LANSCE-PSR Short-Pulse Upgrade for Improved Dark Matter and Sterile Neutrino Searches

Contacts

S.G. Biedron (University of New Mexico) [biedron@unm.edu],
R.G. Van de Water (Los Alamos National Laboratory) [vdwater@lanl.gov]

Authors and Proponents

Coherent CAPTAIN Mills Collaboration,
LANL Accelerator Operations and Technology: E. Huang, A.J. Hurd, J.W. Lewellen, S.V. Milton, N.A. Moody, C.E. Taylor

August, 2020

Abstract

Proton beam dumps are prolific sources of charged and neutral pions enabling a powerful technique to search for dark matter, sterile neutrino oscillations, and precision measurements of coherent nucleus scattering neutrinos (CEvNS). The Lujan neutron scattering center at the Los Alamos Neutron Science Center (LANSCE) consists of a 800-MeV, short-pulse, 100-kW proton source and spallation neutron source where such searches are ongoing with the Coherent CAPTAIN Mills (CCM) 10-ton, liquid argon detector. The employment of fast timing coincidence of the beam with the detector is used to identify signals and reject background. The current beam spill time width is 300 ns with intensity of 2.9×10^{13} protons per pulse at 20 Hz. With upgrades to the Proton Storage Ring (PSR), the beam spill width may be compressed to 30 ns with minimal intensity loss enabling an increase in the signal to background (S/B) of more than 100 and resulting sensitivity increase of an order of magnitude for dark matter and sterile neutrino searches. This can be achieved with PSR accelerator upgrades on the time scale of a few years and at modest cost.

1 Physics Motivation and Setup

Our search is motivated by recent theoretical work that has shown that sub-GeV dark matter candidates can interact with ordinary matter through new light mediator particles [1][2][3]. Concurrent with this, the MiniBooNE experiment running at the FNAL Booster Neutrino Beamline (BNB) carried out a special beam dump run which suppressed neutrino-produced backgrounds while enhancing the search for sub-GeV dark matter via neutral current scattering, resulting in new significant sub-GeV dark matter limits [4]. This result clearly demonstrated the unique and powerful ability to search for dark matter with a beam dump neutrino experiment, especially with stopped pion sources [5]. As well, CEvNS events were recently observed [6][7], and measuring the absolute rate can provide a test of Non-Standard Model Interactions (NSI) [8]. Finally, measuring the prompt muon neutrino CEvNS rate as a function of distance can test sterile neutrino interpretation models of the LSND and MiniBooNE anomalies.

The Lujan spallation tungsten target is fed by 800-MeV protons from the Proton Storage Ring (PSR), providing a high-average power ($\sim$100 kW), 20-Hz, short-pulse (< 300 nsec) source of moderated neutrons, neutrinos, and other beam-related exotic particles, such as dark matter, axions, etc. For a detector placed 20 m from the proton target, neutrons are the main beam related background. In addition, steady state random backgrounds from Ar39 ($\sim$ few kHz) decay and external gamma-rays ($\sim$ few kHz) from long lived activation are present. In both cases, a shortened beam pulse can reduce these backgrounds significantly while not impacting the moderated neutron flux for material diffraction experiments elsewhere in the facility.

The Coherent CAPTAIN-Mills (CCM) detector is a 10-ton, liquid argon (LAr) fast detector instrumented with 120 photomultiplier tubes and 500 MHz readout electronics. In 2019 it was built and ran for four months at Lujan center [9]. Initial measurements demonstrated that the detector can achieve $\sim$1 ns timing resolution, $\sim$20 cm spatial resolution, and an energy threshold of 50 keV (nuclear recoil). Analysis has identified that (LAr) purification is required to achieve 10-20 keV thresholds and will be included for the 2021 beam run.

Mono-energetic muon neutrinos come from charged pion decay at rest with a decay time of 26 ns. This results in prompt muon neutrinos being emitted mostly in time with the beam. As well, dark matter particles that result from π^0 decay (8.4×10^{-17} s) are in time with the fast pulsed beam and can scatter off argon nuclei. These particles are more energetic than muon neutrinos from charged pion decay at rest and can be separated out with a 50-keV energy cut. These unique and powerful timing features of the Lujan beam enable a fairly pure sample of muon neutrinos and dark matter candidates to be isolated in a background clean region. Figure 1 shows the anticipated timing features of the beam and various sources of signals and backgrounds. During normal operations the PSR at LANSCE delivers to the spallation target a proton pulse with a triangular pulse shape that is 300-ns full base width. Detailed timing measurements have determined that moderated neutrons arrive through the extensive bulk shielding at the CCM detector about ∼125 ns after the arrival of the neutrino beam, as shown in Figure 1. This corresponds to beam neutrons with energies of approximately ∼50 MeV or less. This overlap means that CCM can only measure less than 50% of the generated neutrino signal before the wave of beam neutrons arrives.

To achieve the ultimate efficiency, all predicted dark matter particles and prompt neutrinos must arrive before the neutrons. If the proton beam pulse width can be shortened to less than 100 ns, then about a factor of two improvement can be achieved in efficiency. Further, shorter pulses also reduce the steady-state random backgrounds by one third (100/300), which delivers a combined signal-to-background (S/B) improvement of six times greater for the same charge on target. If the proton beam could be reduced to 30 ns while still maintaining the same charge per pulse, then a S/B of $\sim 2/(30/300)$, or 20 can be achieved. In addition, we can begin to perform robust PID to suppress the Ar39 background using the singlet to triplet light separation technique, achieving up to a another factor of ten or more separation, resulting in a combined S/B of greater than 100.

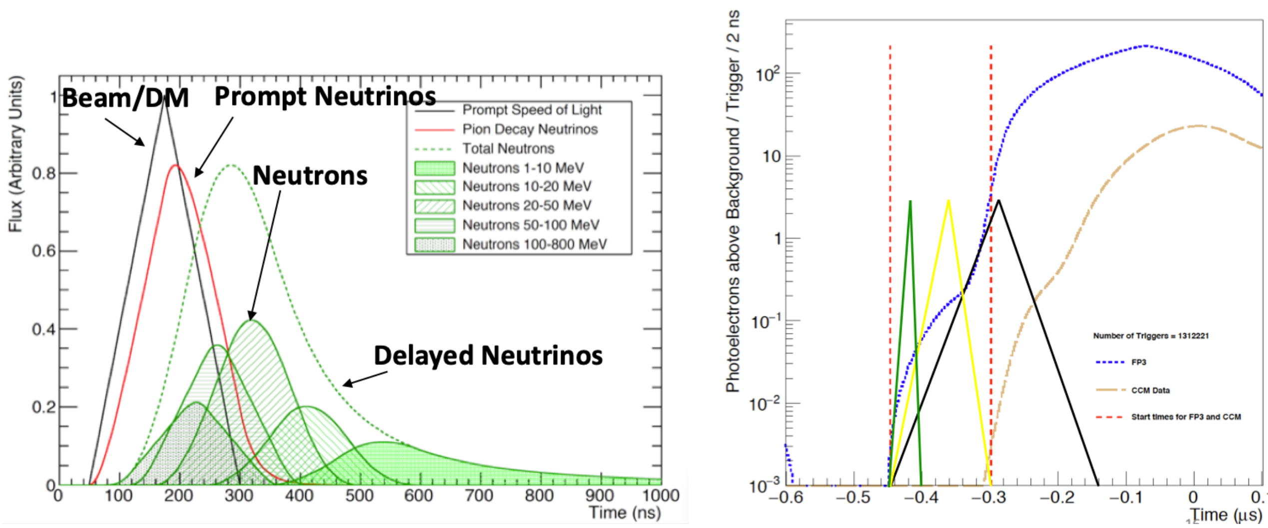

Figure 1: Left is the expected timing distribution relative to the beam for various signals and backgrounds for a detector 20 m from a stopped pion source. Right is the measured beam timing of the gamma-flash (FP3) relative to the CCM data from the Lujan source. This demonstrates that there exists an ∼126 ns window where neutrinos and dark matter events reside free of sub-luminal neutrons. The black triangle is the presumed 300-ns beam current profile, yellow 100 ns, and green 30 ns, demonstrating the increased signal efficiency with shorter beam pulses. Steady state random backgrounds are also reduced accordingly with smaller beam width.

2 LANSCE-PSR Short-Pulse Upgrades

While shorter proton pulses in the PSR are desirable in neutron resonance experiments and would have a profound effect in the CCM detector, achieving sub-100 ns pulse lengths with full beam intensity is hardly straightforward. Here we outline a few pathways for experimental tests to help define the requirements for PSR machine improvements. In this effort, we are leveraging many theoretical and experimental studies that explored the facets of reaching better timing, higher currents, higher peak currents, and shorter pulses in the PSR [10][11]. Instabilities play into the limitations when operating in short-pulse mode. For instance, the PSR can suffer from an electron cloud (e-p) instability [12] and initial experiments have been performed for active damping of the instability through the implementation of an analog vertical feedback system [13][14] and through the implementation of heated ferrites. When attempting to reach short pulse mode, the ferrites actually induce a longitudinal microwave instability. There is, therefore, a balance between the mitigation of the transverse and longitudinal instabilities particularly in the quest to achieve short pulses. We believe the following will be required to achieve significantly shorter bunch lengths. An active transverse feedback system in both the vertical and horizontal plane to control the (e-p) instability must be considered. This would be supplemented by the use of novel magnetic materials that would replace the existing ferrites. These new materials will have properties that do not inadvertently induce a longitudinal (microwave) instability [15]. A longitudinal feedback system might be necessary should the threshold of the microwave instability occur at the higher peak currents we are aiming for. In addition to the above, the use of a 2nd harmonic RF cavity might also prove advantageous to achieve the shortest bunch lengths. Such a cavity could be tuned to cancel the 4th order term in the $\cos(\theta)$ expansion of the RF field, creating a broader region in longitudinal phase space where the synchrotron period as a function of amplitude is held constant. This would mitigate nonlinear rotation that creates longitudinal tails.

3 Timescales, Budget, and R&D needs

It is expected that once designed, the PSR upgrades to achieve 30-ns timing could be implemented in 2-3 years and for under $5M. The risks are anticipated to be medium and, if successful, would have significant impact on the physics capability of the CCM experiment to search for dark matter, CEvNS, and sterile neutrinos.

References

[1] "Dark Sectors 2016 Workshop: Community Report", arXiv:1608.08632", 2016

[2] Battaglieri *et al.*, "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report", arXiv:1707.04591", FERMILAB-CONF-17-282-AE-PPD-T", 2017.

[3] "Basic Research Needs For Dark Matter Small Projects New Initiatives", https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf, 2018

[4] A. A. Aguilar-Arevalo *et al.* [MiniBooNE DM Collaboration], "Dark Matter Search in Nucleon, Pion, and Electron Channels from a Proton Beam Dump with MiniBooNE," Phys. Rev. D **98**, no. 11, 112004 (2018) [arXiv:1807.06137 [hep-ex]].

[5] P. deNiverville, M. Pospelov and A. Ritz, Phys. Rev. D **92**, no.9, 095005 (2015) doi:10.1103/PhysRevD.92.095005 [arXiv:1505.07805 [hep-ph]].

[6] D. Akimov *et al.* [COHERENT], Science **357**, no.6356, 1123-1126 (2017) doi:10.1126/science.aao0990 [arXiv:1708.01294 [nucl-ex]].

[7] J. Zettlemoyer, doi:10.5967/3wza-6w73

[8] D. K. Papoulias, T. S. Kosmas and Y. Kuno, Front. in Phys. **7**, 191 (2019) doi:10.3389/fphy.2019.00191 [arXiv:1911.00916 [hep-ph]].

[9] R.G. Van de Water, "Searching for Sterile Neutrinos and Dark Matter with the Coherent CAPTAIN-Mills Experiment", http://meetings.aps.org/Meeting/APR19/Session/Z14.9, APS 2019

[10] Lawrence Rybarcyk, Rodney McCrady and Thomas Spickermann, LANSCE-ABS, "A Test of Short-Bunch Stacking in the PSR," PSR TechNote 06-001, Los Alamos National Laboratory.

[11] Andrew J. Jason, "Short-bunch stacking mode for the PSR – an overview," LA-UR-12-20465, Los Alamos National Laboratory.

[12] M. A. Plum et al., ”Recent experimental evidence for the Los Alamos Proton Storage Ring beam instability,” Proceedings of the 1997 Particle Accelerator Conference (Cat. No.97CH36167), Vancouver, BC, Canada, 1997, pp. 1611-1613 vol.2, doi: 10.1109/PAC.1997.750775.

[13] R. J. Macek, S. Assadi, J. M. Byrd, C. E. Deibele, S. D. Henderson, S. Y. Lee, R. C. McCrady, M. F. T. Pivi, M. A. Plum, S. B. Walbridge, and T. J. Zaugg, “Active damping of the e-p instability at the Los Alamos Proton Storage Ring,” Cite as: J. Appl. Phys. 102, 124904 (2007); https://doi.org/10.1063/1.2825624.

[14] R. J. Macek, R. McCrady, T. Zaugg, S. B. Walbridge, (LANL); C. Deibele, S. Henderson, M. A. Plum, S. Assadi, (SNS); J. Byrd (LBNL); S. Y. Lee (Indiana University); M. F. T. Pivi (SLAC), “Experimental Test of a Prototype System for Active Damping of the e-p Instability at the LANL PSR,” PSR TechNote 06-005, LANSCE-ABS:06-017.

[15] C. Taylor et al, “Study for Alternative Cavity wall and Inductive Insert Material,” Los Alamos National Laboratory LDRD 2021.