Snowmass2021 - Letter of Interest

Physics Opportunities in ANNIE

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
□ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is designed to measure the neutron abundance in the final state of neutrino-nucleus interactions. This class of measurements will have a direct impact on our understanding of neutrino interactions and could lead to a reduction of systematic uncertainties and improvements in signal-background discrimination for future neutrino detectors. ANNIE is a platform for advanced neutrino detector technology in addition to pursuing an ambitious physics program in the Fermilab Booster Neutrino Beam. The current detector consists of a 26-ton gadolinium-loaded water target with Large Area Picosecond PhotoDetectors (LAPPDs) in addition to a suite of conventional PMTs. The experiment is expected to run in this configuration in the time frame 2020-2022. During this run, ANNIE will measure neutron yields in kinematic bins of muon momentum and direction for inclusive charge current final states. This LOI describes an extended physics program beyond this initial measurement. A separate LOI on ANNIE Detector R&D describes an extension to the program 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.

The ANNIE Experiment: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) [1–3] is a 26-ton Gadolinium-loaded, water-based detector located on the Fermilab Booster Neutrino Beam (BNB) with the goals of: (1) performing a measurement of the production of neutrons from ν_μ interactions as a function of Q^2 to constrain neutrino-nucleus interaction models, and (2) demonstrating advanced neutrino detection technology. ANNIE is the first Gd-loaded water Cherenkov detector [4] deployed on a neutrino beam dedicated to the study of neutrino interactions and will soon be the first deployment of LAPPDs. ANNIE benefits from close proximity to the intense Booster Neutrino Beam (BNB) at Fermilab. Simulations predict roughly 11,000 Neutral Current (NC) interactions and 26,000 Charge Current (CC) interactions in the 2.5 ton fiducial volume per year.

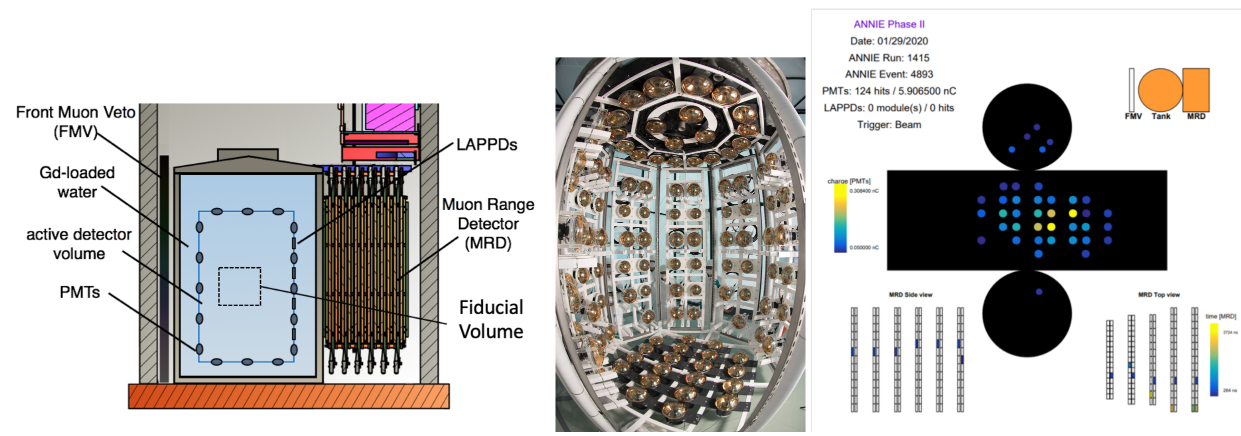

FIG. 1. (left) ANNIE detector (beam comes in from the left). (center) NTT before installation. The rails allow LAPPDs to be inserted between the PMTs. (right) ANNIE first event showing a muon leaving the NTT and entering the MRD (Jan. 2020) [5].

The primary physics goal of ANNIE is to study the abundance of final state neutrons from neutrino-nucleus interactions, using gadolinium (Gd) enhanced water. Measurements of final-state neutron multiplicity will improve our understanding of the neutrino-nucleus interactions. The complex many-body physics of neutrino-nucleus scattering is among the dominant systematic uncertainties in precision long-baseline oscillation measurements [5, 6]. It also represents one of the largest unknown unknowns. For example, studies in DUNE have shown that underestimating the amount of recoil energy going to undetected particles such as neutrons can significantly bias the resulting measurements of oscillation parameters [7]. Beyond their value in understanding neutrino scattering models, identifying and counting final state neutrons also provides a new experimental handle for signal-background separation for future neutrino experiments. The baseline analysis will study high energy Charged Current (CC) events with muons entering the Muon Range Detector, with focus on multi-nucleon events, quasielastic-like inelastic events, and their relationship to energy reconstruction for oscillation physics.

Studying Low Visible Energy Neutrino Scatters: A potential extension of the ANNIE physics program would focus on measuring a class of neutrino interactions with Low Visible Energy (LVE) in conventional Water Cherenkov detectors: quasi-elastic NC scatters and CC interactions with undetectable, low-energy muons. These events are particularly problematic for rare searches such as Diffuse Supernova Neutrino Background (DSNB), where the missing energy contributions can make GeV-scale atmospheric neutrino interactions look like the inverse beta decay (IBD) signal.

ANNIE is capable of measuring the final-state neutron multiplicities of these LVE events with world-leading statistical power. The presence of neutrons beyond the single neutron produced by IBD is a smoking gun for many background components in DSNB searches. The addition of WbLS in ANNIE, combined with LAPPDs will allow ANNIE to see the elements of the nuclear recoil system with energies below the detection thresholds of conventional Water Cherenkov Detectors [8]. The capabilities and cross sections measured in ANNIE will also help with background suppression and confidence estimation in other rare searches such as proton decay [9].

Joint Measurements with the SBND LArTPC: ANNIE's location immediately upstream of the Short-Baseline Near Detector (SBND) [10], a 112 ton active mass Liquid Argon Time Projection Chamber (LArTPC), creates a unique opportunity for joint measurements using H2O and argon targets in a nearly identical flux. Building from the neutrino-nucleus scattering measurements in these detectors individually, joint multi-detector analysis of neutrino interactions with ANNIE and SBND together can provide strong constraints on nuclear modeling across a range of target masses as well as a precise measurement of the H2O/40Ar cross section ratio at the GeV scale. Relating the water and argon cross sections is highly relevant in the context of the upcoming international long-baseline neutrino oscillation program, as it would provide a vital link for precision global analysis of the (argon target) DUNE and (water target) Hyper-Kamiokande experiments, deepening our knowledge of lepton CP violation and beyond.

Furthermore, the excellent neutron identification capabilities of ANNIE, coupled with powerful proton reconstruction in SBND, enable a novel joint measurement of final-state nucleon multiplicity and kinematics, which will tightly constrain nuclear models, and in particular neutron production in argon. As energy losses to unreconstructed final state neutrons represents a significant challenge in LArTPC neutrino energy reconstruction [11], such a constraint provides important input to the future LArTPC program, including DUNE and the Short-Baseline Neutrino Program.

A potential deployment of a WBLS target in ANNIE (see separate LOI) would further enhance this program, by enabling an additional calorimetric measurement of total hadronic vertex activity in ANNIE. We anticipate that these joint measurements, and resulting generator tunes, would be of great interest to a broad community, including: theorists building models that describe neutrino-nucleus interactions across a range of nuclear targets, seeking a strict test of approximations in modeling heavy nuclei; experimentalists performing both neutrino oscillation and neutrino-nucleus scattering measurements, as this provides a new connection between the DUNE/SBN and Hyper-Kamiokande/T2K targets; and event generator developers interested in which models work best, and where approximations and factorizations in code implementation break down or work well.

Neutrino beam timing: ANNIE can also provide a first ever context in which to show a relationship between neutrino beam composition and the timing of the neutrino interactions. It has been shown that the arrival time of incident neutrinos preserves information about the energies of their parent pions and, although this effect requires small bunch sizes, it is possible to superimpose a higher frequency bunch structure on top of the existing Fermilab RF. Therefore, the arrival of neutrinos with respect to the bunch center can be used to select different energy neutrino spectra. Later arriving neutrinos have lower energy. This effect, similar to off-axis techniques, could be used to better understand and control systematic uncertainties in long-baseline experiments such as DUNE [12]. This technique requires precise measurements of the T_0 of the event vertex. Advances in photodetector technology could enable the necessary time resolutions, and there is even potential to achieve these resolutions within the context of the LAr-TPCs planned for DUNE [13]. While this effect is smeared out by the current structure of the Booster RF, beam simulations show that the effect should still be observable within ANNIE.

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