Background studies for the COHERENT experiment at the Spallation Neutron Source

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Abstract. The COHERENT experiment is designed for a first measurement and N² dependence study of coherent elastic neutrino-nucleus scattering (CEvNS) at the Oak Ridge Spallation Neutron Source (SNS). CEvNS is a standard model process that is important in understanding supernova neutrinos, the structure of the weak interaction and backgrounds for dark matter searches. The COHERENT collaboration is placing a suite of detector technologies in a basement location at the SNS: 14 kg CsI[Na] crystals; 185 kg NaI crystals; 35 kg single-phase LAr; 10 kg high-purity, point contact Ge. Previous attempts to measure the CEvNS process have grappled with very high background rates. One class of troublesome backgrounds is accelerator-correlated neutrons because a simple accelerator on/off background subtraction procedure fails to remove these events. The collaboration has completed a comprehensive background study in the basement region where the experiments are located. We conclude from these studies that the neutron background is sufficiently low for successful CEvNS measurement in the SNS basement region. Neutron measurements from the Indiana University SciBath detector and the Sandia Neutron Scatter Camera are presented here.

1. Introduction
Coherent elastic neutrino-nucleus scattering (CEvNS) occurs when a neutrino interacts with the nucleus by the exchange of a Z-boson, and the nucleus recoils as a whole. Although predicted over 40 years ago [1], this interaction has not yet been observed as a result of difficult technical requirements for a successful measurement. The nuclear recoil energy is the only accessible observable for this process. The coherent scattering condition exists for neutrino energies up to about 50 MeV in which the maximum nucleus recoil energy is on the order of 30 keV, depending on the target nucleus. These very low recoil energies prevented detection until recent technological advances in dark-matter experimentation and the development of detectors sensitive to 1 keV to 10's of keV recoil energies.

To enable a successful measurement, a strong source of relatively energetic neutrinos below the coherent limit is desired as the cross section and nuclear recoil energy increase with increasing neutrino energy. At the Spallation Neutron Source (SNS) located at the Oak Ridge National Laboratory (ORNL), a pulsed (60 Hz, ~400 ns FWHM) proton beam of ~ 1 GeV impinges a liquid mercury target producing an abundance of neutrons through the spallation process. In addition, charged pions are produced that slow down and decay at rest on the order of 26 nsec (\( \pi^- \rightarrow \mu^- + \nu_\mu \)) producing a prompt, nearly monochromatic muon neutrino with energy 30 MeV. The subsequent decay of the muon \( \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu \) with characteristic lifetime 2.2 \( \mu s \) produces an electron neutrino and muon anti-neutrino with a range of energies between 0 and \( \frac{1}{2} m_\mu \sim 53 \) MeV.
The goal of the COHERENT collaboration is to unambiguously measure the CEvNS cross section in several nuclear targets (reaching a 5σ result for each target mass) to study the dependence of the elastic cross section on target neutron number. The targets currently deployed are a 14 kg CsI[Na] crystal detector, and a 185 kg NaI crystal detector array. A 35 kg single phase liquid argon (LAr) detector is in preparation for deployment and a 10 kg point-contact, high-purity germanium detector is under development for deployment. Future plans include larger CsI and NaI arrays. The elastic scattering rates are of interest for supernova models and for characterizing the low-energy background in dark-matter experiments. The process can then be used as a tool to search for new physics beyond the standard model. For a detailed discussion of the COHERENT experiment, the motivation and the plan, please see the white paper posted on the arXiv website [2].

2. Background Studies

Understanding and reducing sources of background are critical goals of the COHERENT experimental program and are necessary for a successful CEvNS measurement. The basement location is shielded by an 8 meters-water-equivalent overburden and the surviving steady-state backgrounds including from cosmogenic sources can be greatly reduced, by a factor of ~10^3, by taking data within the delayed timing window and characterized by taking data in the time window before the protons on target for a given beam pulse. In the absence of beam-related backgrounds, subtraction of pre-pulse from post-pulse data would in principle provide a clear CEvNS signal. However, beam-correlated fast neutrons require additional measurements and modelling for characterization.

The CEvNS signal is based on the detection of recoil nuclei with no visible incoming or outgoing particle, the neutrino. Timing cuts and pulse shape can be used to eliminate other interactions based on the energy deposition characteristics of nuclear recoil events. However, fast neutrons (.1 to 1 MeV) can produce nuclear recoil events that mimic the neutrino signal. Passive high-Z material shielding can remove low-energy neutrons, and convert high-energy incident neutrons into showers of lower energy neutrons. Simulations have shown that fast neutrons in the 10 to 100 MeV range pose the most dangerous threat to background signals that mimic the neutrino signal of interest.

Gamma-ray backgrounds are easily shielded and do not pose a problem for the detectors. Measurements of the gamma-ray flux from a nearby pipe indicate a source of 511 keV gammas with a flux of about 25 γ/s/cm²/s. Measurements and simulations indicate a gamma flux from the wall and floor of about 1 γ/s/cm²/s.

3. Neutron Background Measurements

A combination of multiple detector technologies and complementary analysis by multiple groups provides confidence in the background results. Initial studies were carried out using portable liquid scintillator cells, and a coded aperture imager by ORNL and University of Tennessee personnel. Systematic studies were performed with the Sandia National Laboratory Neutron Scatter Camera detector [3] in various locations at the SNS including at a possible beam line location and in the basement. In addition, background studies were carried out using the Indiana University single-plane, single-scatter (SciBath) detector [4] in the basement at the designated LAr detector position.

3.1. Scatter Camera Measurements

Neutron Scatter camera measurements show that backgrounds in the basement area are orders of magnitude less than near the beam lines. The data indicate that fast neutron backgrounds in the basement are clearly associated with the protons on target and arrive within 1.3 μs of the pulse. In the 2.2 μs window after the beam the muon decay neutrinos (anti-νμ, νe) dominate. The neutron backgrounds are reduced by at least an order of magnitude and are lower in energy in the delayed window compared to the prompt timing region. (Refer to figure 1.)
3.2. SciBath Measurements

Measurements using the SciBath detector were taken in the LAr detector position in the basement of the SNS. (See figure 2.) The prompt neutron flux was measured as \((2.1 \pm 0.4) \times 10^{-5} \text{ n/m}^2/\text{spill}\) and the muon flux was measured as \((60 \pm 3) \mu \text{s/m}^2/\text{s}\). The delayed neutron flux is expected to be low with the fast neutron flux consistent with zero. Simulations that propagate the prompt neutron flux through the LAr detector with shielding indicate a background rate of 3.3 events/year. With a greatly reduced delayed neutron flux, the expected event rate will not pose an issue for the LAr detector measurement.

4. Conclusions

Data taken with various neutron detection systems in the basement area of the SNS indicate the neutron backgrounds are sufficiently low to not interfere with CEvNS measurements. The fast neutron backgrounds in the detector locations are associated with the prompt window, within 1.3 \(\mu\text{s}\) of the protons on target. There is an order of magnitude reduction in neutron flux during the 2.2 \(\mu\text{s}\) delayed window and measurements show these neutrons are lower in energy and therefore are easy to shield.

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