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ANNIE: Neutron multiplicity in neutrino interactions and new technologies

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Abstract. The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) aims at measuring the neutron abundance in the final state of neutrino-nucleus interactions. This measurement will have a direct impact on our understanding of neutrino interactions and will lead to a better reduction of systematic errors and an improvement of signal-background discrimination in future large neutrino detectors, thus impacting long baseline oscillation experiments as well as proton decay searches and supernova detection. With a volume of about 26 tons of pure water doped with gadolinium to enhance neutron tagging efficiency, ANNIE will provide a measurement of the neutron yield of neutrino interactions as a function of the neutrino energy in the well-characterized Booster Neutrino Beam at Fermilab. The modularity of ANNIE will allow it to perform several fundamental tests of new technologies to be used in neutrino detectors, such as a novel kind of photodetectors called Large Area Picosecond Photodetectors and Water-based Liquid Scintillator, a newly-developed detection medium. The technology behind the ANNIE detector will have a noticeable impact on the development of future large water Cherenkov detectors as well as on detection techniques for neutrino physics.

1. Introduction

A precise understanding of neutrino-nucleus interactions will be crucial in bringing the next generation of long baseline oscillation experiments towards the path to discovery of leptonic CP violation as well as manifestations of BSM physics. To correctly reconstruct the energy of an interacting neutrino, all final state particles need to be accounted for and properly reconstructed. Intra-nuclear processes that could lead to the creation of one, or several, uncharged particles, such as neutrons, need to be studied in detail using detectors sensitive to such particles [1]. Unfortunately, neutrons are quite elusive in most current large neutrinos detectors as both their interaction cross section and signature are faint. Hence the need for a small scale detector capable of measuring the production of final state neutrons, as a function of the neutrino energy, using a well-known neutrino beam.

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a gadolinium-loaded water Cherenkov detector installed 100 meters down the Booster Neutrino Beam (BNB) line at the Fermi National Accelerator Laboratory [2]. Its goal is to measure the multiplicity of final



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state neutrons in neutrino-nucleus interactions and perform a measurement of the Charged-Current Quasi-Elastic (CCQE) cross section in water.

A background measurement, referred to as Phase I, was performed in 2016-2017 to assess the level of ambient neutron background in the experiment hall using a simplified detector configuration [3]. The amplitude of this background - consisting mostly of beam-induced neutrons - was found to be acceptable for Phase II, the physics phase of the experiment. A publication summarizing these results is currently under collaboration review and is expected to be publicly available soon.

2. The ANNIE Phase II detector

The ANNIE Phase II detector, shown in Figure 1 (left), consists of three major components: (1) a Front Muon Veto to detect and tag beam-induced charged particles produced in the upstream rock, (2) a water tank containing the neutrino target medium and photosensors, and (3) an iron-scintillator sandwich detector, the Muon Range Detector (MRD).

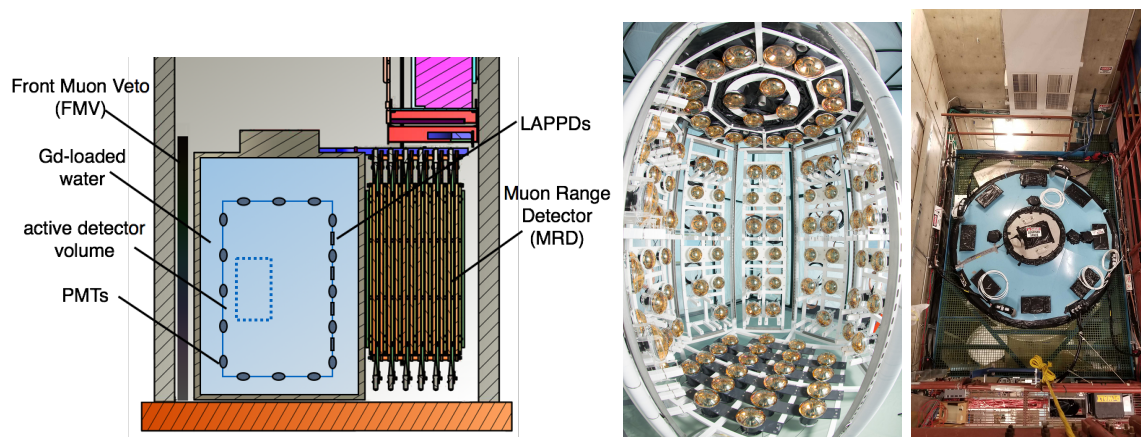


Figure 1. Left: Sketch of the ANNIE Phase II detector setup. Center: The ANNIE Phase II PMT array before its installation in the water tank. Right: Top view of the ANNIE detector installed in its experimental hall. All 8 rectangular deployment ports can be used to inset LAPPDs in the water volume.

The FMV consists of two overlapping layers of scintillator paddles coupled to photomultiplier tubes (PMTs). Its goal is to detect and tag background muons originating from neutrino interactions in the rock upstream of the detector. Given the small size of ANNIE, such muons could be badly reconstructed and mistaken for neutrino interactions occurring in the water volume. The FMV provides a way to tag and discard those events.

The main volume of ANNIE is the water tank containing about 26 tons of ultrapure water loaded with 0.2% (w/w) of gadolinium (Gd) sulfate. The high neutron capture cross section of Gd and the subsequent emission of an 8 MeV gamma cascade upon a neutron capture on Gd enhances the neutron detection efficiency. The Cherenkov light generated by muons from neutrino interactions and gammas from neutron captures is collected by an array of 132 PMTs, shown in Figure 1 (center), and 5 Large Area Picosecond Photo Detectors (LAPPDs). The latter are deployed downstream of the detector in waterproof housings inserted from the top of the tank, as displayed in Figure 1 (right), and used to perform a more detailed reconstruction of the Cherenkov light pattern generated by muons travelling through the water volume.

The MRD consists of 11 alternating vertical (5) and horizontal (6) layers of plastic scintillator paddles with 5 cm iron absorbers in between. Its purpose is to detect and reconstruct the direction, momentum and energy of muons ranging out of the water volume. The MRD was a legacy from the SciBooNE experiment [4] and has been fully refurbished by ANNIE for the physics phase of the experiment.

Using the aforementioned sub-detectors, ANNIE is able to detect a neutrino interaction occurring in the water volume, reconstruct its associated muon momentum and energy using LAPPDs in combination with the MRD and finally detect neutrons through their captures on gadolinium in the water volume.

3. New technologies in ANNIE

3.1. Large Area Picosecond PhotoDetectors

LAPPDs are 20x20 cm microchannel plate based tiles (see Figure 2 (left)) with a single photoelectron time resolution of about 50 ps, and a spatial resolution less than a centimeter [5]. Their design offers a significant advantage over conventional photomultiplier tubes (PMTs). While PMTs are considered single-pixel detectors, LAPPDs are imaging detectors able to reconstruct light patterns, such as Cherenkov rings, in both time and position. The single photon spatial resolution they offer allows precise track and vertex reconstruction as well as separation of complex superimposed patterns, such as pion-induced tracks.

LAPPDs are currently developed and manufactured by the Incom company. While several tiles have been characterized individually on test-stands using LEDs or fast lasers, none have been deployed in an actual high energy physics experiment.

ANNIE will initially operate 5 LAPPDs and studies are being performed to assess the reconstruction enhancement brought by the addition of more tiles at several locations in the water volume. All 5 LAPPDs have been thoroughly tested at Iowa State University and Fermilab (see Figure 2 (left)) in order to assess their capabilities in terms of gain, time resolution, quantum efficiency and noise levels.

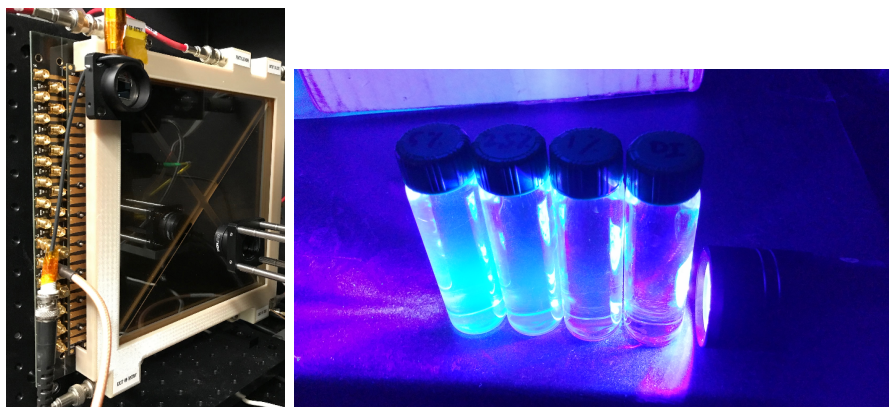


Figure 2. Left: Picture of an ANNIE LAPPD in a dedicated onsite test stand at Fermilab. This setup utilizes a fast pulse laser and an automated scanning system to characterize the gain, quantum efficiency and time response of each LAPPD module that will be deployed in ANNIE. Right: Picture of several WbLS samples under UV light. The scintillation yield from each sample is dependent on its loading. From left to right: 5%, 2.5%, 1% and pure water.

3.2. Water-based Liquid Scintillator

Developed and manufactured at Brookhaven National Laboratory, Water-based Liquid Scintillator (WbLS) is a mixture of pure water and oil-based liquid scintillator [6]. Considering the non-miscibility of these liquids, an additional compound, called a surfactant, is required for the mixture to be homogeneous and stable over time. When in contact with water and scintillator, the surfactant molecules, having an hydrophilic head and an hydrophobic tail, form miscible structures called "micelles" in which scintillator molecules are held homogeneously.

The design of WbLS allows it to be tunable in terms of scintillator content (see Figure 2 (right)). For low energy physics, such as solar neutrinos detection or double-beta decay searches, the advantages of pure liquid scintillator - high light yield and low detection threshold - can be exploited by using WbLS with a high scintillator content (e.g. >20%). However, higher energy physics, such as neutrino oscillations searches, can profit from the advantages of pure water - Cherenkov directionality, low light attenuation and low cost - in a WbLS mixture with a low scintillator content (e.g. <5%).

Studies are ongoing to assess the capabilities that fast-timing photosensors, such as LAPPDs, could bring in reconstructing charged particles tracks in WbLS through the separation of Cherenkov light (fast and directional) and scintillation light (slower and isotropic) using time and charge information [7].

The ANNIE collaboration plans on deploying a WbLS-filled vessel in the water volume within the next year in order to demonstrate the deployment and particle reconstruction capabilities of this innovative detection medium.

4. Conclusion

The physics phase of the ANNIE experiment now entered the commissioning stage and a neutron multiplicity measurement is expected for the end of the beam period in 2020. The deployment of the first 5 LAPPDs, expected in early 2020, will be a significant milestone for the experiment and will demonstrate their potential for high energy physics. With the addition of WbLS, ANNIE, in parallel to its physics goals, will become a testbed for new technologies and pave the way for future, larger and more sophisticated, water-based neutrino detectors.

4.1. Acknowledgments

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