Snowmass2021 - Letter of Interest

Directional detectors for CEνNS and physics beyond the Standard Model

NF Topical Groups: (check all that apply □/■)

□ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (NF8) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (Other) Cosmic Frontier 01: Dark Matter: Particle Like
□ (Other) Cosmic Frontier 07: Cosmic Probes of Fundamental Physics
■ (Other) Theory Frontier 09: Astro-particle physics and cosmology
■ (Other) Theory Frontier 11: Theory of Neutrino Physics

Contact Information:
Daniel Snowden-Ifft (Occidental College) [ifft@oxy.edu]

Authors: D. Aristizabal Sierra, Connor Awe, Phil S. Barbeau, James Battat, Valentina De Romeri, Bhaskar Dutta, John Harton, Samuel Hedges, Dinesh Loomba, Pedro Machado, Diane M. Markoff, Kate Scholberg, Neil Spooner, Louis Strigari, Sven Vahsen, Michael Wood

Abstract: We discuss the prospects for using detectors with directional sensitivity to study Coherent Elastic Neutrino-Nucleus Scattering (CEνNS). Even relatively small detectors would be able to make a significant detection of CEνNS on a year time scale at either NuMI or DUNE. In addition to sensitivity to CEνNS, this technology will be uniquely sensitive to beyond the Standard Model (BSM) physics in the form of low-mass dark matter, heavy sterile neutrinos, and axion-like particles.

Experimental design:

The goal of the Directional Recoil Identification From Tracks (DRIFT) collaboration was the detection of a directional signal from Weakly Interacting Massive Particle (WIMP), halo, dark matter[1]. In order to accomplish this goal a unique, low-pressure, Negative Ion Time Projection Chamber (NITPC) technology was developed. The negative-ion drift allowed DRIFT NITPCs to have the lowest energy threshold and best inherent directional sensitivity of any limit-setting, directional dark matter detector. In addition, all of DRIFT's recent limits have been background-free. As a consequence, DRIFT's sensitivity to dark matter is almost 1,000 times better than other directional WIMP detectors[2].

With its unique directional and background rejection capabilities, the DRIFT NITPC technology is ideally suited to search for nuclear recoils in beam dump experiments. Several of us worked on a proposal to search for light dark matter recoils behind an electron beam-dump at JLab. Preliminary work, including a test run at SLAC, suggests that a Beam Dump experiment using a DRIFT detector, BDX-DRIFT, would have sensitivity rivaling the best limits on light dark matter and provide an unequivocal directional signature in the event of discovery[3]. Placing a BDX-DRIFT detector behind a proton beam dump, such as in the DUNE Near Detector Complex, is perhaps even more interesting and is the subject of this LOI.

The Near Detector Complex is $\sim$ 100 m underground. The beam timing structure at the NuMI beam is such that backgrounds are expected to be reduced to negligible levels. Proton beam-dumps produce a plethora of neutrinos, particularly the LBNF-Dune beam, which is optimized for neutrino production. Thus, in addition to traditional beam-dump searches for light dark matter we can also search for beyond the standard model (BSM) neutrino interactions. We estimate that a 1 m^3 νBDX-DRIFT detector run for one year in the DUNE Near Detector Complex would detect several coherent neutrino-nucleus elastic scatters, potentially confirming recent Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) detection results, but with minimal background[4]. Off-axis and directional sensitivity will provide νBDX-DRIFT signatures to search for physics even in the presence of a neutrino background and opening up a new window to search for BSM physics.

In the near term a 1 m^3 νBDX-DRIFT detector is available to be deployed in the NuMI beam at Fermilab on a year or two timescale. Knowledge gained from those runs will inform proposed a proposed experiment in DUNE in the future.

Search for Physics Beyond the Standard Model: This new detector technology provides a great opportunity to search for BSM physics, e.g., neutrino interactions involving heavy and light mediators, dark matter (DM) up-scattered heavy neutrinos/inelastic DM states, axion-like particles (ALPs), etc. Recently it has been realized that these beam dumps are not only great sources of neutrinos but they also provide a high intensity of photons from radiating protons, Bremstrahlung due to electrons passing nuclei, meson decays etc. These photons can convert into ALPs, light dark gauge bosons and dark scalars, which can provide new sources of neutrinos, dark matter,low-energy excess of MiniBooNE data etc. The directional detectors would not only help to establish these new scenarios, over the standard model background, but would also provide a mechanism to distinguish various new physics ideas.

New directions in neutrino physics: We now highlight the possibilities for the directional detector technology described above in the field of neutrino physics. The characteristic energy of neutrinos in the NuMi beam is a few GeV, with a low-energy tail that extends down to $\lesssim$ 100 MeV. This wide range of energies enables unique sensitivity to neutrinos at these energies.

The CEνNS process, which occures for neutrinos $\lesssim$ 100 MeV was recently detected for the first time by the COHERENT collaboration. In 2017, the COHERENT collaboration announced the detection of CEνNS using a stopped-pion source with a CsI[Na] scintillating crystal detector, followed by the detection of CEνNS with a single-phase liquid argon target[4]. The detection of CEνNS has motivated a flurry of theoretical activity in high-energy physics, inspiring new constraints on BSM physics. The CEνNS process has important implications for high-energy physics, astrophysics, nuclear physics, safeguards applications and beyond.

The experiment proposed here would be the first CEνNS experiment to detect the direction of the nuclear recoil. CEνNS events would be primarily induced by neutrinos in the low energy tail of the beam distribution due to the loss of coherence at higher recoil energies (form factor). Several to tens of CEνNS events per year may be detected for reasonable detector materials, after accounting for the effects of the nuclear form factor.

Detecting the direction of the nuclear recoil in CEνNS is crucial because it provides information that cannot be extracted from the energy spectrum alone. In particular, directional detectors can provide valuable additional information in searches for new physics. For example, if there exists new light, $\sim$ GeV scale mediators that contribute to the CEνNS process, distinct and prominent spectral features are expected in both the angular and the recoil energy spectrum[5]. In the angular distribution, these features may be identified even for nuclear recoil thresholds as high as 50 keV. Combined with energy and timing information, directional information can play an important role in extracting new physics from CEνNS experiments. Further, the scenarios where the neutrinos are sourced from dark gauge light bosons/scalars (i.e., not from pion/muons) emerging from the photon conversions, can also be distinguished from the SM background from the angular and recoil energy spectra.

Low-mass dark matter: Recently, several neutrino experiments have performed searches for light, sub-GeV dark matter produced in Bremsstrahlung processes at beam dumps. The putative experimental signature is a nuclear recoil[6;7]. The primary concern of such an interesting laboratory produced dark matter appearance search is the neutrino background. However, some of the neutrino experiments e.g., COHERENT, CCM, JSNS^2 etc. utilize timing and energy spectra, which isolate the SM background because the source of the SM neutrinos are from the prompt decays of π^+ and delayed decays of μ^+. For various types of Dark Matter interactions with scalars/gauge boson mediators, even in the absence of timing measurements, a dark matter signal can be distinguished from the Standard Model background by measuring the recoil spectra and angular distribution with a directional sensitive detector.

Up-scattered heavy neutrinos and dark matter: The neutrino (or dark matter) nucleus scattering can produce both heavier sterile neutrinos, or heavier states in the inelastic dark matter scenario. These heavy particles may decay within or outside the detector. If they decay occurs within the detector, the angular and recoil energy spectra would be able to distinguish this scenario from the Standard Model background. However if the heavier state decays into electrons or photons within the detector which can explain the low energy excess in the MiniBooNE data (e.g.,[8–10]), then the angular and energy spectra of the electrons or photons would provide important information about this scenario.

Axion like particles: Due to their ability to address the strong CP problem[11–13] and to serve as a dark-matter candidate (e.g., Refs.[14–16]), axions are a well-motivated and extensively explored extension of the Standard Model. Theoretical studies (e.g., Ref.[17]) not only investigate the original QCD axion but also have been extended to incorporate general ALPs in a wide range of models. Recently it has been realized that photons produced in beam dumps at neutrino experiments may be able to create ALPs via the Primakoff (and/or Compton-like) processes. The ALPs would then travel to the neutrino detectors and could be detected after they decay, or via their scattering induced by the inverse Primakoff or Compton-like processes[18]. The ALP can produce two photons or electrons when it decays in the detector, which provides the best constraint of the ALP parameter space. The angular and energy spectra of the electrons and photons, as in the up-scattered case, would be very important to distinguish this signal from the background.

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Additional Authors: