Project Description

D.1 Introduction

One of the most exciting discoveries in particle physics is that neutrinos oscillate from one flavor to another as they travel through space. This quantum mechanical phenomenon implies that the neutrino has a non-zero mass, which provides the first direct evidence of physics beyond the Standard Model. Our understanding of the neutrino oscillation properties has been significantly improved in the past decades, but the Charge-Parity (CP) violation in the neutrinos remains to be measured in the next generation long baseline neutrino oscillation experiments. The measurement of the leptonic CP-violating angle could help answer the question why there is so much more matter than antimatter in the universe. A precise understanding of neutrino-nucleus interactions will be crucial in bringing future experiments towards the path to discovery of leptonic CP violation as well as manifestations of Beyond Standard Model (BSM) physics. The complex many-body physics of neutrino-nucleus interactions is among the dominant systematic uncertainties in precision long-baseline oscillation measurements [1, 2].

The Charged-Current Quasi elastic (CCQE) scattering is one of the most valuable interaction types for neutrino experiments performed at the $O(GeV)$ energy scale. Experimentally, CCQE interactions are identified by the presence of a outgoing lepton and no other particles other than the nuclear recoil. Given a known incident neutrino direction, the neutrino's incident energy can be approximated through the lepton's reconstructed energy and direction alone. However, a number of intermediate states and three-body interactions can lead to inelastic interactions that mimic CCQE. Of particular interest are the two particle-two hole (2p-2h) and the pion-producing interactions that could be misidentified as CCQE interactions. In such events, energy reconstruction based on the lepton momentum underestimates the neutrino energy. A good example is illustrated in Fig. 1. In this simulated example, selecting events with zero neutrons (right plot) results in a considerable reduction of stuck pion and 2p-2h contamination, which improves neutrino energy reconstruction.

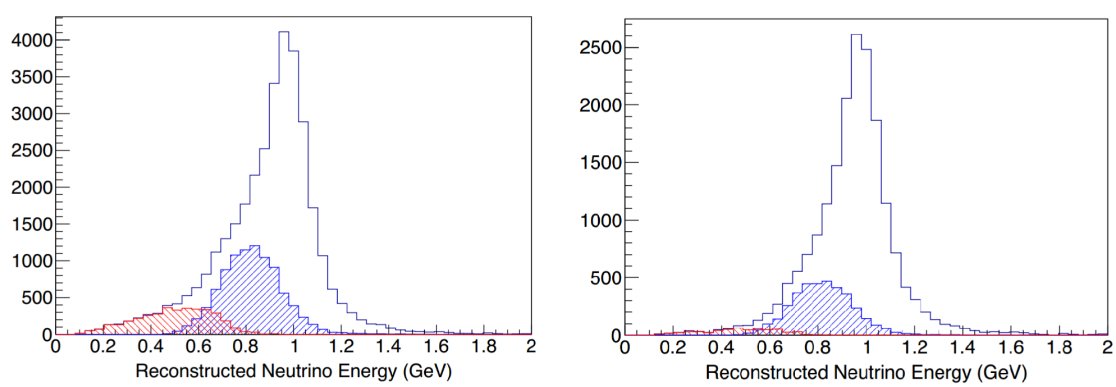

Figure 1: GENIE [3, 4] Monte Carlo simulation showing the reconstructed energy distribution of $1\ \mu + 0\pi$ interactions on ^{16}O from a 1 GeV monoenergetic neutrino beam. Interactions with (left) and without (right) outgoing neutrons are shown. The stuck pion (shaded red) and 2p-2h (shaded blue) contributions to the total distribution (blue) are explicitly shown. Taken from [5].

Increasingly, it has become clear that understanding these multi-nucleon interactions is necessary to explain observed neutrino cross sections [6, 7, 8]. A growing body of literature finds that these contributions have a significant effect in smearing the oscillation spectrum of long-baseline experiments [9, 10]. Most GeV-scale neutrino experiments stand to benefit from measurements of the number of neutrons knocked out of nuclei due to neutrino interactions (referred to as "neutron multiplicity"). 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) [11, 5] is a 26-ton Gd-doped water Cherenkov detector installed in the Booster Neutrino Beam at Fermilab, aiming to make the first detailed measurement of the number of neutrons produced by muon neutrino interaction in water. Measurements of the final-state neutron multiplicity are key to improving our understanding of neutrino-nucleus interactions. Identifying and counting final-state neutrons also provides a new and critical handle on signal-background separation in future proton decay and neutrino experiments [12]. The primary technological goals of ANNIE are to demonstrate new detection technologies such as Large-Area Picosecond Photodetectors (LAPPDs) [13] and neutron tagging in Gd-loaded water. ANNIE is unique in that it will use fast timing LAPPDs to reconstruct neutrino interaction vertices to a precision unprecedented in previous optical detectors. In addition, ANNIE is the first physics detector in a neutrino beam to use gadolinium-doped water. Furthermore, the modularity of ANNIE will allow it to perform tests of new technologies to be used in neutrino detectors, such as a newly-developed detection medium called Water-based Liquid Scintillator (WbLS). The collaboration has been building and developing characterization tests and new reconstruction techniques over the last 2-3 years. The technology being investigated using 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.

The ANNIE collaboration successfully measured the neutron backgrounds in the Phase-I data taking, and showed them to be low enough to proceed to the phase of physics measurement. The Phase-I result of background measurement has already been published [14]. The Phase-II of ANNIE has started taking neutrino beam data since 2020. As a relatively small collaboration, ANNIE has been seeking for new contributions to fulfill its ambitious physics and technological goals. The PI has been an active ANNIE collaborator for years. He participated the detector construction and data taking, and was one of the key developers of the data analysis software. After joining SD Mines, The PI led the Physics Department at SD Mines to join the ANNIE collaboration and is currently advising a graduate student on ANNIE. This proposal aims at developing sophisticated algorithms to achieve ANNIE's physics goal and demonstrate new technologies promised for future experiments.

D.2 Description Of ANNIE Detector

The configuration of the ANNIE detector (Figure 2) 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). For the duration of Phase-I, a smaller neutron sensitive sub-volume, referred to as the Neutron Capture Volume (NCV), was deployed in the pure water, as displayed in the top-left panel of Figure 2. Neutron backgrounds at different locations were measured by moving the NCV across the water tank. Neutron capture signals were detected by the PMTs at the bottom of the tank.

For Phase-II, the tank is filled with Gd-loaded water. More PMTs are deployed providing a much better coverage, and 5 LAPPDs will be deployed to enhance the vertex and track reconstruction capability. The bottom panel in Figure 2 describes the working principle of the ANNIE

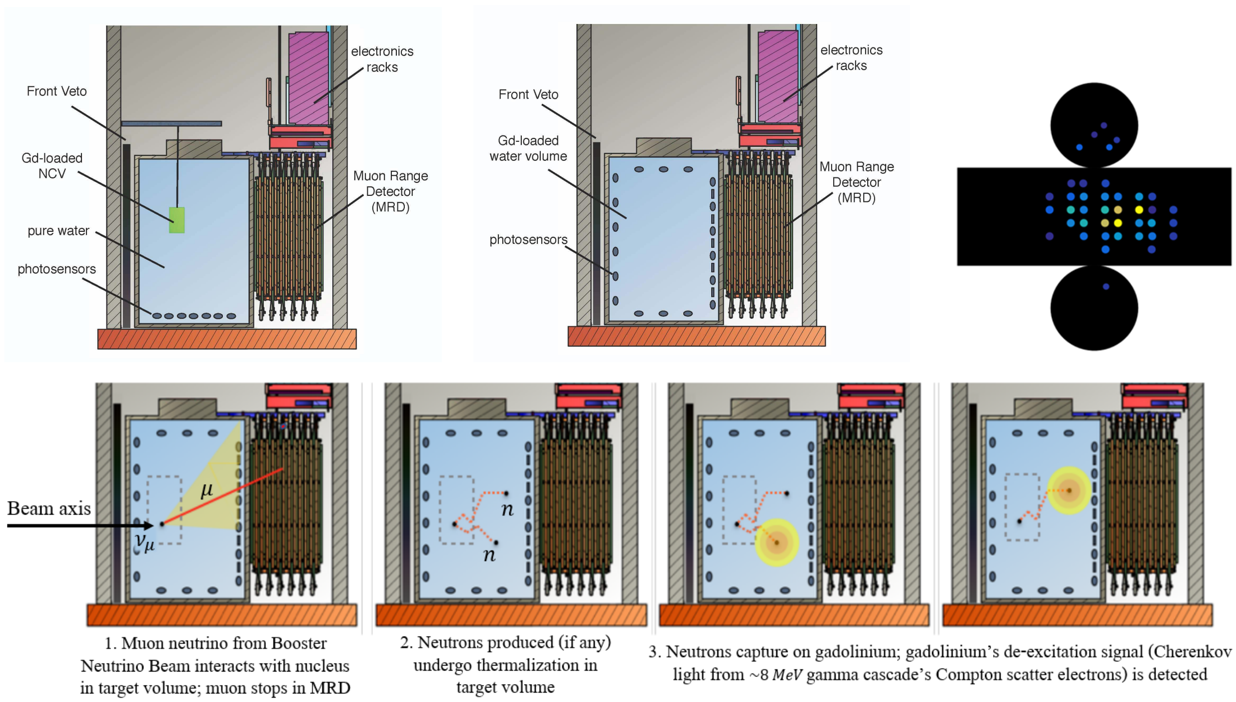

Figure 2: TOP LEFT: Phase I configuration. TOP Middle: Phase II configuration. TOP Right: Event display of a muon neutrino candidate (2020 data, with only PMTs). BOTTOM: A description of each component's role in the reconstruction

Phase-II detector. The goal of the FMV is to veto the muons not originating from the ANNIE tank. A muon produced by a neutrino interaction in the fiducial volume is reconstructed using the tank photodetectors and the muon detection system MRD. Neutrons produced by the neutrino interaction scatter and lose energy through thermalization, allowing them to capture on either H or Gd in the active volume. The capture on Gd produces a delayed signal in the form of an $\sim$8 MeV de-excitation γ-ray cascade that will be detected by the photodetectors.

The baseline goal for the ANNIE Phase-II physics analysis is to provide a measurement of neutron yields from neutrino interactions as a function of muon kinematics. To get the promised physics result, neutrino interaction vertices must be restricted within a 2 ton central fiducial volume. To achieve this goal, ANNIE will deploy 5 LAPPDs with much better timing resolution than previously possible to improve the kinematic reconstruction. Being the first physics experiment using LAPPDs, ANNIE faces a challenge in that no existing algorithms are ready to use for LAPPD-specific reconstruction. The main goal in this proposal is to develop sophisticated algorithms to push LAPPDs to their full potential demonstrating their promise for future experiments.

D.3 Proposed Research

The PI' group at SD Mines plans to visit Fermilab to perform the proposed research. The unique opportunities provided by the fellowship would allow the PI' group to work closely with the ANNIE collaborators who are onsite at Fermilab. A combination of hardware infrastructure and technical expertise at Fermilab is essential to carry out the proposed activities.

While each subsection describes the proposed research in detail, it is useful to list a summary of objectives here in order to put it all into a general context:

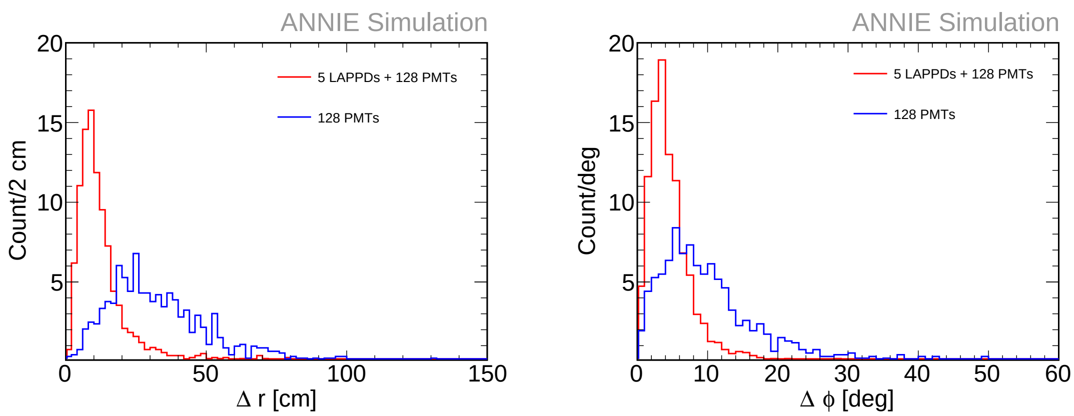

Figure 3: Raw Δr distributions (LEFT) and $\Delta\phi$ distributions (RIGHT), normalized to a percentage of successfully reconstructed events. The panels compare configurations using 5 LAPPDs + 128 PMTs (red), and 20% tank coverage using 128 PMTs only (blue). Taken from [5].

- Develop and optimize the LAPPD-based event reconstruction algorithms. Build a full event reconstruction chain in ANNIE's data analysis software ToolAnalysis to support ANNIE physics.
- Test a new neutrino detection technology by deploying a WbLS target into the ANNIE tank. Develop reconstruction and analysis algorithms to separate the prompt Cherenkov light from the slow scintillation light.
- Perform GENIE and RAT-PAC simulations to investigate the feasibility of measuring the neutron yield from neutrino-argon interaction using the ANNIE infrastructure. The PI plans to develop an Experimental Design course at SD Mines based on this new study.

D.3.1 LAPPD-Based Event Reconstruction And Data Analysis

For ANNIE Phase-II measurement, 5 LAPPDs have already been tested using a laser system at Fermilab, and are ready to be deployed to the ANNIE water tank. To reconstruct a beam neutrino interaction vertex, the technique used in previous Water Cherenkov detectors, such as Super-Kamiokande [15], was further improved by taking into account the LAPPD response. A track of a charged particle produced from a neutrino interaction can be characterized by six parameters: three spatial parameters specifying the vertex position, one time parameter reflecting when the interaction took place and two angular parameters specifying the direction of the primary lepton track. A relativistic particle traveling in water will emit Cherenkov light, which is collected by the photodetectors mounted on the inner surface of the tank. The photon hit timing and the Cherenkov cone pattern are used to reconstruct the six parameters that are determined from a maximum-likelihood fit. These six parameters are varied in the fit to maximize the overall Figure-of-Merit (FOM), which is used to estimate the goodness of the fit.

The PI was one of the key developers of ANNIE's official reconstruction and analysis software, and has been playing a leading role in the Phase-II vertex and track reconstruction utilizing the fast-timing property of the LAPPDs. His work has shown that adding only 5 LAPPDs to the PMT-based photodetector system can significantly improve the vertex and track resolution, which meets the requirements of ANNIE Phase-II physics.

Figure. 3 (left panel) compares the vertex reconstruction performance achieved in two photodetector configurations. It shows the raw distributions of the vertex radial displacement Δr (defined

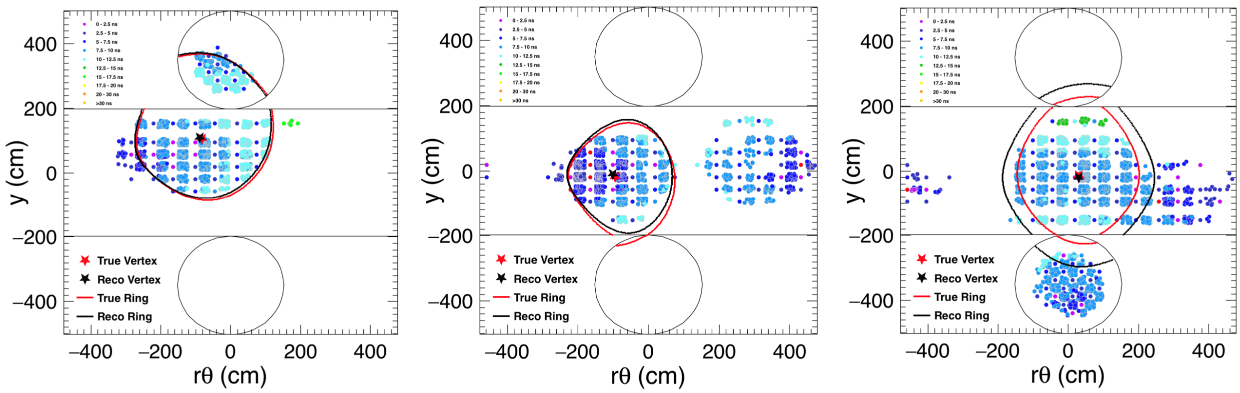

Figure 4: Vertex and ring reconstruction results for different interaction types. LEFT: CCQE event with single ring. MIDDLE: DIS event with double rings. RIGHT: Deep Inelastic Scattering (DIS) event with overlapped rings.The simulation assumes having all 128 LAPPDs and 128 PMTs that cover the inner surface of the ANNIE tank.

as the distance between the reconstructed and the true vertex positions). The vertex resolution is then defined as the value of Δr at the 68th percentile of all successfully reconstructed events from the sample, and use a similar definition for the track angular resolution. With the addition of 5 LAPPDs, the vertex resolution improves from 38 cm to 12 cm. The PI performed a similar analysis to the muon track direction and found that the angular resolution could be improved by a factor of two (from 10° to 5°) with additional 5 LAPPDs (see the ANNIE Phase-II Physics proposal [5] for details). These studies confirm that instrumenting the ANNIE detector with at least 5 LAPPDs will meet the baseline physics needs of the experiment. This work demonstrated the physics capability of ANNIE and was critical in getting the previous funding for the Phase-II run.

The results shown in Figure 3 were obtained within the old data analysis framework called ANNIEReco that was used to do the first studies on reconstruction capabilities. Along with the additional information from MRD, the muon and neutrino energies were determined using machine-learning algorithms [16]. This reconstruction study was described in detail in the ANNIE Phase-II proposal. It could be further improved, as listed below.

- Implement realistic LAPPD detector response. Now the collaboration is developing a sophisticated LAPPD detector response simulation package that can mimic the real data. The PI and the graduate student will develop the reconstruction algorithms using a more realistic LAPPD response modeling. This fellowship would provide the opportunity for the PI's group to participate in the LAPPD modeling, testing and analysis activities at Fermilab.

- Improve the vertex and track reconstruction algorithms using new simulation input. Previously, the muon tracks were reconstructed separately in the water tank and in the MRD. The vertex and track reconstruction was merely based on the tank photodetectors, while the MRD information was not used. This proposal will combine the MRD and the tank photodetector reconstructions into a single algorithm, which will enhance the computing speed and the reconstruction performance significantly. It is expected that the muon energy can be obtained from the combined fitter, complementary to the Machine-learning-based method being presently used .

- Extend the algorithms to reconstruct multi-track events. The vertex and track reconstruction was done with events that have at least one muon produced, regardless of the interaction type.

That's to say, in Figure 4, all these events contribute to the overall vertex resolution reported in the physics proposal. The vertex reconstruction could only reconstruct the most energetic muon if multiple tracks are present (see Figure 4). In this proposal, the PI plans to extend the fitter to reconstruct multi-tracks. The reconstruction will have the capability to run specific fitters for different interaction hypothesizes. The PI will learn to perform GENIE neutrino interaction to aid the development of multi-track identification algorithms, preparing for future detector configuration with more LAPPD coverage. If additional funding (beyond this proposal) is identified, running with more LAPPDs for significantly improved reconstruction would enable the study of neutron yields in resonant pion events, which is beyond the primary physics goals.

- Develop a full reconstruction chain in ANNIE's official software ToolAnalysis. During Phase-II, a lot of progress has been made on reconstruction and the collaboration is currently developing a new simulation and analysis software to combine previously separate efforts into a single framework. If this proposal is funded, The PI's immediate plan is to complete the reconstruction tools and build a full reconstruction and data analysis flow in ToolAnalysis.

To achieve the proposed goals, The PI's group will be in close cooperation with the ANNIE analysis coordinator Dr. Vincent Fischer and simulation expert Dr. Steven Gardiner. Both are located onsite at Fermilab. Dr. Gardiner is an expert in GENIE simulation, working in the Scientific Computing Division. The PI and the trainee will consult Dr. Gardiner about issues in running the GENIE software to perform a neutrino interaction simulation with the ANNIE detector configuration Dr. Gardiner was also the key analyzer of the ANNIE Phase-I background data, and was an expert on neutrino-nucleus interaction. He will pass the knowledge of the ANNIE Phase-I reconstruction and analysis to the PI's group and provide support for Phase-II data analysis. Dr. Vincent Fischer is from Iowa State University but has been physically working at Fermilab to complete the physics phase of ANNIE. Dr. Fischer will train the PI's graduate student on using ANNIE's data analysis software ToolAnalysis, and provide expertise on the simulation and data analysis. During the summer months, the student will visit Fermilab working with the PI's collaborators on a day-to-day basis to complete the proposed research.

D.3.2 WbLS Deployment And Data Analysis

Following the neutron multiplicity analysis using gadolinium-doped water, the ANNIE detector stands to continue operating as a testbed for more upcoming detector technologies. A particularly interesting potential upgrade for ANNIE is the addition of Water-based Liquid Scintillator (WbLS). The utility of WbLS lies in the production of both scintillation and Cherenkov light following a neutrino interaction. Cherenkov light from charged particles provides directionality for particles with energies above Cherenkov threshold, while the scintillation light provides more photons than the Cherenkov signal alone, improving energy resolution.

The particle physics community has expressed considerable interest in constructing the Theia detector that is an advanced optical detector utilizing the WbLS technology for detecting neutrinos. Recently, there has been an increasing discussion about deploying the Theia detector to the fourth (or fifth) cavern at the far site of the Deep Underground Neutrino Experiment (DUNE), for the "module of opportunity". Different scenarios are discussed in the Theia white paper [17]. ANNIE would be a perfect testbed for demonstrating the Theia technology. The time scale of ANNIE would perfectly fit the DUNE schedule to make a decision for the fourth far detector module.

One way suggested by the simulation to improve the vertex resolution is to have a small amount of isotropic light from the vertex that can be separated from Cherenknov light by timing and topology. Thus, ANNIE plans to insert a small 400-liter vessel called SANDI (Scintillator for

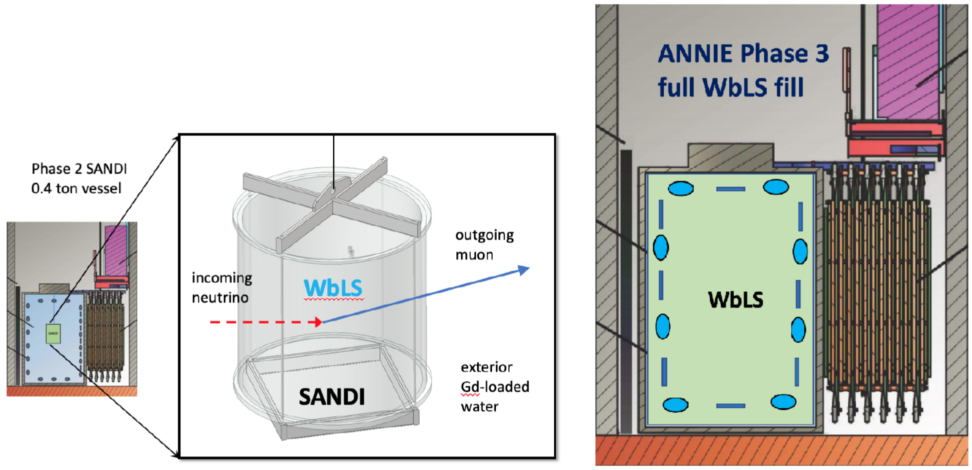

Figure 5: (left) The SANDI 0.4 ton WbLS-filled vessel for testing vertex reconstruction using LAPPDs and combined Cherenkov and Scintillation light. (right) The proposed ANNIE Phase-III detector completely filled with WbLS. Taken from [18].

ANNIE Neutron Detection Improvement) containing 1%-3% WbLS into the central volume. This test will confirm models of event reconstruction and may also allow us to reconstruct hadron energy at the vertex. The proposed research on LAPPD-based reconstruction algorithm would be beneficial to the WbLS data analysis. It is expected that the vertex resolution will be significantly improved with the additional timing information from isotropic scintillation light. In addition, one or more of the 5 LAPPDs would be moved to the backward hemisphere to enhance the reconstruction capability. The PI's group will run simulations and reconstructions to evaluate the performance, leading to an optimized strategy for LAPPD deployment locations.

If this proposal is funded, the PI will immediately relocate to Fermilab to lead the WbLS deployment in ANNIE. The PI's department has agreed that the PI can be take off from teaching and service at SD Mines for 4 academic months to carry out the proposed research at Fermilab. The main task will be leading the WbLS deployment at the ANNIE detector. The timeline of this fellowship is well aligned with ANNIE's plan for WbLS deployment. The deployment procedure would be similar to the NCV deployment during ANNIE Phase-I background measurement. The PI will be supported by Fermilab and the ANNIE collaboration to access the experimental hall, use the ANNIE facilities and perform simulation and analysis on the ANNIE computing clusters. The Fermilab Application Physicist Dr. Carrie Mcgiven, who is an ANNIE collaborator, will provide necessary technical support to complete the proposed activities. If the SANDI test is successful, ANNIE will plan to propose a full WbLS fill in a future Phase-III program. It is a unique opportunity for the PI's group to develop expertise on this new technology, leading to possibilities for developing a future career path on building next-generation neutrino detectors.

D.3.3 Feasibility Study For Neutrino-Argon Interaction Measurement In ANNIE

Besides the currently existing or proposed physics programs, the PI plans to explore synergies between ANNIE and DUNE. It is possible to measure the neutron multiplicity from neutrino interaction on argon by deploying a liquid argon target into the ANNIE detector. If feasible, this measurement would help improve our current understanding of the nuclear effect on neutrino-argon interaction. Measurement of the final state neutrons could help better model the neutrino interaction and improve the accuracy of neutrino energy reconstruction in liquid argon detectors, such as the far detector of the Deep Underground Neutrino Experiment (DUNE).

The DUNE experiment aims at the measurement of the neutrino CP-violating phase and the determination of the neutrino mass ordering. These measurements rely on the precise reconstruction of the incoming neutrino energy. In DUNE's energy regime, a lot of neutrino-argon interactions go through Resonance Elastic Scattering (RES) and Deep Inelastic Scattering (DIS) where hadrons are produced. However, neutrons are difficult to detect in Liquid Argon Time Projection Chamber (LArTPC). The final state neutrons from the neutrino-nucleus interaction could carry up to 20% of the incoming neutrino energy [19], which leads to large uncertainties in energy reconstruction. The measurement of the number of final state neutrons will help constrain the theoretical neutrino-nucleus interaction models.

A possible measurement to get some experimental data is to deploy a liquid argon dewar at the central fiducial volume of the ANNIE tank, which was never investigated before. The outgoing muon and the final state neutrons can be detected by the ANNIE detector, similar to that is planned for the WbLS deployment. As the liquid argon dewar is opaque, additional photodetectors on the outer surface of the dewar for light collection. The whole system will be simulated using GENIE and RAT-PAC.

The graduate student will travel to Fermilab to complete the fesibility study of this new idea. The interaction with experts at Fermilab would greatly facilitate the proposed effort. During the stay at Fermilab, the graduate student will learn GENIE simulation from the Fermilab collaborators, Dr. Hatcher and Dr. Gardiner. The PI's group will also get support from the ANNIE collaboration to integrate ANNIE detector geometry into the GENIE simulation program. Once the outgoing particles are obtained from GENIE simulation, they will be transported using RAT-PAC simulation package. Dr. Fischer will train the PI's graduate student about using the ANNIE RAT-PAC simulation package. The proposed work will bring expertise in neutrino simulation and neutrino detector design to the PI's group at SD Mines. If the idea is feasible, the PI will seek future funding beyond this program to support the experimental activities.

At SD Mines, the PI is currently mentoring an undergraduate student on GENIE simulation through the Experimental Design course. If this proposal is funded, the PI will develop a new Experimental Design course for undergraduates, base on the proposed feasibility study for neutrino-argon interaction measurement in ANNIE. Through this course, the PI will train undergraduates on Monte Carlo simulations for physics experiments. If the feasibility study is successful, the PI will further develop this new research direction as a potential thesis topic for graduate students.

D.4 Timeline Of Proposed Research

In this proposal, the request for supporting the PI is 4 academic months at 50% effort and 2 summer months at 100% effort. The request for the graduate student is 6 summer months at 50% effort.

In the first year, the PI will relocate Fermilab for 4 academic months and 1 summer month to lead the WbLS deployment and its data analysis in ANNIE. The graduate student will visit Fermilab for 3 summer months to help the PI perform WbLS testing and data analysis. Meanwhile, the student will be trained by their Fermilab collaborators on simulation software. The PI's group will also complete the development of the event reconstruction chain in ToolAnalysis.

In the second year, the PI will develop an Experiment Design course for undergraduate students to learn GENIE simulations. The graduate student will help design specific simulation problems for the course. During the summer, the graduate student will visit Fermilab for 3 months focusing on the feasibility study of the liquid argon target deployment in ANNIE. The PI will visit Fermilab for 1 summer month to close the proposed study and write summary reports to the ANNIE collaboration.

The detailed timeline is summarized below.

Time	Activities
• 02/2022 - 05/2022 (at Fermilab)	• Implement realistic LAPPD detector response • Improve and optimize vertex and track reconstruction algorithms • Lead the WbLS deployment and develop data analysis algorithms
• 06/2022 - 07/2022 (at Fermilab)	• Train graduate student to use GENIE and RAT-PAC • Develop multi-track fitter, PID and ring counting algorithms in Tool-Analysis
• 08/2022 - 04/2023 (at SD Mines)	• Complete the full reconstruction chain in ToolAnalysis • Perform a a simplified GENIE simulation of neutrino-argon interaction • The PI will develop an Experimental Design course using the ANNIE simulation tools and mentor undergraduates through the course
• 05/2023 - 07/2023 (at Fermilab)	• Perform detailed GENIE simulation to study the feasibility of liquid argon dewar deployment in ANNIE • Summarize preliminary results and write technical notes to ANNIE
• 08/2023 - 02/2024 (at SD Mines)	• Finalize the proposed work write papers for publication

Table 1: Timetable of project activities.

D.5 Benefits To The PI

This research fellowship would provide the PI with expertise on new neutrino detection technologies and enable the PI to sustain his career in experimental neutrino physics in the long-term. The PI used to work on the LAPPD detector R&D as a postdoctoral researcher at Argonne National Laboratory for more than two years. This proposal would extend the PI's expertise from understanding the LAPPD detectors to applying LAPPDs in an actual physics experiment, which will be important for the PI to sustain his contribution to the current and future experiments based on LAPPDs. The proposed research will allow the PI to become a leader in ANNIE Physics reconstruction and analysis, positioning the PI well for future funding proposals to explore the physics potential in the next phases. In addition, the proposal would provide the PI with new necessary expertise in WbLS-based neutrino detectors, putting him in a leadership position in the field.

D.6 Intellectual Merit

ANNIE aims at measuring the neutron abundance in the final state of neutrino-nucleus interactions. This 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. 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 LAPPD 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.

The proposed research will deliver an optimized LAPPD-based reconstruction package for the first time, which is essential for facilitating the current physics analysis in ANNIE, and exploring the physics potential beyond the current phase. The success of the WbLS deployment and analysis will connect ANNIE with the future neutrino detector Theia planning to use the same detection technique that can be demonstrated through this proposal. The proposed feasibility study of neutrino-argon interaction measurement would connect ANNIE with the DUNE experiment using liquid argon medium for neutrino detection. If feasible, ANNIE could measure the neutron yield using a liquid argon target in the next phase, which would help improve our current understanding of the nuclear effect on neutrino-argon interaction that is one of the main source of uncertainty for energy reconstruction.

D.7 Broader Impacts

The success of the project will strengthen the school's physical presence and visibility in the field and increase our reputation as a research institution, helping attract better doctoral students and the funding to support them. It is very important for the school to provide the students with a chance to participate in a collaborative physics experiment and meet with practicing scientists. This will expose the students to the possibility of pursing a STEM-related career at a critical age during which they will decide whether they possess the enthusiasm and aptitude for scientific research. The primary utilization of this funding will be to support a graduate student to develop new simulation and reconstruction tools and present the results to a broader community. The student will participate in physics conferences, publish in peer-reviewed journals, and develop a thesis based on the proposed research.

The development and optimization of the ANNIE reconstruction will form a signature experience of education for undergraduate students and provide excellent training for graduate students. Through this proposal, students will learn data-analysis techniques by analyzing ANNIE Phase-II data, and will gain experience of experimental design by performing simulation for physics beyond Phase-II. The PI will take advantage of ANNIE's future physics potential to develop an Experimental Design course for undergraduates. This course will use well-defined tasks to equip students with the simulation and programming skills necessary for success in physics.

If successful, the results of this research will significantly advance knowledge and understanding in the new technologies for neutrino detection. The results will be important for the development of next-generation neutrino detectors, such as Theia. Advances from the research topics will be disseminated widely through collaborations with other Projects. The results could also be of great importance to the nonproliferation monitor called WATCHMAN (WATer CHerenkov Monitor of AntiNeutrinos). It is expected that WATCHMAN could be upgraded to include WbLS and LAPPDs, which is directly relevant to the proposed research for this program.

Results From Prior NSF Support

The PI does not have prior NSF support.