PROCEEDINGS OF SCIENCE

ANNIE: Overview and Physics Goals

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The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26-ton Gd-doped water Cherenkov detector installed in the Booster Neutrino Beam (BNB) at Fermilab. The main physics goal of the experiment is to measure the final state neutron multiplicity of neutrino-nucleus interactions to improve the systematic uncertainties in oscillation experiments. Complementing this goal, ANNIE tests novel technologies such as water-based liquid scintillator (WbLS) and Large Area Picosecond PhotoDetectors (LAPPDs). This contribution provides an overview of the experiment describing the status and physics goals.

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1. The ANNIE experiment

ANNIE aims to measure the multiplicity of neutrons generated from neutrino-nucleus interactions and charged current neutrino interaction cross-sections, as a function of final state kinematics. The neutrino flux, provided by the BNB, is predominantly composed of muon neutrinos (~93%, in neutrino mode) with a flux peak energy at around 700 MeV. The experiment is performed in two phases. During Phase-I, the beam-induced neutron backgrounds were evaluated to demonstrate the feasibility of the experimental concept. The results are reported in [1] showing that the level of background neutrons was sufficiently low to proceed with the full implementation of the ANNIE detector (Phase-II) and the neutron multiplicity measurements. The experimental setup of the ANNIE Phase-II detector, shown in Figure 1, consists of:

- The gadolinium-loaded water tank of 3-m in diameter and 4-m tall. The tank is instrumented with 132 PMTs and 5 LAPPDs [2]. Neutrino interactions within this volume are detected by observing the Cherenkov light produced by the associated charged lepton during Charged Current interactions (as it is shown in Figure 2a).
- The Front Muon Veto (FMV) to reject entering backgrounds produced during beam neutrino interactions in the dirt and rock upstream the water tank. Such backgrounds can consist of neutrino-induced muons (dirt muons) and neutrons arsing from these interactions (dirt neutrons).
- The Muon Range Detector (MRD) to tag energetic muons ranging out the water tank without having deposited their full kinetic energy into the tank volume.
- Readout electronics and power supplies located on the level above the detector.

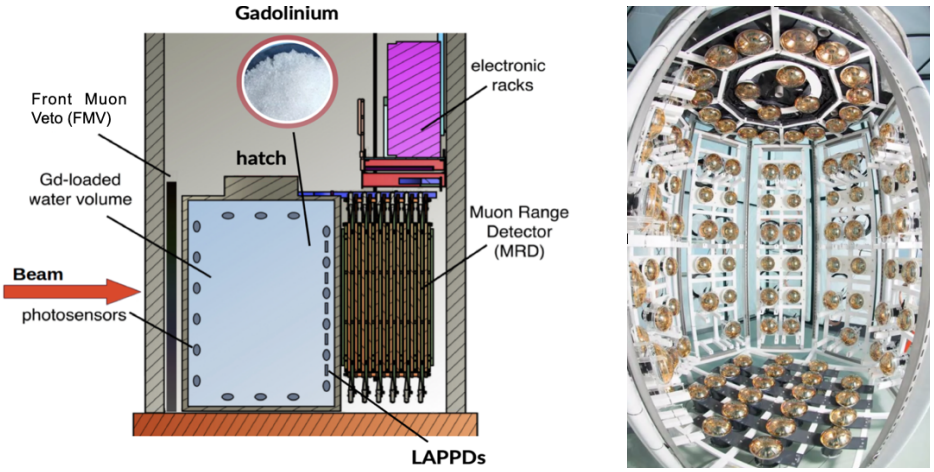

Figure 1: Left: A schematic drawing of the ANNIE detector system. The direction of the BNB neutrino beam is illustrated. Right: An image of the ANNIE inner structure with the photomultiplier tubes mounted in a clean-room environment.

A typical event in ANNIE is illustrated in Figure 2. A muon neutrino interacts with a nucleus, producing a muon. The muon emits Cherenkov radiation as it exits the water tank and ranges out

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to the MRD, generating a prompt signal (Figure 2a). Any final-state neutrons produced by nuclear interactions thermalize and are subsequently captured by gadolinium (Figure 2b). The de-excitation of gadolinium releases a delayed signal within the tank (Figure 2c). Charge and timing data from the detector tank, along with track information from the MRD, are used to reconstruct muon events (muon energy, vertex, direction). The number of neutrons is determined by identifying clusters of hits within the delayed signal window, which are then analyzed in relation to the muon momentum transfer (Q^2).

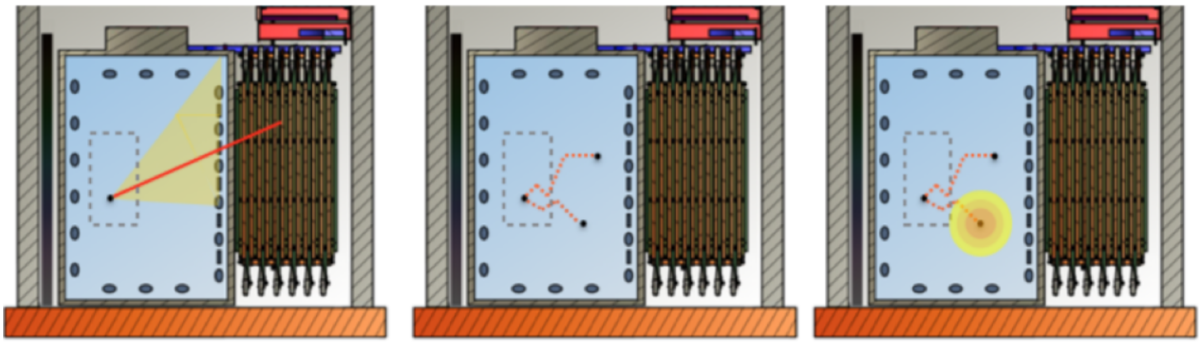

Figure 2: Event signatures in ANNIE: (a) A neutrino Charged Current interaction in the fiducial volume. The Cherenkov radiation from the muon is detected by PMTs and LAPPDs. The muon ranges out in the MRD. (b) Neutrons scatter and thermalize within a few microseconds. (c) Neutrons capture on Gd, producing gammas from the de-excitation of Gd nucleus.

2. Neutrons Detection in ANNIE

Being the first Gd-doped water Cherenkov detector to operate on a neutrino beam, ANNIE is capable of characterizing the neutron yield from neutrino-nucleus interactions. The initial neutron multiplicity measurement involved beam neutrino events with a reconstructed stopping track in the MRD from the entire range of encountered muon energies and interaction angles. For each event, the number of neutrons was recorded, and the resulting distribution was compared to expectations from Monte Carlo simulations. Figure 3 shows the measured data, represented by black crosses, with the extents of the lines indicating the statistical uncertainties of the measurement. The expectations from simulation is shown as dotted lines, with the shaded regions reflecting the statistical uncertainties of the simulation [3]. The results showed that simulation models tend to overpredict high-neutron yield events, and underpredict zero-neutron interactions. More detailed neutron multiplicity measurements are anticipated once the data analysis of ANNIE, with the LAPPDs deployed in the tank, is completed.

3. Testing New Technologies in ANNIE

3.1 Large Area Picosecond PhotoDetectors

Large Area Picosecond PhotoDetectors (LAPPDs) are microchannel plate-based fast-timing photosensors. These planar, large area microchannel plates ($20 \times 20\ cm^2$) are fabricated using a

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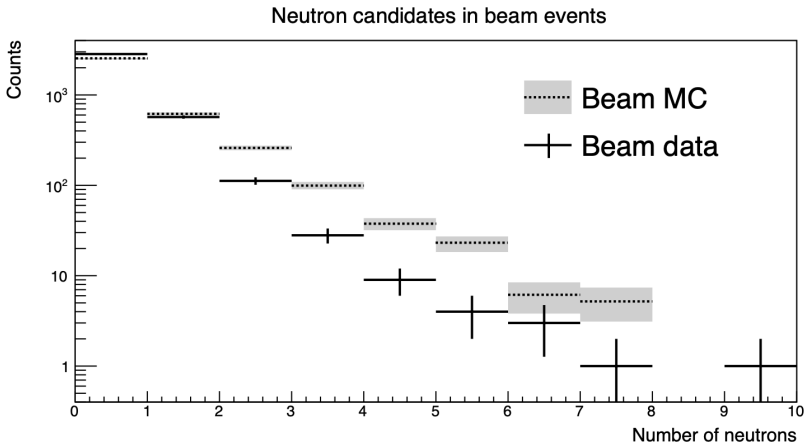

Figure 3: Neutron multiplicity distribution in data (points with error bars) and MC (shaded areas) for beam neutrino events featuring a stopping muon track in the MRD. No fiducial volume requirement has been applied [3].

novel process based upon application of Atomic Layer Deposition coatings to bare glass capillary arrays. Signals are collected on microstrip anodes applied to the bottom plate [2]. LAPPDs feature picosecond timing resolution (~50 picoseconds RMS) and millimeter-level spatial resolution (3.2mm and 0.8 mm RMS respectively) for single photoelectrons [2]. Along with the electron gains achieved of up to 10^7, low dark noise rates (~100 Hz/cm^2 at a gain of $6{\cdot}10^6$) and high (~ 25%) quantum efficiency uniform bi-alkali photocathodes, they constitute good photosensor candidates for neutrino experiments, such as ANNIE. Their excellent timing and spatial resolution are enabling new techniques where fast timing facilitates critical benefits including: more efficient background rejection, high vertex resolution, precise track reconstruction, as well as separation of Cherenkov and scintillation light (which is critical for innovative hybrid Cherenkov detector configurations). According to Monte Carlo simulations the addition of 5 LAPPDs in the ANNIE tank can improve the vertex resolution by a factor of 3 and the directional resolution by a factor of 2 compared to the configuration using only PMTs [4].

The ANNIE Collaboration deployed the first LAPPD in the tank in March 2022, realising the first ever neutrino-detection with an LAPPD. The neutrino beam spill was clearly visible in the first LAPPD data as it is shown in Figure 4. Since then, additional LAPPDs have been installed in the ANNIE tank and are taking data. Figure 5 illustrates the interior of an LAPPD enclosure, complete with the necessary electronics, prior to its deployment in the water tank. ANNIE is the first experiment to successfully deploy and operate multiple LAPPDs over the long term under real experimental conditions.

3.2 Water-based Liquid Scintillator

ANNIE serves as a testbed for hybrid Cherenkov detector configurations, integrating Gd-doped water and water-based liquid scintillator (WbLS). In such concepts, the good optical transparency and event directionality (provided by the Cherenkov cone) are combined with the low-threshold calorimetric capabilities of liquid scintillators thus enhancing the energy resolution of these detectors. To enable hybrid event detection, it is essential to distinguish between the Cherenkov and

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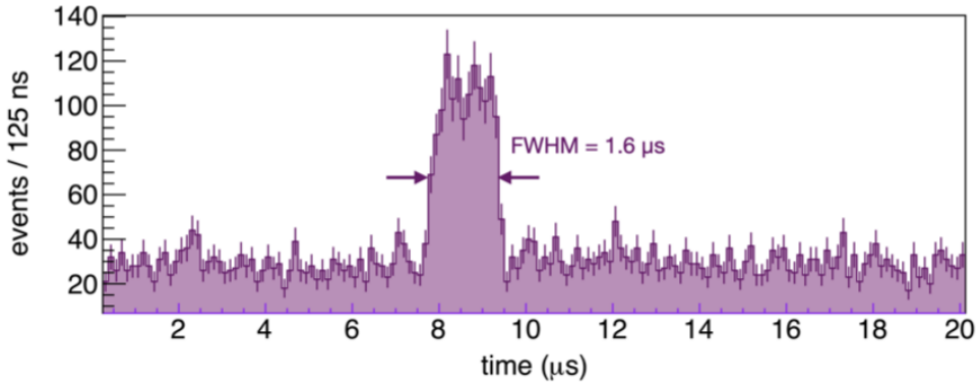

Figure 4: The time distribution of the first LAPPD data taken with the ANNIE detector. An increase of events with a width of 1.6 μs confirms that the LAPPD detects the neutrino beam.

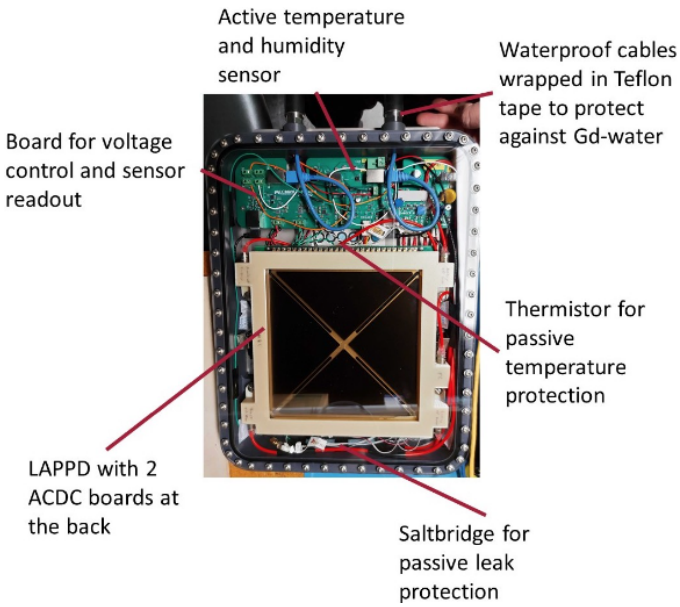

Figure 5: The interior of an LAPPD package before deployment in ANNIE.

scintillation components of the events. The emission of scintillation light is delayed by a relaxation time of ~5-20 ns, compared to prompt Cherenkov emission that typically spans from ~0-5 ns for a point-like event. Employing the picosecond timing capabilities of LAPPDs will allow ANNIE to showcase the potential of these advanced hybrid configurations.

In March 2023, the ANNIE collaboration deployed a 366 L WbLS vessel in the Gd-doped water tank for two months to provide a proof-of-concept of this hybrid detection technology. The results are reported in [5] showing no signs of degradation of optical transparency or light yield, thus indicating the long-term stability of WbLS under real deployment and neutrino beam operation. The scintillation light from beam-induced neutrino interactions in WbLS was detected showing an increase in the number of detected photoelectrons when the WbLS-filled vessel was deployed [5] in the ANNIE tank (compared to ANNIE without the WbLS-filled vessel). Figure 6 shows the increase in the number of detected photoelectrons when the WbLS-filled vessel was in ANNIE for the case

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of throughgoing muon events. These muons are produced in muon neutrino interactions with nuclei in the surroundings of ANNIE thus providing coincidence signals in the FMV, the water tank and the MRD. Throughgoing muons have extended track lengths, crossing the whole ANNIE detector (FMV, tank, MRD) thus producing a relatively well defined photoelectron spectrum. Having a more narrow energy distribution than muons produced in the ANNIE tank, makes throughgoing muons good candidates for the estimation of the impact of the additional scintillation light. The observed increase in the detected number of photoelectrons, produced by scintillation, is in agreement with the expectations given by laboratory experiments [5].

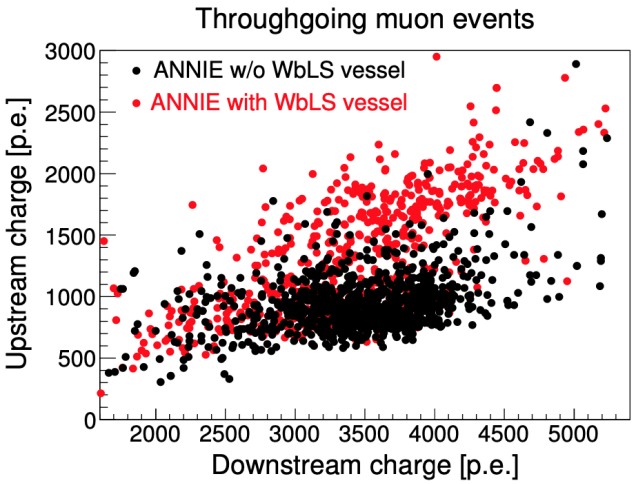

Figure 6: The number of detected photoelectrons for the downstream PMTs with respect to the upstream PMTs for the selected events (throughgoing muon events, with a coincident FMV trigger) of ANNIE without the WbLS vessel in black and for the events of ANNIE with the WbLS vessel in red [5].

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