Snowmass2021 - Letter of Interest:
Noble Liquids for the Detection of CEνNS from Artificial Neutrino Sources

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Coherent elastic neutrino-nucleus scattering (CEνNS) provides a new window to probe neutrino physics with compact and low energy threshold detectors. Noble liquid detectors, especially liquid xenon (LXe) and liquid argon (LAr) detectors developed for direct dark matter searches, have excellent capabilities to detect low energy nuclear recoils produced with CEνNS. Using artificial neutrino sources, large numbers of low energy CEνNS events can be detected with 100-kg scale noble liquid detectors, providing a unique opportunity to study non-standard neutrino interactions, sterile neutrinos and other physics beyond the Standard Model. CEνNS from astrophysical neutrinos will become an unavoidable background in the next generation dark matter experiments. Understanding the response of CEνNS events in noble liquids with large statistics from artificial neutrino sources will enable accurate signal and background modeling for the next generation of dark matter experiments. Further, such compact neutrino detectors can measure the anti-neutrinos produced in the nuclear fuel cycle for nuclear safeguards applications.

Neutrino Frontier Topical Groups:

■ (NF02) Sterile neutrinos
■ (NF03) Beyond the Standard Model
■ (NF05) Neutrino properties
■ (NF07) Applications
■ (NF09) Artificial neutrino sources
■ (NF10) Neutrino detectors

Instrumentation Frontier Topical Group:

■ (IF8) Noble Elements

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I. THE NEED OF CEνNS DETECTION IN NOBLE LIQUIDS

Coherent elastic neutrino-nucleus scattering (CEνNS) is a Standard Model process mediated by neutral weak currents [1], with a cross-section approximately proportional to N^2, the square of the number of neutrons in the nucleus. A precise measurement of the CEνNS cross section can probe the non-standard neutrino interactions (NSI) [2–4] and search for sub-GeV accelerator produced dark matter [5]. CEνNS from solar and atmospheric neutrinos [6] will become an unavoidable background for the upcoming and next generation dark matter direct detection experiments. The process also has one of the largest cross sections relevant for supernova dynamics and plays an important role in supernova core-collapse processes [7, 8].

Despite the large cross section, detecting low energy (sub-keV to tens of keV) nuclear recoils (NR) from CEνNS remains challenging. As of writing, the detection of a CEνNS event has only been achieved by the COHERENT experiment above several keV with a CsI detector [9] and a single-phase liquid argon (LAr) detector [10], using a pulsed source of neutrinos from the Spallation Neutron Source (SNS). The program studies a suite of detectors of various targets, either in operation or planned [11, 12]. Despite their strong capability to detect low energy nuclear recoils, dual-phase xenon and argon detectors have not been used for studying CEνNS at SNS.

Since CEνNS has no neutrino energy threshold and a larger cross section than inverse beta decay (IBD) at fission anti-neutrino energies, it may provide new capabilities in anti-neutrino monitoring for nuclear safeguarding purposes, such as detecting anti-neutrinos produced by nuclear reactors [13–15] and spent fuel [16]. Uniquely, CEνNS could detect breeding blankets in nuclear reactors, where the anti-neutrino spectrum is below the IBD threshold [17]. Unlike the SNS, in reactor monitoring applications the signal source is not controlled in time and the fission antineutrino spectrum largely lies below 10 MeV. Consequently, the recoil energies of interest are low ($\sim 0.1 - 5$ keV). The development of a sub-keV threshold detector with suppressed background is needed to face this challenge.

In dark matter direct detection experiments, understanding the response of solar and atmospheric neutrinos CEνNS in noble liquids is important to the background modeling of the upcoming multi-ton scale liquid xenon(LXe)-based PandaX-4T [18], XENONnT [19], LZ [20] and LAr-based DarkSide-20k [21] experiments. These large experiments, with high electron recoil background rejection capability above a few keV nuclear recoil threshold, are expected to observe tens of CEνNS events from ^{8}B solar neutrinos with $\sim$10-20 ton-years of exposure through analysis of paired scintillation and ionization signals. Sensitivity to light dark matter grows dramatically as the nuclear recoil threshold is lowered, and there is a growing interest in decreasing the threshold below 1 keV by separately analyzing only the ionization signals [22, 23]. Understanding the response of LXe and LAr to CEνNS from a few keV down to sub-keV recoil energies is crucial to this approach to light dark matter detection.

This is a letter of intent to further develop the noble liquid detector technology to enhance its sensitivity to sub-keV nuclear recoils, build and deploy 100-kg scale compact dual-phase noble element detectors at the SNS or near reactors for neutrino physics and practical applications.

II. SIGNAL RATES FROM TWO ARTIFICIAL NEUTRINO SOURCES

The events from CEνNS are low energy nuclear recoils, with energy depending on the energy of the neutrinos and the mass of the target atoms. The expected CEνNS event rate in a liquid xenon detector $\sim$20 m from source of neutrinos at the SNS is shown in Fig.1 (left), calculated following the procedure in [12]. The energy of the nuclear recoils extends to a few tens of keV, allowing a liquid xenon detector to distinguish and suppress the electron recoil background for a sensitive detection of CEνNS. More than 1000 CEνNS events will be observed in six months of operation of a 100-kg liquid xenon detector above a threshold of 5 keV.

Reactor anti-neutrinos produce CEνNS signals with even lower energies than SNS neutrinos. The expected CEνNS rates in noble element targets from reactor anti-neutrinos are shown in Fig. 1 (right), based on the reactor anti-neutrino spectrum in [24] with an anti-neutrino flux of 6×10^{12} cm^{-2}s^{-1}[13] at a distance of 25-m from the core of a 3 GW thermal power reactor. The lighter noble elements provide relatively higher energy nuclear recoils from reactor CEνNS. Regarding the detector technology, liquid xenon detectors have demonstrated sensitivities in the sub-keV region, down to a single ionization electron, corresponding to a nuclear recoil energy threshold of 300 eV [25, 26]. Liquid argon detectors also have sensitivities to single electrons [23], but the signal response in the sub-keV energy region [27, 28] remains to be studied. Liquid neon [29–31] and helium detectors [32–34] are much less developed. Krypton is not a feasible target due to its large intrinsic ^{85}Kr background. With sub-keV nuclear recoil thresholds, noble liquid detectors, especially liquid argon and liquid xenon, can observe $\sim$1000 CEνNS events per day in a 100-kg target.

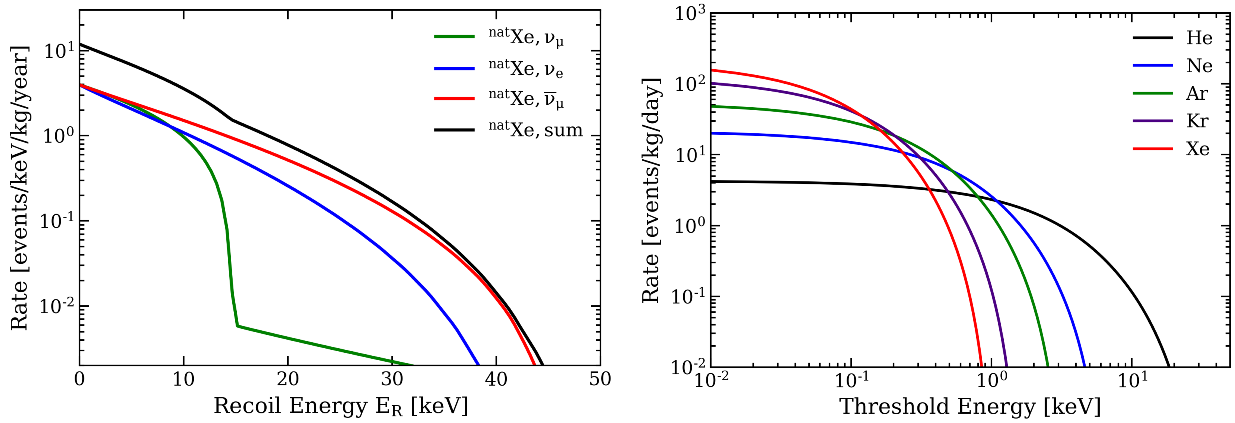

FIG. 1. Left: Expected nuclear recoil spectrum and event rate in natural xenon from each of the neutrino flavors (ν_μ, ν_e and $\bar{\nu}_\mu$) for a detector at $\sim$20 m from the source of neutrinos at the Spallation Neutron Source. Right: Integrated CEνNS rates above a threshold energy in different noble elements from reactor anti-neutrinos with a flux of 6×10^{12}cm^{-2}s^{-1} and assuming a composition of 7.6% ^{238}U, 25% ^{235}U, 14.8% ^{241}Pu, 51% ^{239}Pu fissioning elements.

III. DETECTOR TECHNOLOGY DEVELOPMENT

Thanks to the rapid development of detector technology for dark matter search, liquid xenon and argon detectors of 10 kg [35–37], 100-kg [38–41] and ton scale [42–44] were built and successfully deployed in the last two decades. These noble liquid time projection chambers (TPCs) typically target the detection of nuclear recoils above a few keV. Interactions at lower energies such as those expected from reactor neutrino CEνNS and light dark matter particles have been sought by analyzing only the ionization signal but to date the sensitivity is limited by backgrounds in the few-electron region [22, 23, 45, 46]. In xenon TPCs, the origins of the low-energy electron background have been thoroughly studied [47] and the RED-100 detector [48, 49] has achieved a low background rate down to 4 ionization electrons while operating at the Earth's surface. The electron backgrounds in argon TPCs [23] are believed to have similar origins to that in xenon TPCs, so a strong synergy may be found in developing the background mitigation techniques for TPCs with these two targets.

Improvements of the signal detection efficiency and suppression of the single-to-few electron backgrounds are needed to enhance the capability to sense sub-keV nuclear recoils in these detectors. Some key technical developments include: 1) Improving the scintillation light detection with in-target wavelength shifting, such as xenon-doping in argon [50–55] or neon [56] and using high quantum efficiency photo-sensors to enhance the event rate and electron recoil background rejection. 2) Improving the liquid purity by using hermetically sealed time projection chambers [57, 58] employing large UV-transparent windows, low-outgassing materials, and modular photo-sensors with integrated electronics. 3) Identifying the chemical composition of impurities in the liquid target using luminescence spectroscopy, and developing purification techniques using chemical and physical absorption in the liquid phase. 4) Optimizing single-electron detection by electroluminescence in the gas or liquid [59] phases with a simplified detector design. 5) Developing a modular design that permits independent assembly and cleaning of detector components, including an integrated high voltage system, in a clean room environment to prevent the introduction of deleterious particles.

The detector techniques developed for this research are applicable to light dark matter search [60] and generation-3 (G3) noble liquid experiments for sensing dark matter and astrophysical neutrinos [61].

IV. SUMMARY

In this letter, we present the case of compact (100-kg scale) noble liquid detectors for CEνNS detection of neutrinos from either a spallation neutron source or a nuclear reactor. Successful deployment of such low-background, sub-keV threshold detectors will allow the detection of CEνNS in Ar or Xe targets, probing non-standard neutrino interactions [62], neutrino magnetic moments [63], sterile neutrinos [64, 65] and other physics beyond the Standard Model [66]. It will also provide input for a precise signal and background modeling for LAr and LXe based dark matter experiments and a new way to monitor the nuclear fuel cycle using neutrinos for nuclear safeguarding applications.

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