Fundamental Neutrino Physics at the Lujan Center

A. A. Aguilar-Arevalo[4], J. Asaadi[8], J. Bacon[1], J. Boissevain[1], M. Boswell[1], J. Conrad[5], R. L. Cooper[3], S. Elliot[1], E. Guardincerri[1], E.C. Huang[1], B. Jones[8], D. Lee[1], W.C. Louis[1], J. Mirabal[1], W. Sondheim[1], R. Tayloe[6], C. Taylor[2], R.T. Thornton[1], J. Spitz[7], R. Van De Water[1*]

[1]*P-25 and P-23, Los Alamos National Laboratory, Los Alamos, NM 87545*
[2]*AOT, Los Alamos National Laboratory, Los Alamos, NM 87545*
[3]*Joint appointment P-25 LANL and New Mexico State University, Las Cruces, NM, 88003*
[4]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, 04510, México*
[5]*Massachusetts Institute of Technology, Cambridge, MA 02139*
[6]*Indianna University, Bloomington, IN 47405*
[7]*University of Michigan, Ann Arbor, MI 48109*
[8]*University of Texas at Arlington, Arlington, TX 76019*

Abstract.
We propose to run the CAPTAIN-Mills neutrino detector at a distance of 20m from the Lujan target, which is a prolific source of neutrinos from stopped pion and muon decay. The 10 ton liquid argon scintillation detector will be built to study low energy neutrino interactions as an effort in support of the overall national neutrino program. There are two immediate goals: 1) test the photon detection system that is being built for the Short Baseline Neutrino (SBN) program at Fermilab; 2) perform the first observation of coherent elastic neutrino-nucleus scattering in liquid argon. If these initial efforts during the fall 2018 run cycle are successful, a longer term program will be proposed to search for sterile neutrinos.

Introduction

The most pressing problem in neutrino physics today is the question of the existence of sterile neutrinos. Data hinting to sterile neutrinos were first obtained by LSND in the 1990's and subsequently by MiniBooNE at FNAL and by reactor and radioactive source experiments [1]. The DOE Office of High Energy Physics convened the P5 panel that recommended that 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]. The smoking gun proof of sterile neutrino oscillations, i.e. an observed L/E signal dependence, remains elusive; however, a new and unique experiment can be mounted at the LANSCE Lujan facility that could finally put the issue to rest. The Lujan facility at LANSCE is a ~80 kW short-pulsed neutron source, but it is also a prolific source of neutrinos from stopped pion and muon decay. By instrumenting a ten-ton Liquid Argon (LAr) cryostat (CAPTAIN-Mills) with an array of large area photomulitier tubes (PMT), a measurement of the neutral current coherent elastic neutrino-nucleus scattering rate at distances of twenty and forty meters from the beam dump would be sensitive to sterile neutrino oscillations at the ~1 eV^2 mass scale. This would provide proof, or would refute, an explanation of the LSND/MiniBooNE signal as due to sterile neutrino oscillations.

In order to pursue this exciting and fundamental physics program, a preliminary run needs to be performed to demonstrate that a PMT based scintillation light detection system can work at LAr cryogenic temperatures, and that it has enough sensitivity to detect low energy coherent elastic neutrino-nucleus scattering events. The current proposal is to instrument the CAPTAIN-Mills 10 ton LAr cryostat detector with 160 PMT's and run at the Lujan-ER2 disassembled flightpath-16 area at a distance of 20 m from the target. It will take four months to assemble and test the detector, and another 2-3 months of detector exposure to beam in order to collect sufficient data to search for coherent elastic neutrino-nucleus scattering.

Physics Measurements

The summer-fall 2018 run will have two main goals:

1) Instrument and test the CAPTAIN-Mills detector with the photon detection system that has been designed and built for the Short Baseline Neutrino Detector (SBND) experiment at FNAL.

2) Detect and measure coherent elastic neutrino-nucleus scattering events in liquid argon. This would represent a "First Observation", and lead to a publication. Such a measurement is essential to proving that a longer run to search for sterile neutrinos is achievable.

Test of the SBND PDS system

The CAPTAIN-Mills cryostat will be instrumented with the Photon Detection System (PDS) that has been built for the SBND experiment at FNAL. Due to SBND construction delays, the PDS system will be available for use at Lujan over the next year. Also, it has been decided by ADEPS management and the LDRD office that a full scale test of the system is desirable, and funds have been made available to perform the test run in FY18. Placing the instrumented detector in a neutrino beam line is ideal, as it fully tests the system performance. The detector, shown in Figure 1, will be instrumented with 160 8" PMT's (Hamamatsu R5912 cryogenic), 10 CAEN VX1730 500 MHz digitizer boards, DAQ, and an LED based calibration system. There will be an optical barrier separating the inner volume from the outer region, which will act as an active veto, instrumented with 24 1" cryogenic PMT's. A few prototype light guide bars designed for next generation LAr TPC neutrino detectors will also be deployed for testing.

The detector will be placed in the Lujan-ER2 disassembled flightpath-16 area at a distance of 20 m from the target. Figure 2 shows a picture of the desired location. Also required is about 3 m of steel and concrete shielding between the target and source to reduce the beam-produced neutrons, which are backgrounds to neutrino detection. Running over a 2-3 month period would allow the complete testing of the SBND PDS system.

Detect Coherent Elastic Neutrino-nucleus Scattering on Argon

The Lujan neutron source is a prolific source of neutrinos from stopped pion and muon decays. Figure 3 shows the neutrino particle production from 800 MeV protons on a tungsten target. The estimated neutrino rate for each flavor (electron ν_e, muon ν_μ, and anti-

muon $\bar{\nu}_\mu$), is approximately 0.0425 neutrinos/proton at 800 MeV [3]. Assuming last year's run condition of 5.62×10^{14} protons/sec delivered to the target, yields a neutrino flux of 4.74×10^5 nu/cm^2/s at 20 m from the target for each species. The resulting neutrino energy spectrum and timing is shown in Figure 4. Details of how this information is used in the event reconstruction will be discussed below.

Figure 1. CAPTAIN-Mills detector instrumented with 160 PMT's (left), and the cryostat in transit (right). The blue shows the inner neutrino target LAr volume and outside active veto region which is also filled with LAr.

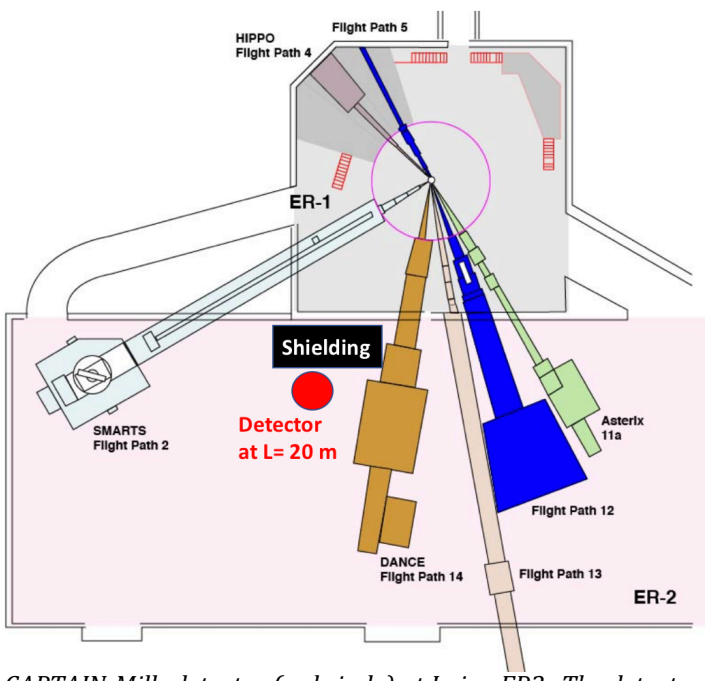


Figure 2. Positon of the CAPTAIN-Mills detector (red circle) at Lujan ER2. The detector will be located 20 m from the target. About 3 m of shielding (black box) will be required to reduce beam-induced neutron backgrounds.

The proton power on the Lujan target is about an order of magnitude less than the SNS facility. However, Lujan makes up for this in two important ways. First, there is abundant space for a large detector and shielding. The SNS is limited to small neutrino detectors, less than a ton in size, versus a 10 ton detector that can be deployed at Lujan. Second, the figure

of merit that is most relevant in neutrino beam experiments is the instantaneous power, which provides the best signal to background ratio. Due to the shorter beam time interval of the Lujan facility (290 nsec triangular pulse, or 145 nsec FWHM), it turns out that the SNS and Lujan have similar instantaneous power delivered to the targets,

P_I(SNS)= 1200 kW/(695 nsec x 60 Hz)= 0.029 kJ/nsec
P_I(Lujan)= 80 kW/(145 nsec x 20 Hz)= 0.028 kJ/nsec

This remarkable fact, coupled with a large LAr detector, makes Lujan extremely competitive with other facilities for neutrino physics measurements.

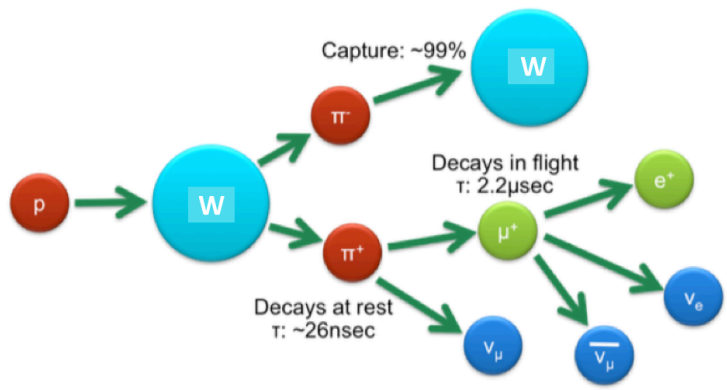


Figure 3. Neutrino production from 800 MeV proton interactions on tungsten target. Every proton interaction results in 0.0425 neutrinos of each species [3].

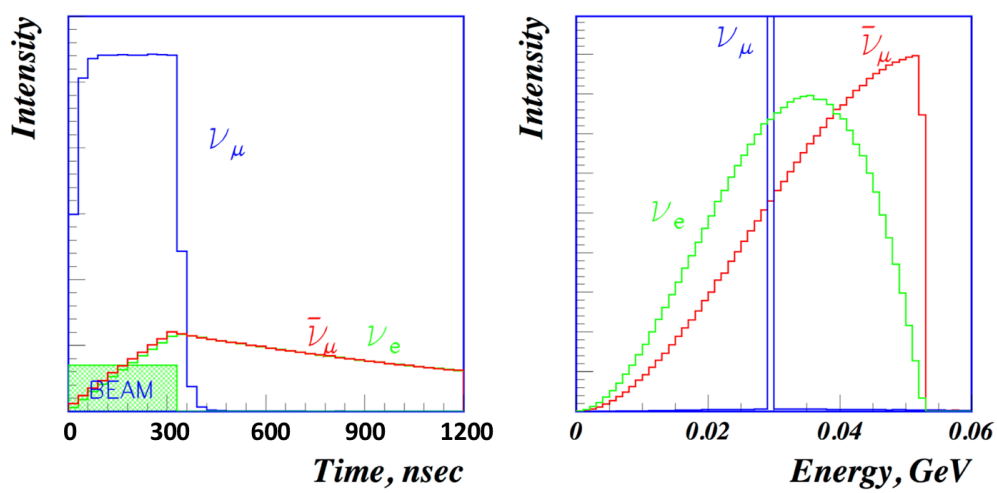
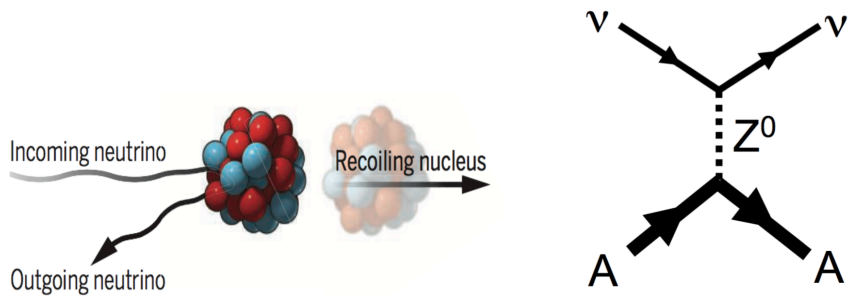


Figure 4. Kinematics of neutrinos from stopped pion and muon decays. The left plot shows timing relative to the beam, and the right plot shows the energy spectrum for each neutrino species. (Note, the timing does not show the true triangular beam pulse shape, but rectangular for display purposes).

The neutrino interactions to be measured in CAPTAIN-Mills are low energy coherent elastic neutrino-nucleus scattering in LAr. This type of neutrino interaction, long theorized, has recently been observed at the SNS (with LANL participation) on a CsI target [4]. Measurements on different types of targets, such as argon, is important as it demonstrates the technique is robust and tests the expected N^2 scattering dependence on the number of neutrons. A benefit of this interaction for neutrino property measurements is that it has a cross section two orders of magnitude higher than other neutrino interactions, such as charged current quasi-elastic scattering, and can be calculated from first principles (see Figure 5).



$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Figure 5. Coherent elastic neutrino-nucleus scattering off a heavy target such as argon. The theoretical cross section is well known with a N^2 dependence, where N is the number of neutrons. There is a small uncertainty of a few percent on the $F^2(Q^2)$ form factor dependence.

The key challenge for the experiment will be to successfully measure low energy (~25-150 keV) coherent elastic neutrino-nucleus scattering interactions. For LAr, the estimated coherent interaction rate for CAPTAIN-Mills at 20 m from the Lujan source is ~1000 events per month at a typical 80 kW beam power. The following key facts make detection possible: 1) The neutrinos are produced in time with the beam; 2) 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.

Using in-beam timing cuts, the signal can be discriminated against random backgrounds such as ^{39}Ar radioactivity and cosmic rays. For Lujan, the proton on-target beam time structure is 290 nsec wide (triangular) at 20 Hz. The neutrinos from pion (muon) decay have an additional 26 nsec (2.2 μsec) time constant. With a beam time cut of two muon decay time constants (~4 μsec), the duty factor is 4×10^{-5}, which reduces ^{39}Ar radioactive and cosmogenic backgrounds to manageable levels.

Another source of background is neutrons from the beam. An in-situ neutron measurement during nominal beam conditions was performed at the expected 20 m position of CAPTAIN-Mills. It is estimated that to reduce beam neutrons to acceptable levels of less than 10^{-5} events/spill will require at least three meters of steel and concrete

shielding. Simulations are ongoing to determine the best shielding configuration (ratio of steel and concrete) and position.

Detailed simulations have demonstrated that a 25 keV detector threshold can be achieved with 160 8" PMT's and reflector foils mounted throughout the detector. The PMT's and reflector foils are coated with tetraphenyl butadiene (TPB) wavelength shifter that converts the 128 nm LAr scintillation light into PMT sensitive visible wavelengths. Many components of the PDS system have been checked and tested, but not the complete system; this will be done with CAPTAIN-Mills.

Requirements and Schedule

Construction and preparation of the detector needs to take place in Lujan at the designated site for running the experiment. This will include installation of the PMT's, electronics, and LAr plumbing and fill line. Care will have to be taken with the PMT's during installation, as they are coated with light sensitive TPB, which degrades over time when exposed to normal lighting. The detector lid will be placed on a stand, and a tent will be hung from under the support structure to reduce lighting to minimal levels. The plumbing requirements for the LAr are minimal and include proper venting and a fill line from the outside to the detector that needs to be built. Power requirements are also minimal, with only about 20 - 30 A at 120 V needed for electronics, DAQ, calibrations, and monitoring. Finally, at least 3 m of shielding (mix of steel/concrete to be determined by ongoing simulations) needs to be deployed at the ER2 wall (or inside ER1) as shown in Figure 2.

Specific Requests

1. Occupy the space in figure 2 from early April until the end of November 2018
2. Run LAr lines (possibly penetrations needed through walls) during May.
3. Deployment of shielding as early as possible at the location shown in Figure 2.
4. Normal beam during September, October November.

Detector construction needs to begin in early April and continue through to the end of July. The LAr fill and commissioning takes place in August. If all systems are operating normally, then beam production running can take place in September through November, which will provide enough time to test the PDS system and collect enough coherent elastic neutrino-nucleus scattering events.

Results

With 2-3 months of good beam conditions and detector running, about 3000 coherent elastic neutrino-nucleus scattering events will be collected. These statistics are sufficient to determine whether such interactions can be observed. If successful, this measurement would lead to a publication on the first evidence of coherent elastic neutrino-nucleus scattering on argon.

If the experiment is a success, then this will be a stepping stone to the next phase, which is a longer 2-3 year run at various positions to measure L/E variations and to test for sterile neutrino oscillations at the LSND ~1 eV^2 mass scale.

References:

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