# Fast neutron measurements at the Booster Neutrino Beamline for a future Coherent Neutrino-Nucleus Scattering (CENNS) Experiment at Fermilab

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**Abstract**

*Low-energy neutrinos (E<50 MeV) have a standard model predicted, but unobserved, coherent elastic neutrino-nucleus scattering (CENNS) mode. Coherent neutrino scattering has important physics reach for understanding supernovae dynamics, direct supernova neutrino detection, standard model tests, nuclear form factors, direct dark matter search backgrounds, and reactor monitoring. The CENNS collaboration proposes to deploy a 1-tonne fiducial volume, single-phase, liquid argon scintillation detector at a far off-axis location at the Fermilab Booster Neutrino Beam (BNB) in order to produce a flux of low-energy neutrinos from decay-at-rest pions. The CENNS detector must be placed relatively close to the BNB target (approximately 20 m) in order to maximise the detected neutrino flux. Because the detector is relatively close to the BNB target, a major concern is the beam-correlated fast neutron fluxes that give the same signal as a coherently scattering neutrino. In order to understand these fluxes, the Indiana-built SciBath detector was deployed to measure fast neutron fluxes 20 m from the BNB target in the BNB target building. The SciBath detector is a novel 80-liter liquid scintillator, particle tracking detector that is read out by a three-dimensional grid of 768 wavelength-shifting fibers. The fiber readout allows SciBath to measure neutral particle fluxes by tracking the recoiling charged particles with uniform efficiency in all directions. This paper will describe the SciBath detector and summarise our previous measurement of the flux of 10 to 200 MeV neutrons at the BNB. This paper will also highlight a plan to improve these neutron measurements at the BNB with the SciBath detector and other neutron detectors. We will systematically change a concrete shielding structure around the detectors to modulate the neutron background fluxes. In this way, we will validate a shielding Monte Carlo simulation of the neutron flux.*

## Introduction

Coherent Elastic Neutrino-Nucleus Scattering (CENNS) has never been observed despite its standard model prediction by Freedman in 1974 [1]. In order to satisfy the coherence condition for CENNS, the neutrinos must have sufficiently low energy such that very little momentum is transferred in a collision. In this way, the scattered waves off each nucleon in the nucleus are all in-phase and add up coherently. The de Broglie relation can be used to estimate the neutrino energy required to satisfy the coherence condition. The coherence condition requires an incoming neutrino wavelength that is comparable to or larger than the size of a target nucleus. For a typical, medium-A nucleus (nuclear radius $R_N \approx$ few fm), the neutrino energy $\boldsymbol{E_\nu}$ that satisfies the coherence condition is:

$$\boldsymbol{E_\nu < hc/R_N \approx 50}\ \text{MeV} \quad (1)$$

where $h$ is Planck's constant and $c$ is the speed of light. The experimental signature for a CENNS interaction is the elastic scattering of the target nucleus within the bulk of the target material. It is a simple kinematics problem to calculate the maximum energy imparted to the recoiling nucleus $E_r^{max}$, and it is:

$$\boldsymbol{E_r^{max} \approx 2E_\upsilon^2/M \approx 50}\ \text{keV} \quad (2)$$

where M is the mass of the target nucleus. The direct detection of CENNS has been hampered largely by the development of large-scale, low-background detectors that are capable of low-threshold detection. However, recent progress in direct detection dark matter experiments has made it possible to attempt a first CENNS measurement.

In this paper, we will subsequently describe the physics motivation for measuring CENNS and the unique method we are developing in order to measure it at Fermilab. A CENNS measurement is tantamount to developing a low-energy neutrino source, a large low-energy neutrino detector, and a background rejection scheme. The most troublesome backgrounds are beam-correlated fast neutrons whose elastic scatters resemble the CENNS signal. We will describe the Fermilab Booster Neutrino Beam (BNB) as a viable, low-energy neutrino source. As previously noted, fast neutrons near the BNB are an indistinguishable background, and we will briefly describe our 2012 measurement of these fast neutrons in the BNB target building. This measurement featured an innovative fast neutron detector called SciBath, which is sensitive to up to 10-200 MeV neutrons. Finally, we will conclude with a description of additional measurements that are planned to further characterise the neutron fluxes around the BNB target building.

## Physics motivation

The recent Snowmass process has identified CENNS as a fundamentally important interaction for particle physics, direct dark matter searches, astrophysics and supernovae, and as a novel technique for monitoring nuclear reactors [2]. Moreover, the recent P5 report strongly supports the "small neutrino experiment portfolio" in all budget scenarios [3]. Below, we outline some important physics motivations and refer the reader to [4] and the references therein for a more detailed examination of these physics motivations.

The neutral weak current via the Z boson mediates CENNS in the standard model. The standard model cross-section for CENNS interactions is:

$$\boldsymbol{\sigma_{\upsilon A} = {}^{4}\!/_{\pi} E_\upsilon^2 \left(Zw_p + Nw_n\right)^2 \approx {}^{G_F}\!/_{\pi} E_\upsilon^2 N^2} \quad (3)$$

where wn, wp are the neutral current weak charges for the protons (Z) and the neutrons (N), and GF is the Fermi constant of weak interactions. We see that the cross-section is the coherent addition of all the nucleons, and that because wp ≈ 0, the CENNS interaction rate scales roughly as the number neutrons squared. Of course, bigger nuclei with more neutrons have a larger interaction rate, but its average recoil energy necessarily drops. For medium-A nuclei, the cross-section is approximately 10-39 $cm^2$, which dominates all other interactions at low energies for a given nucleus.

CENNS is also independent of the neutrino flavour. This is relevant for neutrino disappearance measurements to study short baseline neutrino oscillations and constrain possible sterile flavours of neutrinos. Because neutrinos have mass, they can possess a magnetic moment. An anomalously large magnetic moment (order 10-10 Bohr magnetons) would be measureable in future CENNS experiments by precisely measuring the nuclear recoil spectrum. CENNS is also sensitive to possible non-standard interactions, which could show up as different interaction strength with a particular neutrino flavour when all flavours should be equal. Low-energy neutrino interactions give supernova their positive pressure, and CENNS is a vital contribution. A programme to measure the CENNS interactions on a variety of nuclear targets can help to understand supernova dynamics. A CENNS detector, like dark matter detectors, can also be used as a sensitive supernova observatory. In fact, the sensitivity to CENNS interactions means that CENNS from solar and atmospheric neutrinos is an irreducible background for 10-tonne-scale dark matter detectors. CENNS can also be used probe nuclear form factors because the finite distribution of nucleons alters the coherence condition slightly. Finally, nuclear reactors are a copious source of low-energy neutrinos. A CENNS detector with very low thresholds could be used to monitor reactors at a distance for non-proliferation applications.

## Low-energy neutrino source at the booster neutrino beamline at Fermilab

Fermilab currently operates a pair of GeV-scale neutrino beamlines for a suite of neutrino experiments. These GeV-energy beams are too high energy on-axis to satisfy the CENNS coherence condition. Beam Monte Carlo simulations for the less energetic Booster Neutrino Beamline (BNB) have shown that moving far off-axis ($> 45°$) leads to a nearly isotropic flux of $< 50$ MeV neutrinos from stopped pions [4].

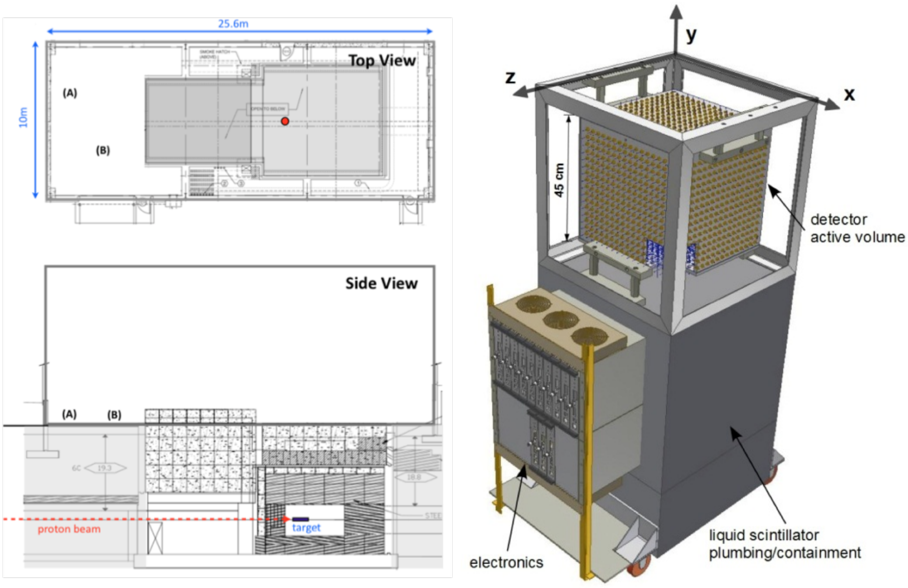
The BNB delivers a 32 kW, 8 GeV proton beam to a beryllium target. This, in turn, produces positive pions that decay with a 26 ns lifetime to a positive muon and a muon neutrino. The muon neutrinos are prompt with respect to the 1.6 $\mu$s beam and are monoenergetic at 29.9 MeV. The resulting muons then decay with a 2.2 $\mu$s lifetime into a positron, muon antineutrino, and an electron neutrino. These neutrinos have a continuous, three-body energy spectrum from 0 MeV to half the muon mass (approximately 50 MeV). Because the beam is 8 GeV, a small fraction of neutrinos are from heavier kaon decays or from muon capture in the surrounding materials. Simulations have shown that the level of contamination from these high-energy neutrinos is tolerable in a CENNS measurement.

To satisfy Fermilab radiation safety regulations, the BNB beam target is surrounded by many tonnes of steel and concrete. The target itself is located about 7 m underground and there is 40 tonnes of steel above and below the target. Around the target are 1600 tonnes of iron blocks and 300 tonnes of concrete shielding above this iron structure. Approximately 30 forward-peaked neutrons are produced per proton on target (approximately $10^{21}$ POT per year), and simple neutron dosimetric attenuation factors predict that about $3.6\times10^{8}$ neutrons per $m^2$ per $10^{21}$ POT emerge 20 m from the target. These estimates predict that 90% of these neutrons have energies below 50 MeV with a tail extending up to 8 GeV. Linearly scaling this attenuation suggests that an additional 8 m of concrete is sufficient neutron shielding for a future CENNS experiment. It is well known that neutron shielding simulation is notoriously difficult, and a programme was started to measure the neutron flux, energy spectrum and direction spectrum in the BNB target building.

## Previous neutron measurements

In spring 2012, a pair of neutron detectors were deployed in the BNB target building to measure the fast neutron fluxes correlated with the beam [4]. A portable EJ-301 [5] liquid scintillator detector was first used to survey the fission-energy neutron fluxes in multiple areas around the building. This detector facilitated finding the best location of the larger, 70-kg neutron detector called SciBath [6-7]. Figure 1(a) shows the running location of these detectors in the BNB target building. SciBath was located at position A and the EJ-301 was run for a significant amount of time after its survey at position B.

**Figure 1. (a) BNB target building: SciBath operated in position A and the EJ-301 collected data at position B, (b) a schematic diagram of the SciBath detector**




### *EJ-301 liquid scintillator detector*

In order to obtain a rough estimate of the neutron fluxes at various locations in the BNB target building, a small, encapsulated, 1-kg neutron detector was deployed. This detector assembly uses 1-kg of Eljen EJ-301 liquid scintillator and is read out by a single, 5-inch PMT. PMT pulses collected around the BNB beam window were digitised and analysed off-line. The electron-recoil energy scale was calibrated with a variety of gamma ray sources. Manufacturer tabulations of the proton-recoil quenching factors for EJ-301 were used to understand the low-energy neutron scatters on hydrogen. For 1 MeV proton recoils, the quenching factor is ~0.16 compared to a 1 MeV electron recoil from a gamma ray.

EJ-301 can discriminate proton recoils from electron recoils using the pulse shape discrimination (PSD). We used the F90 PSD parameter to discriminate proton and electron recoils. The F90 PSD parameter is the fraction of the photons collected in the first 90 ns of a pulse to the total number of photons collected out to 1 μs. Using a $^{252}$Cf source, we found that proton recoils have an F90 that is approximately 0.76-0.91, while electron recoils from gamma ray sources have "faster" pulses with an F90 that is above 0.91. Because of low light levels and digitizer saturation, the effective proton recoil energy range we used was 0.3-1.6 MeV.

The 1-kg detector was moved to various locations in the building in order to scope out an ideal location for the larger SciBath detector (see below). Once a site was located for SciBath, the EJ-301 detector was placed 19 m behind the beam target. Without a precise Monte Carlo simulation of the detector response to neutrons, we roughly estimate that the neutron flux above 0.3 MeV is about 2 neutrons per beam pulse. During our measurements, each BNB beam pulse delivers about $4.5 \times 10^{12}$ protons on the beryllium target.

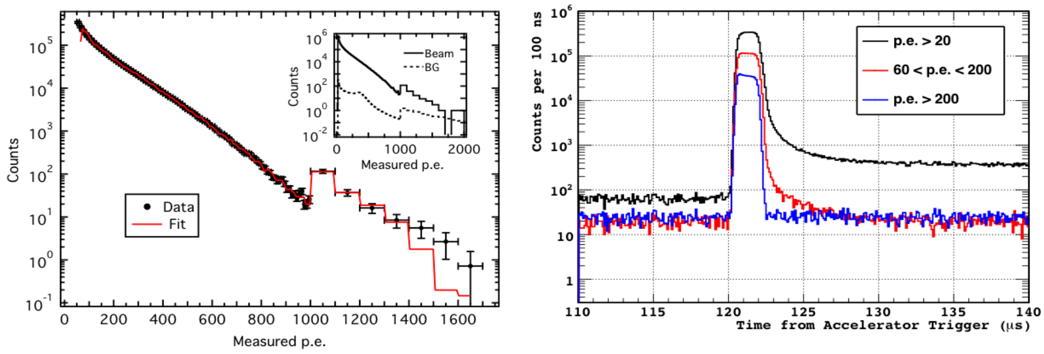
### *SciBath detector*

The Indiana University-built SciBath detector is a particle-tracking detector using 70 kg of mineral oil-based liquid scintillator (15% by volume pseudocumene and 1.5 g/L PPO). The liquid scintillator is contained in a roughly cubic volume (0.5 m × 0.5 m × 0.5 m) that is read out by 768 wavelength-shifting (WLS) fibers. Each of the three cubic axes is readout by a 16×16 square array of fibers with 2.54 cm spacing. The scintillator does not contain a secondary wavelength shifter (e.g. *bis*-MSB or POPOP) because the SciBath principle requires a wavelength shift to occur inside the WLS fiber. In this way, a fraction of the re-emitted, wavelength-shifted light is optically trapped in the fiber and transported to a PMT. Twelve 64-anode PMTs were used to read out each individual WLS fiber. A schematic drawing of SciBath is shown in Figure 1(b).

The SciBath detector electronics and single photoelectrons were calibrated with an LED pulser system. A stable, low-light LED was pulsed at the opposite end of the WLS fiber from the PMT readout during monthly calibration runs. The energy-to-light yield conversion factor was calibrated with minimum-ionising cosmic ray muons. These muons deposited approximately 65 MeV of energy and yielded about 400 total photoelectrons; the energy-to-light yield conversion factor is about 6 p.e./MeV. Cosmic ray muons were also an excellent calibration of the SciBath tracking capabilities, and we were able to reproduce the angular muon flux at the surface. More importantly, we developed topology algorithms that can separate track-like muons from point-like proton recoils with similar light yields. These were essential for reporting the high-energy neutron direction spectrum.

Figure 2(a) shows the background subtracted light output in 3 μs window around the beam. The discontinuity above 1000 p.e. is due to rebinning for added statistical power. It is clear that the beam duty factor significantly reduces the beam-uncorrelated background rates to negligible levels. Figure 2(b) shows the timing around the beam window for various light output groups. The group with the highest light output (blue) is consistent with fast neutrons in time with the beam interacting with the detector. The middle light output group (red) shows a similar beam turn-on, but there is a noticeable few-μs tail that is consistent with slower neutrons taking longer transit times and longer path lengths from scattering in the target building shielding. Finally, the lowest light output group (black) has a similar turn on and few-μs tail, but its post-beam rate is significantly higher than its pre-beam rate. Extending the time scale shows a characteristic lifetime of ~200 μs, which is consistent with neutrons thermalising in SciBath and our tagging on the 2.2 MeV gamma ray from the $n(p, d)\gamma$ neutron-capture reaction. Unfortunately, total event rates at the surface are too high to use this capture-gating technique to uniquely tag neutrons.

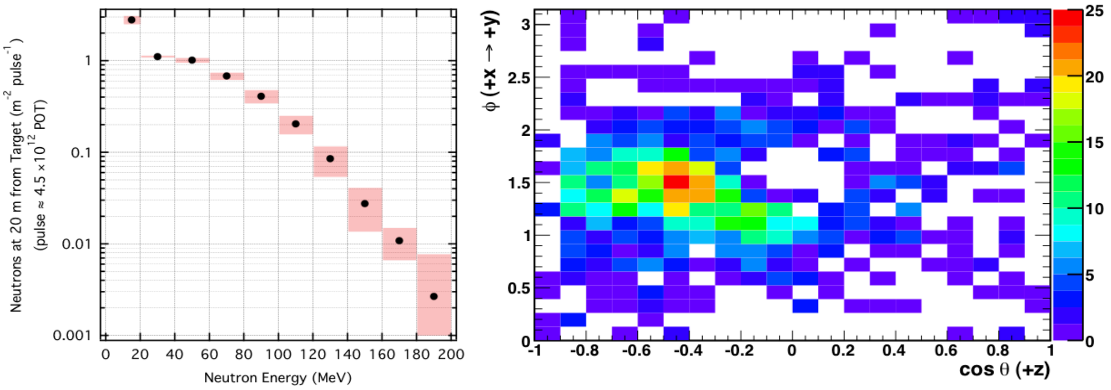
**Figure 2. (a) The background-subtracted photoelectron spectrum collected in the beam time window, (b) the timing spectrum around the beam time spectrum for various groups of total photoelectrons**



### *Results*

Using a Monte Carlo simulation, the incident neutron flux was unfolded from the light output spectra in Figure 3(a). Because SciBath has no ability to discriminate gamma rays from neutrons below 5 MeV, a conservative threshold was placed on the light output to remove most gamma rays. This cut leads to a 10 MeV neutron threshold. At higher energies, the low statistics and finite size of SciBath effectively limit its neutron sensitivity to approximately 200 MeV. Above 10 MeV, 6.3±0.7 neutrons were measured per $m^2$ per BNB pulse ($4.5\times10^{12}$ POT per pulse). Figure 3(b) reports the reconstructed direction spectrum for the highest energy proton recoils. Additional track-like cuts are applied with our topology algorithms. The peak of the direction spectrum is in line with the beam direction but points upstream of the BNB beam target.

**Figure 3. (a) The unfolded neutron energy spectrum, (b) the direction spectrum of high-energy recoiling protons**




They tend to back-project upstream of the BNB target.

## Proposed CENNS experiment at the BNB

Liquid argon (LAr) has several advantages as a detector medium. It has a high light yield, is transparent to its own scintillation light, can be purified, and is relatively inexpensive. This scintillation light has a wavelength of 128 nm, and it comes from the de-excitation of dimers in the form of trapped exciton states. These states can form in a singlet or triplet state and they have very different lifetimes in LAr, 6 ns and 1600 ns, respectively. LAr is also advantageous because the relative amount of the singlet and triplet states produced in an ionising radiation event will depend upon the recoiling particle. Electron recoils from gamma rays will have relatively more triplet state than nuclear recoils from CENNS neutrinos and neutron backgrounds. Therefore, electron recoils will tend to have slower pulses than nuclear recoils. Pulse-shape discrimination (PSD) is then able to separate electron recoils from the desired nuclear recoil signal from CENNS.

For a first CENNS measurement, we are proposing to use a 1-tonne fiducial volume, single-phase, LAr scintillation detector. The single-phase scintillation approach has the advantage of simplicity. The only signal-collecting element is an array of PMTs surrounding the LAr tank. Therefore, signal collection time is only limited by the time-scale of the triplet state. This is in marked contrast to dual-phase systems or time-projection chambers, which collect the ionised electrons over many milliseconds. Fast timing in the single phase allows us to take advantage of the $5\times10^{-5}$ beam duty factor to reject cosmogenic backgrounds, radon progeny, and $^{39}Ar$ beta decays. $^{39}Ar$ is naturally occurring and leads to a natural radioactivity of about 1 Bq/kg of LAr. Because of LAr PSD rejection and the beam duty factor, this natural radioactivity should not be problematic.

The MiniCLEAN experiment has shown that a high level of PSD rejection is possible in large volumes of LAr [8].

For a 1-tonne detector with a 50% detection efficiency (mostly from PSD efficiency) and a low-energy threshold of 25 $keV_{nr}$ (the quenching factor for nuclear recoils at these energies is approximately 25%), we expect about 300 CENNS events to be detected per year at the BNB (nominally $10^{21}$ POT). Our estimates indicate that the backgrounds should be controllable to a few per cent, and with adequate shielding, the beam-induced neutrons can be adequately attenuated. Our calculations from the previous neutron measurements show that about 7 m of concrete is sufficient to discover CENNS with negligible neutron contamination.

A first measurement of CENNS therefore requires a new LAr detector and a new neutron shielding system. Currently, the MiniCLEAN detector is operating underground searching for dark matter, but it may become available in a few years after its initial dark matter search concludes. This detector satisfies most of our operating requirements, though is only 500 kg. We are exploring options to bring it to Fermilab once a neutron shielding structure is designed. The neutron shielding design will require more input measurements of the neutron flux.

## Future neutron measurements

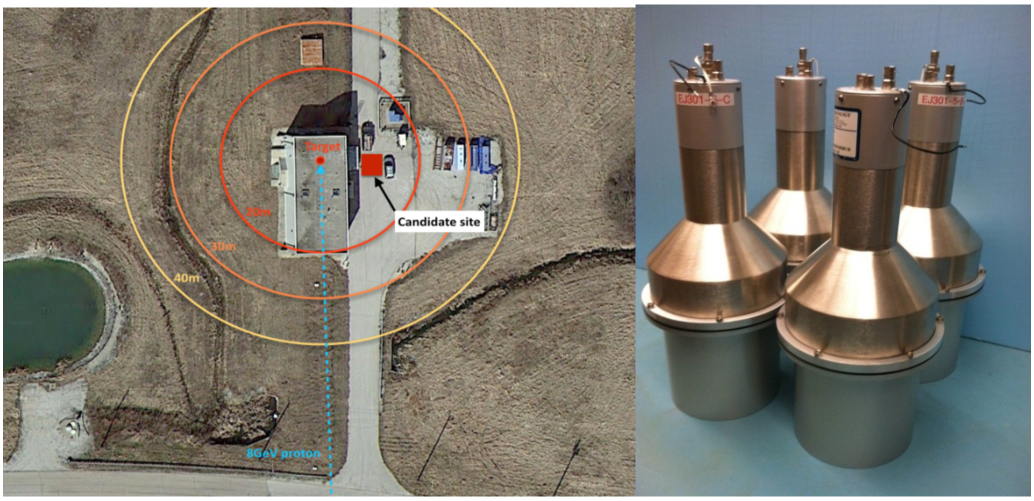
In summer 2014, an effort started to improve neutron measurements at the BNB. The goal of these measurements is to deliver a comprehensive set of neutron measurements at viable locations for a future CENNS experiment (see Figure 4(a)). Because our previous measurements in 2012 were performed with no additional neutron shielding, our proposed measurements seek to modulate the measured neutron spectrum by systematically reconfiguring the surrounding concrete shielding structures. Therefore, we can precisely test our neutron shielding Monte Carlo simulations through a few metres of concrete. With these tests, we will deliver the neutron energy spectrum and flux, direction spectrum, and modulated shielding parameters.

### *Improved EJ-301 detector array*

Three additional EJ-301 neutron detectors were procured from Eljen and have been combined into a single 5-kg detector array. The four-detector configuration is shown in Figure 4(b). These detectors and their data acquisition system are extremely portable, and we will measure the neutron fluxes at a variety of locations around the BNB target building. Until September 2014, the BNB is in an off-target configuration to support a low-mass dark matter search with the MiniBooNE detector [9-10]. This presents a unique opportunity to compare, contrast, and understand the specific processes that govern neutron transport through the BNB radiation shielding with the beam on- and off-target.

The neutron energy sensitivity of an EJ-301 neutron detector was found to be 0.3-1.6 MeV in the previous measurement. A series of precise calibrations were performed in spring 2014 at Indiana University to understand the full energy sensitivity range. We are extending the neutron reconstruction energy range through the full fission-energy-range (approximately 0.5-10 MeV). If the energy range of SciBath does not change, then in tandem, these detectors will be sensitive to 0.5-200 MeV neutrons. These represent the most dangerous neutron energies for a first CENNS experiment in LAr.

**Figure 4. (a) Proposed site for a future CENNS experiment, (b) the 5-kg array of EJ-301 neutron detectors**




### *Improved SciBath detector*

In the previous measurement, the limiting systematic error was our understanding of the detector gain and calibrations. Before delivering SciBath to the BNB in August 2014, we will improve our knowledge of this systematic. The light output of our current mineral oil-based scintillator will be measured with a series of off-line sample tests. We will also perform similar light yield tests by replacing our current scintillator with EJ-309 or linear alkylbenzene (LAB). Oxygenation is known to significantly reduce organic scintillator light yield. Therefore, nitrogen bubbling to remove any dissolved oxygen is an important systematic to control during these tests. Concurrently, a rigorous calibration programme to more precisely extract the energy-to-light yield conversion factor will be performed.

A custom, transport trailer is being designed to facilitate moving SciBath to other interesting locations. We will produce a map of the high-energy neutron flux and direction at multiple points around the BNB target building and will use a combination of pre-existing concrete blocks on the Fermilab campus to rapidly assemble a shielding structure to surround the SciBath trailer. We will also use large, commercially available tanks of water to modulate the incoming neutrons. With these shielding structures, we hope to validate the potentially complex neutron shielding simulations with neutron measurements.

### *CENNS-10 detector*

The CENNS-10 detector is a 10-kg fiducial volume, single-phase LAr scintillation detector. The main goal of the CENNS-10 detector is to understand the detector response and necessary experimental configurations at the practical site of the experiment: detector energy thresholds, beam-induced background response, timing characteristics of the in-beam and out-of-beam events, shielding performance, etc. CENNS-10 consists of a 9-inch diameter inner chamber and a 12-inch diameter outer vacuum jacket. A cooling head equipped with a cryocooler and a heat exchanger module consistently circulate the argon through a hot-getter for argon purification. Two 8-inch PMTs (HAMAMATSU R5912-02MOD) view the active LAr detector volume for the scintillation light readout. The PMT siganal waveform will be used to discriminate between electron- and nuclear-recoil events. The cryogenic components of the detector are currently being commissioned. The full commissioning of the entire detector system and a calibration programme started in summer 2014. The detector operation at the BNB site is expected to begin in spring 2015.

## Summary

CENNS is extremely important for particle and nuclear physics and astrophysics. We are developing the Fermilab BNB at Fermilab as a low-energy neutrino facility for a first measurement of CENNS. We plan to operate a 1-tonne-scale, single-phase, LAr scintillation detector (possibly the MiniCLEAN detector) at a far-off-axis location. We performed fast neutron measurement in 2012 to survey the beam-induced neutron flux near the BNB target. Our calculations based upon these results suggest that a few metres of concrete are sufficient to attenuate these neutrons to acceptable levels for a first CENNS measurement. A second set of neutron measurements was scheduled for summer 2014 to more precisely assess the neutron energy spectrum, flux, and direction and to validate shielding design Monte Carlo simulations for the future experiment.

The CENNS experiment at the BNB represents a new class of accelerator-driven rare search physics experiments. A typical feature of all these experiments is the reduction of beam-induced backgrounds, namely neutrons. We have developed techniques to precisely measure high-energy neutron fluxes, energy spectra, and direction spectra. These techniques are valuable to the radiation shielding community. Our proposed technique to systematically configure shielding to modulate the detected neutron spectrum is unique.

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