Measuring Coherent Elastic Neutrino Nucleus Scattering at an Off-Axis High-Energy Neutrino Beam Target

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(for the CENNS collaboration§)

A measurement of the currently unobserved Coherent Elastic Neutrino Nucleus Scattering (CENNS) process would open a rich program of physics including supernovae, the weak structure of nuclei, and beyond-SM effects. In addition, it presents a fundamental limit for direct dark matter experimental sensitivity. We propose an experiment to measure CENNS using a liquid-argon detector situated transversely to the high-energy neutrino beam production target on the Fermilab Booster Neutrino Beam. The detector would be sensitive to the low-energy neutrinos arising from decay-at-rest pions in the target. Our studies indicate that the existing Fermilab BNB beamline is a prime location for a CENNS experiment.

I. EXCECUTIVE SUMMARY

The Coherent Elastic Neutrino Nucleus Scattering (CENNS) process was first predicted in 1974 [2] yet has never been observed. The CENNS cross section has a precise Standard Model (SM) prediction that is considerably larger than all other neutrino interaction channels below about 50 MeV. The large cross section will enable a next generation CENNS experiment to perform precision electroweak tests of the SM at very low momentum transfers. If CENNS measurements agree with the SM, it will be a very powerful tool in future short-baseline sterile neutrino oscillation searches [3, 4]. Alternatively, any deviation from the very robust SM prediction could be a window to the New Standard Model [5–8]. Designs for first generation experiments are already capable of greatly constraining poor limits on non-standard interactions in the neutrino sector [9]. As CENNS measurements mature, the direct study of supernova-relevant neutrino interactions and direct supernova neutrino detection becomes possible [10]. This could lead to a first measurement of the diffuse supernova background [11]. Detectors and powerful neutrino sources with this capability will also provide complementary probes to the neutron distribution in nuclei [12] and can place limits on the neutrino magnetic moment [8]. To fully explore this rich nuclear and particle physics, a phased approach is necessary. In all cases, low-energy-threshold neutrino detectors, powerful low-energy neutrino sources, and low backgrounds are required.

The Booster Neutrino Beamline (BNB) at Fermilab [13] is a powerful source of pion decay-at-rest (πDAR) neutrinos. The energy spectrum and flux of neutrinos in the backward direction (far-off-axis) of the BNB is excellent for a CENNS discovery measurement. At a conservative position 20 m away from the target, the πDAR neutrino flux would be $5\times10^5\nu/\mathrm{cm}^2/\mathrm{s}$ per flavor at the maximum 32 kW beam power. It is important to realize that CENNS operations require no changes to the existing beamline and do not alter the planned operations for MicroBooNE or other future experiments at the BNB. For this and other reasons, the BNB site is preferable to measure CENNS. First, the beam-uncorrelated backgrounds are suppressed by the BNB beam duty factor which is 2.5×10^{-5}. Second, there are minimal siting issues for future CENNS detectors near the BNB target. Third, as neutrino physics is a high-priority mission of Fermilab, a low-energy neutrino source can become a convenient user facility for studying low-energy neutrino interactions.

The proposed CENNS detector for a first generation measurement at the BNB is a MiniCLEAN-style, single-phase Liquid Argon (LAr) detector [14]. This detector would be placed inside an active cosmic-ray veto water shield that would be placed inside of a concrete neutron shield. The requirements for low energy-threshold and low-background detector technology in LAr are already well developed over the last decade in dark matter searches. To determine the feasibility of this approach, we made neutron background measurements at the Fermilab BNB. Our results indicate that this method can result in a successful experiment with proper neutron shielding. With the BNB neutrino source and its duty factor, beam-uncorrelated backgrounds such as cosmic rays, internal and external radioactivity are substantially suppressed. We expect that a 1000 kg-year exposure a MiniCLEAN-type detector can make a 8 σ discovery of CENNS with a detector energy threshold of 20 keV_{nr}.

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II. COHERENT ELASTIC NEUTRINO NUCLEUS SCATTERING:CENNS

The experimental signature of a CENNS interaction is a recoiling nucleus with 10s-of-keV kinetic energy. Thus historically, the challenge of developing large, low-energy-threshold, low-background detectors have precluded discovery. The coherence condition requires a sufficiently small momentum transfer to an interacting nucleon in a nucleus in order that the nuclear wave function is minimally changed. Therefore, the wavelength of the scattered neutrinos should be much larger than the nuclear diameter, and this leads to a neutrino beam with energy below 50 MeV. Currently, there are two practical sources of low-energy neutrinos: nuclear reactors and accelerators that produce stopped pions (πDAR) and muons. While reactors produce significantly more neutrinos than accelerators, they produce a steady state of few-MeV neutrinos compared to pulses of 10s-of-MeV neutrinos from accelerators. The maximum nuclear recoil energy goes as the square of the incident neutrino energy, and when combined with the background rejection from accelerator duty factor, accelerators are a compelling choice.

The previous Long Range Plan sought answers to the nature of neutrinos, their masses, and how they show the evolution of the cosmos. To these questions, a phased CENNS measurement program offers potentially compelling answers:

- CENNS has a large, well-predicted cross-section in the Standard Model. Therefore, if discovered at its predicted rate, the CENNS process can become a powerful tool for future neutrino oscillation experiments. One can imagine compact, short-baseline oscillation measurements, where the oscillation length is comparable to the size of the detector. In precision searches for active neutrino disappearance, high statistics and very low systematic uncertainties could be attained. Conversely, any measured deviation of the CENNS cross section from the robust SM prediction is a possible contribution to the New Standard Model.
- CENNS and neutrino-driven convection are suggested to be the major mechanism of a core-collapse supernova explosion. Therefore, measuring CENNS in the relevant energy range of supernova processes is an important input to supernova physics. Our understanding of supernova interactions will be enhanced as the target material is changed. Conversely, the CENNS channel is an extremely sensitive way to measure supernova neutrinos that is neutrino flavor independent. Supernova models suggest that the mass hierarchy can be discerned by precision measurement of the supernova neutrino spectrum.
- The CENNS process is sensitive to the neutron distributions in nuclei which is important for a fundamental understanding of the nucleus but also for the physics of neutron stars. In CENNS, at higher momentum transfer, there will be sensitivity to the nuclear form factors which in turn depend on the average neutron radius within the nucleus. This is complementary to using parity violating electron scattering at Jefferson Laboratory PREX experiment [15].
- CENNS interactions by solar and atmospheric neutrinos are irreducible backgrounds of the future dark matter experiments. Additionally, the analogous coherent scattering of WIMPs from the nucleus is the signal used in most direct searches for Dark Matter. Thus, understanding CENNS interactions are an invaluable input to future dark matter search experiments [16].

The measurement of CENNS is extremely beneficial for both particle and astroparticle physics and would open up new experimental programs.

III. OFF AXIS BOOSTER NEUTRINO BEAM

Even though the BNB was designed as a ∼GeV neutrino source for the MiniBooNE experiment [13], low energy neutrinos from stopped pions and muons near the production target are produced as a free by-product. These neutrinos are emitted with a flat angular distribution into 4π. The protons on target from the BNB produce numerous pions, many of which stop in the target area and decay at rest, yielding monochromatic 30 MeV muon-neutrinos followed after a 2.2μs muon decay time by muon-anti-neutrinos and electron-neutrinos with energy distributions having endpoints approximately equal to half the muon mass. According to beam MC studies (see Figure 1), an almost pure πDAR neutrino spectrum can be obtained at far-off-axis angles at the BNB, and only a few percent of neutrinos result from decay-at-rest kaons or muon-captures [1]. Thus, the neutrino spectral uncertainty is very small. The expected neutrino flux is about $5{\times}10^5\text{cm}^{-2}\text{s}^{-1}$ per flavor at 20 m from the target with 32 kW of beam power. The short-pulse time structure (1.6μs, assuming 5μs of detector time window) with maximum 5 Hz pulses provides an order of 2.5×10^5 of ambient background rejection factor.

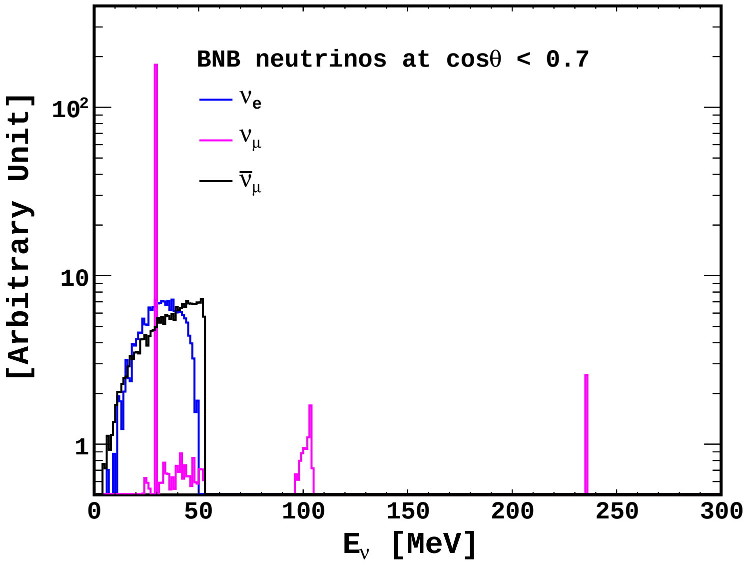

FIG. 1: Estimated neutrino energy spectrum at the angle below $\cos\theta$ <0.7 (far-off-axis) for different flavors.

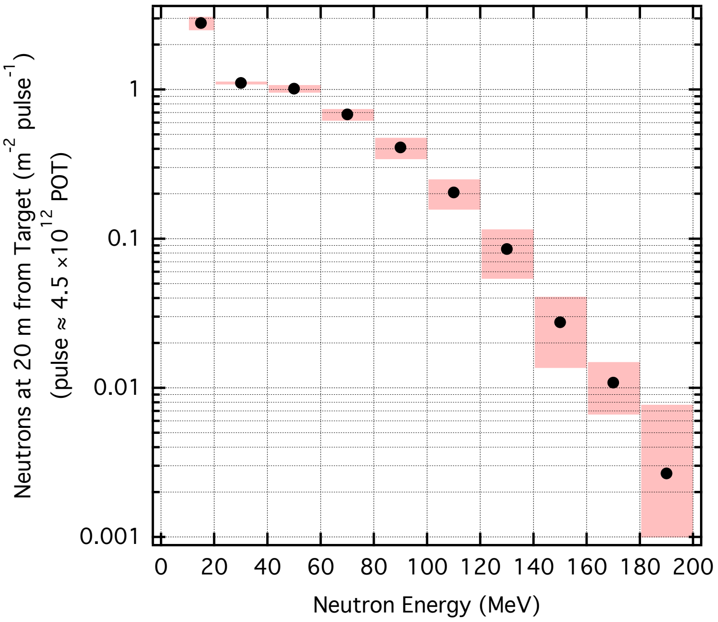

FIG. 2: The measured neutron energy spectrum by SciBath 20 m behind the proton target.

The area around the BNB target hall is a green field site, hence, the detector can be located as close to the target as background considerations allow. Moreover, Fermilab is a strong leader of the current and future neutrino physics program in the US, and has already demonstrated a strong commitment to this kind of experiment.

IV. BACKGROUNDS

Uncorrelated beam backgrounds are mitigated by the BNB beam window as the timing allows a factor of 2.5×10^{-5} rejection of steady-state backgrounds. Therefore, the required detector background level for the CENNS experiment is not as stringent as dark matter search experiments due to the extremely favorable beam duty factor. Timing of individual events in the detector can be known to within $\sim$10 ns using the fast scintillation signal. Additionally, cosmic ray backgrounds are significantly reduced by the water veto system. The existing radioactive shielding at the BNB target (MI-12) is quite extensive and carefully designed in order to satisfy the Fermilab radioactive safety regulations. The target itself is located $\sim$7 m underground and consists of iron blocks totaling 2.6 m in elevation, an additional 3.2 m-thick concrete shielding, and special custom sized steel above and below the horn module. About 3×10^{22} neutrons of all energies per 10^{21} POT are expected to be produced at the target. These neutrons are mostly produced in the forward beam direction with a maximum kinetic energy of 8 GeV. The high energy neutrons scatter off the surrounding materials producing secondaries. With present shielding, the beam-induced neutron flux at approximately 20 m from the target is estimated to be 3.6×10^{8} m^{-2} per 10^{21} POT. A measurement of beam-induced background in the BNB target building was carried out in the spring of 2012 directly above the beamline and 20 meters upstream of the target [1]. It used the SciBath neutral particle detector at Indiana University [17]. The beam-induced neutron flux above 40 MeV was measured to be 3.55 ± 0.38 neutrons/m^2 per spill (or 7.89×10^{8} neutrons/m^2 per 10^{21}POT). The measured neutron energy spectrum from SciBath is shown in Figure 2. Slow components in the neutron background can be easily removed by shielding. However, fast neutron components (above 100 MeV) require further shielding studies. According to the MC study, an additional 6$\sim$7 m-thick concrete barrier would reduce the beam-induced neutrons to acceptable levels.

V. CENNS DETECTOR

Liquid argon is very attractive detector target material for several reasons. Argon is a strong scintillator with a light yield of 40 photons per keV. [18, 19] Event-by-event based pulse shape discrimination (PSD) of nuclear recoil signals from electron backgrounds has been demonstrated thanks to the different population of singlet and triplet molecular decay scintillation channels. The disadvantage of an argon detector is the radioisotope, ^{39}Ar, which is a component of atmospheric argon produced by cosmic rays [19, 20]. This isotope has a β-decay with Q=535 keV with lifetime of 269 years would be costly to separate from the stable isotopes of argon. The decay rate of ^{39}Ar in natural argon is about 1 kBq/ton. The PSD together with the low beam duty factor will adequately rejects these beta decay events in a ton-scale detector.

The CENNS detector would consist of a single-phase liquid argon detector placed inside a cosmic ray veto water tank which would also serve to moderate beam-related fast neutrons. We consider the possibility of moving the MiniCLEAN detector at SNOLab to the Fermilab BNB site after the detector's dark matter mission is complete. Assuming an analysis threshold of 20 keVr is achievable in MiniCLEAN, a CENNS signal of 320 events could be measured in an exposure of 1000 kg-years and with a statistical uncertainty of 5.6%. Estimates of systematic uncertainties, were made in reference [1], where a leading contributor ($\sim$9%) ensues from uncertainties in the BNB neutrino flux itself. The next leading uncertainty ($\sim$6%) follows from knowledge of the scintillation yield from nuclear recoils and the ability to accurately calibrate the energy scale. At the projected background levels for MiniCLEAN (see Figure 4), the uncertainties contribute little to the overall uncertainty (<1%) in the CENNS cross-section. The overall systematics budget indicating that the MiniCLEAN detector at Fermilab BNB can make a 8 sigma discovery of CENNS.

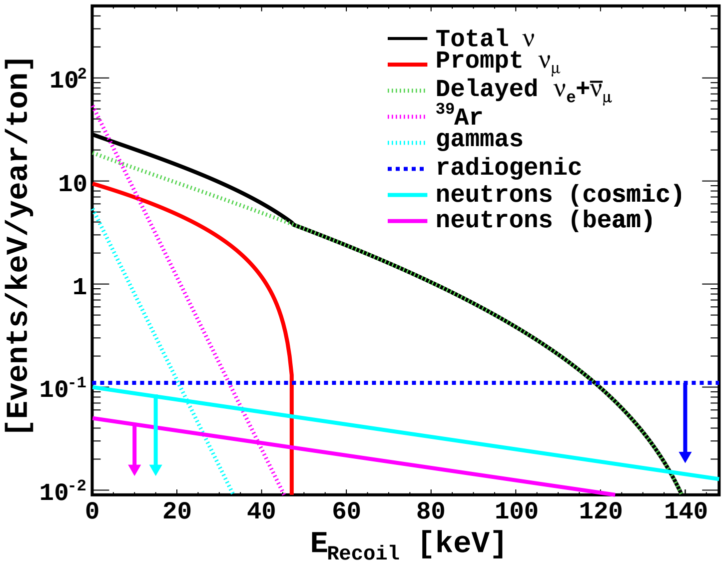

FIG. 3: Number of expected CENNS events with far-off-axis BNB in an exposure of 1000 kg-years. Flat 50% detection efficiencies are applied for nuclear recoil events.

VI. SUMMARY

We propose an experimental method for measuring the Coherent Elastic Neutrino Nucleus Scattering (CENNS), utilizing low-energy neutrinos emitted at the far-off-axis of a high-energy neutrino beam. With the BNB neutrino source, non-beam-related backgrounds such as cosmic rays, internal and external radioactivity are substantially suppressed by the beam duty factor. Based on measurements, the beam-induced neutron backgrounds can be safely reduced with proper shielding. We believe that a repurposed MiniCLEAN detector can be used to discover CENNS and further development of a low-energy neutrino source at Fermilab would provide an excellent resource for future low-energy neutrino physics experiments.

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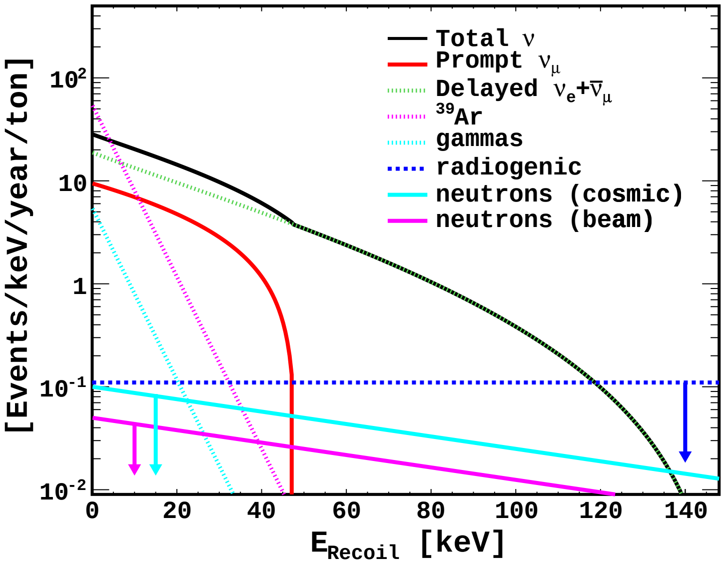

FIG. 4: Number of expected CENNS events with far-off-axis BNB in an exposure of 1000 kg-years. Flat 50% detection efficiencies are applied for nuclear recoil events.