquid Scintillator (WbLS) is a novel detection medium containing a mixture of pure water and oil-based Liquid Scintillator which was originally developed at Brookhaven National Laboratory [9]. Since oil and water generally do not mix well, a surfactant is needed to bind the scintillator into the water and create a chemically stable compound in the form of micelle structures. Due to the presence of both water and scintillator, the WbLS medium creates the opportunity to utilize both the Cherenkov and the scintillation light produced in particle interactions, making it an interesting candidate for future hybrid detector concepts like THEIA [10]. The directionality from the Cherenkov light in combination with additional calorimetric information from the scintillation light (especially for hadrons) has the potential to reduce backgrounds for a number of neutrino physics searches in the future, such as solar neutrinos [11] or the Diffuse Supernova Neutrino Background [12].

In order to test WbLS in a neutrino beam environment, ANNIE plans to deploy a small vessel called *Scintillator for ANNIE Neutrino Detection Improvement (SANDI)* and investigate the impact of the WbLS both on neutrino event reconstruction as well as neutron detection capabilities. SANDI is an acrylic cylinder with dimensions ($d \sim 0.9$ m, $h \sim 0.9$ m) which will be lowered into the main water tank as depicted on the left in figure 5 for a time frame of four weeks during the fall of 2022. A picture of the manufactured vessel is shown on the right side of the same figure. WbLS is expected to improve the neutrino energy reconstruction capabilities of ANNIE due to the additional information about hadronic activity which is otherwise not accessible in a water Cherenkov detector. Similarly, the neutron detection efficiency is estimated to improve when using Gd-loaded WbLS instead of Gd-loaded water in the future.

6. Conclusion

Since the commissioning in early 2021, ANNIE has been continuously taking beam data for its neutron multiplicity and CCQE cross-section measurements. With the insertion of the first LAPPD this year and the planned deployment of the remaining four LAPPDs within the coming fall, the upcoming data taking campaign will provide a data sample which can be characterized even more precisely in terms of the muon kinematics due to the enhanced timing capabilities of the LAPPDs.

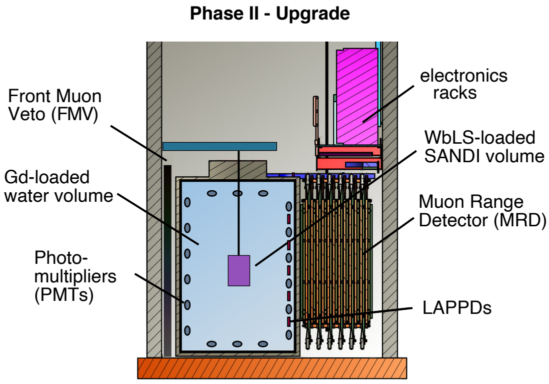

Figure 5: Left: Schematic view of the ANNIE detector for the planned SANDI deployment. **Right:** Picture of the manufactured vessel during a lift test at UC Davis.

Furthermore, the insertion of the WbLS-filled SANDI vessel this fall will provide important insight into the performance of WbLS in a neutrino beam environment and the feasibility of larger-scale hybrid Cherenkov/scintillation detector concepts.

Acknowledgements

The ANNIE collaboration is thankful for the support of the Fermi National Accelerator Laboratory, operated by Fermi Research Alliance, LLC under Contract No. DE-AC02- 07CH11359 with the United States Department of Energy. The activities of the ANNIE experiment are supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under contracts DE-SC0015684 and DE-SC0019214, the DOE National Nuclear Security Administration through the Nuclear Science and Security Consortium under award number DE-NA0003996, together with Science and Technology Facilities Council, Scottish Universities Physics Alliance (United Kingdom) and the Deutsche Forschungsgemeinschaft DFG (Germany) under project numbers 490717455 and 456139317. We also would like to thank to Evan Angelico from the University of Chicago, Dr. Bernhard Adams from Incom, Inc., Paul Stucky from UC Davis, and Paul Rubinov, Albert Dyer and Joe Pastika from Fermilab for their help with the LAPPD preparations at Fermilab.

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