COHERENT Plans for D$_2$O at the Spallation Neutron Source

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Abstract: The Spallation Neutron Source (SNS) is a pulsed source of neutrons and, as a byproduct of this operation, an intense source of neutrinos via stopped-pion decay. The COHERENT collaboration uses this source to investigate coherent elastic neutrino-nucleus scattering (CEvNS) with a suite of detectors. To enable precise cross-section measurements, we must address an estimated 10% uncertainty in our flux calculation associated with the lack of data for $\pi^{\pm}$ production from 1 GeV protons on an Hg target. We present here our Geant4 simulation of neutrino production at the SNS and our plans to experimentally normalize this flux with the development of a 670 kg D$_2$O detector. Using the precise cross section calculations for neutrino interactions on deuterium, we will dramatically reduce our flux uncertainty.

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1 Introduction

Cleanly predicted within the Standard Model (SM) in 1974 [1], coherent elastic neutrino-nucleus scattering (CEvNS) was first observed in 2017 by the COHERENT collaboration [2]. With the goal of precision CEvNS observations on multiple targets (CsI, NaI, LAr, Ge), we note that a global and nearly dominant systematic uncertainty is our understanding of the neutrino flux from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [3].

We use the Geant4 Monte-Carlo framework [4] to calculate the flux of neutrinos in “Neutrino Alley”, a basement hallway (8 m.w.e.) where COHERENT deploys our detectors to take advantage of lower beam-related neutron backgrounds [3]. Section 2 describes the simulation, the results we obtain, and the 10% uncertainty we place on these results. Section 3 discusses the proposed development of a D$_2$O detector that will meet the size constraints of Neutrino Alley, reduce the flux systematic, and improve COHERENT’s physics sensitivity.

2 Geant4 Simulation of SNS Neutrino Production

The SNS accelerates protons to 1 GeV in pulses approximately 700 ns wide, typically 350 ns FWHM. These pulses strike a liquid mercury target at a frequency of 60 Hz to create spallation neutrons, but this process also produces pions which stop in the target and produce neutrinos from $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu$ and $\mu^{+} \rightarrow e^{+} + \bar{\nu}_\mu + \nu_e$. Our simulator generates individual, monoenergetic protons at the edge of the target and tracks the resulting products as they pass through a simplified Geant4 mockup of the SNS geometry. This model was developed in 2015 by the COHERENT collaboration using technical drawings from ORNL, and Figure 2.1a illustrates the simplifications. An example $\nu$ production event is shown in Figure 2.1b.

Simulation results for energy and timing information for the three expected flavors of neutrino are shown in Figure 2.2. In the left hand plot, note the main contributions come from decay-at-rest processes,
resulting in monoenergetic $\nu_\mu$ from the $\pi^+$ decay and $\nu_e$ and $\bar{\nu}_\mu$ between 0 and 50 MeV from the $\mu^+$ decay. We do observe contributions from decay-in-flight $\pi^+$ and $\mu^+$ (the long tails), the decay of $\pi^-$ leading to $\mu^-$ capture (the peak near 100 MeV), and even some kaon production (monoenergetic peak near 235 MeV), but these contributions are $\sim$1% or less. In the right hand plot, we have convolved the simulation neutrino timing results (for single protons) with the $\sim$700 ns proton pulse. We distinguish between two time regions due to the muon lifetime: the prompt $\nu_\mu$, and the delayed $\bar{\nu}_\mu$ and $\nu_e$. Since the neutrinos are well-timed with respect to the beam, the SNS offers substantial reduction of steady-state backgrounds.

Efforts to validate the simulation indicated that we should use the QGSP_BERT physics list, which implements the Bertini intra-nuclear cascade model [5]. Calculations from LAHET [6], a particle transport code that also implements the Bertini model, are noted to have discrepancies with available world data, and COHERENT assigns a conservative 10% uncertainty to our Geant4 calculations [7]. With no pion production data from protons at this energy incident on a mercury target, the best approach for further validation efforts is to improve the available world data. We propose to improve the flux uncertainty using a heavy water detector to normalize the SNS neutrino flux, as is described in Section 3.

For the best comparisons to the future results from a D$_2$O detector, we are also modifying the existing simulation to further our understanding of the SNS neutrino flux. We now include information about a particle’s lineage, its production angle, and its creation position. These updates inform our efforts as we add features of the SNS, like the proton beam window, and investigate how decay-in-flight neutrino
production could change the flux at different positions in Neutrino Alley.

Moreover, these simulation updates help to inform the next generation of experiments as strategies for neutrino physics at the Second Target Station (STS) start to take shape [8]. The only modification to our simulation involves altering the geometry to the planned STS target monolith. The construction of an STS Geant4 model has begun, and additional features will be added as more details become available.

These updates alone will not drastically reduce our flux uncertainty. We do have avenues to compare our simulation results to existing world data on different targets and proton energies, such as from HARP [9], that could help slightly reduce our uncertainty, but an experimental normalization of our neutrino flux is planned to significantly reduce the current 10% uncertainty (goal of 3%).

Figure 2.3: Simulated neutrinos produced per proton on target (POT) as a function of proton energy.
3 Planned experiment – D$_2$O detector

The SNS produces most of its $\nu_e$ from decay-at-rest $\mu^+$, meaning that every $\nu_e$ will be accompanied by a $\nu_\mu$ and a $\bar{\nu}_\mu$. By measuring the number of $\nu_e$, we can multiply by a factor of 3 to obtain the total neutrino flux produced by the SNS. The deuteron is one of the few nuclei with reasonably calculable neutrino interactions, and the cross section for $\nu_e + d \rightarrow p + p + e^-$ has been calculated to 2-3% uncertainty [10–13]. Thus, the construction of a heavy water detector will allow us to take advantage of this well-known cross section and reduce the 10% systematic on our neutrino flux.

As we plan out a design for our D$_2$O detector, we are spatially constrained by our experimental hall, Neutrino Alley (depicted in Figure 3.1a). Since we occupy an access hallway, we must always keep 3 ft clear of all instrumentation, meaning any detector must be smaller than 1 m depth × 3 m height × 3 m width. The largest possible detector to fit within those space constraints could contain up to 1300 kg of D$_2$O within an inner acrylic vessel with dimensions 120 cm × 120 cm × 60 cm. We propose a slightly smaller detector, with an inner volume 100 cm × 100 cm × 60 cm, to contain 670 kg of heavy water that COHERENT has been promised on loan. Our initial design chooses a box-like detector for more straightforward construction, and we use Geant4 to simulate the detector geometry and response.

Spatial constraints will prevent photomultiplier tubes (PMTs) from being placed around the entire detector. For maximal coverage on four sides, we would implement 80, 8” biakali PMTs in staggered rows around an inner acrylic vessel containing the D$_2$O. The PMTs are planned to be submerged in a 10 cm H$_2$O tail-catcher region to aid in energy reconstruction. The two non-PMT sides will be fitted with a Teflon reflector to increase light collection.

We expect to have backgrounds from beam-related neutrons, and we will have shielding around the

![Figure 3.1](image-url)
detector to reduce this. Cosmic backgrounds will be monitored with two layers of muon vetos on all detector sides. Any signals of neutrino interactions on oxygen are also background for the $\nu_e + d$ experiment, as the cross-sections for neutrino interactions on oxygen are not as well known, but we plan a measurement of the $\nu_e + ^{16}\text{O}$ cross-section as a secondary goal of this detector.

For the design presented here, we find that four years of run-time will get us to the percent-level statistical precision to significantly improve our physics goals. Our energy reconstruction comes from the total light collection of the electron created in the neutrino interaction. Figure 3.2 illustrates the separation of the deuteron and oxygen components in our predicted signal after four years of run-time.

As soon as D$_2$O starts taking data, we will begin to reduce our flux uncertainty and can adjust the Geant4 models. We aim to reduce our flux systematic to 3% uncertainty with this experimental normalization, and Figure 3.3 is an example of how this will affect COHERENT’s physics sensitivity. Figure 3.3a plots our predicted constraints on neutrino-quark interactions beyond the Standard Model (BSM) with our current flux systematic of 10%. Using the goal of a 3% flux systematic, Figure 3.3b shows the improved constraints on this parameter space.

As we explore funding avenues for the development of this detector, we are working to optimize the detector design through simulation. Design decisions under investigation include the overall geometry (box-like vs. cylindrical), PMT placement (what is the fewest number of PMTs needed for total light coverage), the use of Teflon reflectors (can we reconstruct Cherenkov rings), and the material in our tail-catcher region (H$_2$O or mineral oil). In order to validate these simulations, a small prototype is under development and will use up to four PMTs. This prototype will also be used to study backgrounds in potential locations for the full-scale detector.

Figure 3.2: Simulated energy reconstruction with 10 cm H$_2$O after 4 years collecting data.
Figure 3.3: Predicted constraints on neutrino-quark interactions beyond the Standard Model with planned COHERENT detectors.

4 Summary

The COHERENT collaboration is moving towards precision measurements of CEvNS, and must reduce a global systematic on our understanding of the neutrino flux. Due to the lack of pion production data for 1 GeV protons on a liquid mercury target, we propose the development of a dedicated detector to reduce our uncertainty to the percent level. Using a loan of 670 kg of D$_2$O, we would reduce our current 10% global flux systematic to the percent level after four years of run time. With funding for the largest possible detector, we would use 1300 kg of D$_2$O and be able to reduce our flux uncertainty with only two years of run time. This detector could then also be used to normalize the neutrino flux from pion production on a tungsten target at the Second Target Station.

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