Convincing Search for Sterile Neutrinos at Lujan

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Introduction

The LANSCE Lujan facility provides a unique opportunity to confirm whether sterile neutrinos, ν_s, exist and mix with the three active neutrinos of the Standard Model (electron ν_e, muon ν_μ, and tau ν_τ). This would have a profound impact on our understanding of particle physics and deep implications for cosmology. It would be a concrete realization of physics Beyond the Standard Model (BSM) and indicate possible connections to the dark sector (i.e., the dynamical sector associated with the dark matter in the Universe). The proposed Coherent CAPTAIN-Mills (CCM) experiment would make use of the mono-energetic 30 MeV muon-neutrino flux at Lujan, together with space to move the detector, to determine if sterile neutrino oscillations are at the heart of the combined LSND and MiniBooNE 6.1σ anomalies, or if other more exotic physics is responsible.

Project Goals

The discovery of neutrino oscillations has opened a new window to BSM physics. Based on the pioneering work of Los Alamos scientists [1], the nation is embarking on a program to search for "sterile" neutrinos – new neutral particles that mix with the three active neutrinos, but that otherwise do not interact via the electroweak forces. The DOE Office of High Energy Physics convened the P5 panel that recommended that the DOE "select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm" [2]. A golden opportunity exists for LANL, in collaboration with a growing list of external collaborators (see Appendix), to convincingly answer the question of sterile neutrinos at the LSND mass scale of ~ 1 eV. The LANSCE Lujan facility is a prolific and unique source of short-pulsed mono-energetic 30 MeV muon-neutrinos. Coupled with an instrumented 10-ton liquid Argon scintillation detector (CCM) measuring Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), and space to move the detector, a convincing search for sterile neutrinos at the LSND mass scale can be made within the time frame of this LDRD. Detailed measurements of CEvNS can be leveraged to make impactful measurements of other BSM physics, such as light (sub-GeV) dark matter. The main goals of the proposal are therefore:

1. *Perform a convincing, timely, and unique sterile neutrino search using the instrumented 10-ton liquid Argon scintillation detector (CCM) and detecting CEvNS interactions at multiple distances from the Lujan neutrino source.*
2. *Leverage CEvNS absolute rate measurements that CCM will deliver in a relatively short timescale to probe new parameter space in models of light sub-GeV dark matter.*
3. *Develop BSM models of sterile neutrinos and dark sector, and improve calculations of SM cross sections that are needed to interpret the experimental results.*

Background and Statement of Problem

Over the last three decades a series of solar, atmospheric, reactor, and accelerator neutrino oscillation experiments have proven the existence of neutrino oscillations among the three active neutrinos, implying that neutrinos have mass and that the Standard Model must be extended. Around the same time, short baseline neutrino experiments at LANL (LSND) and FNAL (MiniBooNE) indicated the presence of neutrino oscillations, but at a much shorter length scale [1]. Short baseline reactor and radioactive source experiments have shown a deficit of electron neutrinos, indicating oscillations at the same mass scale as LSND. Taken together, these data imply the existence of additional neutrinos that are sterile, i.e., they do not have charged or neutral current interactions mediated by the electroweak force carriers (the $W^{\pm}$ and Z^{0} bosons).

Solar and atmospheric neutrino experiments have determined the two mass splittings associated with the three active neutrinos, namely, $\Delta m^2_{21} = 7.6 \times 10^{-5}$ eV^2, and $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV^2. The mass scale suggested by the measured LSND and MiniBooNE oscillation appearance signal $\nu_\mu \rightarrow \nu_e$, on the other hand, is around $\Delta m^2_{41} = O(1)$ eV^2. This can only be reconciled with other mass splittings if active neutrinos oscillate, at much shorter length scales (i.e. $O(10)\ m$ for energy scales $O(10)\ MeV$), into heavier sterile neutrinos ν_s. This is interpreted as $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$, where the oscillation probability is expressed as the product of muon neutrino disappearance $\nu_\mu \rightarrow \nu_s$ and electron neutrino disappearance $\nu_e \rightarrow \nu_s$,

$$P(\nu_\mu \rightarrow \nu_e) = 1/4 \times P(\nu_\mu \rightarrow \nu_s) \times P(\nu_e \rightarrow \nu_s).$$

For the $\nu_\mu \rightarrow \nu_e$ appearance rate of ~0.26% observed by LSND and MiniBooNE [1], and the currently observed electron neutrino disappearance at the level of ~10%, the muon neutrino disappearance rate should be at the ~10% level. This is further confirmed by global sterile neutrino fits that favor a squared mass of ~1.75 eV^2, with muon neutrino disappearance probabilities around 10% [3]. The simplest sterile neutrino model assumes the existence of only one heavy sterile neutrino, which mixes with the three active neutrinos – the "3+1" model [3].

A definitive test of short-baseline neutrino oscillations and sterile neutrinos must demonstrate not only oscillations of active neutrinos into other active neutrinos at the relevant length and energy scales – i.e., neutrino "*appearance*" - but also oscillations of active neutrinos into sterile neutrinos – i.e., neutrino "*disappearance*". The new Short Baseline Neutrino (SBN) program at FNAL will address electron neutrino *appearance* $\nu_\mu \rightarrow \nu_e$ [4], while a suite of *electron neutrino disappearance* $\nu_e \rightarrow \nu_s$ experiments is ongoing [5]. However, this worldwide program will not provide a definitive test of *muon neutrino disappearance* $\nu_\mu \rightarrow \nu_s$, which is required to establish whether sterile neutrino oscillations are the correct interpretation of the global data.

CCM proposes to fill this gap by searching for a muon neutrino disappearance signal via CEvNS, where the neutrino effectively scatters off the entire nucleus - instead of scattering off one of its individual constituents - causing the whole nucleus to recoil [6]. This happens when the neutrino energy is low enough so that the amplitudes for scattering off each individual nuclear constituent interfere constructively, leading to an enhancement in the scattering rate proportional to the $(number\ of\ neutrons)^2$. Furthermore, coherent scattering is mediated by the Z^0 boson couplings to neutrinos and nucleons, which are *identical* for all active neutrino flavors (i.e., ν_e, ν_μ, ν_τ), but *absent* for sterile neutrinos. Three immediate consequences follow from this: (1) the CEvNS rate can be 2 orders of magnitude larger (depending on the size of the target nucleus) than other neutrino-nucleus scattering processes, allowing for high-statistic measurements; (2) because CEvNS occurs at much lower energies, it can be efficiently discriminated from other neutrino scattering processes, such as high-energy charged and neutral current events; and (3) CEvNS is not affected by oscillations of active neutrinos into other active neutrinos; however, if oscillation into a sterile neutrino occurs, the CEvNS rate should decrease proportionally. Therefore, if a decrease in the expected rate of coherent nuclear recoils is observed, and varies with distance, this would provide irrefutable evidence that active neutrinos are oscillating into sterile neutrinos. Another key feature of CCM is that charged pions (π^+) decaying at rest yield monoenergetic muon neutrinos, eliminating complications in the oscillation signal from the dependence on neutrino energy. This, combined with the fact that the detector can be placed at different distances from the source, will allow CCM to precisely determine the length dependence of oscillations.

Table I shows the three oscillation modes ($\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_s$, $\nu_\mu \rightarrow \nu_s$) and how they are being tested around the world with past, current, and future measurements. *Only CCM would conclusively test the muon neutrino disappearance mode with sufficient sensitivity at the LSND mass scale.* Moreover, it is the best opportunity over the next few years to decisively determine if sterile neutrinos are involved at the LSND mass scale.

Oscillation Mode	Experiment Type	Past/Current Experiments	Signal Significance at LSND Mass Scale	Future Experiments (next 5 years)
$\nu_\mu \rightarrow \nu_e$	Short baseline accelerator	LSND, MiniBooNE, MicroBooNE	6.1 σ	SBN@FNAL program, JSNS[2]
$\nu_e \rightarrow \nu_s$	Reactor/source	Daya Bay, RENO, Double Chooz	~2-3 σ	PROSPECT, DANNS, SOLID, BEST, NEOS
$\nu_\mu \rightarrow \nu_s$	Short/Long baseline accelerator	SciBooNE+Mini-BooNE, MINOS+, IceCube	none	CCM

Table 1. Past, current, and future neutrino oscillation experiments searching for sterile neutrinos at the LSND mass scale

Figure 1 shows the expected sensitivity of CCM to the 3+1 sterile neutrino hypothesis, as well as the LSND and global best fit points. Global fits include all short baseline accelerator, reactor, and radioactive source experimental data and the recent IceCube muon disappearance search results [3]. There are no planned experiments in the next five years that will test muon disappearance to the level of sensitivity that CCM can deliver, and it will complement other worldwide experimental efforts testing electron neutrino appearance $\nu_\mu \rightarrow \nu_e$, and electron neutrino disappearance $\nu_e \rightarrow \nu_s$.

Preliminary Studies

Estimates for the sterile neutrino sensitivities have been developed with participation from external collaborators (see Appendix). LANL's P-25/P-23 groups have developed the Photon Detection System (PDS) for the SBND experiment at FNAL with a previous LDRD-DR. This system shares many technologies that will be used in CCM and will rely extensively on this successful experience. We are performing a full PDS system test this summer and the many lessons learned will help with the final design of CCM. A detailed MCNP model of the target is available (developed by P-27 target team) and has been used to estimate neutrino flux, spectrum, and spatial extent. A detailed simulation of the detector scintillation light response is providing guidance on detector design. Preliminary measurements of neutron background rates were made at Lujan at the planned CCM near position and input to GEANT4 simulations to determine how much shielding is required to reduce neutron backgrounds to manageable levels. Results are discussed below.

Proposed Innovation and Significance

Experimental Innovation and Significance

LANL is in a unique position to make a convincing measurement of muon neutrino disappearance at the LSND mass scale and to test the sterile neutrino hypothesis. The LANSCE Lujan neutron source (tungsten pile) is a prolific generator of stopped pions, with an estimated 4π flux of $4.74\text{x}10^5$ $\nu/\text{cm}^2/\text{s}$ for each neutrino species (ν_μ from π^+decay; $\bar{\nu}_\mu$ and ν_e from the decay of the daughter μ^+) at 20 m from the production target for nominal beam conditions [7]. This flux was confirmed by LANSCE MCNP simulations and will allow the measurement of CEvNS rates on a Liquid Argon (LAr) target. CEvNS has been recently observed at the SNS with LANL participation [8]. The proposed detector (CCM – see Figure 2) is a 10-ton LAr cryostat and is available long term

at no cost, including plumbing. The LDRD would pay for the active detector components, as discussed in the budget section. Available space and infrastructure exists at Lujan ER2 for the next three years to run the detector at two positions 20 m and 40 m from the source as shown in Figure 2.
The clear innovation of CCM is that it is the first search for sterile neutrinos using:

1. A ton scale LAr detector sensitive to CEvNS with high event rate.
2. The CEvNS process to detect all three active neutrino flavors; a deficit in this rate would constitute smoking gun evidence of oscillations into a sterile neutrino.
3. A monoenergetic muon neutrino flux, which simplifies the L/E_ν dependence of oscillations, $P(\nu_\mu \rightarrow \nu_s) = \sin^2(2\theta_{\mu s})\sin^2(1.27\Delta m^2 L/E_\nu)$ to a dependence on "L" only.
4. The same CCM detector will be placed at different distances from the source for optimal systematic error cancellation and oscillation parameter space sampling.
5. A short-pulsed 290 nsec beam to reject random backgrounds, and a special run mode where beam timing can be reduced to as low as 30 nsec for short periods of time (5-10% total beam), allowing important systematic checks of backgrounds.

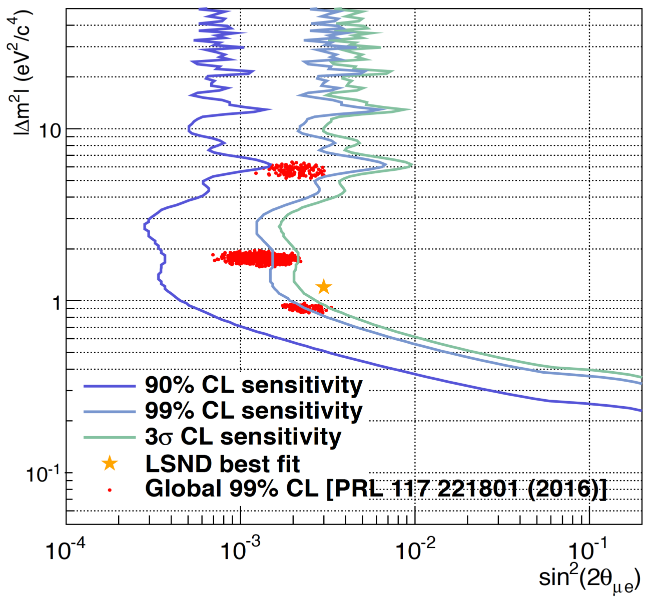

Figure 1. The oscillation mass difference versus mixing angle sensitivity to the LSND and Global Fit best fit points for the proposed CCM experiment at Lujan and a 2.5-year run. Currently, no other experiment has better sensitivity for muon disappearance at the LSND mass scale. The sensitivity includes both prompt and delayed neutrinos and background estimates discussed in the text. Everything to the right/above the curves are tested by CCM.

These aspects of the experiment make it unique to the Lujan facility. Other accelerator experiments, such as SBN, have a wide band beam with a neutrino energy spectrum going up to 2 GeV, and a energy resolution of 10-15%. Both the Lujan and SNS source have similar instantaneous power, which is the metric for background rejection, but the SNS has an order of magnitude more power for signal production. However, the SNS does not currently have room for a large detector (much less than a ton size detector) or the ability to significantly vary the distance from the source. Thus, there is no direct competition for CCM, and it would complement the suite of measurements around the world testing the sterile neutrino hypothesis at the LSND mass scale.

Theoretical Innovation and Significance

The measured relative rates of CEvNS, as a function of distance from the neutrino source, will provide a robust test of active-to-sterile neutrino oscillations suggested by short baseline anomalies. Furthermore, the absolute rate measurement of CEvNS will simultaneously probe models of light (sub-GeV) dark matter. Our investigation will involve phenomenological studies of the allowed parameter space of BSM models, as well as Quantum Monte Carlo methods, to improve, to the few percent-level, the relevant CEvNS form factors on Argon, and to investigate inelastic processes. These will be necessary to determine if BSM effects are contributing to measured rates. Figure 3 summarizes the relevant processes we will discuss below. At the production level (Lujan source), 30 MeV muon neutrinos ν_μ are emitted from π^+ decays at rest, which can then oscillate into ν_e, ν_τ, or ν_s as they propagate towards the CCM detector, Figure 3(a). Dark matter (χ^0) can also be produced, for instance, from rare π^0 decays, Figure 3(b), and propagate towards the detector. These various fluxes, of ν_μ, ν_e, ν_τ, ν_s, and χ^0, can be detected at CCM via different scattering processes: CEvNS Figure 3(c); high energy inelastic nuclear scattering, where a proton or neutron is knocked out of the Argon nucleus Figure 3(d); and electron scattering Figure 3(e).

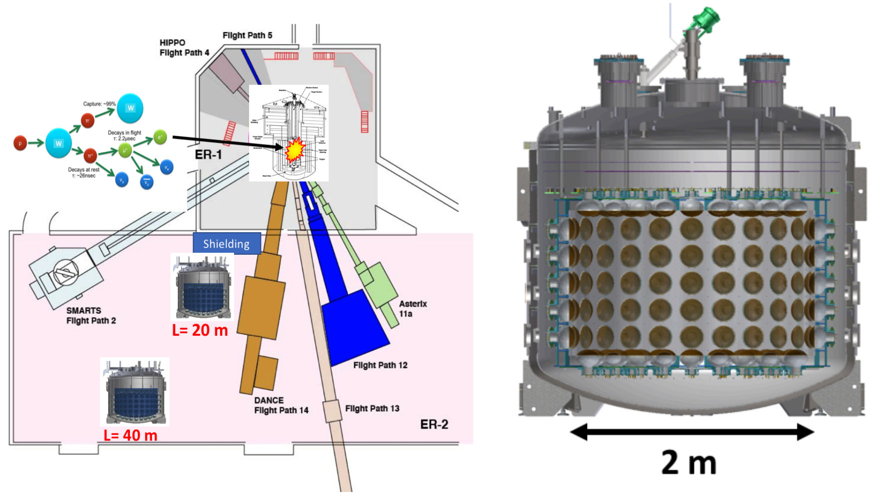

Figure 2. Left: Proposed near (20 m) and far (40 m) run positions for the CCM detector relative to the Lujan target. Right: The CCM detector with 220 8" PMT's, reflector foils (7 tons of fiducial), and instrumented veto region (3 tons).

A - Novel Neutrino Phenomenology

In case a deficit is observed in the expected CEvNS rate, its dependence on the distance from the source combined with measured rates for other neutrino scattering processes at CCM will allow the extraction of oscillation parameters, such as oscillation amplitude and length. This will be especially valuable considering that the simplest sterile neutrino explanation of short baseline anomalies (i.e., "3+1") is in tension with data from other experiments, such as MINOS and IceCube [3]. Evidence of sterile neutrinos in CCM data will narrow down viable sterile neutrino scenarios that are consistent with other experiments. One such possibility involves a sterile neutrino that is not completely "sterile" - instead, it has BSM interactions with matter, mediated by a new light particle, such as a new scalar or vector boson.

A striking consequence of such a new interaction is that, for a special range of energies, an active neutrino propagating in matter will undergo "resonant" (or enhanced) conversion into sterile neutrinos (an effect similar to the resonant conversion of $\nu_e \rightarrow \nu_\mu$ in the solar medium due to Z^0 interactions with electrons, i.e., the MSW effect). This resonant effect, which occurs only in a specific neutrino energy range, would explain anomalies in the MiniBooNE data, as well as the absence of anomalies in experiments probing higher energies outside the resonant range. The phenomenology of this alternative, *quasi-sterile* neutrino scenario is rich – if the sterile neutrino couples dominantly to nuclear spin, or to leptons, then coherent sterile neutrino-nucleus scattering will still be absent, but sterile neutrinos will scatter off nuclei inelastically, or off electrons, leading to different signals to which the CCM detector will be sensitive (i.e., elastic nuclear recoils, inelastic nuclear

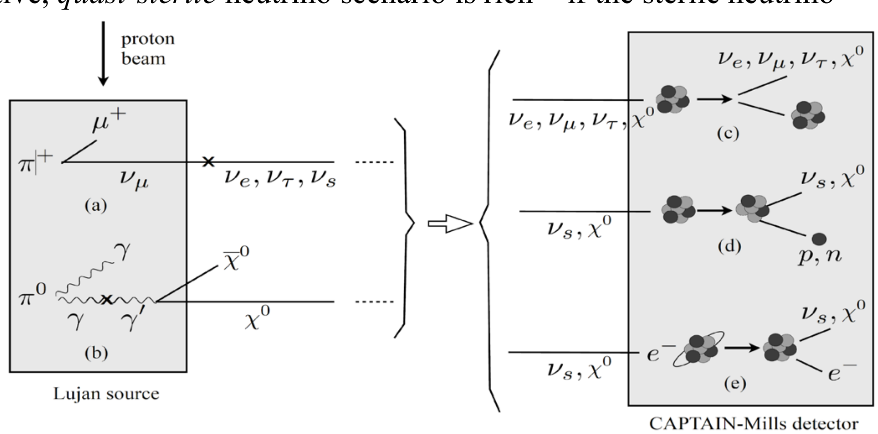

Figure 3. Neutrino and dark matter production at Lujan (left), and detection channels in CCM (right). See text for description.

scattering, and electron recoils).

B - Light Dark Matter and Light Mediators

Another exciting possibility that CCM will test is the production and detection of light sub-GeV dark matter, which will not require any experimental innovations - only a reanalysis of the neutrino data. In principle, dark matter could belong to a complex *dark sector*, which, like the Standard Model, could be comprised of several new particles and gauge interactions. Also belonging to this dark sector are "*mediators", i.e.,* particles that communicate interactions between the dark and visible sectors. Through dark sector mediators, dark matter particles could be produced at the Lujan source (e.g., via rare decays of copiously produced neutral pions) [9]. Some of the dark matter particles produced at the Lujan source will reach the CCM detector and, via a dark sector mediator, scatter coherently off a nucleus, leading to a signal similar to coherent elastic neutrino-nucleus scattering (Figure 3(c)). In this case, dark matter production would lead to an *enhancement* in the expected nuclear recoil rate at CCM. The sensitivity to this particular scenario, where dark matter is a scalar particle, is shown in Figure 4. More generally, CCM will probe novel and viable parameter space of several light dark sector models, including parameter space regions predicting the correct thermal relic abundance of dark matter in the Universe, and motivate theoretical analyses.

Technical impact

Searching for CEvNS and sterile neutrinos at Lujan with the CCM detector would advance the technology of LAr scintillation technology, data analysis, and simulations. There are many new LAr detector technologies that still need to be tested in real physics environments. For instance, we plan to use the DUNE designed light guide bars for the veto region, providing the first real-world test. Also, there are questions to be addressed about the long-term performance and stability of wavelength shifting material Tetra-Phenyl Butadiene (TPB), N_2 contamination, etc. Moreover, the charged current reaction can be studied at E >10 MeV and would provide valuable information on neutrino cross sections at supernova energies of interest for DUNE. All these tests can be performed with high sensitivity at Lujan and are important for future short- and long- baseline programs.

Mission impact (importance for the Laboratory and Nation)

This proposal will have a significant impact on LANL, as it brings neutrino physics back to the place it started in the 1950's with the Nobel Prize winning discovery of the neutrino by Cowen and Reines. High profile R&D attracts the brightest and best students, with most of our postdocs going on to successful careers at LANL and at other national labs and universities. We are developing a significant external collaboration of world leading researchers in neutrino physics (see Appendix), who will bring talented students and postdocs to work on CCM. FNAL has expressed support for the project and is allowing a staff scientist to participate on CCM. The long-term goal is to develop a robust and flexible neutrino facility to attract new NSF/DOE basic science funding to support novel experiments and to test technologies for future short- and long- baseline programs.

R&D Methods and Anticipated Results

Sterile Neutrino Search

The key challenge for the experiment will be to successfully measure CEvNS interactions that result in low recoil energies up to 150 keV. LAr is a prolific generator of scintillation light, about 40 photons/keV, of which a quarter of the light has a fast 6 nsec time constant. The LAr ultraviolet scintillation photons (128 nm wavelength) are emitted following the interactions of charged particles inside the liquid argon [10]. The PMT's are not directly sensitive to this light but are coated with TPB material that wavelength shifts the light to match the PMT response. This technique has been successfully used by many neutrino and dark matter experiments. Detailed

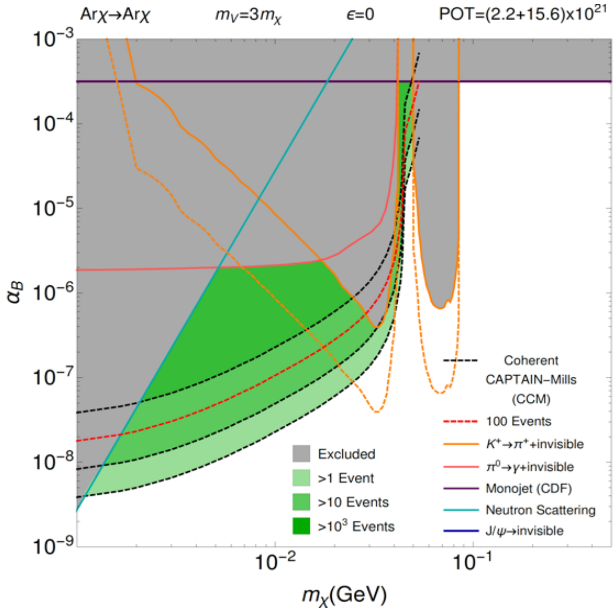

Figure 4. The dark matter baryon coupling versus dark matter mass sensitivity plot. Shown are CCM dark matter event rates and detection sensitivities (dashed red line) corresponding to a 2.5 year run for a benchmark dark matter model with a leptophobic mediator coupling to baryon number.

simulations have demonstrated that a 10 keV detector threshold can be achieved with 220 8" Hamamatsu R5912 PMT's (50% photocathode coverage) and TPB reflector foils instrumented throughout the detector.

The Reactor Analysis Tool Plus Additional Codes (RAT-PAC) simulation package was used to determine the PMT response in CCM. The simulation of the PMT response includes the quantum efficiency of the PMTs as a function of optical photon energy, the loss of photoelectrons from not reaching the dynodes, and the time response of the PMT. Based on a RAT-PAC simulation we expect to see about 1 photoelectron for each keV of energy deposited by nuclear recoil-like interactions (as opposed to electron recoils) inside CCM. The contamination of LAr with N_2 quenches scintillation output and will need to be monitored and controlled to better than 20 ppm (factory delivered N_2 contamination is ~2 ppm). For LAr, the estimated CEvNS rates for CCM at 20 m and 40 m from the Lujan source are shown in Table 2 for a typical 80 kW beam power and eight-month run period.

Another key for CCM success is using fast timing for signal extraction. For Lujan the beam time structure is a triangular pulse of 290 nsec (145 nsec FWHM) at 20 Hz, yielding a 2.9×10^{-6} duty factor. There are two signal samples based on timing: (1) the *prompt* ν_μ events arising from monoenergetic neutrinos from pion decay that are in time with the beam; (2) the *delayed* ν_e and $\bar{\nu}_\mu$ events from muon decay that mostly fall outside the beam window, as shown in Figure 5. An oscillation analysis will use both samples and have different strengths and weaknesses, as outlined below.

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

Table 2. Event rates for 80 kW Lujan source per year (8 months running)

Finally, the success of this experiment depends on mitigating and measuring backgrounds. There are two classes of backgrounds, random and in-time with the beam that require different methods for rejection. The main strategy for random background is to use the short beam duty factor to suppress this background to manageable levels. The signal can be discriminated against random backgrounds, such as radioactivity and cosmic rays, using in-beam timing cuts. Beam off running will precisely measure these backgrounds, allowing the remaining amount to be subtracted. For the prompt analysis, the total beam livetime is about 61 seconds for a run year, and 1681 seconds for a delayed time window of 4 microseconds for muon decay neutrinos. There are three main sources of random background:

^{39}Ar: This is naturally present in LAr and decays with a 269-year half-life via beta emissions with an end point energy of 565 keV. The normal concentration in LAr is 1.5 counts/sec/l, which for the fiducial volume of 7 tons (5000 l), is a 7.5 kHz rate. For the prompt analysis, this represents 4.6×10^5 events from ^{39}Ar decays per run year. There is a factor of ten reduction for an E < 50

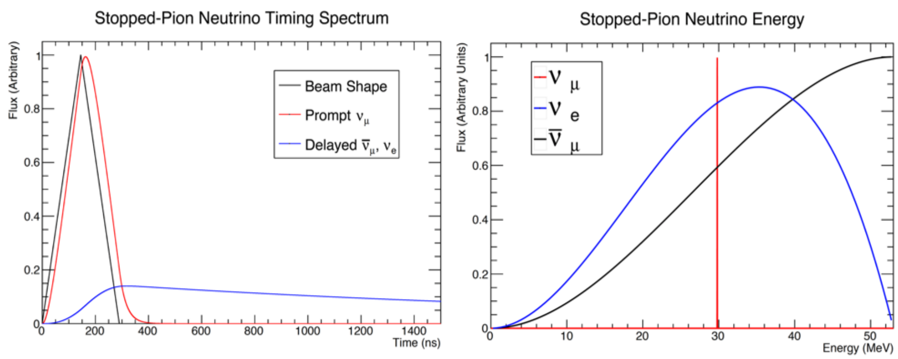

Figure 5. Neutrino timing and spectrum from the Lujan stopped pion source. Lujan MCNP target simulations have confirmed the flux estimate and that the neutrino source extent is 8cm along the target-detector axis.

keV threshold, and a further estimated factor of ~100 reduction from well-established pulse height PID methods that separate electron from nucleon scattering events [11]. This leaves about 456 events in the prompt oscillation sample, which can be precisely measured to less than 1% level using beam off data. The background subtraction will increase the far detector signal statistical errors, which dominate the prompt analysis, from 2.7% to 3.5% for the full 2.5-year run. For neutrinos from muon decay (delayed analysis), even though the beam duty factor is higher, the PID reduction is significantly better due to the higher light output, improving the reduction factor to above 10^5. Here the background rate is 120 events per run year, and with a signal rate of 5920 events in the far detector over the full run, this background has minimal effect on the delayed analysis statistical error level of 1.3%.

Cosmogenic: Cosmic ray background such as muons and low energy showers occur at a rate of 200 Hz/m^2 of detector surface. For CCM this will be about 800 Hz. The beam duty factor rejection will reduce the rate for prompt (delayed) analysis to 9×10^4 (1.3×10^6) events per live year. The active veto cosmic rejection factor is expected to be 10^3, and kinetic cuts will gain another factor of 10, reducing the cosmogenic rate to 10 (130) events, which is small relative to the signal and will be measured precisely with beam off running.

Internal/External Radioactivity: Measured U/Th/K radioactivity in the PMT glass is ~10 Bq/PMT [12]. However, these events can be identified by large charge in a single PMT where the decay originated, with smaller amounts of light scattered around the detector. A rejection factor of better than 10^3 will be achieved, making this background small. Radioactivity from outside the detector and in the cryostat steel will be optically shielded by the reflector foil veto wall, and absorbed by the 30 cm (2-3 radiation lengths) of veto LAr volume. Should external radioactivity still be an issue, outside shielding around the detector can be put in place.

In-time Backgrounds: The only source of in-time background will be the beam-induced gamma rays and neutrons. Of the two, neutrons are more problematic, as they are harder to shield, can avoid the veto, and can low-energy scatter in the detector, mimicking the CEvNS signal. Due to the subluminal speed, only neutrons with

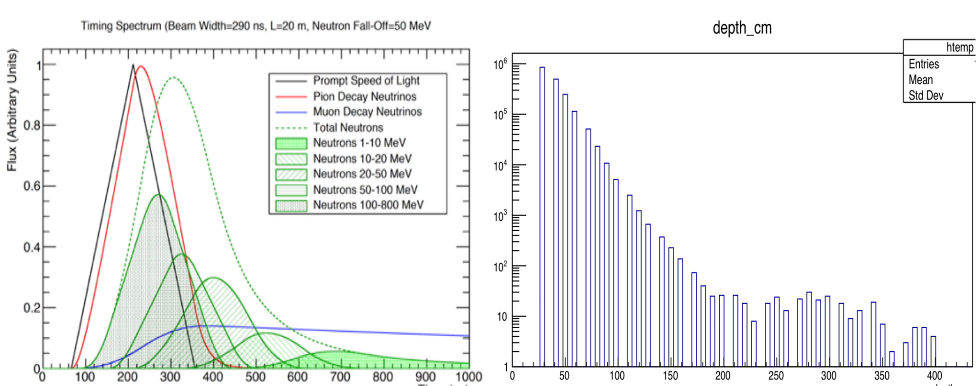

Figure 6. Left: Neutron timing relative to the neutrino signal. Right: Neutron shielding predictions using GEANT4 simulations with input neutron background measured 13.5 m from the source.

energies above 20 MeV will arrive in the beam time window (Figure 6). An in-situ neutron measurement during nominal beam conditions was performed at the expected near position of CCM and yields 2.5 n/spill/m^2 with a spectrum that rapidly falls off to 50 MeV and a long small tail out to ~ 200 MeV. The measured rate and energy spectrum was fed into a GEANT4 simulation. The optimal shielding configuration found is 1 meter of steel followed by 2 meters of concrete with another 0.5 meter of water/poly (Figure 6). With this configuration the neutron flux is reduced by a factor of 10^6, which reduces the neutron rate to about 200 events per run year. A further factor of ten reduction can be achieved by an energy cut. These remaining events will be measured from the time spectrum evolution and subtracted.

Sensitivity Analysis: Putting it all together, Figure 1 shows the expected sterile neutrino sensitivity for a 2.5-year CCM run at the Lujan center assuming nominal beam conditions, a 1:4 (near:far) detector position data sample, and background rates assumed above. Most systematic errors cancel between the near:far comparison, but a residual systematic error of 2% is assumed. The LSND best fit region is probed at over 3σ, and if a signal is observed, a five-year run would yield close to 5σ, providing a definitive test of the sterile neutrino 3+1 oscillation hypothesis. If there is no signal, the global best fit region can be tested in its entirety at the 90% C.L. Should it be warranted, we will seek funding for CCM running beyond the three years of the LDRD from NSF or DOE. The Lujan facility is funded by NNSA and is expected to run for at least ten more years.

Anticipated theoretical methods and results

CCM signal predictions for BSM models will be calculated and compared with data. These models will include: (1) non-standard interactions of neutrinos, (2) sterile neutrino BSM interactions, leading to resonant conversion of active-to-sterile neutrinos when propagating through matter, (3) light dark sector models, including light dark matter interacting via dark photons, leptophobic Z', scalars, and pseudoscalars. The sensitivity of the CCM measurements, including coherent elastic and inelastic processes, will allow for exclusions of nontrivial parameter space in these models, and, in case of an excess, to the selection of a preferred class of models and parameters that best fit the data. Critical to this component will be an accurate calculation of the relevant cross-sections and reduction of associated uncertainties. For the BSM analyses, the largest source of uncertainty will be in the determination of neutrino rate from the source. From studies at LSND, this error is expected to be about 5%. The second largest uncertainties stem from Argon nucleus form factors, and these will be reduced to the level of a few percent by Quantum Monte Carlo methods. Figure 4 illustrates the expected event rate at CCM from a dark matter benchmark model. Unexplored parameter space above the 100-event dashed red line should be fully excludable by CCM.

Project Schedule

The detector will be assembled and commissioned in 9-10 months with 150 PMT's+electronics (2/3 full complement limited to M&S funding constraints) and running started the summer of FY19 for about six months. The remaining 70 PMT's+electronics will be purchased and installed in FY20 for the final two years of running. The schedule is aggressive, but risk is minimized by our extensive experience from building the PDS for SBND where most of the parts are already designed and component delivery and assembly times known. CCM will benefit from that experience and will share the same type of PMT, electronics, DAQ, support structure, calibrations, and simulations. With detector construction aligned with the accelerator schedule, we can achieve ~2.5 years of running during the LDRD (Figure 7). About 20% of the data will be taken with the detector in the near position at 20 m, and the remaining in the far position at 40 m. Data analysis will occur during the duration of the LDRD, and initial physics results will be published as well. The external collaboration has committed to helping with construction, running, and analysis of the experiment (see Appendix).

Data management plan

This project will produce data from running the CCM detector, which amounts to approximately 2 Tera-bytes of data per year, which is considered manageable. The data will be stored on local arrays of raided disk servers and backed up to a local LANL facility.

Transition Plan

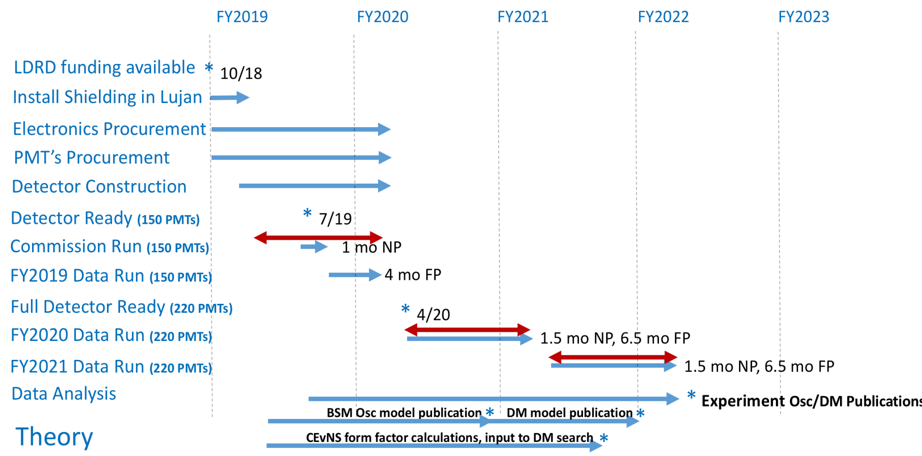

Figure 7. CCM schedule and milestones (blue stars). Quick construction of the detector will enable 2.5 years of running. NP is near position, FP is far position, and red line Lujan run schedule.

This project will have a big impact on the DOE HEP program office. The search for sterile neutrinos is strongly endorsed by the HEP P5 committee [2]. By providing a unique and sensitive measurement of the muon neutrino disappearance at the LSND mass scale, CCM is integral to the overall international sterile neutrino search strategy. Should a signal be observed by CCM during the LDRD time frame, then continued running would improve the significance to 5σ. Even a null observation would be important for understanding the source of the LSND and MiniBooNE anomalies. We will seek further funding from NSF and DOE HEP to continue developing the CEvNS technology and pushing for sensitive sterile neutrino oscillation and dark matter searches.

Budget Request

The 10-ton cryostat and plumbing are free and available, while the LDRD would fund the instrumentation of the cryostat with 220 8" cryogenic PMT's, support structure, CAEN V1730 500 MHz digitization electronics, DAQ, cables, feedthru, and LAr. It would also fund the operation of the experiment for 2.5 years. The hardware M&S is estimated to be \$1.1M, which will be spent in FY19/20 building the detector in stages to maximize run time during the LDRD timeframe. Contingency is 5%, as a similar PDS system has been built before. Should all of the M&S be available up front, then the entire detector could be built and made ready to run during FY19.
The LDRD would provide 1.4 staff FTE over three years to the P-25/P-23 experimental neutrino groups for design, construction, simulation and analysis of CCM, with another 0.2 FTE of mechanical/electrical engineering support in the first two years. As well, there is 0.1 FTE (Chuck Taylor) for AOT expertise, and 0.1 FTE (Charles Kelsey) for P-27 Lujan target simulations expertise, which will provide crucial understanding of beam and target performance. An experimental postdoc would be hired within the first six months to provide full time support for the above activities. Theory will have 0.7 FTE of staff support provided to carry out the calculations outlined in this LDRD. Including their extensive neutrino expertise, external collaborators (see Appendix A) will provide the TPB reflector foils, light guide bars system for the veto region, and central trigger hardware. They will also make available students and postdocs for detector construction, running, and data analysis.

Glossary of acronyms

BSM - Beyond the Standard Model
DAQ – Data Acquisition
DOE – Department of Energy
CAPTAIN – Cryogenic Apparatus for Precision Test of Argon interactions with Neutrinos
CCM - Coherent CAPTAIN-Mills instrumented 10-ton LAr detector
CEvNS - Coherent Elastic Neutrino-Nucleus Scattering
DUNE - Deep Underground Neutrino Experiment
FNAL – Fermi National Accelerator Laboratory
FWHM – Full Width at Half Maximum
GEANT4 - GEometry ANd Tracking simulation software (HEP standard)
HEP – High Energy Physics
LANL – Los Alamos National Laboratory
LAr – Liquid Argon
LANSCE – Los Alamos Neutron Science Center
LSND - Liquid Scintillator Neutrino Detector
MCNP – Monte Carlo N-Particle code
NSF – National Science Foundation
P5 - Particle Physics Project Prioritization Panel
PMT – Photomultiplier
PDS - Photon Detection System
RAT-PAC - Reactor Analysis Tool Plus Additional Codes
SBN - Short Baseline Neutrino (LAr-TPC experiments at FNAL)
SNS – Spallation Neutron Source
SNO – Sudbury Neutrino Observatory
SBND – Short Baseline Neutrino Detector
TPC – Time Projection Center
TPB – Tetra-Phenyl Butadiene

Citations

[1] A. Aguilar et al., “Evidence for Neutrino Oscillations from the Observation of Electron Anti-neutrinos in a Muon Anti-Neutrino Beam”, Phys. Rev. D 64, 112007, (2001); A. A. Aguilar-Arevalo et al., “Improved Search for Electron Apperace Oscillations in the MiniBooNE Experiment”, Phys. Rev. Lett. 110, 161801 (2013); J. Kopp, P.A.N. Machado, M. Maltoni and T. Schwetz, ``Sterile Neutrino Oscillations: The Global Picture”, JHEP **1305**, 050 (2013), arXiv:1303.3011.

[2] 2014 HEPAP P5 Report, “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context”, http://www.usparticlephysics.org/p5/.

[3] G.H. Collin, C.A. Argüelles, J.M. Conrad, and M.H. Shaevitz, “First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino”, Phys. Rev. Lett. 117, 221801 (2016).

[4] M. Antonello, *et al.,* [MicroBooNE and SBND and ICARUS-WA104 Collaborations], ``A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab

Booster Neutrino Beam," arXiv:1503.01520.

[5] S. Gariazzo, C. Giunti, M. Laveder and Y. F. Li, “Model-Independent Anti-Electron Neutrino Short-Baseline Oscillations from Reactor Spectral Ratios”, arXiv:1801.06467 [hep-ph] 2018.

[6] Freedman D Z, Schramm D N and Tubbs D L 1977 Ann. Rev. Nucl. Part. Sci. 27 167–207: Drukier A and Stodolsky L 1984 Phys.Rev. D30 2295.

[7] P. Plishke, "Neutrino Fux Calculations for the Tungsten Target of the ISIS Spallation Neutron Facility," Institut fur Kernphysik, 2001.

[8] D. Akimov, et. al, “Observation of coherent elastic neutrino-nucleus scattering”, Science 03 Aug 2017.

[9] P. deNiverville, M. Pospelov and A. Ritz, “Light new physics in coherent neutrino-nucleus scattering experiments”, Phys. Rev. D92, no. 9, 095005 (2015).

[10] T. Heindl et. al., “Table-top setup for investigating the scintillation properties of liquid argon”, JINST 6, P02011 (2011).

[11] W.H. Lippincott, K.J. Coakley, D. Gastler, A. Hime, E. Kearns, D. N. McKinsey, J.A. Nikkel and L.C. Stonehill, ``Scintillation time dependence and pulse shape discrimination in liquid argon," Phys. Rev. C 78, 035801 (2008).

[12] P.Agnes, et al. [DarkSide Collaboration], “The veto system of the DarkSide-50 experiment”, JINST 11, no. 03, P03016 (2016)

Computing Resource Needs

The calculations of elastic and inelastic neutrino and dark matter scattering are computationally intensive and rely on Quantum Monte Carlo methods to calculate the relevant path integrals on large-scale supercomputers. We will use LANL institutional computing resources for the work outlined in this proposal, and also an INCITE grant that we have had at ANL and are preparing for a renewal. This INCITE grant is tied to the NUCLEI SciDAC-4 project on nuclear structure and reactions (computingnuzlei.org), where Carlson is the PI.

Appendix

External Collaboration List (PI's):

1. **Janet Conrad, MIT**: Provide TPB reflector foils, sterile neutrino sensitivity calculations. NSF supported student Alejandro Diaz to work on construction, shifts, and data analysis. Will hire a new postdoc to work on CCM.
2. **Robert Cooper, Joint appointment LANL-NMSU**: Design and construction of DAQ, participate in running detector and data analysis leadership.
3. **Josh Spitz, University of Michigan**: Provide light guide bars system (VETO), sterile neutrino sensitivity calculations.
4. **Matt Toups, FNAL**: Provide light guide bars system (VETO).
5. **Josh Klein, University of Pennsylvania**: Provide trigger system hardware.
6. **Ben Jones and Jonathan Assadi, University of Texas at Arlington**: Perform basic scintillation light properties studies.
7. **Rex Tayloe, Indiana University**: CEvNS expertise and data analysis.

FNAL management has expressed support for this proposal, as it aligns well with neutrino efforts at FNAL and tests technology for future short- and long- baseline neutrino programs.

LANL Participants:

Richard Van de Water (PI) (P-25) has extensive experience leading, building, commissioning, and analyzing large-scale neutrino experiments. This experience makes him more than qualified to lead this LDRD-DR and ensure a successful outcome. Richard is a Scientist 4 with the P-25 Subatomic group focusing on measuring neutrino properties, searches for sterile neutrinos, and uncovering the dark sector. He received his Ph.D. in particle physics from the University of Toronto in 1993. With over 110 papers and more than 17,000 citations, he is working at the forefront of particle physics and making significant contributions. He has had a long and successful history building, running, analyzing, and leading world-class neutrino experiments such as SNO and MiniBooNE. On SNO he was the commissioning and detector manager, and on MiniBooNE the co-spokesperson from 2006 to present. Under his leadership, the MiniBooNE experiment continues to publish significant new physics results such as dark matter searches, first observation of stopped Kaon neutrinos, and new oscillation results with double the neutrino data. Richard is the L2 manager and co-convener for the SBND photon detection system. He also is the PI for 20160037DR, *"Dark Matter Search with a Neutrino Experiment"*. His broad and detailed knowledge of many aspects of neutrino physics and experiments makes him ideally suited to lead CCM. His skills set spans the range from low energy backgrounds, sensitive neutrino detection technologies, large-scale complex electronics and detector systems, large data set analysis, and physics modeling and interpretation. Richard's extensive scientific leadership experience will be crucial to ensuring the project's success.

Daniele Spier Moreira Alves (Co-PI) (T-2) has expertise in particle phenomenology and physics beyond the Standard Model. She will investigate BSM neutrino models that will be probed by CCM, including neutrino Non-Standard Interactions (NSI), neutrinos' anomalous magnetic dipole moment, and modifications of active-to-sterile neutrino oscillations when propagating matter, including "MSW-type" resonant effects. She will also study the production and scattering signals of sub-GeV dark matter models, and implications for dark sector properties.

Elena Guardincerri (Co-PI) (P-25) has significant experience in operating neutrino detectors similar to the one proposed. She worked for three years on the Borexino experiment at the Gran Sasso National Laboratory, she demonstrated the feasibility of the Mini-CAPTAIN experiment at WNR and coordinated its data taking. She is a member of the LANSCE NPAC committee and she is knowledgeable about the LANSCE beam. Her skill sets include electronics and detector systems, data analysis, data acquisition and physics modeling will be valuable to CCM.

Joseph Carlson (T2) will work on neutrino and dark matter interactions with matter for both coherent and low-energy inelastic scattering. Carlson has a strong background in nuclear many-body theory, he is the PI of the NUCLEI SciDAC-4 collaboration which leads the effort in computational approaches to nuclei and dense nuclear matter. Carlson is an APS and lab fellow and the winner of the 2017 APS Feshbach prize in nuclear theory. In this project we will collaborate with collaborators from JLAB, FNAL, ANL, and Washington University.

Bill Louis (P-25) came to LANL as a staff member in 1987 and is now a member of the P-25 sub-atomic group. He is a LANL Fellow, an APS Fellow, and an AAAS Fellow. For the past 25 years, he has worked on short-baseline neutrino experiments and has served as spokesperson of the LSND experiment at LANL and co-spokesperson of the MiniBooNE experiment at Fermilab. Presently, he is serving as IB chair and as co-convener of the physics working group for the Fermilab SBND experiment. Louis will contribute to the design, construction, running and analysis of the CCM experiment.

Rajan Gupta (T-2) will be developing codes for calculating the matrix elements leading to axial form-factors for neutrino scattering and the interaction of dark matter with nucleons on emerging high-performance architectures. Gupta has over 40 high impact publications in lattice QCD and has been the leader of the LANL lattice effort since 1985. He has pioneered the methods and carried out amongst the first Lattice QCD calculations of relevant form factors. He will be responsible for obtaining computer time at national centers (including LANL). Together with Daniele Alves, he will constrain BSM models based on results for both neutrinos and dark matter scattering.

Steve Elliott (P-23) received his B.S. in physics from the University of New Mexico in 1982 and an M.S. in physics from the University of California (UC), Irvine in 1984. He was awarded his Ph.D. in physics from UC, Irvine in 1987 based on the first observation of two-neutrino double beta decay in ^{82}Se. He was a Post-Doctoral Research Fellow at LANL from 1988 to 1991 and at LLNL from 1991 to 1994. Prior to becoming a Technical Staff Member with the Weak Interactions Team in P-23 in 2002, he was a Research Assistant Professor in the Physics Department at the University of Washington (UW) from 1995 to 2001 and Research Associate Professor at UW from 2001 to 2002, where he served as Project Manager during the Neutral-Current-Detector construction phase for the SNO project. He is a world expert on the subject of double beta decay and was elected Fellow of the American Physical Society in 2004 for his many contributions to the field and a Laboratory Fellow in 2013. He was spokesperson for the Majorana Demonstrator Project for 8 years and presently one of the co-spokespeople for LEGEND. Steve's low energy physics expertise will be crucial to understanding and mitigating low energy backgrounds.

Melissa (Mitzi) Boswell (P-23) received her B.S. in physics from Randolph-Macon Woman's College in 2001 and an M.S. in Physics from the University of North Carolina in 2004. She was awarded here Ph.D. in physics from UNC in 2008 with a study on nuclear structure. She was a postdoc at UNC and North Carolina State University until April 2009, and then at LANL from 2009-2014 working on double beta decay and the MAJORANA project. She became a staff scientist at LANL in 2014. Since joining LANL, she has worked on weapons physics experiments, NIF and LANSCE neutron experiments. She plans to work on CCM detector construction, running, and data analysis.

Charles (Chuck) Taylor (AOT) received his Ph.D. in particle physics from Idaho State University in 2012, then became a P-25 postdoc at LANL from 2013 to 2016. During this time, he was instrumental in the successful design, construction, and operation of the MiniCaptain detector at WNR. In 2016, he transitioned to staff member in AOT. Chuck has extensive experience building and operating particle physics LAr detectors, and is an expert accelerator physicist. He will participate in the design, construction, and running of CCM, as well, his LANSCE/Lujan accelerator expertise will be crucial to understanding the beam and target performance during CCM running.

Charles Kelsey (P-27) has extensive experience performing radiation transport calculations supporting the design and operation of accelerator facilities and their experiments. He been at LANSCE since 2001 and contributed to the design of the UCN facility and many successful experiments and capabilities at the Lujan and WNR facilities, including the East Port irradiation capability and LEU Mo-99 production experiments in the Blue Room. Charles' MCNP simulations of the Lujan spallation target facility will contribute to the understanding of the radiation sources important to this experiment.