Snowmass2021 - Letter of Interest

ANNIE Detector R&D

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
□ (NF2) Sterile neutrinos
□ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (IF2) (IF2) Instrumentation Frontier/Photon Elements

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Collaboration: ANNIE

Authors: on behalf of the ANNIE collaboration

Abstract: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) will continue to develop advanced neutrino detector technology in addition to pursuing an ambitious physics program in the Fermilab Booster Neutrino Beam. The current detector consists of a gadolinium-loaded water target with Large Area Picosecond PhotoDetectors (LAPPDs) in addition to a suite of conventional PMTs. The experiment took preliminary neutrino data in spring 2020, and is expected to run in this basic configuration in the time frame 2020-2022. During this run ANNIE will test reconstruction techniques used these fast ($<$100 ps) light detectors to reconstruct muons from neutrino interactions in the forward direction. This LOI describes using ANNIE to take the next step in the development of hybrid (Cherenkov plus Scintillation) optical detectors by replacing the current Gd-water target with Water-based Liquid Scintillator (WbLS) to allow reconstruction of neutron capture vertices, and increasing the coverage of LAPPDs to allow multi-track fitting in all directions using fast timing and precision photon location. This is a critical step towards demonstrating the power of hybrid detectors.

The ANNIE Experiment: The Accelerator Neutrino Neutron Interaction Experiment[1,2,3] is located in the Booster Neutrino Beam at Fermilab. This beam is about 93% pure ν_μ in neutrino mode and has a spectrum that peaks at about 700 MeV, an energy scale of great interest to current and future neutrino oscillation experiments. The two main goals of ANNIE are; (1) precision measurements of the neutron yield from neutrino interactions at the 1 GeV scale, and (2) test the effectiveness of Large Area Picosecond PhotoDetectors (LAPPDs) in a realistic physics environment. Approved under the Intermediate Neutrino Program in 2015, was funded in two phases. ANNIE Phase 1 built up the basic infrastructure needed for the experiment: 26 ton Neutrino Target Tank (NTT), Front Muon Veto (FMV) to reject "dirt" muons, and a Muon Range Detector (MRD) to track and range out muons. Completed in 2018, Phase 1 demonstrated that neutron backgrounds were sufficiently low to proceed with the Phase 2 program of physics measurements, including the neutron yield as a function of energy transfer to the nucleus [4]. Figure 1 shows the current Phase 2 detector layout. ANNIE took preliminary beam data in early 2020, and plans to run 2020-2022 to complete the basic physics measurement goals, as described in a separate LOI. This LOI describes for a Phase 3 extension of the ANNIE to use Water-based Liquid Scintillator (WbLS), plus addition of more LAPPDs in order to enable additional physics measurements and test new technology.

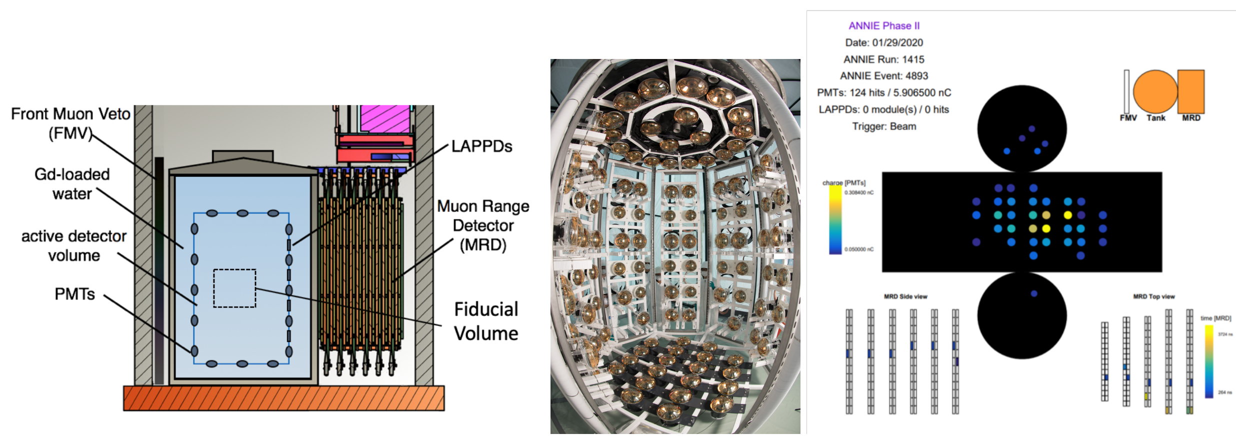

FIG. 1. (left) ANNIE detector (beam comes in from the left). (center) NTT before installation. The rails allow LAPPDs to be inserted between the PMTs. (right) ANNIE first event showing a muon leaving the NTT and entering the MRD (Jan. 2020) [5].

Scintillator for ANNIE Neutron Detection Improvement (SANDI): Using Cherenkov light detected by LAPPDs (for fast timing) and PMTs for imaging the Cherekov ring edge, the current ANNIE detector should be able to reconstruct the vertex of CC neutrino interactions with a muon to about $\Delta r = 12\ cm$, a significant improvement over the $\Delta r = 38\ cm$ expected just using the 128 conventional PMT array. This vertex resolution performance is needed in order to confine the analysis to events with a vertex located within a 2 ton central volume. This will better contain low energy neutrons produced during the neutrino interaction, a major goal of ANNIE. Note that even with a relatively small fiducial volume, ANNIE expects $O(10^5)$ good neutrino candidate events/year. Thus systematics associated with containment of neutrons will dominant the final sensitivity rather than statistics.

From simulation studies, we know that the vertex resolution suffers from the need to image the ring edge with the conventional PMT array, as there is a timing degeneracy in single track particles that makes the vertex location parallel to the track entirely dependent on ring edge imaging. One way to improve on this is to have a small amount of isotropic light from the vertex that can be

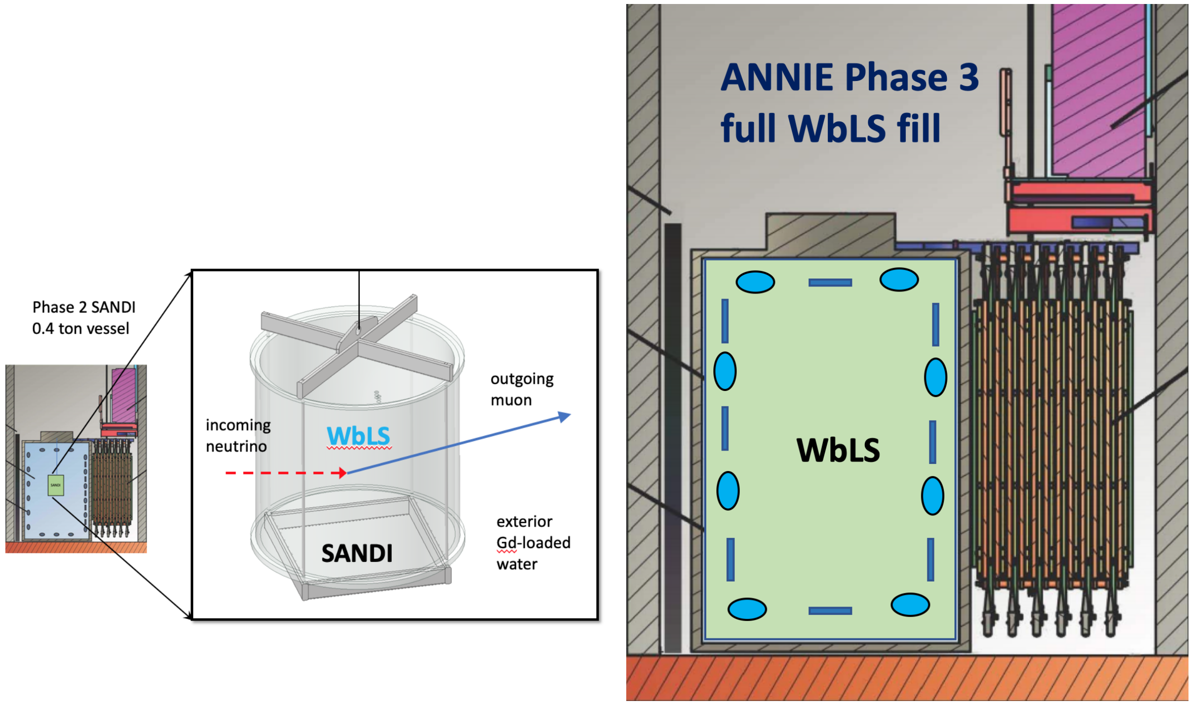

FIG. 2. (left) The SANDI 0.4 ton WbLS-filled vessel for testing vertex reconstruction using LAPPDs and combined Cherenkov and Scintillation light. (right) The proposed ANNIE Phase 3 detector completely filled with WbLS.

separated from Chereknov light by timing and topology. Thus, ANNIE plans to insert a small 400 liter vessel (SANDI) containing 1%-3% Water-based Liquid Scintillator (WbLS) into the central volume in the 2021-2022 time frame. In addition we may move one or more of the five LAPPDs to the backward hemisphere (the NTT was designed so that these are movable). Done mostly with funds from Germany and BNL, this test will confirm models of event reconstruction and may also allow us to reconstruct hadron energy at the vertex. Following a successful SANDI test, ANNIE then plans to propose a full WbLS fill in a Phase 3 program.

ANNIE Phase 3: In order to be able to better understand the energy spectrum of the final state neutrons, it is necessary to be able to reconstruct the position of the neutron capture with respect to the production vertex. The addition of WbLS to the full ANNIE volume, aided by the addition of more LAPPDs would make this possible. The additional LAPPDs would also make it possible to consider moving beyond simply reconstructing forward-going muons to reconstructing all long-track particles, even backward-moving pions. A full calorimetric measurement of the cross-section (including vertex hadronic energy) may also be possible. With these ambitious goals in mind, ANNIE is investigating the possibility to reconstruct the inner part of the NTT to make it compatible with WbLS, including encapsulation of PMTs and other components, in addition to the first-ever deployment of a WbLS liquid recirculation system. Such systems are being developed for Theia[6,7] and NEO[8] and use nanofiltration and phase separation technology to separate the organic components of WbLS from the water matrix, cleaning them separately, then re-combining in such a way as to preserve light yield. **Thus, ANNIE Phase 3 would be a significant step towards realization of hybrid optical detectors in addition to making neutron-inclusive neutrino cross-section measurements of unprecedented scope and quality.**

References:

[1] I. Anghel, *et al.* "LETTER OF INTENT: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)," arXiv:1504.01480, FNAL Report No. P-1063 (2015).
[2] A.R. Back, *et al.*, "Accelerator Neutrino Neutron Interaction Experiment (ANNIE): Preliminary Results and Physics Phase Proposal," arXiv:1707.08222 (2017)
[3] Teal Joel Pershing, "The Accelerator Neutrino-Neutron Interaction Experiment," Fermilab Thesis 2020-09, Ph.D. Thesis UC Davis (2020)
[4] A.R. Back, *et al.*,"Measurement of Beam-Correlated Background Neutrons from the Fermilab Booster Neutrino Beam in ANNIE Phase-I," JINST 15 P03011 (2020)
[5] ANNIE See First Neutrinos with More Firsts to Come, Fermilab News, March 11 (2020)
[6] J.R. Alonso, *et al.*, "Advanced Scintillator Detector Concept (ASDC): A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator," arXiv:1409.5864 (2014)
[7] M. Askins, it et al., "Theia: An advanced optical neutrino detector," European Physics Journal C 80 416 (2020)
[8] M. Askins, *et al.*, "The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A WAter CHerenkov Monitor for ANtineutrinos," arXiv:1502.01132 (2015)

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