Expression of Interest

Coherent Elastic Neutrino Nucleus Scattering

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Executive Summary

Coherent Elastic Neutrino Nucleus Scattering (CENNS) has yet to be observed since its first prediction in 1974 [1]. The CENNS cross-section is precisely known in the Standard Model (SM) [2]. It is considerably larger than the other neutrino interaction channels at MeV energies. If measured at its predicted value, CENNS can be a very powerful tool for future neutrino oscillation experiments. Alternatively, any deviation from the very robust SM prediction could be a window to beyond-SM physics [3,4,5,6,7]. The discovery of CENNS requires an intense source of low energy neutrinos, and a large-scale low energy threshold detector, both of which complement and build on existing programs at Fermilab.

The Booster Neutrino Beamline (BNB) at Fermilab [8] is a surprisingly 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 the closest practical location, the πDAR neutrino flux at BNB would be about a fifth of the neutrino flux of Spallation Neutron Source (SNS at Oak Ridge) [9,10]. The BNB site is preferable in almost every other aspect, however. First, the beam duty factor of BNB (2.5×10^{-5}) is about a factor of four better, which will help to reduce ambient backgrounds. Second, the potential experiment site, close to the BNB target, allows optimal placement of the detectors, with minimal sitting issues.

The CENNS experiment would be completely parasitic to any running of the BNB. It would require no changes to the beamline, and place no additional requirements on the running mode or times. The πDAR neutrinos from the BNB are a by-product of running the beamline for MicroBooNE [11], and will be available for the foreseeable future.

The CENNS detector would be a ton-scale single-phase Liquid Argon (LAr) detector, placed inside a water shield with an active cosmic ray veto. The low energy threshold and low background detector technology is already well developed thanks to work over the last decade in Dark Matter detector physics. Moreover, Fermilab is equipped with very strong technical and engineering resources in liquid argon detector development.

One issue that must be addressed prior to the development of a full CENNS proposal is the question of whether the beam-related fast neutron background is low enough that it can be practically shielded.

By this letter we are requesting the PAC:

(1) Endorse the physics case for using the far-off-axis Booster Neutrino Beam to discover Coherent Elastic Neutrino Nucleus Scattering.

(2) Endorse the expenditure of modest ($200k) Fermilab resources to pursue shielding and site placement study so that a full proposal can be developed.

Coherent Elastic Neutrino Nucleus Scattering: CENNS

CENNS has not been observed since its first prediction in 1974 by Fermilab theorist, D.Z. Freedman [1]. Its sole signature in a practical experiment is a recoiling nucleus with 10s of keV kinetic energy. Thus historically, the technical difficulties of developing a sufficiently large, low-energy threshold, and low-background detector have prevented discovery. The condition of coherence 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 that the nuclear diameter, and this leads to a neutrino beam with energy below 50MeV. Only two such sources seem practical – a nuclear reactor and a beam-dump source of stopped pions and muons.

There are strong motivations for pursuing the CENNS experiment:

(1) CENNS is a large and well-predicted cross-section in the Standard Model [2]. 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 an indication of the beyond-SM physics [3,4,5,6,7].

(2) 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 [12,13,14].

(3) CENNS interactions by solar and atmospheric neutrinos are irreducible backgrounds of the next generation 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 [15].

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

The Off-Axis Booster Neutrino Beam

Even though the BNB was designed as a ~GeV neutrino source for the MiniBooNE experiment [8], 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 30MeV 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. Thus, the neutrino spectral uncertainty is very small. The expected neutrino flux is about $5\times10^{5}cm^{-2}s^{-1}$ per flavor at 20m from the target with 32kW of beam power. The short-pulse time structure (1.6μs) with maximum 15Hz pulses provides an order of $2.5x10^{-5}$ of ambient background rejection factor.

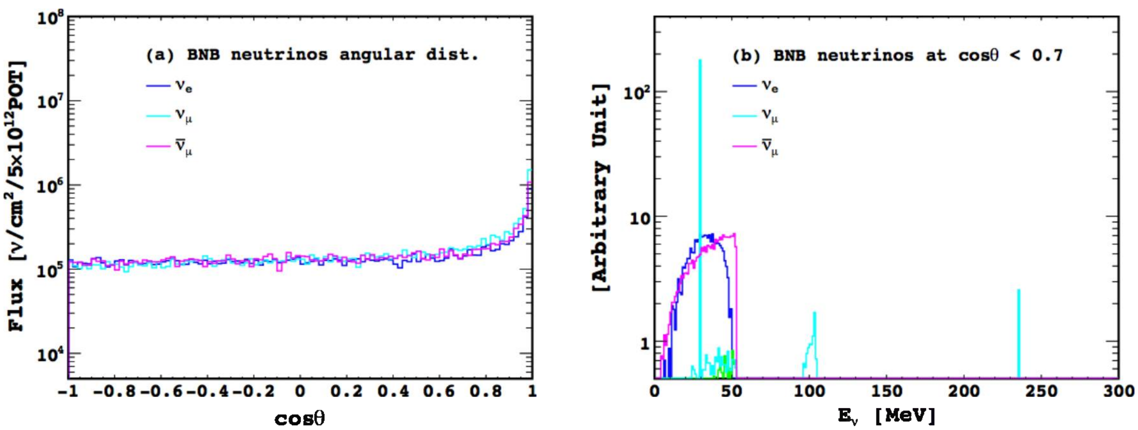

Figure 1: Estimated neutrino flux from BNB MC in ν-mode, 173kA horn current. The neutrino flux is normalized per 5×10^{12} protons on target. (a) The angular dependence of the neutrino fluxes for different flavors. (b) Energy spectrum of neutrinos below cosθ<0.7 (far-off-axis) for different flavors.

Another potential source of πDAR neutrinos exists at the SNS [9,10]. The various instruments, on-going experiments and building structures, limit the possible experimental sites at SNS. Therefore the neutrino fluxes at a closest possible site is about 4.4×10^{6} $cm^{-2}s^{-1}$ (at 30m from the target, about 6m × 6m available space). Although these fluxes are five times higher than the BNB flux at its practical experimental site, 8.8×10^{5} cm^{-2} s^{-1} (at 15m from the target), the beam duty factor at BNB ($2.5x10^{-5}$) is a factor of four better than that of SNS (10^{-4}). 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.

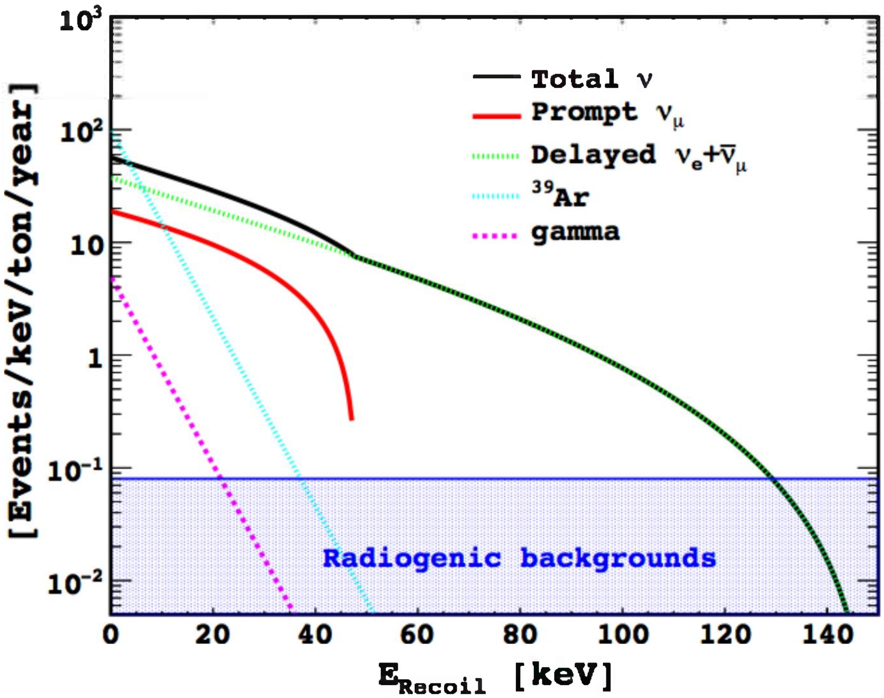

Figure 2: Number of expected CENNS events with far-off-axis BNB (32kW) neutrinos. The detector is located at 20m away from the target.

CENNS Detector

The CENNS detector would consist of a ton-scale, single-phase liquid argon detector placed inside a cosmic ray veto water tank which would also serve to moderate beam-related fast neutrons. A conceptual design of the detector is very similar to the single-phase liquid argon dark matter detectors [16,17]. For the past eight years, Fermilab has invested in R&D efforts for large-scale liquid argon neutrino detectors such as the LBNE, MicroBooNE and ArgoNeuT. As a result, Fermilab hosts world-class LAr detector R&D facilities. Moreover, Fermilab is now involved in liquid argon-based dark matter searches (Darkside) and is developing a unique distillation column for argon purification. The most outstanding component of the facility is the experienced and specialized engineering and technical human resources, which cannot be easily obtained. All of these collective elements make Fermilab an ideal place to carry out CENNS liquid argon detector development.

Liquid argon is very attractive as a detector target material for several reasons. Argon is a strong scintillator with a light yield of 40 photons per keV. 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 [18,19,20]. The disadvantage of an argon detector is the radioisotope, ^{39}Ar, which is a component of atmospheric Argon produced by cosmic rays. This isotope has a βdecay 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 low beam duty factor will helps to reject these beta decay events in a ton-scale detector. The expected CENNS event rate (see Figure 2) is about 200 events/ton per year (or per 10^{21}POT), detector placement 20m from the target, and a 50% of detection efficiency using a threshold cut of 30keV in nuclear recoil energy.

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 (mainly cosmic rays). 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 ~10ns 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 ~7m underground and consists of iron blocks totaling 2.6m in elevation, an additional 3.2m-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 (a year operation with 32kW beam power) 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 20m from the target is estimated to be 3.6×10^{8} m^{-2} per 10^{21} POT. If this simple scaling of neutron shielding holds, an additional 8m-thick concrete barrier would reduce the beam-induced neutrons to acceptable levels. However, predicting neutron leakage rates through massive shielding material is notoriously difficult. Especially fast neutrons require extensive study for the shielding design. Therefore a measurement of the beam coincident neutron flux and energy spectrum at the experimental site is necessary.

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. It used the SciBath neutral particle detector, newly developed by Rex Tayloe's group at Indiana University [21]. The beam-induced neutron flux above 40MeV 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 3. Slow components in the neutron background can be easily removed by shielding. However, fast neutron components (above 100MeV) require further shielding studies. The study also should include additional neutron measurements at the potential experimental site using the same SciBath detector after additional neutron shielding is added.

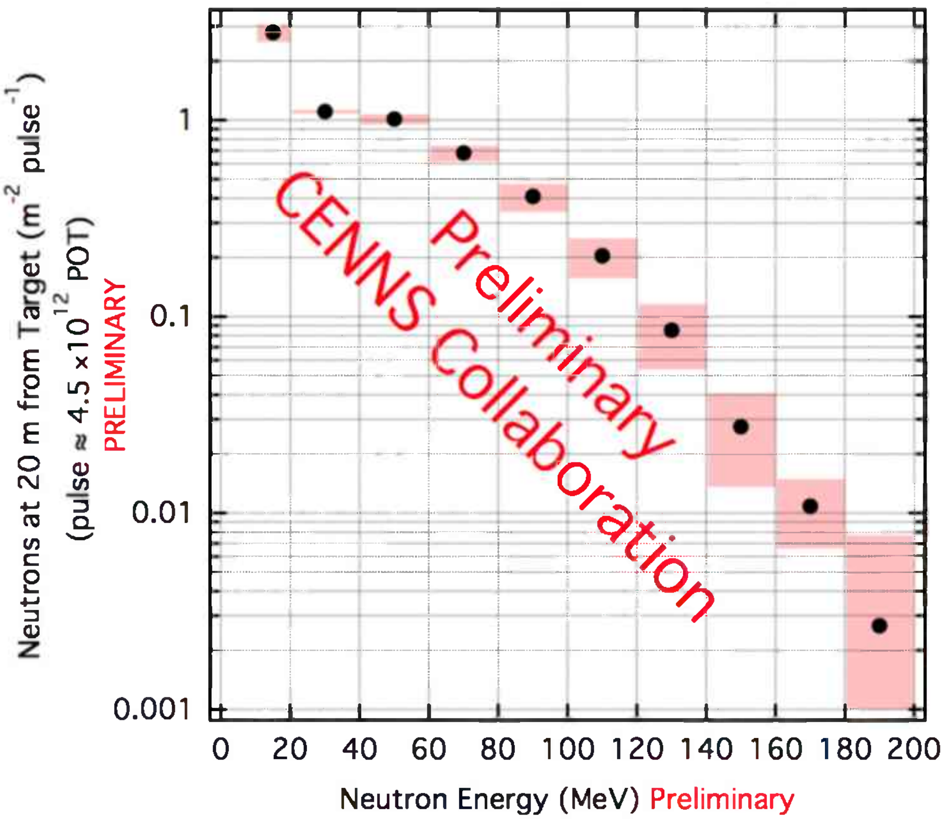

Figure 3: Measured neutron energy spectrum per BNB pulse as measured by SciBath at 20m behind the proton target.

The additional efforts to move from the current EOI to a full proposal requires a more complete study of fast neutron shielding, detector design, and details of the systematic uncertainties the neutrino beam MC. A team, including the collaboration of Los Alamos National Laboratory and North Carolina State University, has been formed to study fast neutron shielding. Hime's group at LANL is spearheading the detector design based on their expertise and leadership in constructing the MiniCLEAN detector and a proposal for R&D funds for CENNS has been submitted to the Los Alamos LDRD program.

Request to the PAC

We propose to use the Booster Neutrino Beamline as a source of πDAR neutrinos and mount an experiment to measure Coherent Elastic Neutrino Nucleus Scattering. Additional effort is required to demonstrate the feasibility of the CENNS experiment and move to a full proposal. Therefore by this EOI we request the PAC:

(1) Endorse the physics case for using the far-off-axis Booster Neutrino Beam to discover Coherent Elastic Neutrino Nucleus Scattering.

(2) Endorse the expenditure of modest ($200k) Fermilab resources to pursue shielding and site placement study so that a full proposal can be developed.

By the fall of 2014, we hope to provide a definite answer to the question of whether the far-off-axis configuration of the BNB is adequate for the CENNS experiment.

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